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MURRAY FUTURES
Lower Lakes & Coorong Recovery

Determining the Environmental Water Requirements for the Coorong, Lower Lakes and Murray Mouth Region

Methods and Findings to date

July 2011

WATER FOR GOOD

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Foreword

The Coorong and Lakes Alexandrina and Albert wetland is one of Australia's most important wetland areas.

Designated as a Wetland of International Importance under the Ramsar Convention in 1985, the 142 500 ha site is a complex array of many bioregions and environments including permanent and seasonal freshwater lakes and marshes, streams, estuarine waters, coastal lagoons, intertidal mudflats and forested wetlands.

These provide habitat for more than 1000 species including many listed under the EPBC Act such as the southern emu wren (*Stipiturus malachurus*), migratory wader birds protected under international agreements, the orange-bellied parrot (*Neophema chrysogaster*), the southern bell frog (*Litoria raniformis*), and several threatened native fish species.

In addition to the conservation and environmental significance, the culture and wellbeing of the region's Traditional Owners, the Ngarrindjeri, are directly linked to the health of the Lakes and Coorong.

Central to the region's economy is a mix of primary industries (sheep and beef production, dairy, cereals, and wine production), as well as boat building, tourism, and a vibrant commercial and recreational fishing industry.

Everyone should be concerned with the state of the Murray-Darling Basin – and the Coorong, Lower Lakes and Murray Mouth (CLLMM). While the extent of the problems facing the CLLMM region may have only become apparent relatively recently, ecological degradation has been taking place for several decades. Over-allocation of water in the Murray-Darling Basin has been the main cause.

To ensure the region's economic, cultural and social future, it is critical to determine the environmental water requirements. Years of drought and over-use of water caused this internationally-significant wetland to dry, the lakes and aquatic biota to disconnect, the community and industries to suffer significant stress, and native species to be at risk of being lost. We must establish the needs of this system and then seek to meet them within the constraints imposed on a developed river system.

The long-term plan for the CLLMM region was prepared to ensure the region and its people have a healthy, viable and sustainable future in the context of variable climatic conditions and water resources. A key element of the overall strategy is the determination of the site's Environmental Water Requirements.

A healthy CLLMM region will depend on everyone accepting responsibility for its future. This document provides a foundation on which everyone can work together to build a sustainable and viable environment for the future.

The Australian and State Governments have allocated more than $186 million in funding to support the projects and actions outlined in the long-term plan for the region. For it to be effective, we need to secure sufficient environmental flows through the Basin Plan. This report seeks to provide a useful input into that process.

Alan Holmes
Chief Executive
Department of Environment and Natural Resources

Acknowledgements

The development of this environmental water requirement for the CLLMM region has largely been a task of synthesis, and we would like to acknowledge the contribution of, and sincerely thank, the following researchers, managers and institutions:

- those researchers whose initial work formed the basis of many of the chapters contained herein, including the researchers associated with the CLLAMMecology Research Cluster and the monitoring undertaken by the SA Murray-Darling Basin Natural Resource Management Board as a part of The Living Murray initiative;
- those researchers who reviewed various drafts of the sections on fish and vegetation indicators, particularly Jason Nicol, Chris Bice & Brenton Zampatti for their useful input;
- those researchers and managers who have contributed their time and expertise to comment on various aspects of this body of work, especially the government reference group who provided guidance throughout the process (named below) and those from the Department of Environment and Natural Resources and the Department for Water who provided helpful review comments on earlier drafts of this report; and
- Professor Ed Maltby from the University of Liverpool for his thoughtful review of this and the associated individual reports. His comments were particularly useful in improving the clarity and accessibility of this report, and led to two new sections including an extension of the investigation into the findings of less water and the investigation of the interaction with the USED scheme.

Finally, a special thank you to Rebecca Langley, Courtney Cummings and Ben Hamilton who provided excellent research assistance throughout this process and contributed to many aspects of the work, particularly the ecological modelling for the Coorong, the development of the indicator sets and the compilation of this report.

This report was prepared for the South Australian Government by Flinders University, Deakin University, Kerri Muller NRM, the Department for Water and the Department of Environment and Natural Resources. It supports Securing the Future: A long-term plan for the Coorong, Lower Lakes and Murray Mouth (DEH 2010). The long-term plan is part of the South Australian Government's Murray Futures project, funded by the Australian Government's Water for the Future initiative and the South Australian Government.

Executive Summary

A method for determining an environmental water requirement was developed using the aspects of previously-used, published methods that were best suited to this application, tailored to suit the data, tools and resources available for the Coorong, Lower Lakes and Murray Mouth region. The method involved setting ecological objectives and outcomes that were linked to the overall management aim of maintaining a healthy, productive and resilient wetland of international importance under the Ramsar Convention. Flow-related requirements were identified for a diverse suite of indicator taxa, assemblages and processes, each of which was linked to the ecological outcomes. Salinity thresholds were distilled from these data and modelling identified 3-year sequences of rules for barrage flows that would maintain salinities below those thresholds. Extensive testing across the Coorong and under climate change explored the robustness and feasibility of those rules, and the implications of failing to meet them.

Eight ecological objectives were developed to define a healthy, productive and resilient wetland of international importance. Thirty-three ecological outcomes were defined as evidence that the ecological objectives were being met. These were general and could be applied to a wide range of aquatic ecosystems, as well as the CLLMM region.

Indicator taxa and assemblages were selected that were likely to respond directly to flow or to be an early indicator of environmental change under flow regimes. Listed threatened taxa and invasive species were also included as indicators, with vegetation, macroinvertebrates and fish the primary focus. Ecological processes were also included as indicators. Combining different indicator groups was a holistic approach exploiting the range of properties of different components of the ecosystem. Varying amounts of literature were available for the range of indicators from which to identify flow-related thresholds. Trade-off tables were developed to summarise the available data on thresholds and tolerances of indicator taxa, but the variability in the quantity and quality of data available meant that these need to be used with care. Salinity was identified as the water quality component most likely to affect ecological character for this region with freshwater communities likely to be negatively affected by an increase in salinity above 1 g L^{-1}.

A total of ten vegetation species and/or assemblages were assessed as being potential indicators for the range of ecological outcomes. Samphire and saltmarsh communities was the most generally-applicable indicator assemblage, but many taxa within this group lacked local data on tolerances and thresholds. No vegetation indicators were considered to provide evidence of the oxidation of sulfidic material. Nineteen macroinvertebrate taxa were used as indicators, with the polychaete *Capitella* spp. the most generally applicable, and segmented worms and marsh beetles the most specialist of the indicators investigated. The macroinvertebrate community as a whole was also considered to be a useful indicator. Local data on macroinvertebrates, particularly in the Lakes, is patchy and incomplete. Seventeen fish species were used as indicators, particularly of self-sustaining populations and connectivity within the region. Ecological processes occur between organisms, within populations or among communities. Processes tend to integrate effects across multiple species. They are most applicable to the functions (rather than the structure) of an ecosystem, and so tend to be more sensitive to, and provide earlier warning of, change than taxon-based indicators. Decomposition, functional connectivity and response to terrestrialisation were the most general indicators, but many were particularly relevant to a subset of ecological outcomes, suggesting that an ‘ecoassay’ approach would provide important information if developed locally.

Additional work is needed to distil the indicator suites here into a useable suite of reliable indicators for management of the region.

Heneker (2010) defined rules for minimum barrage flows over three years to meet target salinities Lake Alexandrina. Scenario modelling showed that maintaining salinities in Lake Alexandrina also supported Lake Albert and Coorong salinities, and water levels throughout the region. An average annual barrage outflow of 4000 GL per annum over three years was required to maintain salinities of a mean of 700 µS cm^{-1} electrical conductivity (EC), while averages of 2000 and 1000 GL per annum maintained maxima of 1000 and 1500 µS cm^{-1} EC, respectively. Flows in any one year could fall below these averages provided sufficient flow was provided to meet the shortfall in subsequent years.

Hydrodynamic modelling (using a one-dimensional model) investigated the effect of these flows on Coorong hydrodynamics (i.e. water levels and salinity). Scenarios explored the effects of various combinations of environmental flows, delivery patterns and climate change. These were compared to 'baseline' (or 'no change') and 'natural' (or 'without-development') scenarios. No environmental flows compared well to the natural flow scenario, but environmental water was sufficient to safeguard the Coorong against the simulated effects of climate change, although increasing additional volumes would be required to achieve this as the severity of climate change increased. Flows to support either a mean of 700 or a maximum of 1000 µS cm^{-1} EC in Lake Alexandrina resulted in substantial improvements in the simulated hydrodynamics of the Coorong. Flows to support a maximum of 1500 µS cm^{-1} EC were an improvement over baseline conditions, but would not prevent extreme conditions occurring during very dry periods. The pattern of flow delivery also affected Coorong hydrodynamics, so some optimisation of the delivery pattern during dry conditions could reduce the overall volume required to prevent degradation.

The same scenarios were also used to explore the possible ecological impacts using an ecosystem states model for the Coorong, with the objective of avoiding the appearance of degraded ecosystem states and maintaining the frequency of one state that is thought to be associated with high-flow events. The pattern of flow delivery affected the predicted mix of ecosystem states, consistent with the effect on Coorong hydrodynamics. Environmental flows to support salinities in Lake Alexandrina resulted in an improved mix of ecosystems states, suggesting that the flow sequences investigated were sufficient to maintain the ecological diversity and health of the Coorong but, as for Coorong hydrodynamics, increasing volumes were required to meet those targets as climate change projections were more severe.

An environmental water requirement for the Coorong was described based on the relationships between the percentage of degraded ecosystem states and South Lagoon salinities with barrage flows in one-, two- and three-year sequences. To maintain ecological character, there should be no years of zero barrage flows, with an absolute minimum of between 50 and 120 GL flowing over the barrages in any year. In any two-year period, delivery of 600 GL is required to prevent certainty that South Lagoon salinities will exceed 117 g L^{-1} (a threshold linked to future degraded ecosystem states; Fairweather & Lester 2010) but, in 95% of years, at least 2500 GL over a two-year period is needed to prevent the whole Coorong supporting degraded ecosystem states. Flow rules developed to meet salinity targets in Lake Alexandrina were sufficient to meet these minimum flow volumes for the Coorong. However, high flows were also required for ensuring Coorong ecosystem health, with flows of 6000 GL $year^{-1}$ occurring at least every three years, and 10 000 GL $year^{-1}$ every seven years.

The hydrodynamic and ecological implications of delivering less water than specified were also investigated. For each of North and South Lagoon salinities and water levels, and the percentage of degraded ecosystem states, thresholds were identified that were associated with increasing levels of degradation for each of the three salinity targets. These steps in the trajectory of decline were typically associated with either the discrepancy in flow volume (relative to the environmental water requirement) for a single year (e.g. resulting in trajectories of decline for North and South Lagoon water levels), or the cumulative discrepancy through time (e.g. trajectory of decline for South Lagoon salinity). The outcomes on this trajectory of decline can be thought of as increasing levels of risk of permanent changes in the ecological character of the region, with recovery from increasingly-severe degradation being less likely. Thus managers can use this analysis as a tool to understand the level of risk associated with different minimum volumes of water (e.g. allocated via a sustainable diversion limit).

Finally, the interaction between barrage flows and flows from the Upper South East Drainage (USED) scheme were explored. Large volumes of additional water from the USED scheme (i.e. in the order of 60 GL $year^{-1}$ on average) could improve the hydrodynamics (particularly maximum South Lagoon salinity) and ecosystem states of the South Lagoon, particularly in low barrage-flow years. Very little or no change due to USED flows was predicted for North Lagoon hydrodynamics and ecosystem states, and during medium and high-barrage flow years the effects of additional water were equivocal, even in the South Lagoon. An analysis of potential for additional USED flows (using rainfall gauged along the flow path as a surrogate) indicated that high USED flow years tend to occur in high barrage-flow years, but it is possible that some high USED flows could coincide with periods of low barrage flows. This analysis demonstrated that the River Murray must continue to be the primary source of fresh water to the Coorong to maintain ecological condition, although there were benefits from USED flows in some years within the South Lagoon. Additional investigation would be required should the proposal for the expanded scheme were to change or to explicitly attempt to trade off EWR requirements with USED flows.

Thus, we have developed an environmental water requirement for the Coorong, Lower Lakes and Murray Mouth that we believe will support the Ramsar-listed ecological character of the region, and maintain the site as a healthy, productive and resilient wetland of international importance. This environmental water requirement includes low-flow requirements of long-term average flows of at least 4000 GL $year^{-1}$, with a minimum average flows of 2000 GL $year^{-1}$ in 95% of years, and an absolute minimum average of 1000 GL $year^{-1}$ in 100% of years (although flows for single years may fall below that volume). High flow requirements were specified as at least 6000 GL $year^{-1}$ every three years and at least 10 000 GL $year^{-1}$ every seven years. Given the inherent variability of the region, this EWR consists of both high- and low-flow requirements and is specified as a three-year regime. These EWRs are feasible under current climatic conditions, and are likely to support the region as climates change, thus securing a long-term, freshwater-driven future for the CLLMM region.

Summary of key findings

No existing method was directly suited to the task of developing an environmental water requirement for the Coorong, Lower Lakes and Murray Mouth region, so a composite method was developed.

The goal for the region to be a healthy, productive and resilient wetland of international importance was defined as having: self-sustaining populations; population, hydraulic and aquatic-terrestrial connectivity; habitat complexity and diversity; a persistent salinity gradient; flow and water level variability; and redundancy and appropriateness of ecological function.

A suite of indicators, including data relating to vegetation, macroinvertebrates, fish and ecological processes were required to adequately represent all ecological objectives for the region holistically. This suite could be distilled into an operational set of indicators for the management of the site.

Salinity in Lake Alexandrina was identified as the most flow-responsive variable affecting indicator taxa and processes. Thresholds of a long-term average of 700 µS cm^{-1} electrical conductivity (EC), a maximum of 1000 µS cm^{-1} EC in 95% of years and 1500 µS cm^{-1} EC in 100% of years were set to maintain the Ramsar-listed ecological character.

Three-year sets of rules for minimum barrage flows were developed to support each salinity target for Lake Alexandrina. These included average annual barrage flows of 4000, 2000 and 1000 GL for the 700, 1000 and 1500 µS cm^{-1} EC targets, respectively. Flows in any single year could fall below these averages, but then additional flow would be required in subsequent years.

These flow rules were sufficient to maintain Coorong hydrodynamics and ecosystem states, even under climate change. Flows to meet the 1500 µS cm^{-1} EC target were not sufficient in very dry periods to prevent ecological degradation and increasing volumes of additional water would be required to meet the rules under future climate change scenarios.

The pattern of flow delivery can be optimised for the Coorong to maximise the hydrodynamic and ecological benefits of coming from a given volume of water.

In addition to low-flow requirements based on salinity targets in Lake Alexandrina, high-flow requirements were also needed for the Coorong, with flows of more than 6000 GL $year^{-1}$ required once every three years and of more than 10 000 GL $year^{-1}$ every seven years.

Increasing discrepancies in actual barrage flows compared with the described environmental water requirements over one year, or cumulatively through time, were associated with increasing salinities and ecological degradation and lower water levels. Steps in the trajectory of decline were identified that represent increasing levels of risk of permanent ecological degradation being associated with delivering less water to the site than is recommended.

There were benefits of providing additional water to the South Lagoon via an expanded Upper South East Drainage (USED) scheme, particularly when volumes approached 60 GL $year^{-1}$ and during low barrage-flow years. It is possible that high USED flows may coincide with periods of low barrage flows. However, the limitations of these localised and occasional effects indicate that the River Murray must continue to be the major source of fresh water for the Coorong to support ecological condition.

Contents

1. Introduction

Rebecca E. Lester

Current attempts to maintain and restore ecological condition in aquatic ecosystems are often focused on the specification of environmental water requirements (EWRs) for iconic sites and to support ecological processes (e.g. see MDBA 2009a). Once the EWR of a site or process is known, this information can then be used to inform decisions regarding a sustainable level of diversion for fresh water from a river system (MDBA 2009a).

The specification of an EWR can be a complex task and there is no single best methodology for doing so. The most appropriate methodology depends on the individual case, including the specific objectives of the task, the amount of data and other information available and whether other tools (e.g. hydrodynamic models) are available. Approaches in the past have tended to focus on developing EWRs based on restoring a particular aspect (or combination of aspects) of a hydrograph, meeting the habitat requirements of a particular group (e.g. fish) or via a rule of thumb (Table 1.1). Some strategies have attempted to take a whole-of-ecosystem approach (e.g. see Thoms & Sheldon 2002), but many of these have lacked explicit links between hydrodynamic and ecological outcomes.

Practitioners involved in setting policy or making recommendations regarding flow regimes and environmental water requirements generally accept that riverine ecosystems are dependent on natural flow variability suitable to the region in which they occur (Petts 2009). By the mid-1990s, the concept of environmental flows was well-established, and protocols, theory and methods were being developed to allow environmental flow requirements and sustainable diversion limits to be set (Petts 2009). Since then, a wide range of methods have been developed, ranging from simple rules of thumb and look-up tables (Dyson *et al.* 2003) to extremely complex agent-based models that can include individuals within a population being modelled separately, including their likely decisions in response to their environment (e.g. Goss-Custard *et al.* 2006). Despite this, the proliferation of largely empirical models has limited their transferability and, in the main, simple operational models, focused on a single species or group remain common (Arthington *et al.* 2006). In response, scientists have recommended that tools based in ecology are necessary for setting environmental flow requirements for healthy aquatic ecosystems to allow for sustainable management of those systems (Petts 2009).

The existing methods explored had many advantages, but none were directly suited to the task of developing an EWR for the Coorong, Lower Lakes and Murray Mouth (CLLMM) region given the resources available and the constraints within which the EWR needed to be developed (of which timely delivery for application to an ongoing planning processes was the most critical). Rules of thumb had the advantage of being relatively quick to develop, but tended to lack explicit links to the available ecological data and would not take advantage of the modelling tools available for the region. Mimicking aspects of a natural hydrograph using a method such as ELOHA (Poff *et al.* 2010) had some extremely relevant points, given the impossibility of returning all flow to the region, but needed to be applied at a truly ecosystem scale, so was likely to be an onerous task, with unknown interactions among the response of various taxa. Habitat-based assessments, including IFIM and PHABSIM (Ward & Stanford 1979) have usually been applied at small spatial scales and for a limited numbers of species but the links drawn between available habitat, flow and species requirements were important. Methods such as the DRIFT methodology (King *et al.* 2003) and agent-based modelling (e.g. Perry & Bond 2009) are extremely comprehensive, but also expensive and time-consuming to apply. The latter also tends to be difficult to apply at an ecosystem-scale, as is required for the CLLMM region. Thus, the methodology applied to the CLLMM region (Chapter 2), attempts to incorporate the best and most-applicable aspects of the methods described, and others, while being practical for the CLLMM region. Practicality was largely driven by the available timeframe, existing knowledge, tools and other resources, and the flora and fauna for which the EWR recommendations were designed.

The CLLMM region is the coastal lagoon and freshwater lake complex that sits at the terminus of the Murray-Darling Basin (MDB). It is a Ramsar Convention-listed Wetland of International Importance, and was identified by the then-Murray-Darling Basin Commission as one of six Icon Sites in the MDB (DEH 2000). The CLLMM region meets eight of the nine criteria specified by the Ramsar Convention for determining Wetlands of International Importance (while its status against the ninth is unknown due to a lack of data but the region is likely to qualify; see Box 1.1, Phillips & Muller 2006). There has been a long-term decline in the condition of the region, particularly over the last five years, when reduced freshwater inflows from the River Murray, as a result of prolonged drought and upstream extractions, exacerbated this decline. Changes have included increasing salinities, decreasing water levels and the threat of large-scale acidification precluding the presence of healthy aquatic ecosystems. The recent condition in the Coorong, for example, has been described as the worst ever recorded (Mudge & Moss 2008).

Table 1.1: Examples of alternative approaches previously used previously to develop environmental water requirements

Approach	Example method	Description of method	Example applications	Relevant references
Rules of thumb	Various rules of thumb	• Available information & expert opinion used to derive rules of thumb, or look-up tables equating levels of flow alteration with increasing environmental disturbance • Usually purely hydrological, but can incorporate ecological data where available	• Rule of thumb for the proportion & variability of flow over several parameters for the Murray-Darling Basin, Australia • Index of natural flow used in the UK to set environmental flows & rules for extraction	Dyson *et al.* (2003) Jones *et al.* (2002) Barker & Kirmond (1998)
Mimicking aspects of a hydrograph	Ecological Limits of Hydrologic Alteration (ELOHA), Building-block method (BBM)	• Recognition that naturally-variable flow regimes are needed to support healthy ecosystems • Empirical relationships are derived for flow-ecology responses • In ELOHA, rivers are classified into ecologically-meaningful categories • Methods focus on minimising differences in the hydrograph compared to the natural condition for ecologically-important parameters • Recommendations for flow regimes arise from minimising such differences • Instream flow requirements for individual rivers determined from best available knowledge & expert opinion • For BBM, base flows are usually the most important factor, followed by the flows required for channel & habitat maintenance & then for spawning & migrations	• Pilot study data used to identify relationship between aquatic invertebrate metrics & the amount of water diverted, using five stream-type categories in Pennsylvania, USA (ELOHA) • Functional relationships between insectivorous fish & hydrologic metrics for the Tennessee River valley, USA (ELOHA) • In-stream flow requirements for numerous South African rivers & the Logan River, Australia (BBM)	Poff *et al.* (2010) Kendy *et al.* (2009) King & Louw (1998)

Approach	Example method	Description of method	Example applications	Relevant references
Habitat-based assessments	Physical Habitat Simulation (PHABSIM), based on Instream Flow Incremental Method (IFIM)	• Uses understanding of the physical habitat requirements of biota with field measurements of hydraulic & hydrological conditions within rivers at different stages to predict habitat availability for a range of discharges • Often based on flow-response curves for biota & the concept of 'wetted useable area' within streams • This assessment is used to provide guidance as to minimum flow requirements, especially for breeding salmonid fishes	• Most frequently applied to improve fish habitat • Used in the Olifants River, South Africa, to determine whether there would be sufficient habitat for native fish if exotics were removed & the possible effects of future dam-building activities • Developed guidelines for flow regimes to maximise habitat for adult & juvenile rainbow trout in the South Platte River, Colorado, USA	Ward & Stanford (1979) Gore *et al.* (1991) Thomas & Bovee (1993) See Petts (2009) for a review of the method
Species-specific requirements	Agent-based (or individual-based) modelling	• Complex simulation models that attempt to describe the processes linking individuals within a population & those individuals to their environment • Can include models of behaviour & 'choice' among individuals	• Model of the response of shorebirds (as mortality) to habitat loss in the UK • Model of habitat dynamics & the persistence of fish in SE Australia	Goss-Custard *et al.* (2006) Perry & Bond (2009)
Holistic approaches	Downstream Response to Imposed Flow Transformation (DRIFT) framework	• Biophysical studies link response of ecological components to specified flow changes • Incorporates socio-economic considerations • Social studies link subsistence & local livelihoods to river health • Scenario modelling predicts change & identified compensation required for selected flow regimes	• Method has been applied in the Breede & Palmiet Rivers in South Africa	King *et al.* (2003)

Box 1.1: Ramsar Qualifying criteria for Wetlands of International Importance.

In order for a site to qualify, one or more of the following criteria must be met:

	Criteria	Status in the Coorong (Phillips & Muller 2006)
1	Contains a representative, rare, or unique example of a natural or near-natural wetland type found within the appropriate bioregions	✓
2	Supports vulnerable, endangered or critically endangered species or threatened ecological communities	15 species qualify: 6 plant, 1 amphibian, 5 fish and 3 bird species
3	Supports populations of plant and/or animal species important for maintaining the biological diversity of the region	42 species qualify: 7 plant, 1 amphibian, 25 fish and 9 bird species
4	Supports plant and/or animal species at a critical stage in their life cycles, or provides refuge during adverse conditions	106 species qualify: 1 amphibian, 41 fish and 64 bird species
5	Regularly supports 20 000 or more waterbirds	29 bird species qualify
6	Regularly supports 1% of the individuals globally in a population of one species or sub-species of waterbird	16 bird species qualify
7	Supports a significant proportion of indigenous fish sub-species, species or families, life-history stages, species interaction and/or populations that are representative of wetland benefits and/or values and thereby contributes to global biological diversity	48 fish species qualify
8	Is an important source of food for fishes, spawning grounds, nursery and/or migration part of which fish stocks, either within the wetland or elsewhere, depend	32 fish species qualify
9	Regularly supports 1% of the individuals in a population of one species or sub-species of wetland-dependent non-avian animal species	Insufficient data to confirm

Detailed investigations into the likely future of the region under climate change clearly indicated that, despite the current poor conditions, the recent lack of water is highly unusual, and will continue to be so, even under moderate or severe climate change scenarios (CSIRO 2008). Therefore, it is highly likely that a freshwater-driven future for the region is possible, and there is good potential for recovery in the medium to long term, with recent good flows (since late 2010) prompting hopes of the beginning of such a recovery. Therefore, we have based our assessment of an EWR for the region on the assumption that maintenance of the Ramsar-listed ecological character of the region (Phillips & Muller 2006) is possible, a position which is consistent with that currently being taken both the South Australian and Federal Governments (e.g. see DEH 2010).

The Lower Lakes, comprising Lakes Alexandrina and Albert, are the largest permanent lakes in South Australia, covering an area of approximately 400 km^2 (Figure 1.1). Lake Alexandrina is the larger of the two lakes and is connected to the terminal Lake Albert via a channel aptly named the Narrows. The vast majority of freshwater inflows into Lake Alexandrina originate in the River Murray (Phillips & Muller 2006), although additional freshwater inputs come from other tributaries (e.g. the Finniss River or Currency Creek) or via groundwater or local rainfall (DEH 2000). These inflows are then transmitted to Lake Albert via the Narrows (although recently, relative to the time of writing, emergency drought measures had included a temporary embankment artificially separating the two lakes). Lake Alexandrina is separated from the Coorong, the estuary of the Murray-Darling Basin, by a series of barrages that can be operated to control the flow of water between the Lakes and the Coorong.

The Coorong comprises the estuary for the MDB and is a long, shallow, lagoonal system. In total, the Coorong stretches approximately 110 kilometres in a south-easterly direction (Figure 1.1). The Coorong is connected to Encounter Bay in the Southern Ocean via the Murray Mouth, which is the only connection to the sea. Otherwise, two narrow sand peninsulas (Sir Richard and Younghusband Peninsulas) separate the Coorong and the ocean. The system is an inverse estuary, which means that freshwater inflows enter the system from the same end as the mouth, rather than the more-usual configuration of having fresh inflows enter at the opposite end to the connection to the sea. This creates a natural gradient from usually-estuarine conditions around the Murray Mouth through to hypersaline conditions in the South Lagoon.

Natural resource managers for the region use spatial 'management units' to assist in their task of safe-guarding the ecological condition of such a complex region. There are seven units commonly used, which are: the Lower Murray River; Lake Alexandrina; Lake Albert; the Goolwa Channel; the Murray Mouth region; the North Lagoon; and the South Lagoon (Figure 1.1).

This document aims to document the work that has been done to date to develop an EWR for the Lower Lakes and Coorong Ramsar site that has been led by, or included significant amounts of work by, researchers at Flinders University. This document is one of two reports that sit behind Lester *et al.* (2011) which summarises and synthesises the research undertaken to determine an EWR for the CLLMM region. The second report outlines the work undertaken by Heneker (2010), while work undertaken by Muller is included here, either as authored chapters, or an appendix (see Appendix H), but all contribute to the same overall goal. Different components of the work included in this report were undertaken by different groups of researchers, and so each chapter explicitly includes a list of the authors for that section of the work.

In summary, this report contains a description of the overall methodology used to develop an EWR for the CLLMM region (Chapter 2), justification of the ecological objectives and outcomes that were used to define a healthy, productive and resilient wetland of international importance (Chapter 3), which is consistent with the management goals for the region, and a synthesis of how indicators were linked to each of those ecological objectives and outcomes and then used to set salinity targets for Lake Alexandrina (Chapters 4-5). Detailed descriptions of the work linking the vegetation, macroinvertebrate, fish and ecological-process indicators are then included (Chapters 6-9).

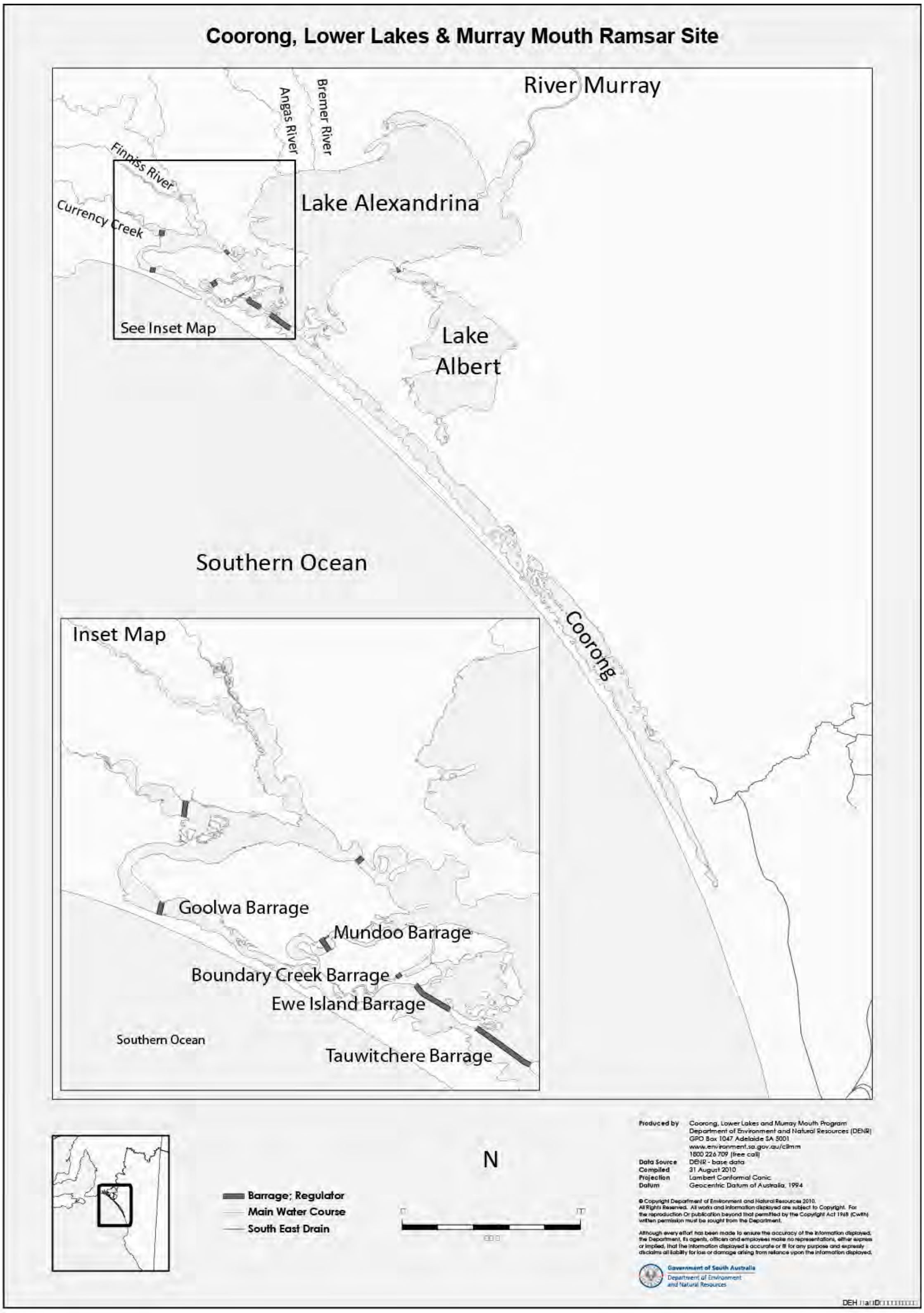

Figure 1.1: Map of the CLLMM region illustrating primary water sources and permanent flow regulation structures (Source: Felicity Smith, DENR)

Hydrological modelling to determine the EWR for the Lower Lakes is reported elsewhere (Heneker 2010), but the same scenarios and flow volumes have been modelled herein to determine the hydrodynamic implications for the Coorong (Chapter 10) and the ecological responses predicted for each (Chapter 11). An investigation into additional Coorong-specific water requirements is also included (Chapter 12), with further investigations of the effects of delivering less water than has been recommended here (Chapter 13) and interactions with a proposed expansion of the Upper South East Drainage scheme (Chapter 14) also included.

Each chapter reported herein is a stand-alone chapter. Each contains an introduction, methods (where appropriate) and the results of the investigations. A discussion of the findings, including relevant limitations and the implications of each (both for the development of this EWR and for management of the region in general), is also included in each chapter. A detailed synthesis and summary of this work (as well as that reported by Heneker [2010]) is contained in a separate report (Lester *et al.* 2011). Therefore, this report does not contain a separate chapter synthesising and discussing the findings contained herein. It is, instead, intended to provide the relevant documentation compiled by Flinders University to support Lester *et al.* (2011), rather than be a stand-alone piece of research in its own right.

In reading this report, it is important to be aware of some bounds that were placed on the task of developing an EWR for the region. We did not attempt to address the need for recovery from the current degraded condition but, instead focused on the longer-term water requirements of the region. While we recognise the importance of short- to medium-term interventions to restore the region's ecological character to that described by Phillips & Muller (2006), and potentially to improve the ecological health beyond that point (i.e. as anecdotal accounts suggest that the CLLMM ecosystems may have already suffered degradation by 1985; see Phillips & Muller 2006), the aim of this work is to determine what flow regime would support the ecological character in the long term. We view these as distinct objectives: the restoration of ecological character to at least that at the time of Ramsar listing will involve a series of management actions, not all of which will be related to setting an EWR, while the long-term health of the system can only be supplied by securing an appropriate EWR for the region. A management plan to address the current degraded state of the region will be prepared separately by the South Australian Department of Environment and Natural Resources.

We also assumed that the current ecological character of the region (as described as a part of the process of Ramsar-listing by Phillips & Muller [2006]), was the desired ecological condition for the region, and so our selection of indicators and targets was based on that assumption. If climate change, or the implications of the forthcoming Murray-Darling Basin Authority's Basin Plan, make that unfeasible, then this assumption (and possibly the EWR as a whole) may need to be reviewed. It is also possible that the work that has been included here, as well as potential future work, could be used as a first step in updating the ecological character described for the region. While many aspects of the region's ecological character may have declined in health, it is also likely that additional information now exists regarding species and assemblage distributions than was available at the time that Phillips & Muller (2006) was written.

It should be recognised that this is a first iteration of the research needed to specify an EWR for the region. So far, the implications of climate change have been touched upon, but a more detailed analysis is warranted. Further work is also required to refine the indicator sets presented and to set limits of acceptable change that will form an assessment of the success of the EWR in maintaining or enhancing the ecological character of the region. It is also important to recognise the limitations associated with some of the modelling tools used in this process. All models are imperfect representations of reality and have specific limitations associated with them. For example, the ecosystem states model (Lester & Fairweather 2011) used to verify the

EWR requirements for the Coorong was developed using data from a particularly dry period, and so may not predict the effects of high flows well. Limitations associated with each model have been included in the relevant chapters describing their use, and should be borne in mind when using the EWRs described here.

Finally, it is worth explaining the conventions used throughout this document for reporting salinities. There is very little consistency in the way salinity is reported across freshwater, estuarine and marine sciences. Freshwater research tends to measure electrical conductivity (EC), which is a surrogate for salinity, directly measuring the number of charged particles in solution. However, at higher salinities, the relationship between EC and salinity does not hold, so marine research often uses the concentration of chloride ions in solution, measured in grams per litre (g L^{-1}). This measure is particularly useful at very high salinities such as those observed in the Coorong (see Appendix A). In order to maintain consistency with previous work undertaken in the region (and avoid too many conversions between units, which can be problematic for salinity), we have tended to report salinity levels in the Lakes using EC, and in the Coorong using g L^{-1}. Formulae that allow approximate conversions between the two are given in Appendix A.

1.1 Summary

- **Robust environmental water requirements should be developed with explicit links between hydrodynamic and ecological outcomes. No previous methodology, of which we were aware, could be directly applied to this problem but the strengths of a number were incorporated for this application.**
- **The Coorong, Lower Lakes and Murray Mouth region is a Ramsar-listed Wetland of International Importance.**
- **This report documents the work done to develop an environmental water requirement for the CLLMM region, including the methodology used, the objectives and outcomes determined for the region and how ecological indicators were linked back to these objectives and outcomes.**
- **The development of the environmental water requirement for the CLLMM region was intended to support the Ramsar-nominated ecological character in the long term.**

2. Methodology for developing a robust environmental water requirement to support the ecological character of the CLLMM Ramsar site

Rebecca E. Lester, Kerri L. Muller, Theresa M. Heneker, Jason S. Higham & Peter G. Fairweather

In the past, several attempts have been made to determine an environmental water requirement target for the Coorong, Lower Lakes and Murray Mouth (CLLMM) Ramsar site. Although these have usually been based on the best available knowledge, suggested targets have tended to take the form of a single volume, or combinations of a few volumes, the ecological outcomes are often inferred rather than directly tested or modelled, and the inherent trade-offs not usually fully articulated.

Here, we outline a methodology for updating previous environmental water requirements to include knowledge arising from recent research within the region, including tools like hydrological and ecological response models, recently completed ecological literature reviews and other information.

This proposed methodology is explained in more detail below (Figure 2.1) and includes the following steps:

- define the ecological objectives and associated outcomes that would be associated with a healthy, productive and resilient wetland of international importance;
- identify a range of indicator species and processes that are indicative of the described ecological character of the region;
- determine a flow regime (rather than a single value) that will support the desired ecological character and test the potential impact of that regime across the CLLMM site;
- investigate the impact on the ecological character of the region of smaller flow volumes reaching the site, specifically identifying trade-offs in the components of ecological character that result;
- investigate the likely effects of climate change to assess how realistic the identified environmental water requirement may be in the future; and
- identify likely operational constraints and interactions with other management actions (e.g. the Upper South East Drainage scheme) associated with the delivery of water to meet the environmental water requirement.

Figure 2.1 summarises the methodology used to determine an EWR for the CLLMM region of each step, which are described in more detail in the following chapters. These steps are designed to identify and then support the water requirements for components of the ecosystem that comprise the overall aim for the region specified by DENR, that region continues to support a "healthy productive and resilient wetland system that maintains its international importance" (DEH 2010; p. 84).

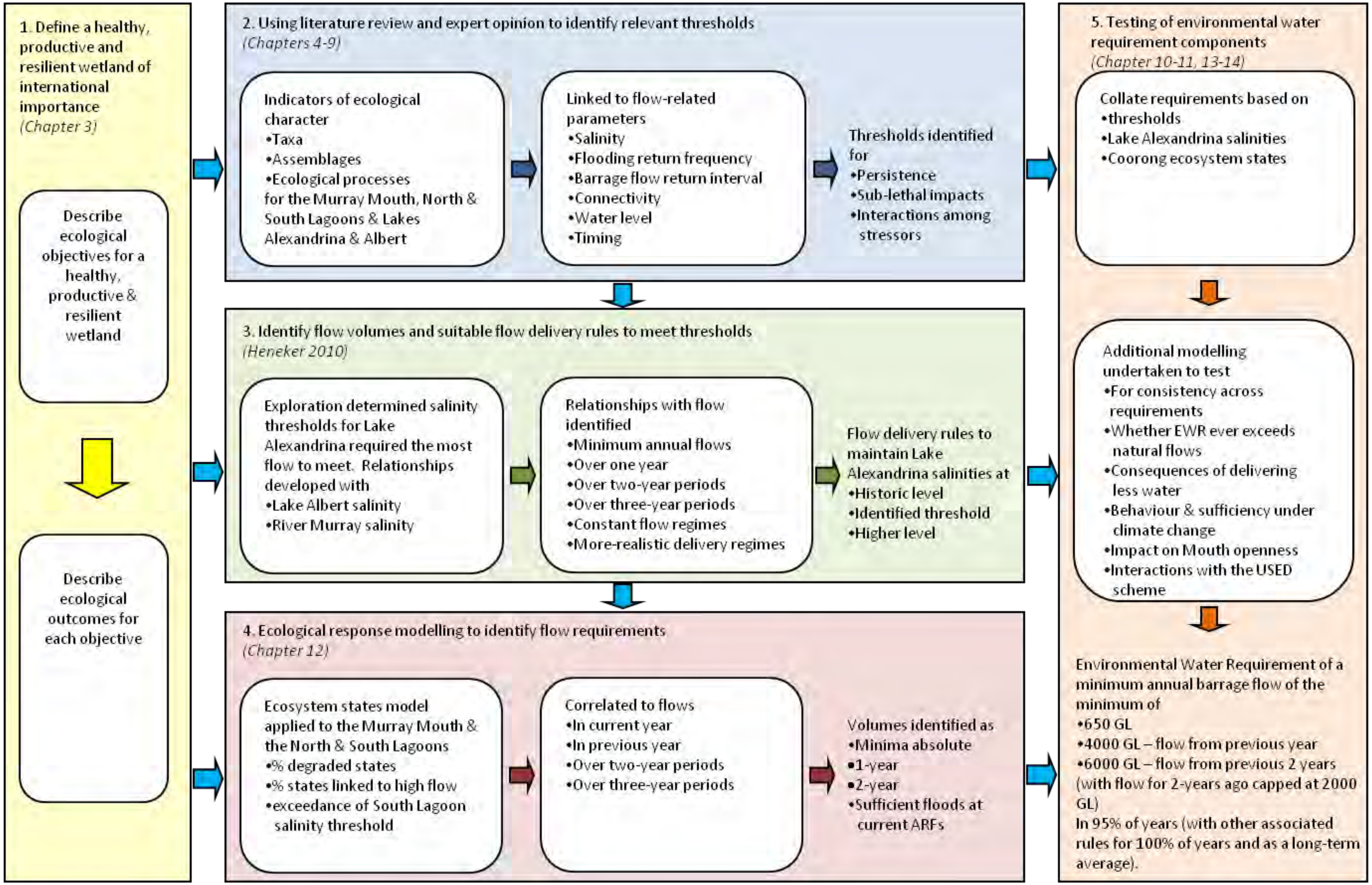

Figure 2.1: Summary of the methodology used to determine an environmental water requirement for the CLLMM region

2.1 Defining a "healthy, productive and resilient wetland system"

The objective for the CLLMM region specified by the DEH Long Term Plan for the site is that it continues to be a "healthy productive and resilient wetland system that maintains its international importance" (DEH 2010; p. 84). While a broad objective of this kind is useful for planning in the long term, it is difficult to use this statement to determine the environmental water requirement as it is relatively general and does not easily link to specific objectives around species or processes and is open to various interpretations. To enable modelling, the ecological processes, biota and conditions that are included in such a statement need to be specified, so that these can be related to flow regimes. This objective for the site has therefore been specified as a series of ecological character processes and components that are more easily quantified.

This list of processes and components was based on expert opinion elicited during workshops with local scientists and managers in April and August 2009.

2.2 Identification of indicator species and processes

A substantial body of knowledge exists on the ecology of the CLLMM region. This has been collected over many years by a variety of researchers and government agencies. In addition, several literature reviews summarising information on the ecology of the region have recently been compiled as a part of the development of the DEH Long Term Plan (e.g. Bice 2010a, Ecological Associates 2009) and external to that process (Lester *et al.* 2008), summarising the body of knowledge in the region.

This relative wealth of information was used to identify locally-relevant indicator taxa for each of the ecological processes or attributes identified in the process described in Section 2.1. Where taxa were used as indicators, this process focussed on identifying those taxa that were:

- key species in the region (e.g. *Ruppia tuberosa* is a key species in the South Lagoon due to its habitat value and as a food resource for a range of other species);
- 'canary' species (i.e. those sensitive species that are likely to be early indicators of deteriorating conditions); or
- threatened species as matters of National Environmental Significance (as defined by the Commonwealth *Environment Protection and Biodiversity Conservation Act*, *1999*).

2.3 Identification of critical thresholds for indicator processes and species

The literature utilised in the process described in Step 2.2 was then to identify the critical thresholds of each of the indicator species and processes. Critical thresholds were identified, where possible, for:

- water quality (focussing on salinity);
- flow regime (indicating an annual return frequency for barrage and flooding flows);
- connectivity (specifying intra-site connections and timing);
- water levels (links to water quality [e.g. acidification and salinity] and connectivity); and
- timing.

This allowed the indicators of ecological condition to be directly related to the hydrodynamics and flow regime of the Lower Lakes and Coorong. A process of consolidation then occurred, where the large number of likely thresholds identified was used to produce a short list of water quality, quantity and flow targets to be achieved and the corresponding ecological outcomes. The rationale for consolidation was reported. These targets were then used as a base for hydrological modelling in the Lakes and Coorong.

2.4 Exploration of flow regimes to meet water quality, quantity and flow targets

Hydrological and hydrodynamic modelling used the historical flow record from the River Murray and existing models for the Lakes and Coorong to explore various flow regimes and the likelihood of meeting the targets identified during the process described in Section 2.3. The minimum one-, two- and three-year flow sequence requirements needed to maintain the salinity targets, and thus water levels, were also explored. The above modelling specified the characteristics of each regime (such as median flow volume, annual return frequencies, for example) and identified how well each potential flow regime met the targets or how often the targets were not met.

2.5 Exploration of the ecological implications of that flow regime for the CLLMM region

Outputs from the hydrological modelling were used to assess the ecological implications of the recommended flow regime for the ecology of the CLLMM region. For the Lakes, this was a qualitative assessment, based on the available literature regarding flow and water quality tolerances identified during the process described in Section 2.3. For the Coorong, a similar qualitative assessment also occurred, but a quantitative assessment using the existing ecosystem states model was also possible subject to modelling and time availability. This identified the likely mix of ecosystem states that would potentially be supported by the recommended flow regime. A similar assessment may be possible at a later date for the Lakes, upon completion of a Lakes ecosystem state model.

2.6 Identifying the implications of smaller flow volumes

The results of the hydrological modelling were then used to identify the implications of smaller flow volumes or longer return frequencies than the recommended flow regime identified during the process described in Section 2.4. For ecological implications, a similar approach to that identified in Section 2.5 was followed, explicitly highlighting the likely differences in ecological character arising from smaller flow volumes. Steps in the trajectories of decline associated with increasingly small barrage flows were identified for North and South Lagoon salinities and water levels and the percentage of degraded ecosystem states in the Coorong in order to provide managers with a preliminary assessment of the level of risk associated with accepting lower barrage flow volumes than specified by the EWR.

2.7 Identifying the likely effects of climate change

The likelihood of delivering the recommended flow regime, and several smaller volumes, under a number of future climate scenarios were explored. These future climate scenarios were based on the updated modelling arising from the CSIRO Sustainable Yields project (CSIRO 2008). The effect of climate change on the return frequencies and other hydrological attributes of the flow regime were quantified. A brief exploration of the relative effects of climate change and extraction levels was undertaken to support Basin Plan negotiations. The implications of these climate scenarios on the desired ecological character as well as for the available management options for the region were explored, in the manner identified in Section 2.5.

2.8 Identifying operational constraints & interactions with other actions

Operational constraints relating to the availability of the specified amounts of water under without-development conditions were assessed. Potential interactions with other management actions (i.e. and thus alternative possible sources of water) were also explored to determine whether all water identified by the EWR needed to be delivered from the River Murray. These investigations provide management context to the EWR work described in this report.

2.9 Synthesis of findings

This report has been produced to report the complete set of findings from this investigation. A synthesis report has also been produced to provide a summary that is less technical and more management-oriented (Lester *et al.* 2011), and to highlight the implications and limitations of the work. Explicit links between the methodology used here and other ongoing approaches elsewhere in the Basin (e.g. the Aquatic Ecosystem Task group and the Basin Plan requirements) were drawn. Future steps to improve the recommended environmental water requirement were also identified.

The South Australian Government reference panel for the project consisted of Di Favier (the then-DWLBC), Lisa Mensforth (DWLBC), Paul Harvey (Leda Consulting), Theresa Heneker (DWLBC), Piers Brissenden (the then-DEH), Louisa Halliday (DEH), Russell Seaman (DEH), Jason Higham (DEH), Judy Goode (DWLBC), Heather Hill (DWLBC). Through regular meetings and review of the interim outputs, the SA Government project reference panel provided feedback and assistance with the development of rationale and review of the project team findings.

2.10 Summary

- **Modelling of the CLLMM region required specification of the ecological objectives identification of indicator species and processes at a local scale.**
- **Taxa that were either key species in the region, 'canary' species or threatened in the CLLMM region were focused on.**
- **Thresholds for each of the indicator taxa and processes were identified allowing for the indicators to be linked with the hydrodynamics of the system.**
- **How the flow regimes met water quality, quantity and flow targets, and the ecological implications of that flow regime, were explored.**
- **The implications of smaller water volumes than the recommended levels and the likely effects of current climate change scenarios, delivery constraints and any interactions with other management actions (e.g. USED scheme) were explored.**

3. Describing a "healthy, productive and resilient wetland system": Description of ecological objectives and associated outcomes

Rebecca E. Lester, Peter G. Fairweather, Kerri L. Muller & Jason S. Higham

This section represents the output from Step 1 in the process to justify an environmental water requirement (EWR) for the Coorong, Lower Lakes and Murray Mouth region. For a description of the methods used to develop that EWR, refer to Chapter 2 above.

The stated management goal for the CLLMM Ramsar site is to maintain it as a 'healthy, productive and resilient wetland system'. In order to achieve this goal, a suite of ecological objectives is required that, if met, would constitute a healthy, productive and resilient wetland that would continue to be of international importance and could adapt to future changes in climate and flow. In developing these ecological objectives, we have deliberately focused on ecological processes and attributes that should occur within the site, rather than specifying particular species or wetland types that should be present. This will enable the site to be managed through the recent crisis, but is also is realistic in the future, given the uncertainties around necessary short-term actions and the longer-term effects of climate change. Objectives for the mix of species and conditions supported by the site were drawn from the Ecological Character Description for the region (Phillips & Muller 2006), based on the understanding that this may need to be re-described over time to accommodate changing site conditions and climate change in the longer-term.

Each objective is accompanied by a short description and rationale, and then outcomes that would be indicative that the objective was being achieved. The objectives and outcomes are inter-linked and some objectives could be considered outcomes of other objectives, but the objectives have been developed based on the challenges associated with recent and/or current management of the site, and considering recent debates (e.g. whether seawater should be used in the Lakes to remediate acid sulfate soils).

Throughout this report the following outcomes have been referred to with abbreviated names to assist in identifying the respective outcome. See Appendix B for a full list of the outcomes with their respective numbers and abbreviated titles.

3.1 Self-sustaining populations

Populations of organisms that are self-sustaining in the long term, without intervention, are a key component of a functional ecosystem (Boulton & Brock 1999). This objective requires that populations have the conditions and resources they require to complete their life cycle successfully through time (e.g. spawn, recruit, feed and breed for fauna) and sufficient connectivity to link these conditions and resources (Closs *et al.* 2004). The caveat exists that not all species rely on the CLLMM region for their entire life cycle, so this objective is limited to that part of the life cycle that falls within the CLLMM region.

Outcomes:

I. Successful recruitment of local breeding species occurs through time (i.e. individuals recruit often enough to sustain the population)
II. Suitable habitat exists for breeding, feeding, shelter and development of individuals to accommodate all life history stages (Closs *et al.* 2004)
III. Suitable food resources exist for a variety of species (Closs *et al.* 2004)
IV. Water quality within tolerances for all life history stages for a variety of species for the majority of time (Boulton & Brock 1999; Closs *et al.* 2004)

3.2 Population connectivity

Population connectivity occurs when a population is able to successfully reproduce in space and time without interruption by natural or artificial barriers. Such barriers could include physical barriers, such as weirs that do not allow fish passage, temporal barriers, such as extended droughts that lead to depletion of seed banks, or seasonal barriers, such as changes to the hydrograph so that flooding does not align with breeding seasons (e.g. see Closs *et al.* 2004). In addition, many species use different habitats during different life stages (Closs *et al.* 2004), and connection between these is necessary to allow life cycles to be completed (e.g. diadromous fish using both marine and freshwater habitats, and there are likely differences in habitat requirements for male and female congolli) (Edgar 2001).

Outcomes:

V. Exchange of species occurs between Lakes, Coorong, from upstream habitats, regional wetlands and tributaries (including the South East of South Australia), the ocean (and possibly other nearby estuaries) and terrestrial environments to enable spatial connectivity (Closs *et al.* 2004)

VI. Viable propagule banks exist to enable temporal connectivity (Boulton & Brock 1999)

VII. No barriers to connectivity (either physical, temporal or seasonal) exist that prevent eventual intraspecific connectivity amongst life history stages/sexes for the purpose of breeding or recruitment (Closs *et al.* 2004)

3.3 Hydraulic connectivity

Hydraulic connectivity relates to the flow of water through and within the site. Hydraulic connectivity through the site originates in the River Murray upstream of the site, and moves through the different management units within the site and then further downstream (in this instance, mostly to the Southern Ocean, via tidal influences through the Murray Mouth). Flows also enter Lake Alexandrina from the tributaries that drain the Eastern Mount Lofty Ranges and the Coorong via Salt Creek. Hydraulic connectivity also includes connections between permanently-inundated areas, riparian zones, floodplains, ephemeral wetlands and occasionally-inundated areas like mudflats (Boulton & Brock 1999). The movement of water not only provides appropriate levels of moisture or inundation for different communities, but also transports energy (i.e. in the form of food items), nutrients (including nitrogen and phosphorus) and carbon (e.g. particulate organic matter) throughout the site (Boulton & Brock 1999; Edgar 2001). Hydraulic connectivity can also play a major role in the flushing of pollutants (such as sediments, salt, mobilised heavy metals and acid) through the region and out to sea (e.g. see Boulton & Brock 1999).

Outcomes:

VIII. Floodplains (& mudflats, island habitats etc.) are hydraulically connected laterally to permanent water bodies (e.g. via a variable flow regime) (Boulton & Brock 1999; Edgar 2001)

IX. Residence times for water in each of the management units are not infinite

X. The River, Lakes, tributaries, Coorong, ocean and South East are hydraulically connected. Ideally this would mimic natural levels of connectivity but at a minimum it needs to occur often enough during periods that are critical for ecological functionality (e.g. seasonally and inter-annually) (Boulton & Brock 1999)

XI. Exchange of energy, nutrients and carbon between management units, and from upstream or to downstream of the site, indicating longitudinal connectivity of these parameters (Boulton & Brock 1999; Edgar 2001)

XII. Pollutants delivered to the site are passed through and do not accumulate at abnormally high rates (e.g. sediment, salinity, acid, metals, agrochemicals)

XIII. Water quality within tolerances for all life history stages for a variety of species for the majority of time (Boulton & Brock 1999; Closs *et al.* 2004). NB: This outcome also appears under Section 3.1.

3.4 Habitat complexity and diversity

Habitat complexity refers to the mix of structural habitat features that are available within the site. In many instances, habitat complexity is conferred from diverse native aquatic vegetation but un-vegetated habitats, such as mud flats, rocky shores and sandy/pebble shorelines are also important components of complex habitats at the site scale and across whole landscapes. Complex habitats provide many types of food and shelter, making it more likely that the site will be able to support a wide range of biota than if available habitats are simple or homogeneous (Boulton & Brock 1999; Closs *et al.* 2004).

Outcomes:

XIV. A diverse range of habitat units exist across the site both above and below the water line (e.g. submerged plants to reed beds to paperbark or samphire to ephemeral mudflats to clean shorelines)

XV. There is temporal and spatial variability in available habitats

3.5 Persistent salinity gradient across site

One of the main reasons for the diversity of biota supported by the CLLMM region is the historical salinity gradient that has existed across the site, from freshwater lakes to an estuarine, marine and hypersaline Coorong. Maintaining a persistent gradient within the tolerance limits of wetland species will help ensure that this diversity is maintained. A persistent salinity gradient could be considered an outcome for the region, rather than an objective. However, the project team considers that the recent debate regarding possible future management actions, such allowing seawater into the Lakes, and potentially-conflicting evidence between palaeoecological research (e.g. Fluin *et al.* 2009) and anecdotal accounts of site history mean that an explicit objective is warranted. By including a persistent salinity gradient as an objective, we also allow flexibility in the future adaptation to long-term processes such as climate change while maximizing the likelihood that the region will continue to support the diverse range of biota from which its international importance stems.

Outcomes:

XVI. Spatial and temporal variability of salinity stays within maximum salinity tolerances of a variety of species within discrete habitat areas maintaining fresh, estuarine, marine and hypersaline communities. A range of salinities are represented across the site (with no areas outside maximum salinity tolerances for all life histories of a variety of species for extended periods or across extended areas) (Edgar 2001)

XVII. Salinities vary through time (with no areas outside maximum salinity tolerances all life histories of a variety of species for extended periods or across extended areas) (Edgar 2001)

XVIII. Communities requiring a variety of salinity regimes are supported across the site (e.g. ranging through fresh, estuarine, marine and hypersaline) (Edgar 2001)

3.6 Flow and water level variability

Australian wetlands, particularly in the Murray-Darling Basin, are characterised by very high diversity in flow volumes and frequencies (Boulton & Brock 1999), which naturally lead to high levels of variability in water levels. The biota supported by these wetlands have evolved to depend and thrive on this variability as cues to spawning and recruitment, for example, and as a mechanism by which energy and nutrients are transferred within the system (e.g. from floodplains to permanently inundated regions, and vice versa). Many species thus rely on variable flows and changing water levels, in addition to the delivery of a single minimum volume of water per annum (Boulton & Brock 1999). This variability occurs at many different time steps (Boulton & Brock 1999), from hourly in tidal areas, to seasonally, annually and decadally for flow volumes, both from the River Murray and other tributaries.

Outcomes:

XIX. A range of flow volumes are delivered to the site through time (Boulton & Brock 1999)

XX. Seasonality of flows exists (mimicking the pattern of the natural hydrograph) (Boulton & Brock 1999)

XXI. Seasonality of water levels exists (mimicking natural patterns) (Boulton & Brock 1999)

XXII. Communities requiring a variety of hydrological conditions are supported across the site (e.g. patches of dry, ephemeral and permanently-inundated habitats)

XXIII. Communities and processes requiring occasional flooding (e.g. to cue spawning or stimulate germination) are supported by the site

XXIV. A tidal signal is apparent in the Murray Mouth region

3.7 Redundancy and appropriateness of ecological function

Redundancy in ecological function simply implies that there is more than one possible species or pathway by which each ecosystem function occurs. This is a key factor in maintaining the resilience of an ecosystem (Walker & Salt 2006). Ecosystem functions include ecological processes such as competition, predation, migration, reproduction, productivity and the proliferation of pest species (Boulton & Brock 1999; Fairweather 1999a; MDBA 2009). Physical functions include biogeochemical processes such as decomposition, nutrient cycling, acidification, salinisation and terrestrialisation (e.g. see Boulton & Brock 1999; Fairweather 1999a). Most ecosystem processes, in a natural environment, have ranges of normal or expected operation (i.e. one does not dominate over all others) (Boulton & Brock 1999) and often occur via more than one pathway. In a stressed ecosystem, a few processes dominate (Walker & Salt 2006), including some that are less-desirable from a management perspective (e.g. acidification). Another feature of stressed ecosystems is that processes are more likely to occur via only one pathway (e.g. only bacterial decomposition of organic matter occurs if conditions are not suitable for other decomposers like invertebrates) (Fairweather 1999a). Increasing redundancy in ecological function increases the likelihood of an ecosystem being resilient to future stressors, and minimises the likelihood that less-desirable ecosystem processes will dominate.

Outcomes:

XXV. Complex, diverse food webs across the site

XXVI. Multiple species are present that are capable of performing similar functions (e.g. shredding of organic matter, microbial processing, food sources) within the site

XXVII. Working, efficient and appropriate cycling of nutrients and carbon occurs throughout the site with appropriate biogeochemical pathways present at each location (also with connections to upstream/downstream etc.)

XXVIII. Invasive species do not dominate and are not spreading uncontrollably through the region (Walker & Salt 2006)

XXIX. Proportions of acid-tolerant, saline-tolerant and terrestrial species remain approximately constant in the medium to long term (although these should vary spatially and on short temporal scales)

3.8 Aquatic-terrestrial connectivity

Aquatic-terrestrial connectivity allows for links between the CLLMM water bodies and the surrounding terrestrial ecosystems. Many species and processes (both terrestrial and aquatic) rely on resources from both terrestrial and aquatic ecosystems (e.g. invertebrates that have flying adult phases but aquatic larvae or aquatic decomposers that rely on the provision of terrestrial detritus) (Boulton & Brock 1999). A variable water level is one way in which aquatic-terrestrial connectivity can be maximised. In the CLLMM region, this would have the added benefit of intermittently exposing, and therefore "burning-off" sulfudic material that has formed during the inundation phase, thus limiting the formation of new acid sulfate soils.

Outcomes:

XXX. Variable water levels allow wide riparian and littoral zones to develop and persist through time (both as plants and as propagules) (Boulton & Brock 1999)

XXXI. Interconnected mosaic of diverse vegetation from terrestrial, through riparian and submerged down to the extent of the euphotic zone (Boulton & Brock 1999)

XXXII. Ecosystem supports a balanced mix of terrestrial and aquatic taxa through space and time

XXXIII. Exchange of energy, nutrients and carbon occurs between aquatic and terrestrial ecosystems (Boulton & Brock 1999)

XXXIV. Variable water levels regularly oxidise sulfidic material and limit the formation of new acid sulfate soils around the shallow water margin

3.9 Summary

- **A suite of ecological objectives were compiled to constitute a healthy, productive and resilient wetland of international importance, focussing on ecological processes but also including species identity and persistence.**
- **The eight ecological objectives derived were: self-sustaining populations, population connectivity, hydraulic connectivity, habitat complexity and diversity, persistent salinity gradient across sites, flow and water level variability, redundancy and appropriateness of ecological function and aquatic-terrestrial connectivity.**
- **A total of 33 ecological outcomes were identified from the eight ecological objectives for the CLLMM region.**

4. Selecting Ecological Component Indicators for evaluating performance and assessing resource condition against the ecological objectives for the Coorong and Lakes Alexandrina and Albert

Kerri L. Muller

4.1 Introduction

The Coorong and Lakes ecosystem is known to support more than 1,000 species across the different biological groupings from plankton to vertebrates (Phillips & Muller 2006). Such a vast number of species prevents complete inventory and monitoring, yet sound knowledge and complete databases are needed to manage the site in order to achieve the long-term vision for the site as a healthy, productive and resilient wetland of international importance. One strategy, therefore, is to focus monitoring on indicator taxa (Kremen 1992) and associated metrics that can be used as evidence of whether a given objective for the site has been met. The term 'ecological component' was used here as a descriptor of these types of indicators that focus on taxa and assemblages. This was consistent with the Ramsar Convention definition of wetland ecological character being made up of ecosystem components, processes, services and benefits (Ramsar 2005; Phillips & Muller 2006).

The previous chapter (Chapter 3) detailed the ecological objectives and associated outcomes for the site. These objectives were nested below the overall vision of a healthy, productive and resilient wetland of international importance. It is currently standard practice to develop a series of targets to assess performance against set objectives (Wilkinson *et al*. 2007). Targets relevant to the objectives will be set as part of a related project determining the limits of acceptable change in ecological character for the Ramsar Management Planning process for the site. This chapter describes how the method for evaluating performance against these objectives over time was determined. Specifically, criteria for selecting indicator taxa or assemblages best suited to determining whether the eight ecological objectives and 33 outcomes have been met were detailed (see Step 2 in Chapter 2). As well as describing the methodology used to select ecological components (taxa and assemblages) to be used as indicators the rationale for why they were selected is given. Ecological process indicators were also selected, and criteria for their selection are given below in Chapter 5.

In Chapters 6 to 8, each ecological component selected was evaluated as an indicator of each of the 33 ecological outcomes (Chapter 2). This process yielded a series of tables of which indicators could be used as evidence for meeting each ecological outcome (Chapters 6-8). Following those sections, Chapter 9 describes the series of ecological processes that were selected as indicators to complement the ecological components. An integrated discussion of both the ecological component and process indicator results appears in Chapter 5 where the indicators were used together to show how targets were set for primary ecological determinants such as lake water levels, salinity or return frequencies for flows and which indicators would be supported and which would not if targets were set at a given value. From there hydrological, hydrodynamic and ecological modelling were undertaken to identify the level of River Murray flows required to meet the environmental water needs of the site based around targets for these primary ecological determinants (see Heneker 2010 and Chapters 10 & 11). These indictor-level targets will be used in the future to develop the limits of acceptable change in the components and processes that make up the ecological character of the site as defined by the Ramsar Convention.

Indicator information will also be useful as a record of any changes in resource condition that occur over time, because performance evaluation will be based on ecological component and process indicators that are representative of the site's Ramsar-nominated ecological character, along with subsequent additions to cover new components and processes.

4.2 Indicator selection methodology

The focus for selecting the ecological components (taxa and assemblages) that best indicate whether or not the ecological objectives and outcomes have been achieved, was on vegetation, fish, macroinvertebrates and processes for this first iteration. The first three sets were selected because these biotic groups are likely to be highly, and directly, affected by environmental water variables such as water levels, flows and water quality, and also because they form the lower rungs of the trophic web (Boulton & Brock 1999). In the case of vegetation, this focus was also warranted because vegetation is a key determinant of habitat complexity and one of the key determinants of food availability (directly and indirectly) in the Coorong and Lakes (see Phillips & Muller 2006). Prolonged low flows, and the recent drawdown of the Lakes, in particular, coupled with high salinity levels in the Coorong have resulted in widespread loss of submerged and emergent vegetation in recent years and decades (i.e. thought to be a 'top-down' change; Brookes *et al*. 2009; Gehrig & Nicol 2010), and presumably decreased resilience in floodplain vegetation dependent on inundation for completion of life cycles, making vegetation a major indicator group for evaluating wetland resilience. In adopting this methodology, it has been assumed that if the lower trophic levels such as vegetation, macroinvertebrates and fish indicate that the system is meeting the objectives for a healthy, productive and resilient ecosystem, then the higher trophic levels are likely to also be supported and would, if assessed, also indicate that the objectives are being met and the wetland is indeed healthy, productive and resilient. Consequently, birds have not been part of the process so far, except for the Environmental Protection and Biodiversity Conservation (EPBC) listed orange-bellied parrot (*Neophema chrystogaster*; indirectly through inclusion of samphire & saltmarsh communities). This is because birds are less likely to be directly affected by environmental water variables at a site-scale because they are highly mobile, generalist and/or opportunistic in use of habitats and food selection (Ecological Associates 2009) and thus may be poor indicators of some specific ecological outcomes listed in Chapter 3. It was envisaged that more work would be conducted on linking birds to habitats and processes in the related project looking at the limits of acceptable change for input into Ramsar Management Planning at the site by the SA Department of Environment and Natural Resources, and thus more bird indicator species, particularly those like banded stilts that are characteristic of certain ecosystem states in the Coorong (Lester & Fairweather 2009a), would be likely to be included in any future iteration of determining the environmental water requirements of the Coorong and Lakes.

Ecological components were chosen to reflect a range of functional groups and on the basis of their tolerances to change or absolute values of environmental water variables such as water level, flow regime and water quality. Preference was given to those taxa or assemblages that were:

- likely to be directly affected by key water quantity and/or quality variables (e.g. depth of inundation or salinity);
- considered to be highly responsive to one or more of the outcomes identified for the site (e.g. dependent on population connectivity);
- considered to be potential keystone taxa and thus indicative of conditions for multiple other taxa (Scheffer *et al.* 2001; Davis *et al.* 2003);
- listed under the EPBC Act (e.g. Murray cod *Maccullochella peelii peelii)*;

- likely to respond to early changes in environmental variables (i.e. analogous to canaries in a coal mine); or
- known to be invasive taxa and thus were needed to kept under observation as well as for assessing the 'Control of invasive species' outcome.

For each indicator, the available literature was searched for and collated, and where necessary expert opinion was sought or provided, as to whether each could be considered indicative of the various ecological outcomes, and under the following categories:

- Common name;
- Scientific name;
- Functional group;
- Location (within Coorong and Lakes site);
- Life span;
- Flow related requirements:
- Salinity;
- Turbidity;
- Annual Return Frequency (barrage flows or floodplain inundation);
- Connectivity;
- Water levels (Lakes or Coorong);
- Timing; and
- Metrics (measures that could be used for that indicator).

Where data were found in the literature they were cited, as was expert opinion where that was used to yield an entry against one of the above categories for which data was not available. In both cases, a description of the rationale for inclusion was also given. Literature reviews prepared for SA Department for Environment and Natural Resources were used as pointers to the primary scientific literature for vegetation and fish (i.e. Bice 2010a; Gehrig & Nicol 2010, respectively). A review by Aldridge *et al.* (2009a) was used as a pointer for literature on processes related to nutrient cycling. Information on estuarine macroinvertebrate taxa was partially identified from the literature review by Rolston & Dittmann (2009). For all sections, these literature reviews were supplemented by additional searches of the scientific literature, and contribution or review by experts in the field for each section.

Once the information for each ecological component indicator (taxon or assemblage) was collated, a table was populated for each showing which outcomes it was indicative of and why, including the metrics that would be most useful for indicating whether the given outcome was achieved and any relevant knowledge gaps. If insufficient evidence existed regarding whether a taxon or assemblage could be considered to be a primary indicator or an indicator at all for a particular outcome, this was recorded to ensure traceability and transparency in the indicator selection process. This record structure also facilitates peer review and continuous improvement as new knowledge comes to light or understanding of interactions is improved.

4.3 General results and discussion

In total, ten vegetation species or species assemblages, 17 fish species and 19 macroinvertebrate species have been selected as taxon and assemblage indicators in this first iteration (Table 4.1) along with 12 ecological processes. The ecological component indicators that have been selected are heavily inter-dependent and inter-linked but each was considered separately (in terms of tolerances to key environmental variables and suitability as an indicator for meeting each ecological outcome) to ensure that an understanding of how they may indicate the full suite of objectives was developed. Plants have been nominated as either individual species or species assemblages with the dominant (or visually-apparent) species used in the label. The selected plants occur across all parts of the site and across the full elevation gradient and include plants that are known to support EPBC-listed species (e.g. samphire & saltmarsh communities supporting orange-bellied parrots) and a diverse range of fauna and ecological processes.

As stated above, birds were not considered for selection as indicators in this first iteration. This was because birds do not tend to be directly affected by changes in water quality or other wetland parameters (e.g. increased salinity) but instead are largely indirectly affected through changes or reductions in food sources (e.g. plants, macroinvertebrates, fish). Many birds are highly mobile and can be opportunistic in their feeding and breeding locations as well as being able to escape poor environmental conditions provided that refugia are available (Rogers 2009b). It was therefore assumed, for this iteration, that most birds, like orange-bellied parrots, would be catered for through their association with, or dependence on, particular vegetation, fish and/or macroinvertebrates (Ecological Associates 2009). A selection of bird indicators, including migratory birds for which the site meets the relevant Ramsar selection criteria, could be chosen for the next iteration of this process.

Other fauna, such as the EPBC-listed southern bell frog (*Litoria raniformis*), were similarly assumed to be catered for if the vegetation, fish and macroinvertebrate indicators were supported and specific associations have been mentioned where known. Southern bell frogs are known to be highly dependent on freshwater submerged and emergent vegetation (DEC 2005) which has been lost or severely degraded in the Lakes since 2006 (Gehrig & Nicol 2010) and they are likely to be sensitive to key risks at the site such as rising salinity, heavy metals and acidification. It is documented in the Southern bell frog Recovery Plan (DEC 2005) that males call from August to April and the species breeds in permanent wetlands usually with extensive reed beds from which adults call. However, little was known about the species at this site at the time of writing, so it was not selected as an indicator in this iteration, although consideration should be given as to whether to include it in future iterations if some of the knowledge gaps have been filled. Freshwater tortoises could also be included in future iterations, particularly given the high levels of injury and death they suffer from tubeworm (*Ficopomatus enigmaticus)* infestation (i.e. *F. enigmaticus* can also use crabs and mussels as a substrate and these were included in as indicators; Chapter 7).

Phytoplankton species were evaluated for use as indicators using Aldridge *et al.* (2009a) but none have been included as component indicators in this iteration because it was concluded that the species-level response to environmental water variables was unpredictable and poorly understood. It was clear that a healthy, productive and resilient wetland would support a diverse range of phytoplankton species rather than having one or a few, possibly toxic, species dominating (i.e. algal blooms). Even though it could be argued that algal blooms occurred in the natural state, it is unlikely that they would have been widespread or common and thus occurrence of algal blooms was not considered an indicator of a healthy, productive and resilient wetland. It was also clear that a functional estuary relies on inputs of freshwater phytoplankton. Therefore, phytoplankton assemblages have been used to indicate whether some of the selected process indicators were occurring and appear as metrics against several process indicators even though they were not included at the taxon or assemblage level as a component indicator (see Chapter 9).

Table 4.1: List of ecological component indicators (taxa and assemblages) selected for evaluation of performance against ecological objectives for the site, including functional groups and locations within the Coorong and Lakes site, where known. Vegetation functional groups are after Gehrig & Nicol (2010).

Indicator species common name	Scientific name	Functional Group	Location where found
Vegetation			
Samphire & saltmarsh communities	Various species including: *Tecticornia pergranulata* ssp. *pergranulata*, *Suaeda australis*, *Sarcocornia quinqueflora & Juncus kraussi*	terrestrial damp terrestrial dry	Lx, Lb, MM, NL, SL
Paperbark woodlands	*Melaleuca halmaturorum*	amphibious fluctuation tolerator - woody	Lx, MM, NL, SL
Lignum	*Muehlenbeckia florulenta*	amphibious fluctuation tolerator - woody	Lx, Lb, MM
Diverse reed beds	Various species including: *Phragmites australis*, *Typha domingensis & Schoenoplectus validus*	amphibious fluctuation tolerator- emergent reeds	Lx, Lb
Water milfoils	*Myriophyllum salsugineum & M. caput-medusae*	amphibious fluctuation responder-floating	Lx, Lb
Ribbonweed	*Vallisneria australis*	submergent *K*-selected*	Lx, Lb
Water ribbons	*Triglochin procerum*	semi-emergent *r*-selected*	Lx, Lb, T
Spiny rush	*Juncus acutus*	pest, amphibious fluctuation responder-floating	Lx, Lb, MM
Large-fruited sea tassel	*Ruppia megacarpa*	Submergent *K*-selected*	Lx, Lb, (NL)
Tuberous sea tassel	*Ruppia tuberosa*	Submergent r-selected*	Lx, Lb, NL, (SL)
Fish			
Murray Cod	*Maccullochella peelii peelii*	large-bodied native fresh predator	RM, Lx, Lb
Golden perch	*Macquaria ambigua ambigua*	large-bodied native freshwater	RM, Lx, Lb, MM(f)
Bony herring	*Nematolosa erebi*	large-bodied native freshwater	RM, Lx, Lb, MM(f)
Australian smelt	*Retropinna semoni*	common small native freshwater	RM, Lx, Lb, MM(f)
Murray hardyhead	*Craterocephalus fluviatilis*	rare small native freshwater	RM, Lx, Lb
Yarra pygmy perch	*Nannoperca obscura*	rare small native freshwater	Lx, T
Carp	*Cyprinus carpio*	exotic freshwater	RM, Lx, Lb, MM(f)
Congolli	*Pseudaphritis urvillii*	diadromous (catadromous)†	RM, Lx, Lb, MM, NL
Common	*Galaxias maculatus*	diadromous	Lb, Lx,

Indicator species common name	Scientific name	Functional Group	Location where found
galaxias		(catadromous)†	MM
Short-headed lamprey	*Mordacia mordax*	diadromous (anadromous)†	RM, Lx, Lb MM, O
Yellow-eyed mullet	*Aldrichetta forsteri*	estuarine	Lx, Lb, MM, NL
Black bream	*Acanthopagrus butcheri*	estuarine	Lx, Lb, MM
Small-mouthed hardyhead	*Atherinosoma microstoma*	estuarine	RM, Lx, Lb, MM, NL, SL
Mulloway	*Argyrosomus japonicus*	marine predator	Lx, Lb, MM, O
Sandy sprat	*Hyperlophus vittatus*	marine	MM, NL, O
Australian salmon	*Arripis truttacea*	marine	MM, NL, O
Bronze-whaler shark	*Carcharhinus brachyurus*	marine predator	MM, O
Macroinvertebrates			
Freshwater mussel	*Velesunio ambiguus*	freshwater sessile (mobile larvae)	RM, Lx, Lb
Freshwater crayfish (yabby)	*Cherax destructor*	freshwater mobile	RM, Lx, Lb,
Mayflies	Ephemeroptera	freshwater mobile (terrestrial flying adults)	RM, Lx, Lb, T
Stoneflies	Plecoptera	freshwater mobile (terrestrial flying adults)	RM, Lx, Lb, T
Caddisflies	Trichoptera	freshwater mobile (terrestrial flying adults)	RM, Lx, Lb, T
Sandhoppers	Amphipoda. Various species including *Melita zeylanica*, *Paracorophium* sp. & *Megamphopus* sp.	freshwater/estuarine mobile	RM, Lx, Lb, MM, NL, SL, T
Segmented worms	Oligochaeta	freshwater/estuarine sessile	RM, Lx, Lb, MM, NL, SL, T
Freshwater cnidaria	*Hydra* spp.	freshwater sessile	RM, Lx, Lb, T
Freshwater limpets	Ancylidae	freshwater sessile	RM, T
Brackish water crab	Hymenosomatidae	brackish mobile	Lx, Lb, MM
Marsh beetles	Scirtidae	freshwater mobile (terrestrial adults)	RM, Lx, Lb, T
Blackflies	Simuliidae	freshwater mobile (terrestrial flying adults)	RM, T
Tubeworm	*Ficopomatus enigmaticus*	estuarine sessile	MM, NL, SL
Microbivalve	*Arthritica helmsi*	estuarine sessile	MM, NL

Indicator species common name	Scientific name	Functional Group	Location where found
Polychaete worm	*Nephtys australiensis*	estuarine motile	MM, NL
Polychaete worm	*Simplisetia aequisetis*	estuarine/marine mobile	MM, NL
Polychaete worm	*Capitella* spp.	estuarine/marine mobile	MM, NL
Brine shrimp	*Parartemia zietziana*	hypersaline mobile	SL
Goolwa Cockle	*Donax deltoides*	marine sessile	MM, O

*Life history strategies: *K*-selected taxa are typically long-living organisms, have larger body sizes and produce fewer offspring; *r*-selected taxa typically have a high fecundity, small body size, early maturity and short generation time.

†Functional group definitions: diadromous fish species use both freshwater and marine habitats, catadromous species live primarily in freshwater and migrate into marine habitats to spawn, anadromous fish species migrate from marine waters into freshwater habitats to spawn.

Location key: RM River Murray; Lx Lake Alexandrina; Lb Lake Albert; T tributaries; MM Murray Mouth region from Goolwa to Tauwitchere barrages and out to ocean side of Murray Mouth; MM(f) MM region as above during freshwater flows; NL North Lagoon of the Coorong; SL South Lagoon of the Coorong; O Southern Ocean. Locations in parentheses are historical locations from which the indicator may be currently absent.

Zooplankton (i.e. animals living in the water column) were also considered for selection as indicators because they tend to be highly specific and thus representative of water source origins or certain water quality conditions. Zooplankton are likely to be important indicators for the site, particularly in terms of indicating whether functional connectivity has been achieved between the river, lakes and estuary. They were not selected in this iteration, primarily due to the lack of relevant understanding for the site and resource constraints for this iteration. It was envisaged that zooplankton indicators could be included in future iterations of the determination of environmental water requirements for this site.

Success in finding information on flow-related requirements of these indicators in the literature was highly variable. For some taxa and associated requirements there was very accurate and specific information for at least some parts of the life cycle (e.g. salinity tolerances for some of the fish species) but for others, very few data existed. Tolerances for salinity were found for some of the species, although on the whole these were LC50 values (lethal concentration for 50% mortality) and thus represented the concentration (e.g. salinity) at which 50% of the test animals exposed to that toxin died. It was difficult to apply such laboratory-based tests to environmental management because the setting of targets for salinity levels and other water quality variables should be based on values that support self-replicating populations in good health, and thus target values for wise management would be lower than LC50 values and perhaps significantly so.

For vegetation, few specific values for turbidity were found with the only relevant information being that the euphotic depth was approximately 75 cm prior to the drawdown that began in 2006 (Gehrig & Nicol 2010). Very few records for optimal return frequencies were found and thus life span, knowledge of life-cycle dynamics and recruitment watering needs have been used on the whole to generate return frequencies for barrage releases and inundation to lake levels of >0.6 m AHD through expert opinion. Connectivity needs were based on assessing the locations of different vegetation types, inter-specific interactions (e.g. access to vegetated habitats for spawning, food or shelter), life-cycle dynamics, movement patterns (including migrations), energy-flow dynamics and nutrient cycling (Chapter 5, Appendix B).

Additional results and further discussion for each set of indicators and their links to flow-related variables are presented in Chapters 5 (Links to flow-related variables), 6 (Vegetation), 7 (Macroinvertebrates), 8 (Fish) and 9 (Processes).

4.4 Summary

- **Using indicator taxa can be an effective way to monitor and assess whether a complex ecosystem is a healthy, productive and resilient wetland of international importance & this chapter describes how the method for evaluating performance against these objectives was determined.**
- **Criteria for selecting indicator taxa, assemblages or processes best suited to determining whether the eight ecological objectives and 33 outcomes have been met are detailed, including the rationale for their use.**
- **Vegetation, macroinvertebrate, fish and process indicators were selected as potential indicators because these groups were likely to be affected by environmental water variables and because they form the lower rungs of the trophic web (for the most part), with the assumption that if the lower trophic levels reflected a healthy, productive and resilient ecosystem, then this would also be reflected in higher trophic levels.**
- **In selecting taxa as potential indicators, preference was given to those which were: likely to be directly affected by environmental water conditions including key water quantity and/or quality variables, considered to be highly responsive to**

one or more of the outcomes identified for the site, considered to be potential keystone taxa, listed under the EPBC Act, &/or known to be invasive taxa.

- **A total of ten vegetation, 17 fish, 19 macroinvertebrate and 12 process indicators were selected.**
- **Some taxa, assemblages or processes were identified as being potential indicators but have not been included here due to a lack of knowledge or because they were not considered to be directly affected by changes in flow-related variables. Such potential indicators include the southern bell frog (*Litoria raniformis*), cutting-grass sedgelands, black swamp assemblages, zooplankton and phytoplankton.**
- **Extensive literature searches were used to provide rationale, the relevant metric to be used in monitoring and any knowledge gaps for the use of each taxa, assemblage and process, but the amount and quality of literature available on each taxa, assemblage and process varied between indicators.**

5. Using the links between indicator sets and flow-related variables, and identified tolerances to set targets for flow-related variables

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In order to assess local ecological condition within the CLLMM region, a linked suite of taxon-specific indicators were developed for the region (Chapter 4). Often indicator suites are chosen without an explicit description of the rationale behind their selection or of the alternatives that could have been chosen (Fairweather 1999a). Here instead, we aimed to take a comprehensive approach, attempting to include a representative range of indicators for the ecological character of the region. In particular, we attempted to include species and assemblages that were:

- likely to be directly affected by hydrodynamic parameters (e.g. water levels and water quality);
- considered to be key species or assemblages within the region (primarily based on previous research in the region or expert opinion);
- threatened and thus considered to be a Matter of National Significance under the *Environmental Protection and Biodiversity Conservation Act* 1999 (EPBC Act); and/or
- considered to be sensitive to environmental change (i.e. analogous to the canary in the coalmine).

We also included some invasive species as indicators. This ensured that the potential for changes in the distribution of pest species, as well as natives, would be assessed when considering the effects of environmental water requirements.

In addition to taxon- and assemblage-specific indicators, we have included a set of ecological processes. Process indicators tend to integrate responses across many species and provide an understanding of ecosystem function and resilience. By using a combination of taxon- or assemblage-specific and process-based indicators, a balance can be achieved between conservation of particular species and the provision of a functional, resilient wetland.

This chapter is a synthesis of the findings of the work undertaken to link the various indicator suites to environmental flow requirements and targets for the CLLMM region (Chapters 4, 6-9; Appendices C & D). It is based on detailed assessments of the relationship between the various indicators and the eight ecological objectives and 33 ecological outcomes. The following four chapters below contain the detailed rationale for the links between the list of objectives and outcomes and the vegetation, macroinvertebrate, fish and ecological-process indicator sets (Chapters 4-9, respectively). Those chapters provide rationale for why each species, assemblage or process could (or could not) be considered to be indicative of each of the 33 identified ecological outcomes. Also listed are key knowledge gaps and the metrics that could be used to measure each indicator in the field (see Appendix D for metric definitions and more information on their application).

Where indicators were thought to be representative of ecological outcomes, the available literature was searched and collated (in addition to expert opinion where necessary and/or possible) on the requirements of each indicator to a suite of environmental conditions that were thought to be flow related. These included salinity, turbidity, the annual return frequency (ARF) of barrage flows and/or floodplain inundation, connectivity, water levels and the timing of events. Information relating to the functional grouping (e.g. feeding groups for invertebrates), and location of each within the region were also included. This information was then used to identify thresholds for each of the flow-related parameters for the region, and to construct tables ('trade-off tables') that provided a summary of the known tolerances for each indicator for several of the parameters where most information was available. These tables provide some indication of the consequences of setting different objectives for the region, although caution is needed in their interpretation due to a lack of relevant, local field data for many indicators.

The suite of indicators covers a range of biotic and ecological processes. These are briefly described in the following sections.

5.1 Vegetation

The ten selected vegetation indicators species and assemblages cover a range of possible aquatic vegetation from the terrestrial edge of the floodplain to the lower edge of the euphotic zone (i.e. zone within which light penetrates the water column) in the CLLMM region (Chapter 6). Phytoplankton has not yet been included here but may be useful as a collective group to indicate whether the populations present are likely to be representative, or not, of a healthy, productive and resilient wetland. The group of vegetation indicators were considered potentially very useful for providing evidence for the achievement of long-term self-sustainability of populations and surrogacy for other organisms (e.g. habitat provision, food sources), habitat complexity and connectivity (i.e. diversity of habitats within system and links between aquatic and terrestrial habitats and taxa). The vegetation indicators included samphire & saltmarsh communities, paperbark woodlands (*Melaleuca halmaturorum*), lignum (*Muehlenbeckia florulenta*), diverse reed beds, water ribbons (*Triglochin procerum*), ribbonweed (*Vallisneria australis*), water milfoil (*Myriophyllum* spp.), spiny rush (*Juncus acutus*), and two species of *Ruppia* (sea tassels; *R. megacarpa* and *R. tuberosa*). *Gahnia* sedgelands and Black Swamp vegetation were also considered as potential indicators but were not included in the rationale tables due to insufficient knowledge in the scientific literature and the limited distribution of these two assemblages within the CLLMM region (although the available literature on tolerances is summarised in Appendix C). A summary of how the various vegetation indicators were linked to the identified ecological outcomes is presented in Table 6.11 (see Chapter 6 for additional detail). The specific literature compiled linking each vegetation indicator to flow-related parameters is presented in Table 18.1 in Appendix C.

5.2 Macroinvertebrates

The 19 selected macroinvertebrate indicator taxa were chosen to cover the gradient of freshwater, estuarine, marine and hypersaline habitats within the CLLMM region. The level of knowledge regarding their functional role within the region varied significantly among taxa. One of the main limitations in using macroinvertebrates as indicators for this region was the lack of specific knowledge and local data, particularly for the Lower Lakes, so much of the rationale for this group was drawn from research and management undertaken elsewhere. The freshwater macroinvertebrate indicator species considered were the freshwater mussel (*Velesunio ambiguus*), freshwater crayfish (*Cherax destructor*), mayfly larvae (Ephemeroptera), stonefly larvae (Plecoptera), caddisfly larvae (Trichoptera), amphipods (Amphipoda), segmented worms (Oligochaeta), hydra (*Hydra* spp.), freshwater limpets (Ancylidae), brackish water crab (Hymenosomatidae), marsh beetle (Scirtidae) and black fly larvae (Simuliidae). The estuarine and/or marine indicator species included the tubeworm (*Ficopomatus enigmaticus*), various errant polychaete worms (*Nephtys australiensis*, *Simplisetia aequisetis* and *Capitella* spp.), the microbivalve (*Arthritica helmsi*), and Goolwa cockle (*Donax deltoides).* The hypersaline macroinvertebrate indicator considered was brine shrimp (*Parartemia zietziana*). A summary of how the various macroinvertebrate indicators linked to the identified ecological outcomes is presented in Table 7.20 (see Chapter 7 for additional detail), with the compiled literature linking each indicator to flow-related parameters presented in Table 18.2 in Appendix C.

5.3 Fish

The 17 identified indicator species cover the range of freshwater, estuarine and marine habitats across the site, as well as different strategies for using the site (e.g. migratory versus resident). Pest species (i.e. carp *Cyprinus carpio*) were also included as an indicator of decline in site conditions and/or fish communities. As a group, the fish indicators were considered potentially useful for providing evidence for long-term self-sustainability, particularly in relation to successful recruitment, suitable habitats and food resources. They were also considered potentially-useful indicators of outcomes relating to hydraulic connectivity, particularly in relation to longitudinal biological connectivity (i.e. the exchange of energy, nutrients and carbon within and through the system). The fish indicators that were considered included Murray cod (*Macquaria peelii peelii*), golden perch (*Macquaria ambigua ambigua*), bony herring (*Nematolosa erebi*), Australian smelt (*Retropinna semoni*), Murray hardyhead (*Craterocephalus fluviatilis*), Yarra pygmy perch (*Nannoperca obscura*), carp, congolli (*Pseudaphritis urvillii*), yellow-eyed mullet (*Aldrichetta forsteri*), black bream (*Acanthopagrus butcheri*), small-mouthed hardyhead (*Atherinosoma microstoma*), mulloway (*Argyrosomus japonicus*), sandy sprat (*Hyperlophus vittatus*), Australian salmon (*Arripis truttacea*) and bronze whaler shark (*Carcharhinus brachyurus*). A summary of how the various fish indicators linked to the identified ecological outcomes is presented in Table 8.18 (see Chapter 8). The specific literature compiled linking each fish indicator to flow-related parameters is presented in Table 18.3 in Appendix C.

5.4 Ecological processes

Ten ecological processes were identified as key processes for indicating the overall health and productivity of an ecosystem without the need to monitor every species that is present. Ecological processes selected as indicators included basic ecological functions such as photosynthesis, decomposition, nutrient cycling, along with ecological responses to changing environments such as responses to salinity, acid/base and sediment dynamics, water clarity, terrestrialisation (or re-wetting), food-web functionality, and functional connectivity. Other ecological processes included were colonisation (including of invasive taxa) and bioaccumulation (both of potential pollutants but also carbon sequestration). Because of a current lack of knowledge regarding how processes link to various ecological outcomes, each process was only allocated to those outcomes for which we were sure a link existed. In some instances, information was also not available about the response of each ecological process to hydrological properties, particularly specific to the CLLMM region, so knowledge gaps were highlighted. Thresholds for the ecological process indicators were therefore not used to create trade-off tables but, with sufficient data on the processes, could be valuable for future management. Table 9.1 summarises the identified links between each process and the ecological indicators (see Chapter 9 for additional detail), with the compiled literature regarding links to flow-related parameters presented in Table 18.4 in Appendix C.

5.5 Trade-off tables

In order to summarise the available information which relates this comprehensive list of indicators with the flow-related parameters, a set of tables were produced illustrating known thresholds and tolerances. These trade-off tables were developed to allow the relationships between indicator taxa, assemblages and processes and hydrologic conditions to be easily visualised. Literature searches were used to identify critical thresholds, where possible, for water quality (focusing on salinity), flow regime (indicating an ARF), connectivity (specifying connections and timing) and water levels (links to water quality [e.g. acidification and salinity] and connectivity) for the

Coorong and Lower Lakes. This allowed the indicators for ecological condition to be directly related to the hydrodynamics and flow regime of the Lower Lakes and Coorong regions, and the various trade-offs associated with increasing salinities and decreasing flows to be highlighted. Therefore, the different outcomes, in terms of the biota and processes supported, arising from a range of possible environmental watering decisions can be assessed.

However, it is important to note that identifying critical thresholds for some indicators was difficult or impossible, because the available information varied widely across the different indicators. For example, some indicators were well-studied with precise information regarding their tolerances but others were poorly understood and very little information was available. As a result of the heavy reliance on previous work for identifying thresholds, most of the hydrological conditions that were investigated (e.g. links to salinity and water levels) were considered separately, as very few studies have been done that consider multiple factors simultaneously. Therefore, where tolerances are known, for almost all taxa, only a single stressor (or condition) has been considered. However, interactions between potential stressors are also known to be important. It is likely that individuals would be able to withstand more extreme conditions under a single stressor than they could for the same stressor when other stressors were also operating (i.e. interactions between stressors will be synergistic). Additional research into the interactions between common stressors in the region for a selection of representative species would be of significant benefit in understanding the overall magnitude of these effects. Thus, the illustrated thresholds should be interpreted as being maxima, and a conservative approach to interpreting the tables would be wise.

In addition, the salinity tolerances included were developed using two different methods: reporting those salinities at which organisms or processes have occurred in the field; or based on toxicological studies performed in the laboratory. In the laboratory experiments, values tend to be LC50 values (Lethal Concentration 50%), which is where 50% of the test population are dead. This represents a much higher risk to the population than would usually be considered acceptable in practice. We have identified where known tolerances are LC50 values, rather than field tolerances, and again, these values should be treated with caution, and used conservatively.

We focused on the trade-offs associated with various salinities, water levels and annual return frequencies for flooding in the Lakes and for barrage flows. Trade-off tables are presented for the salinity tolerance of vegetation (Table 5.1), macroinvertebrate (Table 5.2) and fish (Table 5.3) indicators in the Lakes, and the Coorong (Tables 5.4 to 5.6). A trade-off table is presented for the ARF of flooding in the Lakes for the vegetation indicators (Table 5.7). Similar tables for ARF for flooding in the Lakes are not presented for macroinvertebrate and fish indicators because it is not clear how changes in flooding regimes will affect either set of indicators. In fact, it is likely that both would respond indirectly, largely based on the response of the vegetated habitat with which each is associated. For fish, water quality was considered an over-riding consideration for the likely response to changes in flooding frequency. Trade-off tables are also included for the ARF of barrage flows to the Coorong for vegetation (Table 5.8), macroinvertebrate (Table 5.9) and fish (Table 5.10) indicator sets. Water level requirements in the Lakes are summarised for vegetation indicators (Table 5.11), but insufficient information exists to predict how water levels will affect other indicator sets (or it is likely that other species and assemblages would only be indirectly affected) or how Coorong water levels would affect any indicator set.

Insufficient information relating ecological processes to flow-related parameters were available yet to produce trade-off tables for process indicators.

Table 5.1: Salinity tolerances of vegetation indicators in the Lakes

Note: Dark grey shading denotes preferred ranges, light grey shading denotes marginal ranges and no shading denotes outside of range. Arrows indicate that tolerances extend beyond the salinity range shown here.

Indicator species	Lakes Salinity (µS cm^{-1} Electrical Conductivity [EC])						References & comments
Vegetation	**700 EC**	**1000 EC**	**1500 EC**	**2500 EC**	**5000 EC**	**10000 EC**	
Samphire & saltmarsh	High elevation, saline tolerant						Short & Colmer 1999, Clarke & Hannon 1970, Wardle 1991, Naidoo & Kift 2006
Paperbark	High elevation, saline tolerant						Marcar *et al.* 1995
Lignum							van der Sommen 1980
Diverse reed beds							J. Nicol pers. comm.
Water ribbons							Tolerant of pulses of saline water, Goodman *et al.* 2010
Ribbonweed							Brock 1981
Water milfoil							Orr *et al.* 1988
Spiny rush	Highly-tolerant invasive species					➔	Greenwood & MacFarlane 2009
Ruppia megacarpa						➔	Brock 1982a
Ruppia tuberosa						➔	Brock 1982a

Note: the increments of increase in salinity across the columns are not uniform.

Table 5.2: Salinity tolerances of macroinvertebrate indicators in the Lakes

Note: Dark grey shading denotes preferred ranges, light grey shading denotes marginal ranges, blue shading denotes LC50 values (i.e. where 50% of the test population are dead) and no shading denotes outside of range. Arrows indicate that the actual value exceeds the maximum illustrated on the table.

Indicator species	**Lakes Salinity (µS cm^{-1} EC)**						**References & comments**
Macroinvertebrates	**700 EC**	**1000 EC**	**1500 EC**	**2500 EC**	**5000 EC**	**10000 EC**	
Freshwater crayfish							Mills & Geddes 1980
Mayfly larvae						LC50 →	Kefford *et al.* 2003
Stonefly larvae						LC50 →	Kefford *et al.* 2003
Caddisfly larvae						LC50 →	Kefford *et al.* 2003
Amphipoda							Geddes 2005; Kangas & Geddes 1984
Hydra							Kefford *et al.* 2003; Zalizniak *et al.* 2006
Freshwater mussel							Walker 1981
Segmented worms							Highly variable tolerances
Freshwater limpets							Kefford *et al.* 2003
Brackish water crab						LC50 →	Kefford *et al.* 2003
Blackfly larvae							Velasco *et al.* 2006
Marsh beetle						LC50 →	Kefford *et al.* 2006
Tubeworms							Geddes & Butler 1984
Bivalve	Do not occur in fresh water						Wells & Threlfall 1982
Polychaete worms							Dittmann *et al.* 2006
Brine shrimp	Do not occur in fresh water						
Goolwa cockle	Do not occur in Lakes						Nell & Gibbs 1986

Note: the increments of increase in salinity across the columns are not uniform.

Table 5.3: Salinity tolerances of fish indicators in the Lakes

Note: Dark grey shading denotes preferred ranges, light grey shading denotes marginal ranges, blue shading denotes LC50 values (i.e. where 50% of the test population are dead) and no shading denotes outside of range. Arrows indicate that the actual value exceeds the maximum illustrated on the table.

Indicator species	Lakes Salinity (µS cm^{-1} EC)							References & comments
Fish	700 EC	1000 EC	1500 EC	2500 EC	5000 EC	10000 EC		
Murray cod						LC50	➔	Jackson & Pierce 1992; O'Brien & Ryan 1999
Golden perch						LC50	➔	Jackson & Pierce 1992; O'Brien & Ryan 1999
Bony herring						LC50	➔	SKM 2003
Australian smelt	Tolerates estuarine conditions						➔	Williams & Williams 1991
Murray hardyhead	Tolerates elevated salinities in Lakes & wetlands						➔	SKM 2003
Yarra pygmy perch								Prefers <1000EC; SKM 2003; McNeil and Hammer 2007
Common carp	Highly-tolerant invasive species						➔	Clunie *et al.* 2002
Congolli	Fresh adults, estuarine/fresh juveniles, marine/estuarine larvae					LC50	➔	SKM 2003; Hart *et al.* 1991; Clunie *et al.* 2002
Common galaxias							➔	Hart *et al.* 1991; Clunie *et al.* 2002
Short-headed lamprey							➔	Koehn & O'Connor 1990
Yellow-eyed mullet	Rare visitors						➔	Chubb *et al.* 1981
Black bream	Rare visitors						➔	Sarre *et al.* 2000
Small-mouthed hardyhead	Rare visitors						➔	Lui 1969; Potter *et al.* 1986; Molsher *et al.* 1994
Mulloway	Historical use						➔	Ferguson & Ward 2003
Sandy sprat	Rare visitors						➔	Marine/estuarine fish
Australian salmon	Unlikely to occur							Estuarine/marine fish
Bronze-whaler shark	Unlikely to occur							Marine visitor

Note: the increments of increase in salinity across the columns are not uniform.

Table 5.4: Salinity tolerances of vegetation indicators in the Coorong

Note: Dark grey shading denotes preferred ranges, light grey shading denotes marginal ranges and no shading denotes outside of range.

Indicator	**Coorong Salinity (g L^{-1}; ‰ TDS)**								**References & comments**
Vegetation	**0**	**36**	**60**	**90**	**120**	**150**	**180**	**200**	
Samphire & saltmarsh									Nicol 2007; Short & Colmer 1999; Purvis *et al.* 2009
Paperbark									van der Moezel *et al.* 1991
Lignum	Unlikely to occur in Coorong								Tolerant of salinities >100 ppt; van der Sommen 1980
Diverse reed beds	Unlikely to occur in Coorong. Perhaps around freshwater soaks.								Soaks would then provide water needs, not Coorong water
Water milfoil	Does not occur in Coorong								
Water ribbons	Does not occur in Coorong								
Ruppia megacarpa									Brock 1982a
Ruppia tuberosa		**Germination**							Brock 1982a

Note: the increments of increase in salinity across the columns are not uniform.

Table 5.5: Salinity tolerances of macroinvertebrate indicators in the Coorong

Note: Dark grey shading denotes preferred ranges, light grey shading denotes marginal elevations and no shading denotes outside of range.

Indicator	Coorong Salinity (g L^{-1}; ‰ TDS)								References & comments
Macroinvertebrates	0	36	60	90	120	150	180	200	
Freshwater crayfish	Do not occur in Coorong								
Mayfly larvae	Do not occur in Coorong								
Stonefly larvae	Do not occur in Coorong								
Caddisfly larvae	Do not occur in Coorong								
Amphipoda									Geddes 2005; Kangas & Geddes 1984
Hydra	Do not occur in Coorong								
Freshwater mussel	Do not occur in Coorong								
Segmented worms									Highly variable tolerances
Freshwater limpets	Do not occur in Coorong								
Brackish water crab	Do not occur in Coorong								
Blackfly larvae	Do not occur in Coorong								
Marsh beetle	Do not occur in Coorong								
Tubeworms									Geddes & Butler 1984
Bivalve									Kanandjembo *et al.* 2001
Polychaete worms									Dittmann *et al.* 2006
Brine shrimp									Geddes 1976
Goolwa cockle									Murray-Jones & Johnson 2003; Nell & Gibbs 1986

Note: the increments of increase in salinity across the columns are not uniform.

Table 5.6: Salinity tolerances of fish indicators in the Coorong

Note: Dark grey shading denotes preferred ranges, light grey shading denotes marginal ranges and no shading denotes outside of range.

Indicator	Coorong Salinity (g L^{-1}; %o TDS)								References & comments
Fish	0	36	60	90	120	150	180	200	
Murray cod	Does not occur in Coorong								
Golden perch	Does not occur in Coorong								
Bony herring									SKM 2003
Australian smelt									Only in MM estuary during freshes; McNeil 2004; SKM 2003; Hart *et al.* 1991
Murray hardyhead									Only in MM estuary during freshes; SKM 2003; Clunie *et al.* 2002
Yarra pygmy perch	Does not occur in Coorong								
Common carp	Does not occur in Coorong								
Congolli									SKM 2003; Clunie *et al.* 2002; Hart *et al.* 1991
Common galaxias									Chessman & Williams 1974; Bice 2010a
Short-headed lamprey									
Yellow-eyed mullet									Juvenile salinity tolerance <86 g L^{-1}; adults < 25 g L^{-1}; Chubb *et al.* 1981
Black bream									Bice 2010a; C. Bice pers. comm.
Small-mouthed hardyhead									Hart *et al.* 1991
Mulloway		Juveniles							Bice 2010a
Sandy sprat									Prefers less than marine salinities
Australian salmon									SARDI unpub. data
Bronze-whaler shark		Rare visitor							PIRSA unpub. data

Note: the increments of increase in salinity across the columns are not uniform.

Table 5.7: Annual return frequency (ARF) requirements for flooding in the Lakes of vegetation indicators

Note: Dark grey shading denotes preferred ranges, light grey shading denotes marginal ranges, hatching denotes ranges where persistence is possible but the population is likely to be at risk and no shading denotes outside of range.

Indicator	**ARF of lake water levels > 0.7 m AHD**						**References & comments**
Vegetation	**1**	**3**	**5**	**7**	**10**	**10+**	
Samphire & saltmarsh							Long-lived, requires freshes to recruit, seed for orange-bellied parrot
Paperbark							Long-lived, requires freshes to recruit; Marcar *et al.* 1995
Lignum							Long-lived, recruitment required every 3-5 years, likely to need freshes to germinate & flooding or rain to flower.
Diverse reed beds							Long-lived beds with vegetative replication, frequent inundation promotes diversity
Water ribbons							Sexual reproduction, recruitment near high water mark
Ribbonweed	**Littoral zone**						Sexual reproduction but spreads with permanent inundation, submergent *K*-selected; Gehrig & Nicol 2010
Water milfoil	**Littoral zone**						Long-lived beds with individuals replicating vegetatively
Spiny rush							Long-lived beds with vegetative replication
Ruppia megacarpa							Short-lived with sexual reproduction; Brock 1982a
Ruppia tuberosa							Inhabit water levels 0.1 – 0.4; Brock 1982a

Note: the increments of increase in ARF across the columns are not uniform.

Table 5.8: Annual return frequency (ARF) requirements for barrage flows of vegetation indicators in the Coorong

Note: Dark grey shading denotes preferred ranges, light grey shading denotes marginal ranges, hatching denotes ranges where persistence is possible but the population is likely to be at risk and no shading denotes outside of range.

Indicator	**ARF of barrage flows**						**References & comments**
Vegetation	**1**	**3**	**5**	**7**	**10**	**10+**	
Samphire & saltmarsh							Long-lived, requires freshes to recruit, seed for orange-bellied parrot
Paperbark							Long-lived, requires freshes to recruit Marcar *et al.* 1995
Lignum	Unlikely to occur in Coorong						Freshwater shrub
Diverse reed beds	Unlikely to occur in Coorong; except possibly around freshwater soaks						Soaks would then provide water needs, not Coorong water
Water milfoil	Does not occur in Coorong						
Water ribbons	Does not occur in Coorong						
Ruppia megacarpa							Short-lived, sexual reproduction, needs estuarine salinities
Ruppia tuberosa							Still present after extended no/low flows

Note: the increments of increase in ARF across the columns are not uniform.

Table 5.9: Annual return frequency (ARF) requirements for barrage flows of macroinvertebrate indicators in the Coorong

Note: Dark grey shading denotes preferred ranges, light grey shading denotes marginal ranges,hatching denotes ranges where persistence is possible but the population is likely to be at risk and no shading denotes outside of range.

Indicator	ARF of barrage flows						References & comments
Macroinvertebrates	**1**	**3**	**5**	**7**	**10**	**10+**	
Freshwater crayfish	Does not occur in Coorong						Lakes only
Mayfly larvae	Does not occur in Coorong						Lakes only
Stonefly larvae	Does not occur in Coorong						Lakes only
Caddisfly larvae	Does not occur in Coorong						Lakes only
Amphipoda							In both Lakes and Coorong
Hydra	Does not occur in Coorong						Lakes only
Freshwater mussel	Does not occur in Coorong						Lakes only
Segmented worms							Both in Lakes and Coorong, more in Lakes
Freshwater limpets	Does not occur in Coorong						Lakes only
Brackish water crab	Does not occur in Coorong						Lakes only
Blackfly larvae	Does not occur in Coorong						Lakes only
Marsh beetle	Does not occur in Coorong						Lakes only
Tubeworms							In both Lakes and Coorong
Bivalve							Only in the Coorong
Polychaete worms							*Nephtys australiensis* and *Simplisetia aequisetis* in both Lakes and Coorong; *Capitella* spp. in Coorong only
Brine shrimp							Coorong only
Goolwa cockle							Coorong beach only

Note: the increments of ARF of barrage flows across the columns are not uniform.

Table 5.10: Annual return frequency (ARF) requirements for barrage flows of fish indicators in the Coorong

Note: Dark grey shading denotes preferred ranges, light grey shading denotes marginal ranges, hatching denotes ranges where persistence is possible but the population is likely to be at risk and no shading denotes outside of range.

Indicator	ARF of barrage flows						References & comments
Fish	1	3	5	7	10	10+	
Murray cod	Does not occur in the Coorong						
Golden perch	Does not occur in the Coorong						
Bony herring							Found in Lakes and Coorong when connected
Australian smelt							Only in Murray Mouth estuary during freshes
Murray hardyhead							Only in Murray Mouth estuary during freshes
Yarra pygmy perch	Does not occur in Coorong						
Common carp	Does not occur in Coorong						
Congolli							Live for < 5 years, sexual reproduction, ideally free access, estuarine
Yellow-eyed mullet	Estuarine dependent						Observed trying to move into fishways, estuarine/marine
Black bream	Estuarine dependent						Observed trying to move into fishways, estuarine/marine
Small-mouthed hardyhead							Complete life cycles on either side of barrages, prefer access
Mulloway							Aggregations during spring/early summer discharge
Sandy sprat	Marine estuarine-opportunist						Estuary used as a nursery ground for juveniles
Australian salmon	Estuarine dependent						Barrage flows to maintain estuarine conditions
Bronze-whaler shark	Rare visitor						Access requires open Murray Mouth

Note: the increments of increase in ARF across the columns are not uniform.

Table 5.11: Water level requirements of vegetation indicators in the Lakes

Note: Dark grey shading denotes preferred elevations, light grey shading denotes marginal elevations and no shading denotes outside of range.

Indicator	Lake water levels (m AHD)										References and comments
Vegetation	**-1.0**	**-0.8**	**-0.6**	**-0.4**	**-0.2**	**0**	**0.2**	**0.4**	**0.6**	**0.8**	
Samphire & saltmarsh											Requires inundation for germination (Purvis *et al.* 2009)
Paperbark											Riparian species tolerant of periodic inundation (Denton & Ganf 1994)
Lignum											Inundation of >0.6 m AHD for > 1 year increases mortality; Rogers 2010a
Diverse reed beds											Rogers 2010a
Water ribbons											Sainty & Jacobs 1994
Ribbonweed											Submerged, limited by photic zone; J. Nicol pers. comm.
Water milfoil											Amphibious, limited by photic zone, readily colonises down gradient; J. Nicol pers. comm.
Ruppia megacarpa											Brock 1982a
Ruppia tuberosa											Brock 1982a

5.6 Summary of relevant thresholds and key learnings

5.6.1 Vegetation indicators

Vegetation indicators tended to be relatively well-studied and thus lent themselves well to links with flow-related parameters.

While a wide range of vegetation species and assemblages was considered as a part of this assessment, several were considered to be key to the ecological condition of the region and so could be considered as 'Ramsar significant biota' for the region. These included submerged macrophytes (Phillips & Muller 2006), and the sea tassel species (i.e. *Ruppia megacarpa* and *Ruppia tuberosa*), in particular for the estuarine and saline habitats in the region. However, the diversity and coverage of these species has been declining in recent years as a result of prolonged drought and low-flow conditions. For phytoplankton, species such as *Nodularia* spp. and *Anabaena* spp. may be likely to become more common and potentially form blooms if ecological conditions deteriorate (Muller 2010a). Small decreases in salinity in the Coorong may also lead to increased growth of the green algae *Enteromorpha* spp. which were predicted to have a minor negative impact on distribution of *Ruppia* spp. (Muller 2010a). *Enteromorpha* is not a taxon that was considered here, but may be one that should be considered in future iterations of the work.

5.6.1.1 Relationship between vegetation indicators and ecological objectives & outcomes

Of the objectives, the vegetation indicators were the most useful for providing evidence for of the long-term self-sustainability of populations, surrogacy for other organisms (e.g. vegetation as a habitat provision and a food source), habitat complexity and connectivity (e.g. the diversity of the vegetation and links between aquatic and terrestrial species) and for communities requiring varied hydrology. The indicators were considered moderately useful for identifying where outcomes related to population connectivity (temporal and spatial) and maintaining a persistent salinity gradient were achieved, due to the general longevity and physical position of the vegetation species and assemblages across the region.

The vegetation indicators were considered least useful in providing evidence for the achievement of outcomes relating to flow of water through and within the site (although lateral connectivity was important for some indicators), associated flow and water level variability, and redundancy in ecological function. The vegetation species and assemblages used were not able to be related to one of the 33 outcomes, Regular oxidation of sulfidic material. This is likely to be due to the currently limited knowledge on the implications of acid sulphate soils on vegetation communities, particularly specific to the CLLMM region.

For those outcomes which the vegetation indicators were considered very or moderately useful, the most common metrics suggested were abundance, including seedling, seedbank abundances, and distribution (Refer to Appendix D for definitions of each metric).

5.6.1.2 Key thresholds identified for vegetation

Many of the vegetation indicators, particularly the aquatic vegetation found in the Lakes, had preferred salinity ranges of less than approximately 1500 $\mu S\ cm^{-1}$ EC, with water ribbons having the lowest preferred salinity of less than approximately 1000 $\mu S\ cm^{-1}$ EC. Other vegetation indicators including the sea tassels and paperbark communities were considered much more tolerant to elevated salinities in the Lower Lakes region. However, sea tassels (i.e. *Ruppia* spp.) do not usually occur in freshwater lakes (< 1000 $\mu S\ cm^{-1}$ EC) and paperbark communities, although highly tolerant once established, require freshes for recruitment; so together these indicators do not represent the full range of vegetation expected at the site. For those species and assemblages that were found in the Coorong, the majority had salinity thresholds of approximately 45 g L^{-1}, with only paperbark communities and tuberous sea tassel tolerating more than 120 g L^{-1}.

Vegetation indicators showed a wide variation in the preferred ARF for lake water levels (i.e. ARFs for water levels >0.7 m AHD). Most species and assemblages were considered to be at risk when ARFs extended to between 5 and 10+ years, with every 3 years or lower being the thresholds for preferred frequency of flooding around the Lakes for most indicators. Similar thresholds for barrage flows were observed for the vegetation indicators in the Coorong, with the preferred thresholds of up to ARFs of 3, with marginal conditions including ARFs up to 7 and persistence possible but with populations likely to be at risk when ARFs exceeded 7 years.

Most vegetation indicators had preferred lake water levels of between 0.6 and 0.85 m AHD or greater. Between 0.2 and 0.6 m AHD, some vegetation indicators were still in preferred or marginal ranges. The operating range that has been suggested for the Lakes in the future as a part of this environmental water requirement assessment (Muller 2010b; Appendix H) is between 0.3 and 0.65 m AHD, with regular increases to 0.85 m AHD. This is where most vegetation indicators are within their preferred or marginal ranges. The most tolerant vegetation taxa were lignum and diverse reed beds, which still showed marginal tolerances to -0.5 m AHD. The influences of Coorong water levels, associated thresholds and tolerance zones have not yet been established.

5.6.1.3 Limitations and caveats associated with the vegetation indicators

Some of vegetation species and assemblages have contracted dramatically, or been lost to the region in recent years. Regulation and the homogenisation of the water regime is largely responsible, with species better suited to variable regimes the most affected (Walker *et al.* 1994; Norris *et al.* 2001). Submerged aquatic vegetation has become increasingly restricted to the margins of the lakes and shallow wetlands as a result of declines in water quality and low lake levels in recent years have changed community structure (i.e. there has been a shift to a more terrestrial community with the lowering of lake levels). Despite these changes in the diversity and distribution of vegetation communities, historically-significant taxa and assemblages have still been considered as vegetation indicators, due to their ecological importance and their potential ability to recolonise or regenerate upon Lake levels recovery.

A range of species and communities found in the region are listed under the EPBC Act (e.g. Black swamp communities; Phillips & Muller 2006) but were not used as indicators in this assessment. Many of these are found at high elevation, acting as terrestrial species and so are only directly influenced by River Murray flows or water levels. Thus, we do not consider them to be primary indicators for the determination of environmental water requirements for the site.

5.6.2 Macroinvertebrate indicators

For many macroinvertebrate indicators there was very little local information available, particularly within the Lakes. In fact, for many areas, the presence or absence of many taxa was unknown. Thus, in selecting macroinvertebrate indicators, we relied on taxa that were known to be useful indicators elsewhere, where there was a lack of local knowledge.

Macroinvertebrates are not usually assessed as a part of a Ramsar ecological character description, so they were not covered in Phillips & Muller (2006). However, they form a vital part of an aquatic ecosystem and contribute to the ecological character of the region. Several species have been suggested as being key in the Lakes, including *Velesunio ambiguus* (freshwater mussel), which is particularly sensitive to salinity levels in the Lakes and has recently experienced a die-back (see Chapter 7), and *Cherax destructor* (freshwater crayfish), which is a mobile species that typically migrates to avoid poor water quality, although is susceptible to long-term increases in salinity (Muller 2010a). The tubeworm *Ficopomatus enigmaticus* has recently expanded in range in Lake Alexandrina in response to rising salinities, so could be a good indicator of change from freshwater to estuarine or marine habitats (which may be desirable or not, depending on where it is located) (Muller 2010a).

5.6.2.1 Relationship between macroinvertebrate indicators and ecological objectives & outcomes

Macroinvertebrate indicators were considered to be very good indicators of self-sustaining populations, habitat and food web complexity (i.e. a range of suitable habitats and food sources exist). Numerous macroinvertebrate indicators were also good indicators for water quality, and salinity in particular; so they are good indicators that a persistent salinity gradient is present within the region. Macroinvertebrate indicators were moderately useful for identifying where outcomes related to population connectivity, hydraulic connectivity, flow and water level variability, redundancy and ecological function were met. This was primarily because some taxa were sensitive to water quality (e.g. dissolved oxygen and pH) or variable flow speeds, were intolerant of flooding without refugia, or had seasonal flow preferences. The macroinvertebrate indicators were considered less useful for indicating temporal and spatial habitat complexity and connectivity (i.e. aquatic and terrestrial habitats). This is due to many selected indicators being primarily aquatic and any reliance on terrestrial systems being unclear.

Macroinvertebrate indicators were not considered for identifying Lateral connectivity of vegetation, so did not apply to only one of the 33 outcomes. For the other outcomes, the most common metrics suggested were abundance, distribution and recruitment events (Appendix D).

5.6.2.2 Key thresholds identified for macroinvertebrates

Most of the macroinvertebrate indicators had recorded LC50 values greater than the salinity range considered here for the Lakes (i.e. 700 to 10 000 µS cm^{-1} EC). The remaining indicators (i.e. freshwater crayfish, caddisfly larvae, hydra and brackish water crab) had preferred or marginal salinities ranges that included the values that we considered, suggesting that they were quite tolerant of elevated salinity levels. Freshwater mussels, mayfly larvae and hydra had the lowest threshold for preferred salinity at 5000 µS cm^{-1} EC. Most of the selected macroinvertebrate indicators did not occur in the Coorong (i.e. were freshwater taxa), but of those that occurred there, a majority had preferred salinity ranges of up to approximately 45 g L^{-1}. Only the polychaete worms and brine shrimp had higher preferred tolerances (i.e. 70 g L^{-1} and >200 g L^{-1}, respectively).

Preferred ARFs for flooding in the Lakes for macroinvertebrate indicators were not assessed using trade-off tables because any influence on the selected indicators would be linked to water quality (e.g. pH < 6) or to the presence of littoral vegetation as habitat for some taxa. Of the macroinvertebrate indicators that were found in the Coorong, most preferred an ARF of less than 1 for barrage flows, with marginal tolerance to ARFs of up to 3. Only Amphipoda and brine shrimp had higher preferred ranges, of 3 and greater than 3, respectively.

Trade-offs associated with changes in water levels in the Lakes and Coorong were not assessed. This was primarily because it is difficult to determine whether water level is a driving factor, as other variables including water quality variables and flow are thought to be more important. Most macroinvertebrates are mobile and tend to be reasonable colonisers, so they respond quickly to changes and would not persist in areas of declining conditions (e.g. drying areas). Thus, no water-level thresholds for the macroinvertebrate indicators of the Lakes and Coorong could be identified.

5.6.2.3 Limitations and caveats associated with the macroinvertebrate indicators

The extent of our knowledge on macroinvertebrates present within the CLLMM region is both spatially and temporally limited. Benthic and edge-dwelling macroinvertebrates have been studied in the Coorong and around the Goolwa Channel and tributaries, respectively. Other macroinvertebrates such as those in the water column, edge habitats and those broadly distributed in the Lower Lakes have been less well-studied. As a result, the macroinvertebrate indicators have been selected based on various levels of understanding regarding their functional roles within the region. As there is likely large variability in feeding guild responses to changing environmental conditions, the strength of predictions may be limited.

One possible reason for this variability in the level of understanding of macroinvertebrate indicators that existing policies or management plans do not explicitly include macroinvertebrates in their own right. Birds, fish and vegetation are often the focus of management plans and guidelines and the importance of macroinvertebrates (e.g. as a food source for these so-called charismatic megafauna) is often overlooked. This should be addressed and the importance of a healthy macroinvertebrate assemblage recognised as contributing to the ecological character and resilience of the region.

5.6.3 Fish indicators

As for vegetation indicators, there has been a significant amount of research on many of the species used as fish indicators in this assessment, particularly regarding tolerances to salinity and pH, as well as habitat requirements. However, for some species, particularly non-commercial species, significant gaps in our understanding remain.

Any assessment of Ramsar-significant fish species would include Murray cod and Yarra pygmy perch, both of which are listed as threatened species within the region. Yarra pygmy perch was considered to be one of the less-mobile species in the region, and so is more reliant on environmental conditions of sufficient quality. At the time of writing, conditions in Lake Alexandrina were above tolerances and Yarra pygmy perch was considered to be locally extinct. At the same time, congolli and common galaxias were also in danger of losing the remainder of their preferred habitat, and Murray cod, golden perch and common carp were considered unlikely to persist in Lake Albert after March 2011 under unchanged conditions, given that Lake Albert was predicted to exceed their salinity tolerances by that time and the barrier at Narrung Narrows would prevent their escape (although that has subsequently been breached). Thus, all the species listed could be considered to be Ramsar-significant biota.

5.6.3.1 Relationship between fish indicators and ecological objectives & outcomes

Of the identified objectives, the fish indicators were considered potentially useful for providing evidence of long-term self-sustainability, particularly in relation to successful recruitment, suitable habitats and food resources. This was primarily due to fish being highly mobile, with many species requiring access to a range of habitats for feeding, reproduction and the ability to move to avoid unfavourable conditions. Fish also tended to be useful indicators of outcomes relating to hydraulic connectivity (particularly indicating longitudinal biological connectivity), due to the importance of movement as part of the life cycles of some species. Fish indicator species were moderately useful for identifying where outcomes related to redundancy and appropriateness of ecological function, particularly in relation to the role that fish species play in forming complex food webs and the presence of acid- and saline-tolerant fish species within the site. Fish indicators were also moderately useful in assessing the maintenance of a persistent salinity gradient at the site due to the range of salinity tolerances represented.

The fish indicators were least useful in providing evidence for the achievement of outcomes relating to ecological function, in particular the functions performed by multiple species, efficiency of nutrient cycling and the control of invasive species. Variability in flow and water levels were also outcomes for which the fish indicators were least useful in providing evidence. It is possible that this is because fish tend to be indirectly affected by changes, partly as a result of their ability to move from adverse conditions. Fish indicators were also not considered useful in providing evidence for outcomes relating to the existence of viable propagule banks to enable temporal connectivity, efficient nutrient cycling and the regular oxidisation of sulfidic material.

For those outcomes where fish indicators were considered useful or moderately useful, the most common metrics included abundance, demographics (e.g. size and age distributions of populations) and recruitment events (i.e. young of year).

5.6.3.2 Key thresholds identified for fish

Many of the fish indicators were either rare visitors to parts of the region (e.g. the Lakes) and/or were tolerant of elevated salinities (particularly common carp, an invasive species). Of those found within the Lakes region (i.e. Murray cod, golden perch, bony herring and congolli) all had recorded LC50 values higher than the salinity range considered here (i.e. 700 EC to 10 000 µS cm^{-1} EC). The only fish from the Lakes region that had LC50 values within this range, the Yarra pygmy perch, had preferred salinity levels of up to 1000 µS cm^{-1} EC and LC50 values of approximately 10 000 µS cm^{-1} EC. For fish indicators found in the Coorong, most had preferred salinities ranges of up to 36 to 50 g L^{-1}. LC50 values for these species (e.g. congolli, bony herring, yellow-eyed mullet and black bream) tended to be less than 100 g L^{-1}. The most tolerant fish indicators (i.e. Murray hardyhead and small-mouthed hardyhead) had preferred ranges up to 90 g L^{-1} or greater. It is also interesting to note that for some fish species (e.g. small-mouthed hardyhead) the salinity tolerance in the field was actually substantially higher than the lowest known LC50 value, further complicating the use of LC50 values in setting target thresholds (*cf.* Wedderburn *et al.* 2008; Bice 2010a).

The trade-offs for the ARF for flooding lake levels were not assessed. This was primarily because the influence of high water levels in the Lakes is not considered to be independent to the influence of other environmental variables on fish indicator species or assemblages, and thus it was not straightforward to assess requirements. For example, the influence of high water levels can be linked to water quality (e.g. pH and salinity) or vegetation conditions (e.g. fish dependence on littoral vegetation). For barrage flows, most of the fish indicators were not found in the Coorong and/or were not estuary-dependent, but for those that were, ARFs >5 for the return of barrage flows tended to result in populations for which persistence was possible, but such a long time without connection and exchange would put the majority of these species at risk (e.g. bony herring, mulloway and small-mouthed hardyhead). As for ARFs for flooding water levels in the Lakes, trade-offs for water levels in the Coorong were not assessed. Again, this was due to the likely dependence of fish indicators on the linked effect of water quality variables and dependence on littoral and riparian vegetation.

5.6.3.3 Limitations and caveats associated with the fish indicators

Many abiotic and biotic variables exert important influences on fish indicator species and assemblages. Flow regime, physicochemical drivers and connectivity were considered to be key abiotic drivers that were important in structuring fish assemblages within the Lower Lakes and Coorong region (Bice 2010a). Biotic factors such as habitat availability and vegetation patterns also influence fish assemblage patterns. As conditions change within the region, the relative importance of each of these factors in shaping fish assemblages varies. For example, under good conditions, where the system is functionally connected and water quality is favourable, physicochemical factors tend to be relatively unimportant, and biological interactions become the primary drivers of fish populations. Under unfavourable physicochemical conditions, tolerances to water quality become more important. Therefore, it is the links between these variables which can be important when considering fish indicators, a limitation to the trade-off tables which currently represent only a single stressor.

In addition, for many fish species, different life-history stages are likely to have different tolerances to the stressors considered here. Wherever information was available, we have drawn the values shown from those stages that are likely to be most sensitive (e.g. larval or juvenile stages), but this information is not available for all taxa, and is also not likely to be independent of multiple stressors.

5.6.4 Process indicators

Ecological processes are rarely considered when suites of indicators are selected. Part of the reason for this may be a general lack of understanding of how ecological processes relate to ecological health. However, they have the potential to provide much richer sources of information that measuring species identity and abundance alone is able to, particularly when constructs such as resilience are of interest.

To date there have been no specified Ramsar-significant processes identified for the region. How ecological processes could be used to represent ecological character remains a key knowledge gap in the CLLMM region, as elsewhere.

5.6.4.1 Relationship between process indicators and ecological objectives & outcomes

Ecological process indicators tended to be most useful as indicators of self-sustaining populations and appropriateness and diversity in ecological function. Decomposition was identified to be the single most useful ecological process as an indicator across a range of outcomes. Ecological processes were moderately useful for identifying when outcomes related to population connectivity, a persistent salinity gradient across the region and aquatic-terrestrial connectivity were met. They were considered less useful as indicators of flow and water-level variability across the region.

The ecological processes were not useful as indicators of five of the outcomes, including that water residence times were finite, signifying that a range of flows were delivered to the site, a tidal signal apparent, wide riparian & littoral zones supported and lateral connectivity of vegetation.

Where the ecological processes were identified as being useful indicators, the identified metrics included the rates of change in the level of that process occurring through space or through time or changes in ratios of two types of organisms (e.g. saline-tolerant vs. saline-sensitive).

5.6.4.2 Key thresholds identified for ecological processes

The explicit use of ecological processes is a relatively new concept and is not frequently applied in the management of aquatic ecosystems. Despite the advantages of using ecological processes (e.g. integrate responses across multiple species, easy to measure and more directly reflect the consequences of ecological change), due to the limited information available, key thresholds have not yet been able to be defined.

5.6.4.3 Limitations and caveats associated with the process indicators

Given the limited previous focus on ecological processes in the region, in attempting to use processes as indicators, we have focused specifically upon identifying which processes are known to be relevant to the specified ecological outcomes, based on our current knowledge. It is likely that, as our knowledge level increases, it will become apparent that the processes listed are also relevant as indicators of other outcomes. However, at the present time, our incomplete understanding of the links between processes and outcomes and the lack of ground-truthing and measurement protocols, mean that additional links may be tenuous. Also, there are instances where ecological processes would be more difficult to measure than a direct environmental measurement (e.g. of salinity), which should not be overlooked. In these instances, the process indicators may still be relevant to provide further information regarding the ecological consequences of those variables (e.g. the ecological response to flow) but, as stated, the ecological process is considered to be a rather indirect manner of achieving the same answer as is provided by direct physical or chemical measurements.

5.7 Sub-lethal impacts of stress on indicators

This process of developing an environmental water requirement for the Coorong, Lower Lakes and Murray Mouth was focused on ensuring that the region continued to support a healthy, productive and resilient wetland of international importance. Based on predicted river flows under climate change (CSIRO 2008), it was decided that maintaining and restoring the Ramsar-listed ecological character of the region, as described by Phillips & Muller (2006), remained an achievable goal (DEH 2010). In order to meet this goal, thresholds needed to be set for water levels and water quality at levels where we could be confident that the ecological character, as represented by the indicators summarised above, would persist.

Much of the published work relating to species and assemblage tolerances concentrated on environmental conditions under which those species and assemblages have been found in the field, or on the lethal concentration values (LC50). The LC50 value for a species or an assemblage is an extremely coarse measurement of a tolerance (as 50% of the individuals would already be dead), so it is not appropriate for use in setting target environmental conditions to maintain and restore the Ramsar-listed ecological character. Conditions under which the species and assemblages have been detected in the field are a better basis upon which to set target thresholds, but persistence is also not always the most appropriate measure of ecological health, particularly for long-lived species, which may persist in unfavourable conditions for many years or even decades, while suffering significant sub-lethal stress.

Sub-lethal stress (or sub-lethal impacts) has been defined as stress that changes the condition of an organism without causing mortality (Barton & Iwama 1991). Such changes may include increased incidence of disease, slower or lower levels of growth, failure to reproduce successfully or changes in tissue, organ or cellular functions (e.g. changes in osmoregulation) (Hassell *et al.* 2006). In some instances, behavioural change is also possible. There is a continuum of severity of sub-lethal impacts, tending to increase as the lethal threshold for a stressor (or combination of stressors) is approached. Where environmental conditions resulting in sub-lethal impacts persist for long periods, and, where they are severe enough, they are capable of causing the loss of the species or assemblage in the long term (e.g. due to a failure to successfully reproduce), even though conditions may not be severe enough to kill all individuals outright. Thus, any assessment of environmental conditions suitable to support a healthy, productive and resilient wetland of international importance needs to consider the variables for which sub-lethal impacts may be important (e.g. salinity and pH), and set thresholds to minimise the likelihood of their occurrence.

Little specific information is available in the literature for thresholds at which sub-lethal impacts appear, although vegetation is considered less tolerant than macroinvertebrates, for example. Nielsen & Brock (2009) cite an example of corixid beetles in English wetlands being tolerant of a wider range of salinities but the aquatic plants, which provide critical habitat for those beetles, were more sensitive. For vegetation indicators in the region, there is some information available relating to sub-lethal effects of salinity. Even less information is available relating to sub-lethal thresholds of aquatic faunal assemblages.

Submerged aquatic plants, which are considered to be Ramsar-significant biota (see Section 5.6), and have been called the "architecture of the system" (Phillips & Muller 2006; p183) because they create physical habitat structure, provide an environment conducive to respiration and to carbon and nutrient cycling, while also creating a direct and indirect source of food and generating organic matter and oxygen via photosynthesis (Phillips & Muller 2006). Thus the loss of this assemblage from the ecosystem would significantly alter the ecological character of the region because of associated impacts on food resources and reduced habitat quality for other biota (Nielsen & Brock 2009).

Upper lethal salinity thresholds for most freshwater plant species are between 3 and 4 g L^{-1} (Nielsen *et al.* 2003a; Nielsen & Brock 2009). Above these salinities, non-halophyte species (i.e. species that are sensitive to salinity) tend to be replaced with halophytic species (i.e. salt-tolerant species) such as *Ruppia* spp. and *Lepilaena* spp. (Nielsen *et al.* 2003a). However, different species have different responses to increasing salinity with some being extremely susceptible to small increases and others tolerating and even benefiting from small increases in salinity (Brock *et al.* 2005; Nielsen *et al.* 2003a, 2007, 2008). At salinities approaching threshold values, aquatic species are less likely to successfully germinate. Where germination does occur, it can be delayed, resulting in a reduced growing season. If the season becomes sufficiently short, the plant may not reach maturity and will therefore be unable to set seed, resulting in the depletion of the seedbank through time and decreasing the overall resilience of the wetland (Sim *et al.* 2006).

Nielsen *et al.* (2003a) outline that for salinities above 1 g L^{-1} (~1500 µS cm^{-1} EC) adverse impacts on aquatic plants begin to occur, such as:

- reduced growth rates (James & Hart 1993);
- reduced development of roots and leaves (Nielsen *et al.* 2003b);
- suppression of sexual and asexual reproduction (James & Hart 1993; Warwick & Bailey 1997, 1998);
- the prevention of flower and tuber development (Warwick & Bailey 1996); and
- reduction in the emergence of plants from dormant propagules in wetland sediments (Brock *et al.* 2005; Nielsen *et al.* 2003b, 2007, 2008).

For aquatic faunal assemblages, the majority of work that has been undertaken has focussed on identifying LD50 thresholds that result in mortality of a species. As for vegetation, however, lower concentrations are likely to result in impairment of survival, growth and reproduction (Hoffman & Parsons 1991). Where long-term recruitment is affected there is a depletion of "biotic reservoirs" (Nielsen *et al.* 2003a; pg 662) (e.g. resistant spores or egg banks that are analogous to seed banks in vegetation), which then decreases the resilience of an assemblage and lowers its ability to respond to freshwater flow events (i.e. floods). It is important to also note that sub-lethal effects are also possible for conditions below preferred tolerance ranges, not just for high levels (e.g. increased incidence of disease of euryhaline fish species at low salinities; Wedderburn *et al.* 2008).

The available data suggest that aquatic biota is adversely affected by salinities exceeding approximately 1 g L^{-1} (Hart *et al.* 1991). Nielsen *et al.* (2003b) found lower diversity of microcrustacean taxa at similar salinity levels (i.e. 1 g L^{-1}) for some species, while increased salinity may also reduce egg viability or block cues that trigger emergence. McEvoy & Goonan (2003) found that the number of halosensitive invertebrate species declines, along with overall richness, and that halotolerant species appear at salinities exceeding 1 g L^{-1}.

Freshwater faunal assemblages are influenced by increases in salinity and changes in hydrology in both the short and long term (Brock *et al.* 2003; Nielsen *et al.* 2003a,b). Fewer eggs and seeds are likely to hatch from sediments in freshwater wetlands experiencing increasing salinity, thus having a marked negative effect on biodiversity (Brock *et al.* 2005; Nielsen *et al.* 2007, 2008). Few freshwater biota will remain at salinities above 5 g L^{-1} (Brock *et al.* 2005; Nielsen *et al.* 2003a, 2007, 2008).

Freshwater fish are also affected. Some species are unable to complete their life cycle in water near their upper salinity tolerance. For example, adult Murray cod and golden perch are able to tolerate moderately-high salinities, but their larval and juvenile stages require fresher waters (Nielsen & Brock 2009). In addition, adult fish persisting in waters close to their upper salinity threshold are also likely to be significantly stressed and may exhibit slower growth, take longer to reach sexual maturity or may be more vulnerable to parasites and diseases (Barton & Iwama 1991; Hassell *et al.* 2006).

There is no evidence that freshwater communities will survive and reproduce under long-term increased salinity, irrespective of whether that increase occurs as a slow gradient of increased salinity or as a sudden challenge (Nielsen *et al.* 2008), although in the short term, the latter is more likely to induce immediate mortality. Even though the dormant egg and seed banks of freshwater animals and plants may be able to survive for periods of time under elevated salinities (Smith 2006), they are unlikely to emerge and survive to reproduce and replenish the egg and seedbank under saline conditions. In general, salinised freshwater wetlands will need to be colonised by salt-tolerant species for a functional wetland to persist (Nielsen *et al.* 2008). This would involve a shift in the ecological character of the region.

In general, naturally-saline wetlands have fewer species than freshwater wetland communities, while in contrast, freshwater wetland communities are more diverse and heterogeneous (see Nielsen & Brock 2009 for references). Although increased salinity reduces diversity (Hammer 1986), salinity will not be the only relevant factor causing a decrease in diversity. Indirect effects, such as food-web cascades or the loss of critical habitat features (which have been impossible to specify here) are also likely to have a negative impact on biota (Williams 1998).

The environmental impact of increasing salinity on the biota of freshwater systems is poorly understood but complex (Hart *et al.* 1990, 1991; James *et al.* 2003; Nielsen *et al.* 2003a,b). In recent years there has been considerable research on the effects of salinity on a range of Australian freshwater organisms but little work has been undertaken in the CLLMM region specifically examining the salinity tolerances of resident freshwater species beyond that of Wedderburn *et al.* (2008), although additional information on field distributions was being collected at the time of writing that may improve this understanding. As a result, the available literature (much of which focuses on wetlands in the east of the Murray-Darling Basin, the Murray floodplains upstream of the CLLMM or outside of the Basin) results in salinity tolerances of local freshwater species and assemblages needing to be inferred from similar studies elsewhere, or for similar taxa or assemblages.

Local salinity tolerances is a key knowledge gap that should be addressed in the near future but given the knowledge that freshwater communities will be influenced by an increase in salinity above salinities of 1 g L^{-1} and changes in hydrology in both the short and long term (Brock *et al.* 2003; Nielsen *et al.* 2003a,b), this should act as an effective maximum level for water quality in the freshwater components of the system that should not be exceeded at the site.

5.8 Discussion

5.8.1 Setting target thresholds for developing an environmental water requirement

The overall goals of the compilation of these indicator sets were:

- firstly to identify a set of taxa, assemblages and ecological processes that would enable managers to determine whether the ecological objectives and outcomes for the region were being met;

- but also, more importantly for the process of determining an EWR for the region, to link those sets to flow-related variables and identify relevant thresholds that could be used in the next modelling stages of the EWR methodology.

Based on the information that we were able to compile, along with preliminary hydrological modelling undertaken for the Lakes (Heneker 2010), we judged that target thresholds focusing on salinity in Lake Alexandrina would be most appropriate. Salinity was identified as the water quality component that was most likely to affect the ecological character of the CLLMM region, because preliminary modelling indicated that maintaining specific salinity levels required the most water to support (e.g. compared to water levels), and it was the best-described variable both for the region and for the selected indicators (Heneker 2010). That is, maintaining salinity levels in Lake Alexandrina required large volumes of water that were also sufficient to maintain targets associated with water level, flooding frequencies and Lake Albert, due to the short hydrological memory within Lake Alexandrina (Heneker 2010). Thus, we have set salinity targets for Lake Alexandrina based on known tolerances of the selected indicators. We have then used these targets as the basis for setting of EWRs for the region (based on hydrological modelling in the Lakes, and hydrodynamic and ecological response modelling in the Coorong).

Other important flow-related variables such as acid/base dynamics were less-well described, are harder to model and had fewer known tolerances for the selected indicators. This is not to suggest that they are unlikely to impact the ecological character of the region, but they were less appropriate for use in the determination of an EWR for the region.

The available literature suggested that many species and assemblages have salinity tolerances in the order of 1000 µS cm^{-1} EC, particularly for the appearance of sub-lethal effects that would lower the resilience of the wetland ecosystems through time. This is true of submerged aquatic vegetation and freshwater invertebrate taxa, in particular. By the time salinities of 1500 µS cm^{-1} EC were reached, sub-lethal impacts would certainly be operating for many species and assemblages, and some indicator taxa would be at risk of local extinction. Thus, setting a salinity threshold of 1500 µS cm^{-1} EC would be appropriate as a management target.

The unique geomorphology of the Lower Lake region means that salinities in Lake Albert are usually directly linked to those in Lake Alexandrina (Heneker 2010). Thus, salinities in Lake Albert also need to be considered when setting a salinity target in Lake Alexandrina. When Lake Alexandrina has an average salinity of 1000 µS cm^{-1} EC, the average salinity in Lake Albert tends to be around 1500 µS cm^{-1} EC (Heneker 2010). An average salinity of 1500 µS cm^{-1} EC in Lake Alexandrina would see a corresponding salinity in Lake Albert of 2300 µS cm^{-1} EC or more (Heneker 2010).

In addition, the level at which salinity targets for Lake Alexandrina are set also largely influences the amount of water flowing through the barrages to the Coorong (as it is barrage discharges that control salinity levels in Lake Alexandrina; Heneker 2010). Thus, the level at which a salinity target for Lake Alexandrina is set will also influence the hydrodynamics and ecological response in the Coorong. The effects of the level at which salinity targets are set therefore needs to be assessed based on its impact on the Coorong and Lake Albert, as well as for Lake Alexandrina.

Salinity tolerances for the ecological indicators found within the Lakes indicated that a target of an average annual salinity of 700 µS cm^{-1} EC would be conservative. This is consistent with the salinity target identified in the Ramsar Ecological Character Description for Lake Alexandrina (Phillips & Muller 2006). Previous research and historical accounts that indicate Lake Alexandrina has been predominantly fresh (>90 % of the time; see DEH 2009 for additional detail). Consequently the biota associated with these wetlands is dependent on freshwater salinities (see Section 5.6). Thus, an appropriate target would be to aim for a flow regime to maintain salinities around a long-term average of 700 µS cm^{-1} EC in Lake Alexandrina but keeping actual salinities below 1000 µS cm^{-1} EC in 95% of years and 1500 µS cm^{-1} EC at all times. However, it is not known how realistic this target may be in the context of the upcoming Murray-Darling Basin Plan and future climate change.

Based on these considerations, we have chosen to investigate three salinity targets for Lake Alexandrina, to assess the differences in impact on CLLMM ecosystems and environmental conditions. Modelling was therefore undertaken to investigate targets of an average annual salinity 700 µS cm^{-1} EC, a maximum annual salinity of 1000 µS cm^{-1} EC and a maximum annual salinity of 1500 µS cm^{-1} EC, all of which were average values for the whole of Lake Alexandrina (and thus did not account for short-term spatial variability). By assessing these three values, the reality associated with delivering less water than would be needed to meet the ideal target of a long-term average of 700 µS cm^{-1} EC, with maxima of 1000 µS cm^{-1} EC in 95% of years and 1500 µS cm^{-1} EC in all years could also be assessed. The modelling and other assessments of these targets can be found in Chapters 10-14 and in Heneker (2010).

5.8.2 Consolidation and complementarity of indicator sets, and links to other measures of ecological condition

In undertaking this process, an extremely broad suite of taxa, assemblages and ecological processes were selected to act as indicators of the ecological objectives and outcomes that were set for the region. These were developed to ensure that the region continued to act as a healthy, productive and resilient wetland of international importance into the future. In linking the various indicators to the 33 identified ecological outcomes, there was a large amount of overlap, with many indicators thought to be indicative of the same ecological outcomes. This suggests that some degree of consolidation of these indicators is possible, and that the same information could have been derived from a smaller sub-set of indicators.

While it was important to explore the use of a wide range of indicators, partly to assist in identifying those that were most sensitive to the flow-related variables investigated, it is not practical to continue to use such a large suite of indicators in the future. The indicators here should be used in future assessments of EWRs as additional information becomes available, and by managers in determining whether the benefits expected from meeting the recommended EWR manifest. Therefore, it would be of significant benefit to reduce the overall number of indicators across which assessments need to be made and monitoring needs to occur.

In consolidating the indicator sets, it is important to acknowledge that different sets of indicators are thought be to better-suited to different ecological outcomes. For example, macroinvertebrate indicators were most consistently associated with outcomes relating to habitat and food web complexity. Fish indicators were consistently associated with hydraulic connectivity outcomes, and vegetation indicators were most consistently associated with the surrogacy for other organisms, habitat complexity and diversity and communities requiring varied hydrology. Indicators across all groups were associated with outcomes for the presence of self-sustaining populations. The variability in the indicator sets that were most consistently associated with each ecological objective made it difficult to simply select one set to concentrate on in the future. It is important to note that selecting the smallest set would not necessarily be the best approach, as different indicators will be better linked than others, and this is unlikely to be consistent across all the outcomes. Also, some indicators will have easier, more repeatable and better developed sampling protocols than others. Thus, specific research is required to develop a robust, defensible and representative sub-set of indicators for future use.

Ecological process indicators were harder to relate directly to the selected outcomes because of a lack of knowledge of each process and how they relate to flow-related variables. However, they had significant potential to greatly reduce the need to monitor large numbers of variables (e.g. individual species) to gain information for outcomes where they are associated, as they tend to integrate responses across taxonomic groups. Thus, additional research into this area is recommended to streamline future monitoring activities.

By selecting a wide range of species, assemblages and ecological processes, we have attempted to ensure that our assessment here is relevant throughout the CLLMM region. So, while the salinity target that has been determined is focused solely on Lake Alexandrina, this is not the case for our overall assessment. As discussed above, the hydrology of the region means that meeting salinity targets in Lake Alexandrina has a flow-on effect for water levels, flooding frequencies and barrage releases in the region, as well as salinity in other management units (e.g. Lake Albert). Therefore, we believe that by meeting the salinity target determined for Lake Alexandrina, the ecological character of the region as a whole will be supported.

One of the limitations of approaching the task in this fashion, as mentioned above, is that there are difficulties associated with treating individual ecological components in isolation (e.g. species by species) and with treating individual flow-related parameters in isolation (e.g. salinity then pH then flooding frequency). The nature of the task meant that some assessment of individual components of ecological character was required, particularly given that the available literature tends to report tolerances on a species-by-species basis and for individual stressors. Our understanding of the links between ecological components and multiple stressors (or even multiple environmental conditions) tends to be poor. However, it is acknowledged that this is likely to seriously limit our ability to predict the complex, interacting ecological effects of changing environmental conditions, and thus our ability to determine an EWR for the region.

However, some of these limitations can be addressed using other available tools. For example, there is an existing ecological response model for the Coorong which operates at an ecosystem scale (Lester & Fairweather 2011). It incorporates assemblages of birds, aquatic plants, fish and benthic macroinvertebrates in the Coorong and identifies groups of these that co-occur under specific environmental conditions. Where environmental conditions are able to be predicted (e.g. using hydrodynamic modelling), it is also possible to predict the mix of assemblages that may also be present. This approach also has limitations, such as a bias towards better prediction of degraded ecological condition (i.e. than of healthy degraded ecosystem states) and lack of validation to date (see Lester & Fairweather 2009a, 2011 for more detail), that need to be kept in mind when assessing the outputs.

Therefore, we have opted for a combined approach, whereby the initial salinity targets set here for Lake Alexandrina are also assessed using the Coorong ecosystem states model (see Chapter 11) to ensure that the volumes of water delivered to the Coorong are also predicted to be sufficient to support ecological condition there (as assessed by the mix of ecosystem states). This is the most robust approach possible, by using multiple methodologies to assess the same problem (i.e. setting an EWR), and so provides confidence that the limitations associated with either the evaluation of individual indicators for individual flow-related variables or with the ecological response modelling do not adversely affect our ability to identify a robust EWR for the region.

5.8.3 Key limitations of the process of relating indicators to flow-related variables as a whole

The environmental impact of increasing salinity on biota in a freshwater system is complex, and, on the whole, poorly understood, particularly at an ecosystem scale. Very little research specifically examining salinity tolerances of resident freshwater species has occurred in the CLLMM region, although some additional work was underway at the time of writing. There is also the added complexity of differential susceptibility of different life-history stages of the same species. However, despite these limitations, substantially more information exists relating to responses to salinity than for many of the other flow-related variables thought to drive the ecological character of the region (e.g. pH). Also, combinations of effects can be very difficult to predict and, for most species and assemblages, we lack the biological knowledge to attempt predictions based on the synergies of two or more factors. This general lack of understanding at an ecosystem scale (both for stressors and indicators) makes it very difficult to identify relevant thresholds at which ecological character will be maintained. Thus, we have attempted to adopt a conservative approach, to maximise the likelihood that the objective of a healthy, productive and resilient wetland of international importance will result from the recommended environmental water requirement. This needs to be balanced against the relative costs of supplying additional environmental water (e.g. socioeconomic costs) in the face of uncertainty regarding flow volumes under climate change, so multiple thresholds have been proposed to assess the implications of providing less water.

One additional limitation of the current approach as a whole that became apparent during the process was the relative difficulty of determining when objectives such as self-sustaining populations were being met based on a single species, assemblage or process. These objectives (and their associated outcomes) were focused at an ecosystem scale or whole-of-site scale. Thus, a single taxon or assemblage is only a small part of that ecosystem or the site as a whole. So, while multiple indicators have been related to these ecosystem-scale outcomes, simply having one indicator meet that outcome (e.g. one taxon has a self-sustaining population) would not be considered sufficient to indicate that the region as a whole was healthy or resilient. One possible solution would be to add additional community- or assemblage-level indicators, and to use community composition, for example, as the metric of interest. Another option would be to develop guidelines for the number or range of individual indicators that would be needed to consider the outcome met at a regional level. This needs to be addressed in future iterations of the work, or at least prior to the implementation of the indicator sets for monitoring and compliance purposes.

5.9 Conclusion

So, in conclusion, we recommend that a salinity threshold for Lake Alexandrina be set against which to determine an environmental water requirement for the region. We anticipate that this will act as a surrogate for other important flow-related variables in the region, thus supporting the ecological character.

Based on known tolerances of indicators, thresholds at which sub-lethal effects occur and the corresponding impacts on salinity and flows for Lake Albert and the Coorong, we recommend that a target salinity be set for Lake Alexandrina of a long-term average of 700 µS cm^{-1} EC, with a maximum salinity of 1000 µS cm^{-1} EC in 95% of years and a maximum of 1500 µS cm^{-1} EC in all years.

5.10 Summary

- **Indicator taxa and assemblages included those likely to be directly affected by hydrodynamic parameters, key species within the region, threatened species or those considered to be sensitive to ecological condition.**
- **Links were drawn between each indicator and each ecological outcome, with rationale and knowledge gaps recorded.**
- **Current ecological character was represented by a comprehensive list of taxa, assemblage and process indicators including vegetation, macroinvertebrates, fish and ecological processes.**
- **A total of ten vegetation taxa and assemblages, 17 fish species, 19 macroinvertebrate taxa and 12 ecological processes were identified.**
- **Vegetation indicators tended to be good indicators of long-term sustainability of populations, surrogacy for other organisms, habitat complexity and diversity, and communities requiring varied hydrology.**
- **Macroinvertebrates were considered to be very good indicators of self-sustaining populations, habitat and food web complexity, although the local knowledge of the macroinvertebrates present within the CLLMM region is scarce.**
- **Fish indicators were considered particularly useful in relation to successful recruitment, suitable habitats and food resources.**

- **Ecological process indicators tended to be most useful as indicators of self-sustaining populations and appropriateness and diversity in ecological function and decomposition was identified as being the single most useful ecological processes.**
- **Trade-off tables were developed to summarise the available information thresholds and tolerances of the indicator sets, although the variability in the quality of data meant that these need to be used with care.**
- **Salinity was identified as the water quality component most likely to affect ecological character in the CLLMM region and the threshold beyond which freshwater communities were likely to be influenced was at 1 g L^{-1}.**
- **Thus, we recommend a salinity target of a long-term average of 700 µS cm^{-1} EC in Lake Alexandrina, with maxima of 1000 µS cm^{-1} EC in 95% of years and 1500 µS cm^{-1} EC at all times.**
- **Combining different indicator groups to assess the ecological condition is a holistic approach that utilises the various properties of different ecological components.**

6. Vegetation indicators

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This chapter provides details of the vegetation taxa and assemblages that are indicators for the ecological outcomes that represent a healthy, productive and resilient wetland for the Coorong, Lower Lakes and Murray Mouth region. These outcomes have been summarised in Chapter 3. Vegetation species can potentially be useful as indicators because they are known to be effective at reflecting the environmental conditions present at a site (Diekmann 2002). Furthermore, different vegetation species and assemblages have variable tolerance and preferred ranges of environmental conditions, reflecting the diversity of the region.

The vegetation communities within the CLLMM region are largely driven by water regime (especially water depth) and salinity (Gehrig & Nicol 2010). Water level is most important above the barrages (i.e. in the Lower Lakes) and in the South Lagoon of the Coorong, whereas salinity is the main driver of vegetation types around the Murray Mouth and in the North Lagoon (Gehrig & Nicol 2010). The vegetation community within the CLLMM region is diverse, where a total of 353 plant and macroalgal taxa have been recorded since 1975, including five species listed as rare in South Australia (Gehrig & Nicol 2010).

There are many knowledge gaps in the information available for the vegetation species present within the region and the extent of the literature available varies for each vegetation species or assemblage. Also, much of the available literature is focused on the eastern states of Australia, so may not be directly relevant to the conditions within the CLLMM region. Some species are known to exhibit different ecological tolerances and characteristics in the CLLMM region than in other regions of Australia (J. Nicol pers. comm.), which increases the uncertainty associated with using literature sourced from other external studies. Thus, in the tables below, where the literature used applied to other basins, this lack of local knowledge is stated.

Significant changes to the vegetation community have occurred in the CLLMM region since European settlement due to the effects of large-scale abstraction of water upstream and increasing levels of river regulation. Barrages were constructed in the 1940s, disconnecting the Murray Mouth and Coorong from the Lower Lakes, resulting in static water levels in the Lower Lakes, a highly variable salinity regime in the Murray Mouth and North Lagoon. Since that time, the South Lagoon has been predominantly hypersaline (Gehrig & Nicol 2010). Prior to these changes, the vegetation communities in the region were adapted to include species that reflected the predominant environmental conditions in each region (Gehrig & Nicol 2010), but assemblages have been simplifying through time as a result of these changing environmental conditions.

In recent years, the vegetation in CLLMM region has undergone further significant changes due to a combination of severe drought and continued water abstraction (Gehrig & Nicol 2010). Both species of *Ruppia* characteristic of the region have changed in distribution. The more saline tolerant, *Ruppia tuberosa*, has declined in abundance in the South Lagoon where it was once common, and has recently been observed colonising the North Lagoon (Rogers & Paton 2009). *Ruppia megacarpa* was once common in the Murray Mouth and North Lagoon but has been absent from the Coorong since the mid-1900s (Rogers & Paton 2009). Many fringing wetland areas have dried completely, resulting in the loss of large areas of submergent vegetation (including aquatic species such as *Vallisneria australis* and *Myriophyllum* spp.) and the decline of fringing communities (e.g. *Typha domingensis* and *Schoenoplectus validus*). Despite these recent changes, an array of vegetation assemblages remain within the CLLMM region, suitable for use as indicators.

A diverse range of vegetation species and assemblages have been selected as indicators for the CLLMM region. Selected vegetation indicators include submerged and emergent taxa, and those that are tolerant of a range of salinities, from freshwater (e.g. water milfoils and water ribbons) through to hypersaline conditions (e.g. sea tassels such as *Ruppia tuberosa*). The vegetation indicator taxa and assemblages considered here are:

- Samphire & saltmarsh communities – *Tecticornia pergranulata* ssp. *pergranulata*, *Suaeda australis*, *Sarcocornia quinqueflora & Juncus kraussi*
- Paperbark - *Melaleuca halmaturorum*
- Lignum - *Muehlenbeckia florulenta*
- Diverse reed beds - *Phragmites australis*, *Typha domingensis & Schoenoplectus validus*
- Water milfoils - *Myriophyllum salsugineum & M. caput-medusae*
- Ribbonweed - *Vallisneria australis*
- Water ribbons - *Triglochin procerum*
- Spiny rush - *Juncus acutus*
- Large-fruited sea tassel - *Ruppia megacarpa*
- Tuberous sea tassel - *Ruppia tuberosa*

Cutting-grass tussocks (*Gahnia* spp.) and black swamp vegetation were considered as potential indicators for the CLLMM region, primarily because of their *Environmental Protection and Biodiversity Conservation Act 1999* (EPBC Act) listings. However, due to the lack of knowledge and the limited local distribution of these assemblages, details are not provided below in indicator tables. The possibility of using these taxa as indicators in the future exists, particularly if they become more prominent within the CLLMM region in future years. The information that has been collated on these additional taxa is provided in Appendix C, along with flow-related tolerances and other data for the remaining vegetation indicators.

6.1 Samphire and saltmarsh communities

Samphire and other saltmarsh communities are assemblages of succulent chenopods dominated by grasses, rushes & shrubs that are tolerant of high soil and water salinities, waterlogging or periodic inundation (Nicol 2007). They flourish in coastal areas where sedimentation is high (Nicol 2007). Samphire and saltmarsh communities are very productive systems and export energy into adjacent estuarine and marine waters, which drive detrital foods webs (Nicol 2007). Samphire and saltmarsh communities also support a range of wading migratory waterfowl (Nicol 2007). The samphire species included here are *Tecticornia* (previously *Halosarcia*) *pergranulata* ssp. *pergranulata*, *Suaeda australis*, *Sarcocornia quinqueflora* and *Juncus kraussi*. Table 6.1 links samphire and saltmarsh communities to individual ecological outcomes.

Table 6.1: List of ecological outcomes that would be indicated by samphire & saltmarsh communities. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Samphire & saltmarsh communities			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Floodplain species that requires salinities less than ~20 ppt for growth & less than ~7 ppt total dissolved solids (TDS) for recruitment of *J. kraussi* (Nicol 2007)	Distribution; Abundance – coverage, shoot density, seed bank; Recruitment events	There is little known about the recruitment of samphire and salt marsh species in the region
Suitable habitat	Samphire communities provide habitat in riparian areas, including for wading migratory waterfowl (Nicol 2007)	Distribution; Abundance – coverage	Use as a habitat needs to be quantified for the region
Suitable food resources	Provide a food source a range of fauna (e.g. black-tailed godwit, curlew sandpiper, red-necked stint, sharp-tailed sandpiper & orange-bellied parrot; Saintilan 2009) in riparian zones	Distribution; Abundance – coverage; Recruitment events – seed production	
Suitable water quality	Can tolerate periods of high salinities. *T. pergranulata* ssp. *pergranulata* shoot biomass is highest in salinities up to 200 mol m^{-3} & above 300 mol m^{-3} (~11 & 17 ppt, respectively) (Short & Colmer 1999)	Distribution; Abundance – coverage; Population demographics	Need to determine ecological preference curves (esp. water regime & salinity) for species, to allow models of potential distribution
Species connectivity	Not an indicator	NA	Connectivity between saltmarshes is important (both along & between estuaries) because of fragmentary nature of habitats but more research is required to determine the natural levels of connectivity with other habitats (Saintilan 2009)
Viable propagule bank	Germination inhibition is proportional to the external osmotic potential, which occurs at high salt concentrations. Samphire seeds only have a small window of opportunity to reproduce & germinate (Purvis *et al.* 2009). Seed germination is reduced at high salt concentrations but can	Distribution; Abundance – shoot density, seed bank	Local information for species in the region is lacking

Indicator species: Samphire & saltmarsh communities			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
	increase once salt is flushed from the seeds with freshwater (Purvis *et al.* 2009)		
No barriers to recruitment	A combination of moisture content & salinity explain the distribution of vegetation communities within the saltmarsh community & inappropriate combinations could thus potentially prevent/limit recruitment (Saintilan 2009)	Distribution; Abundance – seed bank; Population demographics	Could be described by preference curves
Lateral hydraulic connectivity	Species abundance increases with reduced lateral connectivity	Distribution; Abundance – coverage	
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Does not require connectivity to the ocean for survival. Requires intermittent upstream connectivity to provide freshwater flows to provide estuarine habitat	Distribution	
Longitudinal biological connectivity	Saltmarshes may mediate a balance of nutrients & organic matter between the saltmarsh & other interacting systems (e.g. mangroves, sea grass & open water systems), so effectively can act as an ecological buffer (Saintilan 2009). Saltmarshes are among the most productive known ecosystems & usually export energy into adjacent ecosystems (Nicol 2007)	Changes in water quality – nutrient fluxes	Food web interactions need to be quantified
No accumulation of pollutants	Tolerant of sedimentation & salinity fluxes (Saintilan 2009)	Distribution; Abundance – coverage	Tolerances for acid, metals & agrochemicals are unknown
Lateral habitat diversity	Indicator of riparian vegetation	Distribution; Abundance – coverage	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Species can survive up to 80 ppt however reduced growth & germination rates occurs at salinities above 20 ppt. Seeds held at 38.5 ppt germinated after freshwater inflow. *J. kraussi* & *S. virginicus* require freshwater inflows but established plants can survive in 80 ppt (Nicol 2007)	Distribution; Abundance – coverage; Population demographics	Could be explained by preference curves
Temporal variability in salinity	Requires salinities to at least reduce periodically for seed germination (Purvis *et al.* 2009)	Distribution; Abundance – shoot density	Impact of variable salinities needs to be quantified
Communities requiring varied salinities supported	Requires lower salinities to germinate and recruit but grows better and is typically more dominant in areas with higher salinities where there are fewer competing species (J. Nicol pers. comm.).	Distribution; Abundance – coverage; Population demographics	
Temporal variability in flow	Inundation required for seed germination, freshwater flows required to reduce salinity to increase germination &	Distribution; Abundance – shoot density, seed	Inundation may not be required for germination (e.g. it is unlikely that germination would occur

Indicator species: Samphire & saltmarsh communities			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
	growth rates (Purvis *et al.* 2009)	bank; Population demographics	underwater) but freshening is required. Whether rainfall is sufficient or whether inundation is required for that freshening (and germination occurs once the sediment is exposed) is unknown
Seasonal variability in flows	Inappropriate water regimes, resulting in extended inundation, can lead to succulent spp. decomposing as they can only withstand short periods of inundation (Saintilan 2009). Conversely, insufficient flooding is also likely to change the species composition of the marsh	Changes in assemblage composition through space & time – composition of saltmarsh species	
Seasonal variability in water levels	Inappropriate water regimes, resulting in extended inundation, can lead to succulent spp. decomposing as they can only withstand short periods of inundation (Saintilan 2009). Conversely, insufficient flooding is also likely to change the species composition of the marsh	Changes in assemblage composition through space & time – composition of saltmarsh species	At the time of writing, not much information existed about the influence of seasonality of inundation
Communities requiring varied hydrology supported	Indicator of waterlogged & occasionally-inundated habitats (Nicol 2007)	Distribution	
Communities requiring flooding supported	*J. kraussi* & *S. virginicus* require freshwater inflows for germination (Nicol 2007)	Recruitment events – new shoot density	Inundation may not be required for germination (e.g. it is unlikely that germination would occur underwater) but freshening is required. Whether rainfall is sufficient or whether inundation is required for that freshening (and germination occurs once the sediment is exposed) is unknown
Tidal signal apparent	For tidally-influenced marshes, an inappropriate tidal regime, resulting in extended inundation, can lead to succulent spp. decomposing as they can only withstand short periods of inundation (Saintilan 2009)	Changes in assemblage composition through space & time – composition of saltmarsh species	
Complex food webs present	Provides energy from terrestrial areas to detrital food webs of aquatic habitats (Nicol 2007). Also provides a habitat for animals, including waterbirds (Nicol 2007)	Distribution; Abundance – coverage	Role in food web complexity needs to be quantified
Functions performed by multiple species	Not an indicator	NA	The role of multiple spp. to perform the same function is currently unknown
Efficient nutrient	Among the most productive known ecosystems & are out-	Distribution; Abundance	Role in nutrient cycling needs to be quantified

Indicator species: Samphire & saltmarsh communities			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
cycling	welling systems that tend to export energy into adjacent estuarine & marine waters (Nicol 2007)	– coverage	
Control of invasive species	Saltmarshes, under natural conditions, are generally less prone to invasive species (e.g. terrestrial weeds) due to extreme conditions of salinity & waterlogging (Saintilan 2009)	Abundance – coverage	Where introduction of invasive species (e.g. *J. acutus*) occurs, need to establish the effect on the structure & complexity of saltmarsh areas (Saintilan 2009)
Acid- & saline-tolerant & terrestrial species present	Saline-tolerant & terrestrial species	Distribution	Acid tolerance unknown
Wide riparian & littoral zones supported	Reduced water flows result in increased abundance of samphire species (Nicol 2007)	Distribution; Abundance – coverage	
Lateral connectivity of vegetation	Terrestrial species that can handle permanent waterlogging & periodic inundation but intolerant of permanent inundation (Nicol 2007)	Distribution; Abundance – coverage	
Balance of aquatic & terrestrial species	Indicator of terrestrial species only (may invade drying wetlands)	Distribution	
Exchange between aquatic & terrestrial systems	Samphire communities mediate a balance of nutrients & organic matter between saltmarsh habitats & other interacting systems (e.g. mangroves, seagrass beds & open water systems), acting essentially as an ecological buffer (Saintilan 2009)	Distribution; Abundance – coverage	Role in exchange needs to be quantified
Regular oxidation of sulfidic material	Not an indicator	NA	

6.2 Paperbark woodlands – *Melaleuca halmaturorum*

Paperbark woodlands are one of the dominant types of habitats present in the Lower Lakes, Murray estuary and Coorong. They are widely distributed around the edge of fresh to saline wetlands throughout both inland and coastal South Australia (Nicol 2007). Paperbark woodlands have a high salt tolerance, tolerant of soils > 44 ppt TDS. The seeds of paperbark woodlands require exposed sediment to germinate and can remain viable when submerged in freshwater for at least 30 days but less than 80 days (Nicol & Ganf 2000). The survivorship of seedlings and saplings subjected to flooding is dependent on age and size (Denton & Ganf 1994). The interaction between salinity and flooding on paperbark survival (*sensu* Salter *et al.* 2007) has not been investigated. Table 6.2 links paperbark woodlands to individual ecological outcomes.

Table 6.2: List of ecological outcomes that would be indicated by paperbark woodlands. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	**Paperbark woodlands – *Melaleuca halmaturorum***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Long lived species (>100 years), reproduces from wind-dispersed seeds that germinate on mudflats exposed during drawdown (Denton & Ganf 1994)	Distribution; Abundance – coverage; Population demographics	
Suitable habitat	Exposed mudflats during drawdown required for seed germination (Denton & Ganf 1994). Paperbark woodlands also provide a habitat for fauna, with paperbark woodlands being important rookery sites, nesting & sheltered feeding grounds (Phillips & Muller 2006)	Distribution; Abundance – coverage; Population demographics	
Suitable food resources	Flowers in late spring providing nectar food source for insect & bird species (Denton & Ganf 1994); regenerated trees also a food source for rabbits (Cooke 1988)	Distribution; Abundance – coverage; Population demographics	
Suitable water quality	Not an indicator	NA	
Species connectivity	Not an indicator	NA	
Viable propagule bank	Has an aerial seed bank, seeds are held in fruit and released when fruits dry and split (J. Nicol pers. comm.)	Distribution; Abundance – shoot density	
No barriers to recruitment	Not an indicator. No physical barriers to connectivity	NA	
Lateral hydraulic connectivity	Seeds of paperbark woodlands require exposed sediment to germinate & can remain viable when submerged in freshwater for at least 30 but less than 80 days (Nicol & Ganf 2000)	Distribution; Abundance – shoot density	
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Not an indicator	NA	
Longitudinal biological	Not an indicator	NA	

Indicator species:	Paperbark woodlands – *Melaleuca halmaturorum*		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
connectivity			
No accumulation of pollutants	Saline tolerant	Distribution	Tolerances for sedimentation, acid, metals & agrochemicals are unknown
Lateral habitat diversity	Paperbark woodlands are an indicator of floodplain habitats	Distribution	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Salinities of 43 ppt do not affect survivorship of paperbark woodlands but growth is dramatically reduced (van der Moezel *et al.* 1991)	Abundance – canopy coverage	Precise salinity thresholds for paperbark woodlands are unknown. Impact of salinity on germination unknown
Temporal variability in salinity	Requires lower salinities to germinate and recruit but grows better and is typically more dominant in areas with higher salinities where there are fewer competing species (J. Nicol pers. comm.)	Distribution; Abundance – coverage, shoot density	
Communities requiring varied salinities supported	Requires lower salinities to germinate and recruit but grows better & is typically more dominant in areas with higher salinities where there are fewer competing species (J. Nicol pers. comm.)	Distribution; Abundance – coverage, shoot density	
Temporal variability in flow	Inundation of mudflats allows for seed germination (Denton & Ganf 1994)	Distribution; Abundance – coverage, shoot density	
Seasonal variability in flows	Inundation of mudflats allows for seed germination (Denton & Ganf 1994)	Distribution; Abundance – coverage, shoot density	
Seasonal variability in water levels	Inundation of mudflats allows for seed germination. Can tolerate floods of up to 6 weeks (Denton & Ganf 1994)	Distribution; Abundance – coverage, shoot density	
Communities requiring varied hydrology supported	Indicator of ephemeral mudflats	Distribution; Abundance – coverage	
Communities requiring flooding supported	Indicator of ephemeral mudflats	Distribution; Abundance – coverage	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Inputs from riparian sources, such as paperbark woodlands, in the form of dissolved organic matter, leaf litter, woody debris & invertebrates, are recognized as important food resources for aquatic food webs in many systems (Gregory *et al.* 1991)	Distribution; Abundance – coverage	Role in food webs needs to be quantified
Functions performed	Provides an organic matter source for the riparian zone & aquatic	Distribution; Abundance	Functional role needs to be

Indicator species:	**Paperbark woodlands – *Melaleuca halmaturorum***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
by multiple species	habitats (Gregory *et al.* 1991)	– coverage	quantified
Efficient nutrient cycling	Leaf litter can be a long-term nutrient store, providing nutrient (e.g. carbon, nitrogen & phosphorus) exchange between terrestrial & aquatic ecosystems (Greenway 1994)	Distribution; Abundance – coverage	Role in nutrient cycling needs to be quantified
Control of invasive species	Not an indicator	NA	Level of threat from weeds is largely unknown (Walden & Nou 2008)
Acid- & saline-tolerant & terrestrial species present	Saline-tolerant & terrestrial species (Salter *et al.* 2007)	Distribution; Abundance – coverage	Acid tolerance unknown
Wide riparian & littoral zones supported	Variable mudflat inundation allows for seed germination (Denton & Ganf 1994)	Distribution; Abundance – shoot density	
Lateral connectivity of vegetation	Potentially occupies the floodplain to riparian zone	Distribution; Abundance	
Balance of aquatic & terrestrial species	Indicator of terrestrial habit & may invade drying wetlands	Distribution	
Exchange between aquatic & terrestrial systems	Provides energy from terrestrial zone into aquatic zones (Bunn *et al.* 2003), also acts as a buffer zone between habitats, influencing the exchange of nutrients (e.g. nutrient loads & concentrations) & run-off (e.g. siltation) (Joyce 2005)	Distribution; Abundance	
Regular oxidation of sulfidic material	Not an indicator	NA	

6.3 Lignum – *Muehlenbeckia florulenta*

Lignum is a long-lived perennial shrub, common throughout mainland Australia in ephemeral swamps and floodplains (Sainty & Jacobs 1994). This multi-stemmed shrub may form dense thickets in favourable conditions, growing to 2-3 m high and wide, and providing excellent habitat for both native and feral animals (Sainty & Jacobs 1994). Lignum can survive for some time without rainfall or flooding and is somewhat saline tolerant (Rogers 2010a). Lignum occurs in areas which have a flood frequency of between three and 10 years, (and increased water availability stimulates rapid growth of flowers, leaves and shoots; Chong & Walker 2005). Lignum has a wide distribution throughout the Murray-Darling region and is an important breeding habitat for waterbirds (Rogers 2010a). It also provides a refuge for pests such as rabbits and feral pigs (Sainty & Jacobs 1994). Table 6.3 links lignum to individual ecological outcomes.

Table 6.3: List of ecological outcomes that would be indicated by lignum populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	Lignum – *Muehlenbeckia florulenta*		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Recruitment occurs vegetatively or sexually by seed production. Seeds respond to flooding & require floods at least every 10 years for a sustained population (Craig *et al.* 1991)	Abundance – seedling density, coverage; Distribution	
Suitable habitat	Covers banks with flooding at least every 10 years. Flooding of more than 60 cm & for longer than 12 months can result in plant mortality due to anoxia in eastern Australia (Rogers 2010a). Provides excellent habitat for both native & feral animals (Sainty & Jacobs 1994)	Distribution	Local preferences are unknown
Suitable food resources	Not an indicator. Although an important source of habitat, it does not appear to be widely utilised as a food source	NA	
Suitable water quality	Able to withstand salinities of at least 10 000 mg L^{-1} (~100 ppt)(van der Sommen 1980)	Distribution	
Species connectivity	Seeds are dispersed downstream by or sufficient rain or floodwaters in eastern Australia (Rogers 2010a)	Distribution	Local preferences are unknown
Viable propagule bank	In the laboratory, seeds have survived for up to 15 years but within floodplains, seeds deteriorate quickly & do not appear to remain viable for extended periods of time (Rogers 2010a)	Abundance – seedling density; Distribution	Local preferences are unknown
No barriers to recruitment	Physical barriers inhibiting the seed dispersal downstream may prevent recruitment	Distribution; Population demographics	
Lateral hydraulic connectivity	Floodplain habitats that have been flooded within the last 10 years can sustain lignum populations (Craig *et al.* 1991)	Distribution	
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Not an indicator	NA	

Indicator species:	**Lignum – *Muehlenbeckia florulenta***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Not an indicator. Tolerant of salinity up to 10 000 mg L^{-1}(~100 ppt) & highly tolerant of acidic soils (negligible effects in soils with pH 4-8; van der Sommen 1980)	NA	Effects of sediment, metals & agrochemicals on lignum is unknown
Lateral habitat diversity	Lignum populations inhabit floodplains which are flooded frequently & submerged areas with water depth of less than 60 cm & for less than 12 months at a time in eastern Australia (Rogers 2010a)	Distribution	Local preferences are unknown
Habitat variability	Not an indicator, although percent cover does increase with flooding (Capon 2005)	NA	
Range of salinities with appropriate maxima	Indicator of salinities ranging from freshwater to salinities of 10 000 mg L^{-1} (~100 ppt) (van der Sommen 1980)	Distribution	
Temporal variability in salinity	Not an indicator	NA	
Communities requiring varied salinities supported	Indicator of salinities ranging from freshwater to salinities of 10 000 mg L^{-1} (~100 ppt) (van der Sommen 1980)	Distribution	
Temporal variability in flow	In eastern Australia, lignum requires large flow volumes to provide flooding for growth & germination. Seeds are dispersed downstream by floodwaters. Floods during summer promote vigorous growth over the usually drier conditions (Rogers 2010a)	Distribution; Abundance – coverage	Local preferences are unknown
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Indicator of habitat that is flooded every three to 10 years (Craig *et al.* 1991)	Distribution	
Communities requiring flooding supported	In eastern Australia, lignum requires flooding for growth & germination. Lignum responds quickly to inundation with the quick growth of leaves, shoots & flowers. Flooding disperses seeds downstream & receding floodwaters stimulate germination of seeds on floodplains in eastern Australia (Rogers 2010a). Lignum cover is observed to be higher in high flood frequency locations than lower flood frequency zones (Capon 2005)	Distribution	Local preferences are unknown
Tidal signal	Not an indicator	NA	

Indicator species:	**Lignum – *Muehlenbeckia florulenta***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
apparent			
Complex food webs present	Provision of carbon & nutrients in food webs (Robertson *et al.* 1999)	Distribution; Abundance – coverage	Role in food webs needs to be quantified
Functions performed by multiple species	Not a primary indicator	NA	
Efficient nutrient cycling	Provision of carbon & nutrients in food webs (Robertson *et al.* 1999)	Distribution; Abundance – coverage	Role in nutrient cycling needs to be quantified
Control of invasive species	Not an indicator	NA	Impact of invasive species on recruitment is unknown
Acid- & saline-tolerant & terrestrial species present	Moderately saline- & acid-tolerant (Craig *et al.* 1991)	Distribution	
Wide riparian & littoral zones supported	Indicator of areas with inundation between three & 10 years in eastern Australia (Rogers 2010a)	Distribution	Local preferences are unknown
Lateral connectivity of vegetation	Vegetative species inhabiting floodplains & riparian zones in eastern Australia (Rogers 2010a)	Distribution	Local preferences are unknown
Balance of aquatic & terrestrial species	Indicator of terrestrial habit (may invade drying wetlands)	Distribution	
Exchange between aquatic & terrestrial systems	Exchange of energy, nutrients & carbon occurs from terrestrial to aquatic ecosystems via leaf litter & inputs (Robertson *et al.* 1999)	Distribution; Abundance – coverage; Detritus composition & condition – detrital inputs	Role in exchange needs to be quantified
Regular oxidation of sulfidic material	Not an indicator	NA	

6.4 Diverse reed beds – *Phragmites australis, Typha domingensis, Schoenoplectus validus*

Diverse reed beds are a common component of stationary or slow-moving water bodies, creeks and streams (Sainty & Jacobs 1994). They are important for providing food and shelter for biota, stabilising banks, and preventing erosion (Sainty & Jacobs 1994). Diverse reed beds refer here species including *Phragmites australis*, *Typha domingensis and Schoenoplectus validus*. Reed beds support native robust perennial species with extensive rhizome systems (Sainty & Jacobs 1994). Diverse reed beds are tolerant of brackish water (Sainty & Jacobs 1994). Both *P. australis* and *T. domingensis* produce numerous seeds, but vegetative growth is more common for *Phragmites australis* (Sainty & Jacobs 1994). *P. australis* and *T. domingensis* can both form monoculture stands with very few associated species. When *S. validus* is also present, the overall diversity tends to be higher (e.g. including species such as *Juncus* spp., *Isolepis* spp., *Triglochin procerum*, *Myriophyllum salsugineum*). Thus, *S. validus* may be an important indicator of overall species diversity in reed beds (J. Nicol pers. comm.). Table 6.4 links diverse reed beds to individual ecological outcomes.

Table 6.4: List of ecological outcomes that would be indicated by diverse reed bed communities. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	**Diverse reed beds – *Phragmites australis, Typha domingensis, Schoenoplectus validus***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Inhabits areas with high soil water content. Vegetative growth is more common but does produce seeds & germination occurs under saturated soil conditions in eastern Australia (Rogers 2010a)	Distribution; Abundance – coverage, shoot density	Local preferences are unknown
Suitable habitat	*P. australis* & *T. domingensis* prefer shallow permanent water or saturated soils (J. Nicol pers. comm.). *S. validus* will tolerate the deepest water (J. Nicol pers. comm.)	Distribution; Abundance – coverage	
Suitable food resources	Provide microhabitats for macroinvertebrates & attached algae, which in turn can provide food resources for fish species (Horinouchi *et al.* 2008). Young shoots provide a food resource for wetland birds. However, most of the biomass remains ungrazed & enters the detritus system (Asaeda *et al.* 2002)	Distribution; Abundance – coverage	Use as a food resource needs to be quantified
Suitable water quality	In the Lower Lakes, *P. australis* & *T. domingensis* have been observed growing in water in excess of 25 000 µS cm^{-1} electrical connectivity (EC) (~17ppt) (J. Nicol pers. comm.)	Distribution	Tolerances of Lower Lakes ecotypes unknown
Species connectivity	Not an indicator	NA	
Viable propagule bank	*P. australis* regeneration appears to be relatively inefficient & generally grows asexually (J. Nicol pers. comm.). *T. domingensis* seed regeneration is greater in saturated soil conditions rather than flooded conditions (Miao *et al.* 2000) but seeds have been shown to germinate in a range of experimental hydrological regimes ranging from rapid drawdown conditions to static conditions at various inundation depths (Nicol & Ganf 2000).	Abundance – shoot density, seed bank	Seed bank viability is unknown in Australia
No barriers to recruitment	Not an indicator	NA	

Indicator species:	**Diverse reed beds – *Phragmites australis, Typha domingensis, Schoenoplectus validus***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Lateral hydraulic connectivity	Flooding should occur at least every two years for survival of *P. australis* on floodplains (Roberts & Marston 2000)	Distribution; Abundance – shoot density	
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Diverse reed beds can be an indicator of permanently-inundated habitats	Distribution	
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Not saline tolerant	NA	Tolerances for sedimentation, acid, metals & agrochemicals are unknown
Lateral habitat diversity	Indicator of riparian to 2-m deep aquatic habitats in eastern Australia (Rogers 2010a)	Distribution	Local preferences are unknown
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	In the Lower Lakes, *P. australis* & *T. domingensis* have been observed growing in water in excess of 25 000 µS cm^{-1} EC (~17ppt) (J. Nicol pers. comm.)	Distribution; Abundance – coverage; Changes in assemblage composition through space & time (at finer scale)	Tolerances of Lower Lakes ecotypes unknown
Temporal variability in salinity	Not an indicator	NA	
Communities requiring varied salinities supported	Diverse reed beds flourish in areas with constant low salinities (J. Nicol pers. comm.). *P. australis* an indicator of salinities up to 10 ppt. *T. domingensis* can tolerate salinity concentrations up to 50 mM for growth, & 100 mM for survival in eastern Australia (Rogers 2010a)	Distribution; Abundance – coverage; Changes in assemblage composition through space & time (at finer scale)	Tolerances of Lower Lakes ecotypes unknown
Temporal variability in flow	In eastern Australia *P. australis* prefers fluctuating water levels whereas *T. domingensis* prefers more stable water levels (Rogers 2010a)	Distribution; Abundance – coverage; Changes in assemblage composition through time	Local preferences are unknown
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Both *P. australis* & *T. domingensis* prefer stable water levels but *P. australis* can also tolerate fluctuating water levels. *P. australis* can survive inundation up to 2 m (Sainty & Jacobs 1981).	Distribution; Abundance – coverage; Changes in assemblage composition	Local preferences are unknown

Indicator species:	**Diverse reed beds – *Phragmites australis, Typha domingensis, Schoenoplectus validus***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
		through time	
Communities requiring varied hydrology supported	Between the various species, diverse reed beds indicate permanently-inundated (or saturated) waterbodies (Rogers 2010a)	Distribution; Abundance – coverage	
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Provides a primary food source for biota (Asaeda *et al.* 2002; Horinouchi *et al.* 2008)	Distribution; Abundance – coverage	
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	May be an indicator of carbon processing from floodplains to instream habitats	Distribution; Abundance – coverage	Role in nutrient cycling needs to be quantified
Control of invasive species	Reed beds (e.g. *Phragmites australis*) are a problem when & where stands appear to be spreading while other species typical of the community are diminishing (Marks *et al.* 1994). Stresses such as pollution, alteration of hydrologic regime & increased sedimentation & favour invasion & spread (Marks *et al.* 1994)	Distribution; Abundance – coverage	
Acid- & saline-tolerant & terrestrial species present	Not saline-tolerant, can tolerate drought but not strictly a terrestrial species. Reed beds are thought to be acid-tolerant (*P. australis* can tolerate a pH of 2.1-2.5; Fyson 2000; Baldwin & Fraser 2009)	Distribution	Tolerances of Lower Lakes ecotypes unknown
Wide riparian & littoral zones supported	*P. australis* prefers stable water levels but can tolerate fluctuating water levels & can survive inundation up to 2 m (Sainty & Jacobs 1981)	Distribution; Changes in assemblage composition through space & time	
Lateral connectivity of vegetation	Although diverse beds collectively inhabit a range of habitats in eastern Australia, from infrequently-flooded floodplains to permanently-inundated area (Rogers 2010a), diverse reed beds are not present in infrequently-flooded floodplains in the South Australian Murray-Darling Basin (J. Nicol pers. comm.)	Distribution	
Balance of aquatic & terrestrial species	Inhabits aquatic habitats and floodplain habitats which are adjacent to permanent water (J. Nicol pers. comm.)	Distribution	
Exchange between aquatic & terrestrial systems	May be an indicator of carbon processing from floodplains to instream habitats	Distribution; Abundance – coverage	Role in exchange needs to be quantified
Regular oxidation of	Not a primary indicator. Decreases in the abundance of *P. australis* have been	NA	Interactions between

Indicator species:	**Diverse reed beds – *Phragmites australis, Typha domingensis, Schoenoplectus validus***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
sulfidic material	observed in the presence of acid sulfate soils (ASS) in NSW (Johnston *et al.* 2005). However, *P. australis* uses convective flow to oxygenate the rhizosphere & in turn oxidises the surrounding soil (e.g. Sorrell & Hawes 2010), therefore it would be unlikely that ASS would form in the presence of *P. australis* (J. Nicol pers. comm.). *P. australis* will tolerate low pH (Batty & Younger 2004)		diverse reed beds & ASS are unknown

6.5 Water milfoils – *Myriophyllum salsugineum, M. caput-medusae*

Water milfoils are submerged plants that are widely dispersed throughout inland Australia (Romanowski 1992). Here, we refer to *Myriophyllum salsugineum* and *M. caput-medusae* as water milfoils. Water milfoils have seasonally emergent flowers and fruits. They can grow prolifically in lakes, ponds and slow-flowing streams (Orr *et al.* 1988). Water milfoils are native perennial plants. *M. salsugineum* is tolerant of slightly saline water and often grows in brackish waters on the coast and inland waters (Sainty & Jacobs 1994). Milfoils grow in shallow to deep waters and some species can be drought tolerant (Romanowski 1992). Table 6.5 links water milfoils to individual ecological outcomes.

Table 6.5: List of ecological outcomes that would be indicated by water milfoils. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	**Water milfoils – *Myriophyllum salsugineum, M. caput-medusae***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Water milfoils form a seed bank, which germinates underwater or on exposed sediment with high soil moisture & spreads by fragmentation (one node can result in a new plant providing it settles in the right spot; J. Nicol pers. comm.)	Distribution; Abundance – seed bank	
Suitable habitat	Important habitat for small-bodied native fish (Bice *et al.* 2008), also for birds & frogs (DWLBC 2019)	NA	
Suitable food resources	A major dietary source for *Paratya australiensis* (freshwater shrimp; Piola *et al.* 2008) & an important food source for waterbirds (Roberts & Marston 2000)	NA	
Suitable water quality	Indicator of salinities under 9 ppt TDS (Orr *et al.* 1988)	Distribution	Tolerance of local ecotypes unknown
Species connectivity	Not an indicator	NA	
Viable propagule bank	Water milfoils form a seed bank, which germinates underwater or on exposed sediment with high soil moisture & spreads by fragmentation (one node can result in a new plant providing it settles in the right spot; J. Nicol pers. comm.). Salinity tolerance of up to 9 ppt TDS & brackish water (Orr *et al.* 1988); time taken to germinate increased as salinity increased (Nicol & Ward 2010)	Distribution; Abundance – seed bank	
No barriers to recruitment	Prolonged drought may represent a barrier to recruitment as the species are only somewhat drought-tolerant but recruitment has been noted to occur following the restoration of water levels (& inundation) (Nicol & Ward 2010). Water milfoils persist through droughts via the seed bank (Nicol & Ward 2010)	Distribution; Abundance – seed bank	Influence of prolonged drying & exposure to salinity on propagule bank viability unknown
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Intolerant to salinities over 9 ppt TDS (Orr *et al.* 1988)	Distribution	Tolerance of local ecotypes unknown
Regional hydraulically connected	Prefers permanent fresh water (J. Nicol pers. comm.)	NA	
Longitudinal	Not currently an indicator	NA	Reliance on nearby

Indicator species:	**Water milfoils – *Myriophyllum salsugineum, M. caput-medusae***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
biological connectivity			populations is not known
No accumulation of pollutants	Not tolerant of salinity	Distribution	Tolerances for sedimentation, acid, metals & agrochemicals are unknown
Lateral habitat diversity	Indicator of submergent plants	Distribution	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Salinity tolerance of up to 9 ppt TDS & brackish water (Orr *et al.* 1988). *M. Salsugineum* is more salt tolerant than *M. caput-medusae* (Bailey *et al.* 2002)	Distribution	Tolerance of local ecotypes unknown
Temporal variability in salinity	Not an indicator	NA	
Communities requiring varied salinities supported	Indicator of fresh to brackish waters (Orr *et al.* 1988)	Distribution	
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Requires permanently inundated-habitats although can tolerate short periods of drought (Romanowski 1992)	Distribution	
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Not currently an indicator	NA	Role in the formation of complex food webs is not known
Functions performed by multiple species	Not currently an indicator	NA	Functional role is poorly understood
Efficient nutrient cycling	Not currently an indicator	NA	Role in nutrient cycling is poorly understood
Control of invasive species	Not an indicator	NA	

Indicator species:	**Water milfoils – *Myriophyllum salsugineum, M. caput-medusae***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Acid- & saline-tolerant & terrestrial species present	Not saline-tolerant or terrestrial species	NA	Acid tolerance is unknown
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Indicator of submergent plants	Distribution	
Balance of aquatic & terrestrial species	Indicator of aquatic habit only	Distribution	
Exchange between aquatic & terrestrial systems	Not currently an indicator	NA	Role in the exchange between aquatic & terrestrial systems is unknown
Regular oxidation of sulfidic material	Not currently an indicator	NA	Acid & metal tolerances unknown

6.6 Ribbonweed – *Vallisneria australis*

Ribbonweed is a perennial aquatic plant which grows in a range of habitats, from shallow to deep water (Romanowski 1992). Understanding of the ecology of ribbonweed for the South Australian Murray-Darling Basin is limited but information has been provided for this species from eastern Australia where more information is available. In eastern Australia, ribbonweed inhabits both flowing and stationary waters (Rogers 2010a). It has strappy leaves which can grow to 5 m in length, up to 7 m deep in clear waters (Rogers 2010a). In the Lower Lakes, where turbidity is high, the maximum water depth is approximately 1 – 1.5m (J. Nicol pers. comm.). Flowers are produced during the warmer months (Rogers 2010a). Table 6.6 links ribbonweed to individual ecological outcomes.

Table 6.6: List of ecological outcomes that would be indicated by ribbonweed populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	Ribbonweed – *Vallisneria australis*		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Requires persistent water levels for growth. Vegetative growth is the primary method of regeneration for ribbonweed (Sainty & Jacobs 1981) although it does form a (not-very abundant) seed bank (J. Nicol pers. comm.)	Distribution; Abundance – coverage	
Suitable habitat	In eastern Australia ribbonweed can inhabit areas with high constant water levels, frequently-flooded sites that exhibit drying cycles or with complete drying following one growing season (Rogers 2010a). Requires a depth of 10-80 cm in the lower Murray where turbidity if high & light is abundant (Blanch *et al.* 1999)	Distribution; Abundance – coverage	
Suitable food resources	Provides primary food source for aquatic taxa	Distribution; Abundance – coverage	Needs to be quantified
Suitable water quality	In eastern Australia ribbonweed requires turbidity < 100 NTU for growth in waters greater than 1 m (Rogers 2010a)	Distribution	Local preferences are unknown
Species connectivity	Not an indicator	NA	
Viable propagule bank	Not an indicator. Ribbonweed primarily regenerates vegetatively (Sainty & Jacobs 1981)	NA	Requirements for sexual reproduction
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Not an indicator	NA	
Longitudinal biological connectivity	Not an indicator	NA	

Indicator species:	**Ribbonweed – *Vallisneria australis***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
No accumulation of pollutants	Not currently an indicator	NA	Tolerances are unknown
Lateral habitat diversity	Submergent macrophyte	Distribution	
Habitat variability	In eastern Australia ribbonweed populations die back during winter due to cooler temperatures (Briggs & Maher 1985) & extensive drying (Rogers 2010a), providing temporal variability in the submerged habitat available	Distribution; Abundance – coverage	Local preferences are unknown
Range of salinities with appropriate maxima	Not currently an indicator	NA	Salinity tolerance unknown
Temporal variability in salinity	Not currently an indicator	NA	Salinity tolerance unknown
Communities requiring varied salinities supported	Not currently an indicator	NA	Salinity tolerance unknown
Temporal variability in flow	Not an indicator. Tolerant to a range of flow conditions provided it is inundated at least seasonally in eastern Australia (Rogers 2010a). In the Lower Lakes ribbonweed requires permanent water (J. Nicol pers. comm.)	NA	
Seasonal variability in flows	Not an indicator. Tolerant to a range of flow conditions provided it is inundated at least seasonally in eastern Australia (Rogers 2010a). In the Lower Lakes ribbonweed requires permanent water (J. Nicol pers. comm.)	NA	
Seasonal variability in water levels	Not an indicator. Prefers stable water conditions (Rogers 2010a; J. Nicol pers. comm.)	NA	
Communities requiring varied hydrology supported	Has a wide tolerance of flood frequency In eastern Australia (Rogers 2010a)	Distribution	Local preferences are unknown
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Provides primary food source for aquatic taxa	Distribution; Abundance – coverage	Role in food webs needs to be quantified
Functions performed by multiple species	Food source to aquatic grazers & shredders & a form of habitat (Rogers 2010b, Jones 2010)	Distribution; Abundance – coverage	Functional role needs to be quantified; may provide substrate for epiphytes, rather than be a food source itself
Efficient nutrient	Utilises nutrients for growth & provides these nutrients as well as carbon to the	Distribution;	Needs to be quantified

Indicator species:	**Ribbonweed – *Vallisneria australis***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
cycling	aquatic food web by being consumed either directly or as a detrital food source (Briggs & Maher 1985)	Abundance – coverage	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Not an indicator of terrestrial species	NA	Acid- & salinity-tolerance not known
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Indicator of submergent population	Distribution	
Balance of aquatic & terrestrial species	Indicator of aquatic vegetation only	Distribution	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

6.7 Water ribbons – *Triglochin procerum*

Water ribbons is a glossy, broad-leaved plant which can either grow semi-upright (where leaves stand to about 0.5 m above the water surface) or with leaves floating upon the water surface(Romanowski 1992). Seeds of water ribbons germinate in the autumn, generally in shallow water and growth and flowering takes place in the spring and summer months (Sainty & Jacobs 1994). Fruiting occurs in late summer or autumn. Water ribbons are a valuable habitat component for waterbirds and fish (Sainty & Jacobs 1994). Water regime (i.e. water level fluctuation and duration, and flood frequency) is the primary factor determining the productivity of water ribbons (Deegan *et al.* 2010). Table 6.7 links water ribbons to individual ecological outcomes.

Table 6.7: List of ecological outcomes that would be indicated by water ribbons populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	**Water ribbons – *Triglochin procerum***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Seeds are short-lived, a combination of wet & dry conditions facilitates the spread of water ribbon seedlings (Rea & Ganf 1994). Rhizomatous growth & shoot recruitment also occurs but is a much slower process. Water regime is the primary factor determining the productivity of this species (Deegan *et al.* 2010)	Distribution; Abundance – coverage	
Suitable habitat	Water ribbons provide habitat for aquatic fauna	Distribution; Abundance – coverage	
Suitable food resources	Provides a food source for a range of aquatic fauna which consume vegetation directly or indirectly via detritus (Deegan & Ganf 2008)	Distribution; Abundance – coverage	Use as a food source needs to be quantified
Suitable water quality	Not currently an indicator	NA	Water quality tolerances unknown
Species connectivity	Water ribbons can spread downstream following flooding (Deegan *et al.* 2010)	Abundance – seedlings	
Viable propagule bank	Will germinate underwater & on wet sediment (Nicol & Ganf 2000). The number of seeds produced exponentially increases with the depth & duration of flooding (Rea & Ganf 1994) to a maximum depth of about 2 m (Sainty & Jacobs 1994) Will also spread as seedlings as a secondary dispersal mechanism (Nicol & Ganf 2000)	Abundance – seedlings	
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Not an indicator	NA	
Longitudinal biological connectivity	Not currently an indicator	NA	Reliance on nearby populations is unknown

Indicator species:	**Water ribbons – *Triglochin procerum***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
No accumulation of pollutants	Not currently an indicator	NA	Tolerance to pollutants unknown
Lateral habitat diversity	Indicator of submerged plants	Distribution; Abundance – coverage	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Tolerant of salinities of up to 8 ppt for at least 6 weeks (Goodman *et al.* 2010)	Distribution	Salinity tolerance threshold unknown
Temporal variability in salinity	Not an indicator	NA	
Communities requiring varied salinities supported	Indicator of fresh to brackish waters (Goodman *et al.* 2010)	Distribution	
Temporal variability in flow	Not currently an indicator	NA	Reliance on temporally-variable flows is unknown
Seasonal variability in flows	Deep & permanent water levels cause increased abundance & stimulates flowering & seed dispersal (Rea & Ganf 1994)	Abundance – seedlings	
Seasonal variability in water levels	Deep & permanent water levels cause increased abundance & stimulates flowering & seed dispersal (Rea & Ganf 1994)	Abundance – seedlings	
Communities requiring varied hydrology supported	Indicator of permanently-inundated habitats (Rea & Ganf 1994)	Distribution	
Communities requiring flooding supported	Flooding stimulates flowering & seed production although this is not required for survivorship because water ribbons also spread vegetatively (albeit more slowly; Rea & Ganf 1994) & as free-floating seedlings (Nicol & Ganf 2000).	Recruitment events – incidence of flowering; Abundance – seeds	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Supports a range of aquatic fauna which consume vegetation directly or indirectly via detritus (Deegan & Ganf 2008)	Distribution; Abundance – coverage	Role in food webs needs to be quantified
Functions performed by multiple species	Primary producer, cycles nutrients (Rea & Ganf 1994)	Distribution; Abundance – coverage	Functional role needs to be quantified
Efficient nutrient cycling	Utilises carbon & nutrients within the water column (Rea & Ganf 1994)	Distribution; Abundance – coverage	Role in nutrient cycling needs to be quantified
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant	Not a terrestrial species	NA	Acid & salinity

Indicator species:	**Water ribbons – *Triglochin procerum***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
& terrestrial species present			tolerance unknown
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Indicator of submergent vegetation only	Distribution; Abundance – coverage	
Balance of aquatic & terrestrial species	Indicator of aquatic habit only	Distribution; Abundance – coverage	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not currently an indicator	NA	Acid tolerance unknown

6.8 Spiny rush – *Juncus acutus*

Spiny rush (*Juncus acutus*) is an introduced estuarine rush that inhabits brackish soils (Greenwood & MacFarlane 2006). It grows to 1.5 m high in saltmarshes and on dunes. Spiny rush requires wet soils for establishment but is intolerant of high water levels (Florabase 2011) and can reduce soil erosion rates. Spiny rush is not native and is able to displace the native relative *J. kraussi* at moderate to high salinities (e.g. salinities ≤10 ppt are favourable to *J. kraussi*) (Greenwood & MacFarlane 2006). Table 6.8 links spiny rush to individual ecological outcomes.

Table 6.8: List of ecological outcomes that would be indicated by spiny rush populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	Spiny rush – *Juncus acutus*		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Riparian species which requires salinities less than 17.5 ppt for seed germination. Spiny rush does not tolerate high water levels but requires wet soils for establishment (Greenwood & MacFarlane 2006)	Distribution; Abundance – coverage	
Suitable habitat	Inhabits periodically-inundated areas (Greenwood & MacFarlane 2006)	Distribution; Abundance – coverage	
Suitable food resources	Not currently an indicator	NA	Use of *J. acutus* as a food resource is not known
Suitable water quality	Requires salinity of <17.5 ppt for germination (Greenwood & MacFarlane 2006)	Distribution; Abundance – shoot density	
Species connectivity	Not currently an indicator	NA	Role in promoting connectivity is unknown
Viable propagule bank	Seeds have remained viable in laboratory conditions for up to four years but thought to be much shorter in the field (Department of Primary Industries 2011). Seeds are tolerant to periodic salt water inundation (Department of Primary Industries 2011)	Distribution	
No barriers to recruitment	Not currently an indicator	NA	Potential barriers to recruitment are unknown
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Requires salinity of <17.5 ppt for germination (Greenwood & MacFarlane 2006)	Distribution; Abundance – shoot density	
Regional hydraulically connected	Not currently an indicator	NA	Reliance on hydraulic connectivity is not known
Longitudinal biological connectivity	Not currently an indicator	NA	Role in promoting connectivity is unknown

Indicator species: Spiny rush – *Juncus acutus*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
No accumulation of pollutants	Cannot adapt to rapid sand accretion (Jones & Richards 1954)	Distribution	Tolerances for salinity, acid, metals & agrochemicals are unknown
Lateral habitat diversity	Indicator of riparian vegetation only	Distribution	
Habitat variability	Not currently an indicator	NA	Provision of, or reliance on, variable habitat unknown
Range of salinities with appropriate maxima	Tolerant of salinity. Requires salinity of <17.5 ppt for germination (Greenwood & MacFarlane 2006)	Distribution; Abundance – shoot density	
Temporal variability in salinity	Requires salinity of <17.5 ppt for germination (Greenwood & MacFarlane 2006)	Distribution; Abundance – shoot density	
Communities requiring varied salinities supported	Indicator of estuarine habitats	Distribution	
Temporal variability in flow	Cannot tolerate high water levels (Jones & Richards 1954)	Distribution	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Does not tolerate high water level (Jones & Richards 1954)	Distribution; Abundance – coverage	
Communities requiring varied hydrology supported	Indicator of periodically-inundated habitats	Distribution; Abundance – coverage	
Communities requiring flooding supported	Requires wet soils for establishment but can persist through drought periods (Florabase 2011)	Distribution	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Not currently an indicator	NA	Role in promoting complex food webs not clear
Functions performed by multiple species	Not currently an indicator	NA	Functional role performed is not documented
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Able to displace the native *J. kraussi* at low salinities (i.e. ≤10 ppt) (Greenwood & MacFarlane 2009)	Distribution	
Acid- & saline-tolerant & terrestrial species present	Terrestrial species, albeit reliant on wet soils; not tolerant of salinity (Greenwood & MacFarlane 2009)	NA	Acid tolerance unknown

Indicator species:	**Spiny rush – *Juncus acutus***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Wide riparian & littoral zones supported	Indicator of variable water level supporting riparian zone vegetation	Distribution; Abundance – coverage	
Lateral connectivity of vegetation	Indicator of riparian zone vegetation	Distribution; Abundance – coverage	
Balance of aquatic & terrestrial species	Terrestrial species only	Distribution	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not currently an indicator	NA	Acid tolerance unknown

6.9 Large-fruited sea tassel – *Ruppia megacarpa*

Large-fruited sea tassel is a native submerged perennial plant that has an extensive rhizome system. Large-fruited sea tassel flowers in summer and autumn and, in particular conditions, can complete a life cycle from seed to seed in 60 to 80 days (Sainty & Jacobs 1994). *R. megacarpa* is a robust perennial that occurs in permanent waters of salinities between 12 and 50 ppt (Brock 1979). Table 6.9 links *R. megacarpa* to individual ecological outcomes.

Table 6.9: List of ecological outcomes that would be indicated by large-fruited sea tassel populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	**Large-fruited sea tassel – *Ruppia megacarpa***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Submergent perennial species which, although reasonably saline-tolerant (i.e. between 12-50 ppt; Brock 1979), requires freshwater flows for seed germination	Distribution; Abundance – shoot density	
Suitable habitat	Provides important habitat (i.e. through very dense strands) for macroinvertebrates & meiofauna (Geddes 2003; Fogarty 2009)	Distribution; Abundance – coverage	Tests of relationship of *Ruppia* as habitat for macroinvertebrates (Fogarty 2009)
Suitable food resources	Provides a food source for invertebrates, fish & waterbirds (Geddes 2003; Fogarty 2009)	Distribution; Abundance – coverage	Use as a food source needs to be quantified
Suitable water quality	Inhabits water with salinity levels between 12-50 ppt TDS (Brock 1981)	Distribution	
Species connectivity	Not an indicator	NA	
Viable propagule bank	Produces little seed. Primarily reproduces vegetatively (Brock 1982a). Reduced salinities break the dormancy of the seeds within the seedbank (Brock 1982a)	Abundance – shoot density	
No barriers to recruitment	Seeds germinate following freshwater flows (Brock 1982a)	NA	Other potential barriers unknown
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Requires freshwater flows for seed germination	Abundance – shoot density	
Regional hydraulically connected	Spatial distribution of is altered by distance to oceanic & river influences (Boyce *et al.* 2001) (i.e. as a result of changing water quality)	Distribution	
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Indicator of salinities ranging from 12-50 ppt (Brock 1981)	Distribution	
Lateral habitat diversity	Indicator of submergent vegetation only	Distribution	
Habitat variability	Not an indicator	NA	

Indicator species:	**Large-fruited sea tassel – *Ruppia megacarpa***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Range of salinities with appropriate maxima	Indicator of salinities ranging from 12-50 ppt (Brock 1981)	Distribution	
Temporal variability in salinity	Seeds germinate following freshwater flows (Brock 1982a)	Distribution; Abundance – shoot density	
Communities requiring varied salinities supported	Not an indicator. Tolerant of fresh through to saline waters	NA	
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Not an indicator. Inhabits areas with stable water levels (Brock 1981)	NA	
Seasonal variability in water levels	Not an indicator. Inhabits areas with stable water levels (Brock 1981)	NA	
Communities requiring varied hydrology supported	Indicator of permanently-inundated habitats (Brock 1981)	Distribution	
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Provides a food source for invertebrates, fish & waterbirds (Geddes 2003; Fogarty 2009)	Distribution; Abundance	
Functions performed by multiple species	Provides a food source for invertebrates, fish & waterbirds (Geddes 2003; Fogarty 2009)	Distribution; Abundance	
Efficient nutrient cycling	Primary producer, known to cycle nutrients. Is potentially a major source of dietary carbon supporting secondary production through either the detrital or grazing pathways (Boyce *et al.* 2001)	Distribution; Abundance – coverage	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Moderately saline tolerant (i.e. 10-50 ppt), not a terrestrial species	Distribution	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Indicator of submergent vegetation	Distribution	
Balance of aquatic & terrestrial species	Indicator of aquatic habit only	Distribution	
Exchange between	Not an indicator	NA	

Indicator species:	**Large-fruited sea tassel – *Ruppia megacarpa***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
aquatic & terrestrial systems			
Regular oxidation of sulfidic material	Not currently an indicator	NA	Acid tolerance unknown

6.10 Tuberous sea tassel – *Ruppia tuberosa*

Ruppia tuberosa is an annual macrophytic species that grows in ephemeral habitats. The macrophyte grows in shallow waters from 0.1 to 0.4 m deep and has short leaves (Brock 1981). Seeds and turions (asexual perennating organs, over-wintering buds; Brock 1982b) are produced and lie dormant during the dry phase of their habitats (months to years). Germination is stimulated upon rewetting of habitats and also increased salinity (Brock 1983). Table 6.10 links *R. tuberosa* to individual ecological outcomes.

Table 6.10: List of ecological outcomes that would be indicated by tuberous sea tassel populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	**Tuberous sea tassel – *Ruppia tuberosa***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Annual species, flowers & fruits prolifically from September to November, sets seed before habitats dry in November/December. Turions also produced. Saline water & wetting & drying cause germination (Brock 1981)	Abundance – shoot density	
Suitable habitat	Provides important habitat for fish, macroinvertebrates & meiofauna (Fogarty 2009; Rogers & Paton 2009)	Distribution; Abundance – coverage	
Suitable food resources	Provides a food source for invertebrates, fish & waterbirds. Forms the basis of the food chain for waders & waterfowl (Lamontagne *et al.* 2004; Rogers & Paton 2009)	Distribution; Abundance – coverage	
Suitable water quality	In experimental lab conditions can survive in 3-230 ppt (Brock 1981)	Distribution	
Species connectivity	Seeds & turions may be dispersed by bird species or water currents to nearby environments. Turions thought to be more important for dispersal than seeds in the region (Rogers & Paton 2009)	Abundance – shoot & turion densities	Seed viability after gut passage
Viable propagule bank	Seed bank & turion density essential for survival. Fluctuating water level, exposing sediments with seeds & turions required for the germination of *R. tuberosa*; shallow water (< 0.4 m) required for survival (Brock 1981)	Abundance – shoot, seed & turion densities	Quantitative data about the persistence of seeds & turions in propagule bank
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic connectivity	Variable flow regime required for germination of seeds & turions (Brock 1981)	Abundance – shoot density	
Water residence times finite	Not an indicator given the range of salinities in which it can survive	NA	
Regional hydraulically connected	Seasonal connectivity with upstream environments & to Encounter Bay required to provide seasonal flow & variable sea levels that drive changes in water level needed to provide habitat (Paton 2010)	Abundance – shoot density	
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Modelled salinity threshold is 54.3 ppt (Rogers & Paton 2009) although the species has been recorded in salinities of up to 230 ppt (Brock 1981)	Distribution	

Indicator species: **Tuberous sea tassel – *Ruppia tuberosa***			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Lateral habitat diversity	Indicative of submerged plants	Distribution	
Habitat variability	Indicator of temporal variability of habitats. Wetting & drying of habitats essential for germination (Brock 1981)	Abundance – shoot density	
Range of salinities with appropriate maxima	Maximum salinity tolerance threshold modelled at 54.3 ppt (Rogers & Paton 2009) although the species has been recorded in salinities of up to 230 ppt (Brock 1981)	Distribution	
Temporal variability in salinity	Increased salinities stimulate germination of seed bank (Brock 1981)	Abundance – shoot density; Distribution	
Communities requiring varied salinities supported	Indicator of estuarine, marine & hypersaline regions	Distribution	
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Seasonal inundation from flows promote germination of seeds (Brock 1981)	Abundance – shoot density	
Seasonal variability in water levels	Seasonal inundation promotes germination of seeds. After prolonged periods of low water levels, the viability of the remaining seed band may be low & seeds may be buried too deeply in the sediment to germinate (Rogers & Paton 2009)	Abundance – shoot density	
Communities requiring varied hydrology supported	Indicator of ephemeral habitats	Abundance – shoot density; Distribution	
Communities requiring flooding supported	Flooding stimulates germination	Abundance – shoot density; Distribution	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Provides a food source for invertebrates, fish & waterbirds. Forms the basis of the food chain for waders & waterfowl (Lamontagne *et al.* 2004; Rogers & Paton 2009)	Abundance – shoot density; Distribution	
Functions performed by multiple species	One of few submergent macrophytic taxa present within the Coorong	Distribution	
Efficient nutrient cycling	Important primary link in the food web, particularly in hypersaline habitats	Distribution	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Not acid-tolerant or a terrestrial species. Is relatively saline tolerant	Distribution	
Wide riparian & littoral zones supported	Variable water levels provide & maintain suitable habitat for germination & survival	Abundance – shoot density; Distribution	

Indicator species:	**Tuberous sea tassel – *Ruppia tuberosa***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Lateral connectivity of vegetation	Species provides vegetation cover from mudflats as shoots, to full plants down to 0.4 m depth	Abundance – shoot density; Distribution	
Balance of aquatic & terrestrial species	Species exists primarily as aquatic but can germinate in the littoral zone	Abundance – shoot density; Distribution	
Exchange between aquatic & terrestrial systems	Species utilises energy, nutrients & carbon from riparian zone & can be utilised by aquatic species when submerged	Abundance – shoot density; Distribution	
Regular oxidation of sulfidic material	Not an indicator	NA	

6.11 Evaluation of vegetation indicators as evidence for achieving specific outcomes for the site

In total, ten vegetation taxa and/or assemblages were selected (Table 6.11) across freshwater, estuarine, marine and hypersaline inhabitants. The indicator that provided evidence for the highest number of outcomes was samphire & saltmarsh communities, scoring against 28 out of a possible 33 outcomes (85%). Samphire & saltmarsh communities are tolerant of salinity and, although they are floodplain inhabitants, can tolerate periodic inundation and water-logging (Nicol 2007). Despite this, these communities require occasional freshwater flows to facilitate germination and moderate salinity levels (Purvis *et al.* 2009) and thus are useful as indicators. Furthermore, samphire & saltmarsh communities were found to be indicators of two outcomes that no other vegetation species or assemblage could provide evidence for, *viz.* Longitudinal biological connectivity, and Tidal signal apparent.

The indicators that scored the lowest number of outcomes were the water milfoils and ribbon weed (only 12 or 36%). Because these two taxa are both found in submerged freshwater habitats, their potential for being an indicator of a broad range of the outcomes may be reduced. Furthermore, some of the knowledge gaps for these two species may be limiting their potential use as an indicator. However, their presence in the CLLMM region indicates that some submerged freshwater habitats are present, which is likely to indicate that estuarine, marine and hypersaline habitats are also present elsewhere in the system, due to the inherent salinity gradient of the region.

No vegetation taxa or assemblages was found to be indicative of the regular oxidation of sulfidic material but the interaction between many of the species or assemblages and acid sulfate soils is not well known, particularly locally. With further knowledge of these interactions, which may arise following recovery from the recent acidification in parts of the Lower Lakes, it may be possible that one or many of the vegetation indicators assessed here could provide evidence about this outcome.

All of these vegetation taxa or assemblages were found to be indicators of five of the outcomes: Successful recruitment; Lateral habitat diversity; Communities requiring varied hydrology supported; Lateral connectivity of vegetation; and Balance of aquatic & terrestrial species. As a whole, the vegetation indicators performed best for the outcomes linked to the objective of self-sustaining populations.

Many gaps in the knowledge were apparent for the vegetation taxa and assemblages assessed in this study, particularly with respect to local tolerances within the region. Further research and development delving into the ecological characteristics and thresholds of these species, and possibly other taxa known in the CLLMM region, may demonstrate that the vegetation indicators can provide evidence of more outcomes than has been shown here. This is particularly relevant to those taxa and assemblages with larger or more knowledge gaps.

Table 6.11: Summary of outcomes represented by the vegetation indicators

Note: A tick denotes the taxa are an indicator for that outcome. All scientific names and further information can be found in the text above. Note that the quality and spatial extent of data available varied between taxa, as prescribed in the individual sections above. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Outcome		Samphire & saltmarsh communities	Paperbark woodlands	Lignum	Diverse reed beds	Water milfoils	Ribbonweed	Water ribbons	Spiny rush	*R. megacarpa*	*R. tuberosa*	**Count**
Self-sustaining populations	Successful recruitment	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	**10**
	Suitable habitat	✓	✓	✓	✓		✓	✓	✓	✓	✓	**9**
	Suitable food resources	✓	✓		✓		✓	✓		✓	✓	**7**
	Suitable water quality	✓		✓	✓	✓	✓		✓	✓	✓	**8**
Population connectivity	Species connectivity			✓				✓			✓	**3**
	Viable propagule bank	✓	✓	✓	✓	✓		✓	✓	✓	✓	**9**
	No barriers to recruitment	✓		✓		✓						**3**
Hydraulic connectivity	Lateral hydraulic connectivity	✓	✓	✓	✓						✓	**5**
	Water residence times finite					✓			✓	✓		**3**
	Regional hydraulically connected	✓			✓					✓	✓	**4**
	Longitudinal biological connectivity	✓										**1**
	No accumulation of pollutants	✓	✓			✓			✓	✓	✓	**6**
Habitat complexity	Lateral habitat diversity	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	**10**
	Habitat variability						✓				✓	**2**
Salinity gradients	Range of salinities with appropriate maxima	✓	✓	✓	✓	✓		✓	✓	✓	✓	**9**
	Temporal variability in salinity	✓	✓						✓	✓	✓	**5**
	Communities requiring varied salinities supported	✓	✓	✓	✓	✓		✓	✓		✓	**8**
Flow and water level	Temporal variability in flow	✓	✓	✓	✓				✓			**5**
	Seasonal variability in flows	✓	✓					✓			✓	**4**
	Seasonal variability in water levels	✓	✓		✓			✓	✓		✓	**6**
	Communities requiring varied	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	**10**

	Outcome	Samphire & saltmarsh communities	Paperbark woodlands	Lignum	Diverse reed beds	Water milfoils	Ribbonweed	Water ribbons	Spiny rush	*R. megacarpa*	*R. tuberosa*	**Count**
	hydrology supported											
	Communities requiring flooding supported	✓	✓	✓				✓	✓		✓	**6**
	Tidal signal apparent	✓										**1**
Ecological function	Complex food webs present	✓	✓	✓	✓		✓	✓		✓	✓	**8**
	Functions performed by multiple species		✓				✓	✓		✓	✓	**5**
	Efficient nutrient cycling	✓	✓	✓	✓		✓	✓		✓	✓	**8**
	Control of invasive species	✓			✓				✓			**3**
	Acid- & saline-tolerant & terrestrial species present	✓	✓	✓	✓					✓	✓	**6**
	Wide riparian & littoral zones supported	✓	✓	✓	✓						✓	**5**
Aquatic-terrestrial connectivity	Lateral connectivity of vegetation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	**10**
	Balance of aquatic & terrestrial species	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	**10**
	Exchange between aquatic & terrestrial systems	✓	✓	✓	✓				✓		✓	**6**
	Regular oxidation of sulfidic material											**0**
	Count	**28**	**23**	**20**	**21**	**12**	**12**	**17**	**18**	**18**	**26**	

6.12 Summary

- **A total of ten vegetation taxa and/or assemblages were assessed as being potential indicators for the range of outcomes prescribed in Chapter 3.**
- **Samphire & saltmarsh communities provided evidence for the highest number of outcomes of all the indicators (28 out of 33; 85%), including two outcomes that no other vegetation indicator assessed here did: Longitudinal biological connectivity; and Tidal signal apparent.**
- **No vegetation indicators unambiguously provided evidence against Oxidising of sulfidic material.**
- **Knowledge gaps were evident for many of the taxa and assemblages of vegetation detailed here, particularly related to local tolerances (i.e. within the CLLMM region) and further research would provide a more comprehensive evaluation of the outcomes identified at assessing a healthy, resilient and productive wetland of international significance.**

7. Macroinvertebrate indicators

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A number of ecological outcomes have been recognised as representing a healthy, productive and resilient wetland for the Coorong, Lower Lakes and Murray Mouth region. These have been summarised in Chapter 3 above. This section identifies in detail the macroinvertebrate taxa and metrics which provide indicators for these outcomes.

The extent of knowledge of the macroinvertebrates present within the CLLMM region is both temporally and spatially variable. Benthic macroinvertebrates within the Coorong have been studied over a number of years (Dittmann *et al.* 2009), and recently, benthic and edge-dwelling macroinvertebrates around the Goolwa Channel and the lower reaches of the tributaries have also been surveyed (Dittmann *et al.* 2009). However, macroinvertebrates in the water column, in edge habitats in the Coorong and more broadly distributed through the Lakes are poorly understood.

As a result, the macroinvertebrate indicator taxa selected are based on variable levels of understanding regarding their functional role within the region. The distribution, abundance and functional role played by estuarine benthic macroinvertebrate indicators are relatively well-known. Conversely, freshwater indicators for the system have been selected based on taxa lists from recent sampling. The taxa considered as indicators were selected based on knowledge of their life history and habitat preferences in other systems drawn from the literature and from expert opinion.

Macroinvertebrates are important indicators of water quality, habitat quality and biodiversity (Norris & Thoms 1999). They have been defined as invertebrates that are readily visible to the naked eye (greater than 2.5 mm long) (Miller 1983). There are a number of advantages associated with the use of aquatic macroinvertebrates as indicators. These include that they:

- are the major consumers of in-stream organic material, forming the basis of many aquatic food webs (Bunn *et al.* 1999);
- have a diverse ecology and are often the dominant members of food webs in both biomass and richness (Gullan & Cranston 1999);
- have short life-cycles, and therefore respond quickly to changes in their environment (Gullan & Cranston 1999);
- exist in the majority of microhabitats within aquatic environments (Metzeling *et al.* 2003);
- respond predictably to a given stimuli or disturbance in their environment (Gullan & Cranston 1999, Ladson *et al.* 1999); and
- responds quickly to changes in the physical environment in a meaningful and measurable manner (Wallace *et al.* 1996).

Since the 1950s macroinvertebrates have been used across the globe to detect changes in water quality, quantity, flow, substrate quality, contamination (including via heavy metals) and management intervention (e.g. Gaufin & Tarzwell 1955, Wilson 1994). Therefore, despite the limitations in CLLMM-specific information regarding freshwater taxa in particular, macroinvertebrates have been included in this first iteration of the determination of an environmental water requirement for the region, acknowledging that the taxa selected are likely to require refinement as more data become available regarding the mix of taxa present in the region.

In freshwater systems, one measure of the sensitivity of macroinvertebrate taxa is the SIGNAL2 score (Chessman 2003). SIGNAL2 is a score between 1 and 10, with 1 indicating highly-tolerant taxa and 10 indicating highly-sensitive taxa (Chessman 2003). While there are some issues associated with the use of this metric (e.g. generalisations across diverse taxonomic groups), it is a useful broad-brush approach to understanding the relative sensitivity of different freshwater taxa. This has not been used as the only basis for selection of indicator taxa, but has been considered along with other life-history characteristics.

The importance of macroinvertebrates in an estuarine system should not be underestimated as they directly process a significant proportion of primary production whilst also providing vital food sources for crustaceans, fish and birds (Herman *et al.* 1999). Within estuaries, the interface of marine and freshwater environments drives the dynamic nature of abiotic variables such as salinity and sediment characteristics, resulting in highly variable taxon diversity and abundances within and between transition zones (Attrill & Rundle 2002; Giberto *et al.* 2007). Macroinvertebrate assemblages can frequently be classified into three separate communities along the estuarine salinity gradient: a marine community in the polyhaline zone; a brackish community in the mesohaline zone; and a third community in the oligohaline and freshwater mudflat zones (Mannino & Montagna 1997; Ysebaert *et al.* 1998, Giberto *et al.* 2007). However within these zones, taxa distributions are not static as the zonal boundaries fluctuate in time and space, particularly within the mesohaline and oligohaline zones (Chapman & Brinkhurst 1981; Ysebaert *et al.* 1998). However, the rate and magnitude of a salinity change may be a more important factor than the salinity gradient itself in driving macroinvertebrate community composition (Sanders *et al.* 1965).

Significant changes in macroinvertebrate species distributions in the region have been observed since 2006, with many of the more saline-tolerant taxa recently appearing in Lake Alexandrina following seawater intrusion through the barrages as a result of recent low lake levels (A. Rolston, unpub. data). The Lower Lakes provide ideal habitats for many of these invertebrate taxa, particularly if lake salinities continue to rise. Increasing salinities in the Lower Lakes have also led to changes in the distribution of less saline-tolerant taxa away from the barrages and regions of elevated salinities.

Unlike some bird and fish taxa, no macroinvertebrates are listed under the Ramsar listing or the *Environmental Protection and Biodiversity Conservation Act* 1999. Nor are any macroinvertebrates listed as species of National Environmental Significance. Therefore it is not possible to categorise macroinvertebrate taxa into such groups. Macroinvertebrate taxa may be placed into functional groupings such as feeding, locomotive and habitat guilds, however large variability in guild responses to changing environmental conditions are likely, thus limiting the strength of predictions based on this literature review and expert knowledge. Instead, a number of key taxa have been identified as a result of their distributions, abundances, habitat preferences and community and trophic linkages. However, for some outcomes overall measures of community composition were deemed more appropriate.

A diverse range of taxa have been selected as indicators for the CLLMM region. One common taxon, chironomid larvae are not being used as an indicator because they are present throughout the system from freshwater to the lower end of hypersaline and it is very difficult to classify them into the functional groups required to distinguish meaningful trends. Macroinvertebrate indicator species considered here are:

Freshwater:

- Freshwater mussel, *Velesunio ambiguus*
- Freshwater crayfish (yabby), *Cherax destructor*
- Mayflies, Ephemeroptera
- Stoneflies, Plecoptera
- Caddisflies, Trichoptera
- Amphipoda

- Segmented worms, Oligochaeta
- Hydra, *Hydra* spp.
- Freshwater limpets, Ancylidae
- Brackish water crabs, Hymenosomatidae
- Marsh beetles, Scirtidae
- Blackflies, Simuliidae

Estuarine and/or Marine:

- Tubeworm, *Ficopomatus enigmaticus*
- Polychaete worm, *Nephtys australiensis*
- Microbivalve, *Arthritica helmsi*
- Polychaete worm, *Simplisetia aequisetis*
- Polychaete worm, *Capitella* spp.
- Goolwa cockle, *Donax deltoides*

Hypersaline:

- Brine shrimp, *Parartemia zietziana*

7.1 Freshwater mussel – *Velesunio ambiguus*

The freshwater mussel *Velesunio ambiguus* is typically found in the River Murray. This species was previously found in freshwater habitats around the Lower Lakes before salinities increased beyond tolerance levels. *Velesunio ambiguus* adults are sessile and therefore unable to actively escape deteriorating environmental conditions. However, their larval stages act as parasites of fish and can therefore be classed as mobile. *Velesunio ambiguus* can also act as a substrate for *Ficopomatus enigmaticus* colonisation. *Velesunio ambiguus* is tolerant of stable conditions and may survive periods without surface water of up to one year (Walker 1985). Table 7.1 links *V. ambiguus* to individual ecological outcomes.

Table 7.1: List of ecological outcomes that would be indicated by freshwater mussel populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	Freshwater mussel, *Velesunio ambiguus*		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Sessile adult phase & parasitic larval phase indicate that a range of conditions are met to support self-sustaining populations (Walker *et al*. 2009)	Abundance	
Suitable habitat	Indicator of freshwater habitats	Presence of all life history stages	
Suitable food resources	Filter feeder. Possible food source for larger birds & fish. Traditional food source of Ngarrindjeri nation	Abundance	Role in food web
Suitable water quality	Only able to tolerate freshwater environments	Distribution	Upper salinity tolerance level
Species connectivity	Larval dispersal likely to indicate connectivity between lake & riverine populations	Recruitment events	Host species specificity of larvae
Viable propagule bank	Dependent on water temperature for propagule release. Able to withstand prolonged periods out of water (up to one year) (Walker *et al.* 2009)	Host presence; Spawning events	Timing of spawning events, host specificity
No barriers to recruitment	Larval stages dependent on fish host species for development	Host presence; Spawning events	Host species specificity of larvae
Lateral hydraulic connectivity	Dispersal dependent on host fish that may in turn depend on hydraulic connectivity (Walker *et al*. 2009)	Recruitment events	Host species specificity
Water residence times finite	Not a primary indicator because tolerant of stable conditions (Walker 1985)	NA	
Regional hydraulically connected	Not a primary indicator, as larval host specificity & host dependence on connectivity (i.e. diadromous fish) is unknown	NA	Host species specificity
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Bioaccumulator of metals (Jones & Walker 1979; Walker 1981; Millington & Walker 1983)	Tissue composition	Suitability as indicator of accumulation

Indicator species:	**Freshwater mussel, *Velesunio ambiguus***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Lateral habitat diversity	Not an indicator	NA	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Indicator of freshwater only	Distribution	Upper salinity threshold
Temporal variability in salinity	Indicator of freshwater only	Distribution	
Communities requiring varied salinities supported	Would indicate freshwater salinities	Distribution; Recruitment events	Salinity regime needed for recruitment
Temporal variability in flow	Unable to exist in fast-flowing water (Walker *et al*. 2009)	Distribution	Upper flow tolerance
Seasonal variability in flows	Unable to exist in fast-flowing water (Walker *et al*. 2009)	Distribution	Upper flow tolerance
Seasonal variability in water levels	Able to survive out of water for up to one year (Walker *et al.* 2009)	Distribution	Spawning ability following emersion
Communities requiring varied hydrology supported	Ideally requires permanent submersion	Distribution	Spawning ability following emersion
Communities requiring flooding supported	Ideally requires permanent submersion	Distribution	Spawning ability following emersion
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Provides substrate for tubeworm settlement; possible food source for larger fish	Abundance	Settlement of *F. enigmaticus* on live mussels, whether able to tolerate elevated salinities where tubeworm is present
Functions performed by multiple species	Only floodplain bivalve in system. One other freshwater mussel present in system which previously dominated river channel & faster-flowing water (Walker *et al*. 2009)	Distribution	Abundances
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Settlement substrate for tubeworm	Prevalence of *Ficopomatus* infestation	Whether mussels can tolerate elevated salinities where tubeworm can be present
Acid- & saline-tolerant & terrestrial species present	Freshwater tolerant only so presence would indicate that environment. Increasing acidity may affect shells & shell production	Distribution	
Wide riparian & littoral zones supported	Not primary indicator because occurs in permanently-inundated areas	NA	
Lateral connectivity of vegetation	Not an indicator of diverse vegetation	NA	

Indicator species:	**Freshwater mussel, *Velesunio ambiguus***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Balance of aquatic & terrestrial species	Indicator of permanently-inundated low-flow freshwater environments	Distribution	
Exchange between aquatic & terrestrial systems	Secondary consumer of zooplankton, phytoplankton & detritus	NA	Filtration rates
Regular oxidation of sulfidic material	Occur embedded in sediment so presence would indicate tolerable acid levels. Bioaccumulator of metals	Distribution	Tolerance levels

7.2 Freshwater crayfish – *Cherax destructor*

Freshwater crayfish are colloquially known as yabbies. Yabbies are characteristics species of the River Murray and Lower Lakes, although anecdotal community evidence would suggest that they have declined markedly in the Lakes and Lower River Murray. Yabbies are thought to be relatively mobile and are therefore capable of moving from deteriorating environmental conditions, providing that the rate of deterioration is not too rapid or extensive and that connections to better environmental conditions are functional. *Cherax destructor* have been attributed as part of the reason for the decline in the Murray crayfish (*Euasticus armatus*) because of their ability to tolerate slower-flowing floodplain conditions (Walker 1985). Table 7.2 links *C. destructor* to individual ecological outcomes.

Table 7.2: List of ecological outcomes that would be indicated by yabby (*Cherax destructor*) populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	Freshwater crayfish (yabby), *Cherax destructor*		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Breed from late spring until autumn. Length of egg development is temperature dependent (Walker *et al.* 2009)	Recruitment events	
Suitable habitat	Indicator of freshwater habitats	Distribution	
Suitable food resources	Deposit & detrital feeder & occasional predator	Abundance	Feeding rates, frequency of predation
Suitable water quality	Only able to tolerate freshwater environments	Distribution	Upper salinity tolerance level
Species connectivity	Not an indicator	NA	
Viable propagule bank	Able to spend several years underground during drought periods	Abundance – numbers underground	Upper time limit for survival
No barriers to recruitment	Recruitment would indicate lack of intraspecific connectivity barriers	Recruitment events	
Lateral hydraulic connectivity	Not an indicator due to ability to exist in billabongs & dry ponds	NA	
Water residence times finite	Not an indicator due to ability to exist in billabongs & dry ponds	NA	
Regional hydraulically connected	Not an indicator	NA	
Longitudinal biological connectivity	Not a indicator	NA	
No accumulation of pollutants	Juveniles may be more sensitive than other taxa such as juvenile fish, mayflies & amphipods (see Khan & Nugegoda 2006 for details)	Tissue composition	
Lateral habitat diversity	Not an indicator	NA	
Habitat variability	Not an indicator	NA	

Indicator species:	**Freshwater crayfish (yabby), *Cherax destructor***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Range of salinities with appropriate maxima	Indicator of freshwater only	Distribution	Upper salinity threshold
Temporal variability in salinity	Indicator of freshwater only	Distribution	
Communities requiring varied salinities supported	Would indicate freshwater salinities	Distribution; Recruitment events	Salinity regime needed for recruitment
Temporal variability in flow	Response to flow is unknown, but often found in relatively low-flow environments	Distribution	Upper flow tolerance
Seasonal variability in flows	Response to flow variability is also unknown	Distribution	Upper flow tolerance
Seasonal variability in water levels	Able to survive underground for long periods (i.e. years) during drought (Walker *et al.* 2009)	Distribution	Upper timeframe for survival
Communities requiring varied hydrology supported	Ideally requires permanent submersion	Distribution	
Communities requiring flooding supported	Ideally requires permanent submersion	Distribution	Spawning ability following emersion
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Previously an important recreational & commercial fishery; small yabbies are prey for common carp	Distribution	Severity of predation
Functions performed by multiple species	Other crayfish species (the Murray crayfish, *Euastacus armatus*) disappeared from 700 km of natural habitat, including the Lower Murray, possibly due to agricultural pesticides, over-fishing & changes to flow regimes (Walker *et al.* 2009). May be the only crayfish species remaining	Distribution	Abundances
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Freshwater tolerant only so presence would indicate that environment. Increasing acidity may affect homeostasis (Ellis & Morris 1995)	Distribution	Effects of acidity on spawning
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Indicator of predominantly-inundated freshwater environments	Distribution	
Exchange between	Detritivore so contributes to carbon cycling	Abundance;	Consumption rates

Indicator species:	Freshwater crayfish (yabby), *Cherax destructor*		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
aquatic & terrestrial systems		Feeding rates	
Regular oxidation of sulfidic material	Able to exist in soil for long periods during drought	Distribution	Tolerance levels of acid & metals

7.3 Mayflies – Ephemeroptera

Ephemeroptera, or mayflies, have an aquatic larval phase and a terrestrial flying adult phase. Ephemeroptera are commonly used as one of a number of sensitive taxa in freshwater systems, particularly stream environments (Gooderham & Tsyrlin 2002), although they can also be used for lakes environments as well, when they are present. At least two families of Ephemeroptera have been found in the Lakes and tributaries wetlands (Baetidae and Caenidae). These two families are among the less-sensitive families of Ephemeroptera (SIGNAL2 scores of 5 and 4, respectively). Ephemeroptera are commonly associated with flowing water, having external gills.

The diversity of Ephemeroptera, the distribution and the relative abundance of each family are useful indicators of water quality (including dissolved oxygen, turbidity, nutrient levels), habitat structure (most require hard substrates on which to lay eggs) and flow (including water temperature, as well as current speed). Table 7.3 links Ephemeroptera to individual ecological outcomes.

Table 7.3: List of ecological outcomes that would be indicated by Ephemeropteran communities. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Mayflies, Ephemeroptera			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Sensitive freshwater taxa (Gooderham & Tsyrlin 2002), therefore considered indicative of freshwater macroinvertebrate communities	Distribution; Abundance	Extent of distribution in the Lower Lakes
Suitable habitat	Requires suitable habitat for oviposition (i.e. hard substrata) (CSIRO 1991)	Distribution; Taxon diversity	
Suitable food resources	Macroinvertebrates form the basis of many aquatic food webs (Bunn *et al.* 1999)	Distribution; Abundance	Reliance of higher trophic organisms on Ephemeroptera
Suitable water quality	Only able to tolerate freshwater environments	Distribution	
Species connectivity	Terrestrial adult phase so requires connectivity between aquatic & terrestrial ecosystems	Distribution	
Viable propagule bank	Not indicative as do not have a resistant propagule phase	NA	
No barriers to recruitment	Require sufficient connectivity to recruit	Distribution; Abundance	
Lateral hydraulic connectivity	Both Caenidae & Baetidae potentially require fine detritus as a food resource therefore are indicators as this resource requires input of terrestrial vegetation via overbank flows (Chessman 1986)	Distribution; Abundance	Particular species may have quite diverse requirements
Water residence times finite	Requires high levels of water quality therefore residence times cannot be infinite	Distribution; Abundance	
Regional hydraulically connected	Sensitive to altered flow regimes & longitudinal connectivity (Dewson *et al.* 2007)	Distribution; Abundance	
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Intolerant of high salinities (Hassell *et al.* 2006), nutrient enrichment (Lemly 1982), chemical pollution (Södergren & Svensson 1973), trace metals (Lynch *et al.* 1988)	Distribution	

Indicator species: Mayflies, Ephemeroptera			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Lateral habitat diversity	Require hard substrata & flowing water, so indicative of a different suite of habitats from many other Lakes taxa	Distribution	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Indicator of freshwater only	Distribution	
Temporal variability in salinity	Indicator of freshwater only	Distribution	
Communities requiring varied salinities supported	Would indicate freshwater salinities	Distribution	
Temporal variability in flow	Require flowing water with good levels of dissolved oxygen (due to external gills), likely to be intolerant of flooding without refugia	Distribution	Exact flow tolerances
Seasonal variability in flows	Sensitive to changes in flow regime	Distribution	Range of timing of recruitment & impact of flows
Seasonal variability in water levels	Require hard substrate for oviposition & emergence. Water levels must be suitable to provide these habitats	Recruitment events; Distribution	Range of timing of recruitment & impact of water levels
Communities requiring varied hydrology supported	Larval phase require permanent submersion, but are able to migrate with water levels	Distribution	Extent of mobility
Communities requiring flooding supported	Not indicative of flooding, unlikely to persist without refugia	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Play an important role as the basis of aquatic food webs, particularly for fish (Gooderham & Tsyrlin 2002)	Abundance	Extent of contribution to aquatic food webs
Functions performed by multiple species	Mayflies form a diverse order, performing various functions, including filter feeders, predators, or grazers (Gooderham & Tsyrlin 2002)	Taxon diversity	Basic ecology of many species
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Mayflies are acid-intolerant. Increasing salinity may affect mayflies as they have no impermeable exoskeleton (James *et al.* 2003)	Morphology; Distribution	Acid tolerance
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic &	Mayflies have both terrestrial & aquatic life stages	Distribution;	

Indicator species: Mayflies, Ephemeroptera			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
terrestrial species		Abundance	
Exchange between aquatic & terrestrial systems	Diverse feeding group, including filter feeders, predators, or grazers (Gooderham & Tsyrlin 2002), with an adult terrestrial phase	Distribution; Abundance	
Regular oxidation of sulfidic material	Some utilise submerged substrate for shelter, not able to emerge in acidified substrates	Distribution	Acid tolerance

7.4 Stoneflies – Plecoptera

Plecoptera, or stoneflies, are taxa commonly considered to be even more sensitive to water quality and flow than Ephemeroptera (SIGNAL score of 10 at an order level). They are commonly associated with fast-flowing environments (Gooderham & Tsyrlin 2002) and so can be less common in lake environments, although they have been detected within the Lower Lakes and tributary wetlands. The diversity of Plecoptera, the distribution and the relative abundance of each family are useful indicators of water quality (including dissolved oxygen, turbidity, nutrient levels) and flow conditions. Table 7.4 links Plecoptera to individual ecological outcomes.

Table 7.4: List of ecological outcomes that would be indicated by Plecopteran communities. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Stoneflies, Plecoptera			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Sensitive freshwater taxa (Gooderham & Tsyrlin 2002), therefore considered indicative of freshwater macroinvertebrate communities	Distribution	
Suitable habitat	Requires suitable habitat for completion of life stages, mating & oviposition (i.e. hard substrata) (Gooderham & Tsyrlin 2002)	Distribution	
Suitable food resources	Macroinvertebrates form the basis of many aquatic food webs (Bunn *et al.* 1999)	Abundance; Distribution	
Suitable water quality	Only able to tolerate freshwater environments, sensitive to water quality. Prefer cool, flowing water (Walker *et al.* 2009)	Abundance; Distribution	Upper salinity tolerances for individual taxa
Species connectivity	Spatial connectivity restricted due to variable life span & lack of flight, requires habitat connectivity between aquatic ecosystems	Distribution; Abundance	Extent of connectivity required by larvae
Viable propagule bank	Not indicative as do not have a resistant propagule phase	NA	
No barriers to recruitment	Distribution method could be sensitive to barriers to population connectivity (i.e. poor ability to fly so unlikely to recruit from other wetlands) (Gooderham & Tsyrlin 2002)	Distribution; Recruitment events	Maximum distribution range of adults
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Requires high levels of water quality therefore residence times cannot be infinite	Distribution	
Regional hydraulically connected	Sensitive to altered flow regimes & longitudinal connectivity (Nichols *et al.* 2006)	NA	
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Intolerant of high salinities & nutrient enrichment (Lemly 1982)	Distribution	
Lateral habitat diversity	Indicative of diverse range of habitats, both above & below the water line	Abundance	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Indicator of freshwater only, not salt-tolerant	Distribution	
Temporal variability in salinity	Indicator of freshwater only, not salt-tolerant	Distribution	

Indicator species: Stoneflies, Plecoptera			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Communities requiring varied salinities supported	Indicator of freshwater only, not salt-tolerant	Distribution	
Temporal variability in flow	Require cool flowing water (Walker *et al*. 2009) with good levels of dissolved oxygen (due to external gill tufts), likely to be intolerant of flooding without refugia	Abundance	
Seasonal variability in flows	Short adult life begins after emerging around spring or autumn, nymph is solely aquatic (Gooderham & Tsyrlin 2002	Recruitment events	
Seasonal variability in water levels	Short adult life begins after emerging around spring or autumn, nymph is solely aquatic (Gooderham & Tsyrlin 2002)	Recruitment events	
Communities requiring varied hydrology supported	Nymph phase requires submersion, but capable of migration with sufficient water levels	Distribution; Abundance	Distribution range of nymph phase
Communities requiring flooding supported	Intolerant of flooding, unlikely to persist without refugia	Distribution; Abundance	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Play an important role as the basis of aquatic food webs, particularly for fish (Gooderham & Tsyrlin 2002)	Abundance	Extent of contribution to aquatic food webs
Functions performed by multiple species	Stoneflies form a diverse order, including carnivores, grazers, or detrital feeders (Gooderham & Tsyrlin 2002)	Taxon diversity; Abundance	Basic ecology of many taxa
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Stoneflies are acid-intolerant. Increasing salinity may affect stoneflies, as they lack an impermeable exoskeleton (James *et al.* 2003)	Abundance; Distribution	Upper acid tolerance limits
Wide riparian & littoral zones supported	May require hard substrate for protection due to poor flight in adult life stage (Gooderham & Tsyrlin 2002)	Distribution	Terrestrial habitat requirements
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Stoneflies have life stages that utilise terrestrial & aquatic environments	Distribution	
Exchange between aquatic & terrestrial systems	Stoneflies form a diverse order, including carnivores, grazers, or detrital feeders (Gooderham & Tsyrlin 2002), with an adult terrestrial phase	Distribution	
Regular oxidation of sulfidic material	Some utilise submerged substrate for shelter, will not emerge in acidified substrata	Distribution	Acid tolerance

7.5 Caddisflies – Trichoptera

Trichoptera, or caddisflies, are the third order commonly considered to be sensitive to water quality and flow, along with Ephemeroptera and Plecoptera (SIGNAL2 score of 9 at an order level). There is limited data regarding the families found in the Lower Lakes, but those known to occur include Leptoceridae, Ecnomidae and Odontoceridae. Of these, Odontoceridae is the most sensitive (SIGNAL2 score of 7).

As for Ephemeroptera and Plecoptera, the distribution and the relative abundance of each family are useful indicators of water quality (including dissolved oxygen, turbidity, nutrient levels) and flow conditions. Table 7.5 links Trichoptera to individual ecological outcomes.

Table 7.5: List of ecological outcomes that would be indicated by Trichopteran communities. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	**Caddisflies, Trichoptera**		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Sensitive freshwater taxa (Gooderham & Tsyrlin 2002), therefore considered indicative of freshwater macroinvertebrate communities	Distribution	
Suitable habitat	Requires suitable habitat for completion of life stages, mating & oviposition (i.e. hard substrata) (CSIRO 1991)	Distribution	
Suitable food resources	Macroinvertebrates form the basis of many aquatic food webs (Bunn *et al.* 1999). Possible food source for fish, frogs, & other predators (Williams 1980)	Abundance; Distribution	Extent of contribution to aquatic food webs
Suitable water quality	Only able to tolerate freshwater environments, some species sensitive to water quality	Abundance; Distribution	Upper salinity tolerances for individual taxa
Species connectivity	Short-lived adults have the ability to fly (Gooderham & Tsyrlin 2002), but limited life span limits dispersal ability	Distribution; Abundance	Dispersal range of flying adults
Viable propagule bank	Larval survival dependent on temperature (Williams 1980), do not have a resistant propagule phase	NA	Temperature tolerance range
No barriers to recruitment	Dispersal of adults an indication of no barriers to population connectivity. Larvae would need constant submersion for dispersal	Distribution; Recruitment events	
Lateral hydraulic connectivity	Potentially require lateral connectivity for the provision of food resources (Chessman 1986) & habitat e.g. cases made of terrestrial vegetation (Gooderham & Tsyrlin 2002)	Distribution; Abundance	
Water residence times finite	Requires high levels of water quality therefore residence times cannot be infinite	Distribution	
Regional hydraulically connected	Sensitive to altered flow regimes & longitudinal connectivity (Nichols *et al.* 2006)	Distribution	
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Sensitive to nutrient enrichment (Lemly 1982, Gooderham & Tsyrlin 2002), bioaccumulation of agrochemicals (Belluck & Felsot 1981) & heavy metals	Distribution	
Lateral habitat diversity	Indicative of diverse range of habitats, both above & below the water line	Abundance	
Habitat variability	Not an indicator	NA	

Indicator species:	**Caddisflies, Trichoptera**		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Range of salinities with appropriate maxima	Indicator of freshwater only, not salt-tolerant	Distribution	
Temporal variability in salinity	Indicator of freshwater only, not salt-tolerant	Distribution	
Communities requiring varied salinities supported	Indicator of freshwater only, not salt-tolerant	Distribution	
Temporal variability in flow	Require flowing waters with good levels of dissolved oxygen	Abundance	
Seasonal variability in flows	Most adults emerge around spring or autumn (Gooderham & Tsyrlin 2002), so water levels need to be suitable during these periods	Distribution	Timing for egg-laying & larval development
Seasonal variability in water levels	Larvae & pupae require constant submersion	Distribution	
Communities requiring varied hydrology supported	Indicative of permanently-inundated habitats	Distribution; Abundance	
Communities requiring flooding supported	Not tolerant of flooding, unlikely to persist without refugia	Abundance; Distribution	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Play an important role as the basis of aquatic food webs, particularly for fish & amphibians (Gooderham & Tsyrlin 2002)	Abundance	Extent of contribution to aquatic food webs
Functions performed by multiple species	Caddisflies form a diverse order, including predators, grazers & omnivores (Williams 1980)	Taxon diversity; Abundance	Basic ecology of many taxa
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Caddisflies are not acid-tolerant. Increasing salinity may affect caddisflies, which lack an impermeable exoskeleton (James *et al.* 2003)	Abundance; Distribution	Upper acid tolerance limits
Wide riparian & littoral zones supported	Not currently an indicator	NA	Terrestrial habitat requirements
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange between aquatic & terrestrial systems	Caddisflies form a diverse order, including predators, grazers & omnivores (Williams 1980), with an adult terrestrial phase	Distribution	
Regular oxidation of sulfidic material	Not an indicator, although acidification may impact sclerotised larval head	Distribution	Acid tolerance

7.6 Sand hoppers – Amphipoda

Amphipods (including the species commonly known as sand hoppers) are common taxa in aquatic environments including streams, lakes, estuaries and sandy beaches. Relevant species include *Melita zeylanica*, *Paracorophium* spp. and *Megamphopus* spp. Individual taxa have wide ranges of habitat preferences, so the diversity of amphipods present can be indicative of the diversity of habitats and conditions present in a region. Despite this, there are major knowledge gaps regarding the basic ecology of many taxa found in the Lakes. Thus amphipods have the potential to be an important indicator in the region, but a lack of detailed understanding limits their present utility. The freshwater family Eusiridae has a SIGNAL2 score of 7 and *Melita plumulosa* (Amphipoda, Melitidae) has been used in toxicological studies of acute toxicity and bioaccumulation of sediment bound metals in Australia (King *et al.* 2006). Table 7.6 links Amphipoda to individual ecological outcomes.

Table 7.6: List of ecological outcomes that would be indicated by amphipods. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Sand hoppers, Amphipoda			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Observations of large populations in the Coorong (Kangas & Geddes 1984)	Abundance; Distribution	
Suitable habitat	Omnivorous feeding predominately on decaying vegetation; associated with weed beds & submerged wood	Taxon diversity; Distribution	Feeding methods & habitat preferences of individual taxa
Suitable food resources	Can also opportunistically feed on other animals; can use a range of feeding methods including filter feeding & grazing	Abundance; Taxon diversity	Feeding methods & habitat preferences of individual taxa
Suitable water quality	Wide tolerance of fluctuations in environmental conditions but also some lowering of reproductive capacity at higher salinities (Kangas & Geddes 1984); elevated temperatures accelerate growth & condense life cycle (Neuparth *et al.* 2002)	Taxon diversity; Distribution	
Species connectivity	Limited mobility (young have direct development, no planktonic dispersal phase, Kangas & Geddes 1984), making exchange of taxa between habitat units less likely	NA	Range of distribution under different habitat conditions
Viable propagule bank	Not indicative of temporal connectivity as do not have a resistant propagule phase	NA	
No barriers to recruitment	Distribution method limits use as an indicator of barriers to population connectivity	NA	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Not an indicator	NA	

Indicator species: Sand hoppers, Amphipoda			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Currently known species appear particularly well adapted to extreme conditions (Kangas & Geddes 1984)	Distribution - of tolerant taxa	Identification of suitable taxa for use as indicators of extreme conditions
Lateral habitat diversity	Diversity of amphipods may reflect diverse habitats (found in range of habitats, including submerged wood, vegetation etc.)	Taxon diversity	Specific taxa associations with different range of habitats
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Has a wide tolerance range for salinity, including fresher (e.g. 1 ppt) & salt water (62 ppt) (Kangas & Geddes 1984)	Taxon diversity	
Temporal variability in salinity	Has a wide tolerance range for salinity, including fresher (e.g. 1 ppt) & salt water (62 ppt) (Kangas & Geddes 1984)	Taxon diversity	
Communities requiring varied salinities supported	Has a wide tolerance range for salinity, including fresher (e.g. 1 ppt) & salt water (62 ppt) (Kangas & Geddes 1984)	Taxon diversity	
Temporal variability in flow	Found in still to slow-moving waters; moves amongst substrate (e.g. sand, mud) (i.e. so as not to get washed away)	Abundance; Distribution	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Difference taxa have different salinity & habitat requirements	Distribution; Taxon diversity	
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Amphipoda are omnivorous, feeding predominantly on decaying vegetation & opportunistically on other animals (Gooderham & Tsyrlin 2002)	Taxon diversity	
Functions performed by multiple species	Amphipoda form a diverse order of omnivorous invertebrates	Taxon diversity	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Can act as an indicator of saline-tolerant taxa in the medium to long term	Abundance; Distribution, Taxon diversity	Acid tolerance

Indicator species: Sand hoppers, Amphipoda			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	Acid tolerance

7.7 Segmented worms – Oligochaeta

Oligochaetes with the CLLMM region are predominantly freshwater taxa. They are capable of surviving in a wide range of habitats and water qualities (SIGNAL2 score 2) but tend to be intolerant of salinity (although individual species vary). As such, the ratio of oligochaetes to polychaetes (estuarine and/or marine taxa) can indicate the presence of a salinity gradient across a region (Bagheri & McLusky 1982). Table 7.7 links Oligochaeta to individual ecological outcomes.

Table 7.7: List of ecological outcomes that would be indicated by oligochaetes. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	**Segmented worms, Oligochaeta**		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Not an indicator	NA	
Suitable habitat	Oligochaeta may re-suspend & relocate to better conditions	Distribution	
Suitable food resources	Can consume bacteria, whereas some are carnivorous (Gooderham & Tsyrlin 2002)	Abundance; Taxon diversity	Species specific information
Suitable water quality	Oligochaeta can withstand significantly degraded habitats (Gooderham & Tsyrlin 2002)	Abundance	Conditions in which settlement occurs but not recruitment
Species connectivity	Not indicative due to limited mobility, but can relocate with sufficient water flow	NA	
Viable propagule bank	Not indicative as do not have a resistant propagule phase	NA	
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Requires constant submersion, therefore residence times cannot be infinite	Distribution	
Regional hydraulically connected	Not an indicator	NA	
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Relatively tolerant of pollutants, with the exception of salinity	Changes in ratio of two groups – abundance of oligochaetes to polychaetes	
Lateral habitat diversity	Not an indicator	NA	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Indicator of a range of salinities across the site. Has a range of salinity tolerances (but all quite fresh)	Taxon diversity	Species-specific tolerances
Temporal variability in salinity	Indicator of salinities through time. Has a range of salinity tolerances (but all quite fresh)	Taxon diversity	Species-specific tolerances

Indicator species: Segmented worms, Oligochaeta			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Communities requiring varied salinities supported	In conjunction with more saline-tolerant taxa (e.g. polychaetes) can indicate the presence of communities requiring a range of salinity regimes	Distribution; Abundance - of saline intolerant taxa; Taxon diversity	Species-specific tolerances
Temporal variability in flow	Do not require flowing water, can live in water with close to zero oxygen, therefore, not an indicator	NA	
Seasonal variability in flows	Potential indicator of seasonal flow, as they reproduce heavily in summer, decline in winter	Distribution; Abundance	
Seasonal variability in water levels	Potential indicator of seasonal water level, as they reproduce heavily in summer, decline in winter	Distribution; Abundance	
Communities requiring varied hydrology supported	Not an indicator	NA	
Communities requiring flooding supported	Not an indicator. Unlikely to persist without some refugia	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Not an indicator	NA	
Functions performed by multiple species	Oligochaeta can survive in extreme ecological conditions, so not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Have wide salinity tolerance for freshwater taxa (Giere 2006)	Distribution; Abundance	Effect of acidification
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

7.8 Freshwater cnidaria – *Hydra* spp.

Hydra are freshwater cnidarians (and are thus related to sea anemones and sea jellies). They have a low SIGNAL2 score of 2 (Chessman 2003) indicating they are generally tolerant of degraded water quality. However, they have physiological and morphological adaptations make them indicators of saline conditions (James *et al.* 2003) and may be sensitive to particular pollutants such as heavy metals (Karntanut & Pascoe 2002). Table 7.8 links *Hydra* spp. to individual ecological outcomes.

Table 7.8: List of ecological outcomes that would be indicated by Hydra populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Freshwater cnidaria, *Hydra* spp.			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Sensitive freshwater taxa (James *et al.* 2003; Kefford *et al.* 2007a)	Distribution	
Suitable habitat	Requires hard substratum (rocks or wood) for foothold (Gooderham & Tsyrlin 2002)	Distribution	
Suitable food resources	*Hydra* are predators, consuming micro-organisms (Gooderham & Tsyrlin 2002)	Distribution; Abundance	
Suitable water quality	Only able to tolerate freshwater environments, sensitive to water quality	Distribution	
Species connectivity	Limited physical movement across spatial environments, requires water flow to distribute planulae larvae (Gooderham & Tsyrlin 2002)	Distribution	
Viable propagule bank	Not indicative as do not have a resistant propagule phase	NA	
No barriers to recruitment	Distribution methods mean the taxa may indicate barriers to population connectivity. Actively spreads by sexual reproduction, requiring water flow for planulae larvae distribution (Gooderham & Tsyrlin 2002). Budding technique not considered sufficient for broad distribution	Distribution	Reproductive biology
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Sensitive to particular pollutants therefore residence times cannot be infinite	Distribution	Sensitivity to particular pollutants
Regional hydraulically connected	Not an indicator	NA	
Longitudinal biological connectivity	Indicators of poor water quality	Distribution	
No accumulation of pollutants	Intolerant of high salinities (Kefford *et al.* 2007a)	Distribution	
Lateral habitat diversity	Not an indicator of diverse habitats: submerged only (Gooderham & Tsyrlin 2002)	NA	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Indicator of freshwater only	Distribution	
Temporal variability in salinity	Indicator of freshwater only	Distribution	
Communities requiring varied salinities	Indicator of freshwater only	Distribution	

Indicator species: Freshwater cnidaria, *Hydra* spp.			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
supported			
Temporal variability in flow	Can tolerate numerous conditions (Gooderham & Tsyrlin 2002), need freshwater flow for distribution	Distribution	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Requires permanently-inundated habitat	Distribution	
Communities requiring flooding supported	Not indicative of flooding, unlikely to persist without refugia	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Predatory & a range of predatory taxa tend to indicate complex food-webs	Taxon diversity	
Functions performed by multiple species	*Hydra* are unique in morphology, but are unlikely to be in function, so not considered indicative	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	*Hydra* are not acid- or salt-tolerant	NA	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	Unknown tolerance of acidic water & bioaccumulation of metals

7.9 Freshwater limpets – Ancylidae

Freshwater limpets are a relatively tolerant taxon (SIGNAL score 4), but are sensitive to heavy metal contamination (Gerhardt & Palmer 1998) and are often used as indicators in areas affected by mining (Wright & Burgin 2009). They are intolerant of salinity (Kefford *et al.* 2007b). Table 7.9 links Ancylidae to individual ecological outcomes.

Table 7.9: List of ecological outcomes that would be indicated by Ancylidae populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Freshwater limpets, Ancylidae			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Self-fertilisation impossible, life span approximately one year	Distribution; Abundance	Life history
Suitable habitat	Occurs on woody debris, rocky substrate, macrophytes, & submerged leaves	Distribution; Abundance	
Suitable food resources	Graze upon periphyton on hard substrate surfaces	Distribution; Abundance	
Suitable water quality	Only able to tolerate freshwater environments, egg stages sensitive to water quality (Kefford *et al.* 2007b)	Distribution; Abundance	
Species connectivity	Not indicative due to limited mobility	NA	
Viable propagule bank	Not indicative as do not have a resistant propagule phase	NA	
No barriers to recruitment	Limited ability to disperse means absence of taxon could be indicative of barriers to population connectivity	Distribution	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Egg stage requires high water quality; therefore residence times cannot be infinite	Distribution; Abundance	
Regional hydraulically connected	Not an indicator	NA	
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Impact of many pollutants unknown, but egg stages are sensitive to water quality changes. Accumulate heavy metals such as copper (Gerhardt & Palmer 1998) & herbicides (Gunkel & Streit 1980)	Distribution; Abundance	
Lateral habitat diversity	Found on numerous surfaces (including rocks, woody debris & amongst macrophytes) (Gooderham & Tsyrlin 2002)	Distribution; Abundance	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Indicator of freshwater only	Distribution	
Temporal variability in salinity	Indicator of freshwater only	Distribution	
Communities requiring varied	Indicator of freshwater only	Distribution	

Indicator species: Freshwater limpets, Ancylidae			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
salinities supported			
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Requires permanently-inundated habitat	Distribution	
Communities requiring flooding supported	Not indicative of flooding, unlikely to persist without refugia	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Consumes periphyton, so provide a link between primary producers & higher order consumers	Abundance	
Functions performed by multiple species	Consumes periphyton, so a key link in carbon processing cycles	Abundance	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Sensitive to water quality so indicative of sensitive aquatic taxa	Distribution; Abundance	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

7.10 Brackish water crab – Hymenosomatidae

Hymenosomatidae are crabs often found in slightly brackish water. Their ability to tolerate increasing levels of salinity mean that tracking their abundance through time provides a mechanism for detecting shifts in salinity profiles through the region. Table 7.10 links Hymenosomatidae to individual ecological outcomes.

Table 7.10: List of ecological outcomes that would be indicated by Hymenosomatidae populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Brackish water crab, Hymenosomatidae			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	May utilise seasonal variation in water regimes for larval development & dispersal (Johnston & Robson 2005)	Distribution; Abundance	Life history, stages
Suitable habitat	Usually found beneath snags, rocks, & vegetation at a depth of 0.5 m (Williams 1980). Require flow for larval distribution (Johnston & Robson 2005), & numerous habitats for ontogenetic & sex-related changes during life-cycle (Johnston & Robson 2005)	Distribution; Abundance	
Suitable food resources	Feeds on detritus (Williams 1980)	Distribution; Abundance	
Suitable water quality	Able to tolerate fresh or saline streams & lakes (Williams 1980)	Distribution; Abundance	
Species connectivity	Not indicative due to limited mobility	NA	
Viable propagule bank	Not indicative as do not have a resistant propagule phase	NA	Life history, stages
No barriers to recruitment	Dispersal technique could be indicator of barriers to population connectivity	Distribution; Abundance	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Flow required for distribution/breeding. Ideally requires permanent submersion (Johnson & Robson 2005)	Distribution; Abundance	Tolerance to varying water quality
Regional hydraulically connected	May require connectivity between regions for dispersal of larvae (Johnson & Robson 2005)	Distribution; Abundance	
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Unknown ability to tolerate pollutants, relatively saline-tolerant	NA	Accumulation of pollutants
Lateral habitat diversity	Not an indicator: submerged only (Gooderham & Tsyrlin 2002)	NA	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Able to tolerate fresh or saline streams & lakes (Williams 1980)	Distribution	
Temporal variability in salinity	Able to tolerate fresh or saline streams & lakes (Williams 1980)	Distribution	
Communities requiring	Able to tolerate fresh or saline streams & lakes (Williams 1980)	Distribution	

Indicator species: Brackish water crab, Hymenosomatidae			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
varied salinities supported			
Temporal variability in flow	Can be an indicator of a range of flow volumes (Johnson & Robson 2005)	Distribution; Abundance	
Seasonal variability in flows	Can be an indicator of seasonality of flows (Johnson & Robson 2005)	Distribution; Abundance	
Seasonal variability in water levels	Can be an indicator of seasonality of water levels (Johnson & Robson 2005)	Distribution; Abundance	
Communities requiring varied hydrology supported	Requires permanently-inundated habitat	Distribution	
Communities requiring flooding supported	Could be a potential indicator for occasional flooding. Breeding requires stimulation by hydrodynamic events (Johnson & Robson 2005)	Distribution; Recruitment events	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Feeds on detritus (Williams 1980)	Abundance	
Functions performed by multiple species	A detritivore, so provide one process in a carbon cycle	Abundance	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Not an indicator, although acidity may affect exoskeleton	NA	Acid tolerance unknown
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

7.11 Marsh beetles – Scirtidae

Scirtidae (or marsh beetles) have an aquatic larval phase and a terrestrial adult phase. Having an obligate aquatic phase means that larvae require suitable water quality (as opposed to adult beetles which can be terrestrial and can fly to other areas), as for other taxa with aquatic or semi-aquatic adult phases. Scirtidae are relatively sensitive for a Coleopteran (SIGNAL score of 6). Table 7.11 links Scirtidae to individual ecological outcomes.

Table 7.11: List of ecological outcomes that would be indicated by Scirtidae populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Marsh beetles, Scirtidae			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Suitable conditions for reproduction unknown	NA	Life history
Suitable habitat	Requires slow current streams, wetlands, ponds & marshes (Gooderham & Tsyrlin 2002)	Distribution; Abundance	
Suitable food resources	Consume detritus off leaves & stones (Gooderham & Tsyrlin 2002)	Distribution; Abundance	
Suitable water quality	Suitable conditions for reproduction unknown	NA	Life history
Species connectivity	Adults have retained the ability to fly; distribution can occur rapidly (Gooderham & Tsyrlin 2002)	Distribution; Abundance	
Viable propagule bank	Not indicative as do not have a known resistant propagule phase	NA	Life history
No barriers to recruitment	Adults' ability for flight negates barriers to population connectivity	NA	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Not currently an indicator	NA	Implications of residence time
Regional hydraulically connected	Not an indicator	NA	
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Intolerant of high salinities (Kefford *et al.* 2006)	Distribution; Abundance	
Lateral habitat diversity	Indicative of diverse habitats: aquatic & submerged life stages (Gooderham & Tsyrlin 2002)	Distribution; Abundance	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Indicator of freshwater only	Distribution	
Temporal variability in salinity	Indicator of freshwater only	Distribution	
Communities requiring varied salinities supported	Indicator of freshwater only	Distribution	
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water	Not an indicator	NA	

Indicator species: Marsh beetles, Scirtidae			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
levels			
Communities requiring varied hydrology supported	Requires permanently-inundated habitat for larvae	Distribution; Abundance	
Communities requiring flooding supported	Not indicative of flooding, as larvae unlikely to persist without refugia	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Role in food webs is largely unknown	NA	Interactions with other taxa in food webs
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Increasing acidity may affect sheathed wings & sclerotisation. Salinity may affect macroinvertebrates without impermeable exoskeletons (James *et al.* 2003)	Distribution; Abundance	Exact effects of acidification
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Have an aquatic larval phase & a terrestrial adult phase so indicative of terrestrial-aquatic connectivity	Distribution; Abundance	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

7.12 Blackflies – Simuliidae

Simuliidae (or blackflies) have an aquatic larval phase and a terrestrial flying adult phase. Simuliidae larvae are filter-feeders meaning they require reasonable flow and water quality conditions. They are relatively tolerant compared to mayflies, caddisflies and stoneflies (SIGNAL2 score of 5), but are sensitive compared to other true fly larvae. Table 7.12 links Simuliidae to individual ecological outcomes.

Table 7.12: List of ecological outcomes that would be indicated by Simuliidae populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Blackflies, Simuliidae			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Interactions with other taxa not known	NA	Use as a surrogate for self-replicating populations
Suitable habitat	Larvae require running water & solid substrate to survive & feed on (Williams 1980)	Distribution	
Suitable food resources	Filter-feed through specialised mouth parts (Gooderham & Tsyrlin 2002)	Distribution; Abundance	
Suitable water quality	Larvae & adult flies have low tolerance to salinity, between 3.5 & 6.8 g L^{-1} (Velasco *et al.* 2006)	Distribution; Abundance	Implications of poor water quality on larval stages
Species connectivity	Not an indicator	NA	
Viable propagule bank	At least one species has an egg stage that resists drying (Williams 1980), so presence may be indicative of connectivity	Abundance - after adverse conditions	
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Flow required for distribution/breeding. Ideally requires permanent submersion (Williams 1980)	Distribution; Abundance	
Regional hydraulically connected	Rheophylic, filter feeder therefore requires sufficient flow for habitat & food delivery (Horne *et al.* 1992)	Distribution; Abundance	
Longitudinal biological connectivity	Requires sufficient delivery of energy, nutrients & carbon from upstream to feed (Horne *et al.* 1992)	Distribution; Abundance	
No accumulation of pollutants	Bioaccumulation of pyrethroid & organophosphate (Tang & Siegfried 1996), low salinity tolerance	Distribution; Abundance	
Lateral habitat diversity	Indicator of flowing water & sufficient transported food (Horne *et al.* 1992)	Distribution; Abundance	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Not an indicator	NA	
Temporal variability in salinity	Not an indicator	NA	
Communities requiring varied salinities supported	Not an indicator	NA	

Indicator species: Blackflies, Simuliidae			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Temporal variability in flow	Can be an indicator of constant flow (Horne *et al.* 1992)	Distribution; Abundance	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Requires permanently-inundated habitat for larvae	Distribution; Abundance	
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Provides food source for other organisms	Abundance	Predatory species that eat blackflies
Functions performed by multiple species	Filter feeders, so are indicative of that method of processing organic matter	Distribution; Abundance	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Not an indicator of an acid-tolerant species. Increasing salinity may affect blackfly larvae, which do not have an impermeable exoskeleton (James *et al.* 2003)	NA	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

7.13 Tubeworm – *Ficopomatus enigmaticus*

The sessile serpulid polychaete *Ficopomatus enigmaticus* is able to exist in very large aggregations given suitable conditions: high volume of food source (algae/detritus), high turbidity, low water flow and water temperatures above 18 °C for a period of time to allow reproduction to occur (Dittmann *et al.* 2009). They first colonised the Lakes in 2006, indicating increased salinity and high turbidity in the usually freshwater lakes. They grow on tortoises, crabs and mussels rendering them too heavy to move, eat or escape predators and thus contributing to their poor health and death (Dittmann *et al.* 2009). Because of their ability to build reefs of substantial size that can influence water flow rates, sedimentation and subsequently the surrounding invertebrate community, *F. enigmaticus* is considered an ecosystem engineer (Thomas & Thorp 1994). Table 7.13 links *F. enigmaticus* to individual ecological outcomes.

Table 7.13: List of ecological outcomes that would be indicated by tubeworm populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes. Rationale taken from Dittmann *et al.* (2009) unless otherwise indicated.

Indicator species:	**Tubeworm, *Ficopomatus enigmaticus***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Able to recruit year-round if temperature & salinities are within necessary ranges	Recruitment events	Salinity & temperature limits for larval settlement
Suitable habitat	Indicator of brackish water (Benger 2009, Dittmann *et al.* 2009)	Recruitment events	Salinity & temperature limits for larval settlement
Suitable food resources	Filter feeder therefore may have distinct prey size range; high filtration rates; consumed by fish & possibly crabs	Feeding rates	Feeding rates & size frequency of phyto- & zooplankton prey
Suitable water quality	Able to tolerate reasonably wide range of salinities from brackish to marine. Unable to reproduce in lower salinities (Benger 2009)	Distribution	Salinity limits for larval settlement; accurate salinity limits restricting recruitment
Species connectivity	Indicator of increasing salinities & of connectivity between Coorong & Lake Alexandrina (Benger 2009)	Distribution	
Viable propagule bank	Able to reproduce above water temperature of 18 °C	New settlement on old mounds	
No barriers to recruitment	Population connectivity important for spread of distribution	Recruitment events; Distribution	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Not an indicator due to ability to exist in lotic environments	NA	
Regional hydraulically connected	Hydraulic connectivity important for dispersal of larvae (Benger 2009)	Distribution	Salinity limits for larval settlement
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Sensitive to sedimentation & salinity. Acidity may negatively affect tube formation	Tissue composition	Bioaccumulation of metals
Lateral habitat diversity	Not an indicator	NA	

Indicator species:	**Tubeworm, *Ficopomatus enigmaticus***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Able to exist across a reasonable salinity range (fresh/brackish – marine)	Distribution	Accurate thresholds for salinity & recruitment
Temporal variability in salinity	Able to exist across a reasonable salinity range (fresh/brackish – marine)	Distribution	Accurate thresholds for salinity & recruitment
Communities requiring varied salinities supported	Tidal signal would allow possible exchange of larvae with other estuaries	Distribution; Recruitment events	Recruitment through the Murray Mouth. Distributions of tubeworm outside CLLMM
Temporal variability in flow	Indicator of low flow	Distribution	Upper flow tolerance
Seasonal variability in flows	Not an indicator	NA	Upper flow tolerance
Seasonal variability in water levels	Variable water levels would alter available habitat	Distribution	Upper timeframe for survival out of water
Communities requiring varied hydrology supported	Requires permanent submersion	Distribution	
Communities requiring flooding supported	Requires permanent submersion	Distribution	
Tidal signal apparent	Important to retain suitable salinities within tidal region	Distribution	Upper salinity tolerance; recruitment through Mouth
Complex food webs present	Secondary consumer of phyto- & zooplankton & detritus. Prey species for fish & possibly crabs	Distribution	Severity of predation, filtration rates in Lower Lakes
Functions performed by multiple species	Provides additional habitat complexity & can increase species diversity	Distribution	Abundances & species diversity near tubeworm mounds
Efficient nutrient cycling	Important filter feeder with high filtration rates	Feeding rates - filtration rate	Filtration rate in Lower Lakes
Control of invasive species	Indicator of increasing salinities in Lower Lakes due to rapid colonisation rates. Cryptic species, possible of Australian origin, thought to have been present in Coorong for at least 700 years	Distribution	Palaeological confirmation of historic presence; genetic confirmation of species origin
Acid- & saline-tolerant & terrestrial species present	Reasonably wide salinity tolerance. Acidity may affect tube production	Distribution	Effects of acidity on spawning & tube production
Wide riparian & littoral zones supported	Variable water levels will alter habitat. Re-inundation of old mounds provides increased settlement structure	Distribution	Speed of resettlement/colonisation; limits of larval settlement
Lateral connectivity of vegetation	Not an indicator	NA	

Indicator species: **Tubeworm, *Ficopomatus enigmaticus***			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Balance of aquatic & terrestrial species	Not an indicator. Can increase aquatic benthic macroinvertebrate diversity	NA	Effects on species diversity within Lower Lakes & Coorong
Exchange between aquatic & terrestrial systems	High filtration rates	Feeding rates - filtration rate	Filtration rate within Lower Lakes & Coorong
Regular oxidation of sulfidic material	Acidity may affect tube production & formation	Distribution	Tolerance levels of acid & metals

7.14 Microbivalve – *Arthritica helmsi*

The sessile microbivalve *Arthritica helmsi*, like many bivalves, is indicative of good water quality. It occurs in vast numbers in the estuarine region of the Coorong and provides an important food source for wading birds, small fish and predatory polychaete worms. Table 7.14 links *A. helmsi* to individual ecological outcomes.

Table 7.14: List of ecological outcomes that would be indicated by *Arthritica helmsi* populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes. Rationale taken from Rolston & Dittmann (2009) unless otherwise indicated.

Indicator species:	**Microbivalve, *Arthritica helmsi***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Able to recruit year-round within optimal conditions in Coorong	Recruitment events	Salinity & temperature limits for larval settlement; recruitment through Murray Mouth (MM)
Suitable habitat	Indicator of marine salinities	Distribution; Recruitment events	Salinity & temperature limits for larval settlement
Suitable food resources	Filter feeder that may have distinct prey size range; consumed by fish, predatory polychaete worms & possibly crabs	Feeding rates; Food web structure	Feeding rates & size frequency of phyto- & zooplankton prey; Predation rates
Suitable water quality	Able to tolerate reasonably wide range of salinities from brackish to marine	Distribution	Salinity limits for larval settlement; accurate salinity limits restricting recruitment
Species connectivity	Connectivity between Coorong & Lower Lakes may be important for spawning/recruitment events	Distribution	Freshwater signals for recruitment & spawning
Viable propagule bank	Able to reproduce year-round in the Coorong	Recruitment events	Salinity limits for larval settlement
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic connectivity	Indicator of changing lateral connectivity & salinities	Distribution	
Water residence times finite	Tidal flushing possibly important for recruitment & food source	Distribution	Recruitment through MM
Regional hydraulically connected	Hydraulic connectivity important for dispersal of larvae	Distribution	Salinity limits for larval settlement; recruitment may require freshwater signal
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Sensitive to large fluctuations in salinity; acidity may affect shell production & formation; metal bioaccumulator of metals (Lee *et al.* 2000)	Tissue composition	Bioaccumulation of metals
Lateral habitat diversity	Not an indicator: occupies mudflat only	NA	
Habitat variability	Not an indicator	NA	

Indicator species:	**Microbivalve, *Arthritica helmsi***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Range of salinities with appropriate maxima	Sensitive to large fluctuations in salinity	Distribution	Accurate thresholds for salinity for recruitment
Temporal variability in salinity	Sensitive to large fluctuations in salinity	Distribution	Accurate thresholds for salinity for recruitment
Communities requiring varied salinities supported	Tidal signal would allow possible exchange of larvae with other estuaries; freshwater signal may be important for recruitment	Distribution; Recruitment events	Recruitment through MM
Temporal variability in flow	Not an indicator	NA	Upper flow tolerance
Seasonal variability in flows	Not an indicator	NA	Upper flow tolerance
Seasonal variability in water levels	Tidal signal may be important. Able to exist at various mudflat elevations. Able to withstand short periods of mudflat exposure	Distribution	Upper timeframe for survival out of water
Communities requiring varied hydrology supported	Generally requires permanent submersion but able to withstand short periods of exposure	Distribution	Upper timeframe for survival out of water
Communities requiring flooding supported	Generally requires permanent submersion but able to withstand short periods of exposure	Distribution	Upper timeframe for survival out of water
Tidal signal apparent	Tidal & freshwater signal may be important for recruitment	Distribution	Recruitment through MM
Complex food webs present	Secondary consumer of phyto- & zooplankton & detritus. Prey species for fish & predatory polychaete worms	Distribution	Severity of predation, filtration rates
Functions performed by multiple species	Other larger bivalves present in system, but not in such large abundances	Distribution	Interspecific competition
Efficient nutrient cycling	Important filter feeder with high filtration rates	Feeding rates - filtration rate	Filtration rate
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Reasonably wide salinity tolerance, but may be sensitive to large salinity fluctuations. Acidity may affect shell production & formation. Likely bioaccumulator of metals	Distribution	Sensitivity to acidity, degree of bioaccumulation
Wide riparian & littoral zones supported	Tidal signal may be important for recruitment	Distribution	Speed of resettlement & colonisation; limits of larval settlement
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange between aquatic & terrestrial	Not an indicator	NA	

Indicator species:	**Microbivalve, *Arthritica helmsi***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
systems			
Regular oxidation of sulfidic material	Acid may affect shell production & formation; likely bioaccumulator	Distribution	Tolerance of acid & metals

7.15 Polychaete worm – *Nephtys australiensis*

The motile polychaete worm, *Nephtys australiensis* is an active predator of microbivalves and other worms and is also likely to scavenge on detritus (Beesley *et al.* 2000). It is present in large numbers in the areas with estuarine salinity concentrations in the Murray Mouth and Coorong and may act as a food source for larger wading birds and fish (Rolston & Dittmann 2009). The presence of *N. australiensis* in the ecosystem suggests an abundant and diverse food source of other benthic invertebrates will also be present in the system. Table 7.15 links *N. australiensis* to individual ecological outcomes.

Table 7.15: List of ecological outcomes that would be indicated by *Nephtys australiensis* populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes. Rationale taken from Rolston & Dittmann (2009) unless otherwise indicated.

Indicator species:	Polychaete worm, *Nephtys australiensis*		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Able to recruit year-round within optimal marine-type conditions in Coorong	Recruitment events	Salinity & temperature limits for larval settlement; recruitment through Murray Mouth (MM)
Suitable habitat	Indicator of brackish to marine salinities	Distribution; Recruitment events	Salinity & temperature limits for larval settlement
Suitable food resources	Active predator & therefore a potential indicator of diverse & abundant food supply	Feeding rates; Food web structure	Prey identity
Suitable water quality	Able to tolerate reasonably wide range of salinities from brackish to marine	Distribution	Salinity limits for larval & juvenile settlement; accurate salinity limits restricting recruitment
Species connectivity	Connectivity between Coorong & Lower Lakes may be important for spawning & recruitment events	Distribution	Freshwater signals for recruitment & spawning
Viable propagule bank	Able to reproduce year-round in the Coorong	Recruitment events	Salinity limits for larval settlement
No barriers to recruitment	Not an indicator of population connectivity	NA	Salinity limits for larval settlement
Lateral hydraulic connectivity	Indicator of fluctuating lateral connectivity & salinities; Requires inundation but able to survive short periods of emersion	Distribution	
Water residence times finite	Tidal flushing possibly important for recruitment	Distribution	Recruitment through MM
Regional hydraulically connected	Hydraulic connectivity important for dispersal of larvae	Distribution	Salinity limits for larval settlement; if freshwater signal is required for recruitment
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Copper inhibits larval settlement; reduced survival in sulfidic soils; metals induce fitness costs (King *et al.* 2004; Corfield 2000)	Tissue composition	Bioaccumulation of metals

Indicator species:	**Polychaete worm, *Nephtys australiensis***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Lateral habitat diversity	Not an indicator: occupies mudflat only	NA	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Able to tolerate a reasonable range of salinities from brackish to marine	Distribution	Accurate thresholds for salinity for recruitment
Temporal variability in salinity	Able to tolerate a reasonable range of salinities from brackish to marine	Distribution	Accurate thresholds for salinity for recruitment
Communities requiring varied salinities supported	Tidal signal would allow possible exchange of larvae with other estuaries; freshwater signal may be important for recruitment	Distribution; Recruitment events	Recruitment through MM
Temporal variability in flow	Not an indicator	NA	Upper flow tolerance
Seasonal variability in flows	Not an indicator	NA	Upper flow tolerance
Seasonal variability in water levels	Tidal signal may be important. Able to exist at various mudflat elevations but generally most abundant where permanently submerged; Able to withstand short periods of mudflat exposure	Distribution	Upper timeframe for survival out of water
Communities requiring varied hydrology supported	Generally requires permanent submersion but able to withstand short periods of exposure	Distribution	Upper timeframe for survival out of water
Communities requiring flooding supported	Generally requires permanent submersion but able to withstand short periods of exposure	Distribution	Upper timeframe for survival out of water
Tidal signal apparent	Tidal & freshwater signal may be important for recruitment	Distribution	Recruitment through MM
Complex food webs present	Active predator, occasional scavenger & detritus feeder. Presence indicates likely diverse & abundant prey; prey species for larger fish & some birds	Distribution	Prey species; switch between feeding modes; predation rates
Functions performed by multiple species	Few other active predatory polychaete worm species in the system	Distribution	Interspecific competition
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Reasonably wide salinity tolerance; reduced survival in sulfidic soils; copper inhibits larval settlement (King *et al*. 2004). Sensitive to the speciation of aluminium that occurs at different levels of acidification (Corfield 2000)	Distribution	Sensitivity to acidity
Wide riparian & littoral zones supported	Tidal signal may be important for recruitment	Distribution	Speed of resettlement & colonisation; limits of larval settlement
Lateral connectivity of	Not an indicator	NA	

Indicator species:	**Polychaete worm, *Nephtys australiensis***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
vegetation			
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Reduced survivorship in sulfidic soils; copper inhibits larval settlement	Distribution	Tolerance levels of acid & metals

7.16 Polychaete worm – *Simplisetia aequisetis*

A mobile opportunistic-feeding polychaete worm, *Simplisetia aequisetis* is abundant throughout the estuarine and marine region of the Coorong. It likely acts as an important food source for larger fish and possibly for some larger wading birds. It has a relatively wide salinity tolerance (Dittmann *et al.* 2009, Rolston & Dittmann 2009). Table 7.16 links *S. aequisetis* to individual ecological outcomes.

Table 7.16: List of ecological outcomes that would be indicated by *Simplisetia aequisetis* populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes. Rationale taken from Rolston & Dittmann (2009) unless otherwise indicated.

Indicator species:	**Polychaete worm, *Simplisetia aequisetis***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Able to recruit year-round within optimal marine-type conditions in Coorong	Recruitment events	Salinity & temperature limits for larval settlement; recruitment through Mouth
Suitable habitat	Has wide range of salinity tolerance (Dittmann *et al.* 2009, Rolston & Dittmann 2009)	Distribution; Recruitment events	Salinity & temperature limits for larval settlement
Suitable food resources	Opportunistic feeder/scavenger	Feeding rates; Food web structure	Prey identity
Suitable water quality	Able to tolerate wide range of salinities (Dittmann *et al.* 2009, Rolston & Dittmann 2009)	Distribution	Salinity limits for larval & juvenile settlement; accurate salinity limits restricting recruitment
Species connectivity	Connectivity between Coorong & Lower Lakes may be important for spawning & recruitment events	Distribution	Freshwater signals for recruitment & spawning
Viable propagule bank	Able to reproduce year-round in the Coorong	Recruitment events	Salinity limits for larval settlement
No barriers to recruitment	Lack of hydraulic connectivity between Coorong & Lower Lakes may impede spawning & recruitment events	Distribution; Recruitment events	Freshwater signals for recruitment & spawning
Lateral hydraulic connectivity	Indicator of changing lateral connectivity & salinities; requires inundation but able to survive short periods of emersion	Distribution	Maximum periods of emersion
Water residence times finite	Tidal flushing possibly important for recruitment	Distribution	Recruitment through Murray Mouth
Regional hydraulically connected	Hydraulic connectivity important for dispersal of larvae	Distribution	Salinity limits for larval settlement; recruitment may require freshwater signal
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Copper inhibits larval settlement; reduced survival in sulfidic soils; metals induce fitness costs (King *et al.* 2004). Low alkaline tolerance (Geddes & Butler 1984)	Tissue composition	Bioaccumulation of metals

Indicator species:	**Polychaete worm, *Simplisetia aequisetis***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Lateral habitat diversity	Not an indicator: occupies mudflats only	NA	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Able to tolerate a wide range of salinities (Dittmann *et al.* 2009, Rolston & Dittmann 2009)	Distribution	Accurate thresholds for salinity & recruitment
Temporal variability in salinity	Able to tolerate a wide range of salinities (Dittmann *et al.* 2009, Rolston & Dittmann 2009)	Distribution	Accurate thresholds for salinity & recruitment
Communities requiring varied salinities supported	Tidal signal would allow possible exchange of larvae with other estuaries; freshwater signal may be important for recruitment	Distribution; Recruitment events	Recruitment may occur through Murray Mouth
Temporal variability in flow	Not an indicator	NA	Upper flow tolerance
Seasonal variability in flows	Not an indicator	NA	Upper flow tolerance
Seasonal variability in water levels	Tidal signal may be important. Able to exist at various mudflat elevations but generally most abundant where frequently submersed; able to withstand short periods of mudflat exposure	Distribution	Upper timeframe for survival out of water
Communities requiring varied hydrology supported	Generally requires permanent or frequent submersion but able to withstand short periods of exposure	Distribution	Upper timeframe for survival out of water
Communities requiring flooding supported	Generally requires permanent or frequent submersion but able to withstand short periods of exposure	Distribution	Upper timeframe for survival out of water
Tidal signal apparent	Tidal & freshwater signal may be important for recruitment	Distribution	Recruitment through Murray Mouth
Complex food webs present	Mobile scavenger/opportunistic feeder; prey species for larger fish & some birds	Distribution	Prey species; switches between feeding modes; predation rates
Functions performed by multiple species	Few large scavenger polychaete worm species in the system	Distribution	Interspecific competition
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Wide salinity tolerance; reduced survival in sulfidic soils; copper inhibits larval settlement (King *et al.* 2004)	Distribution	Sensitivity to acidity
Wide riparian & littoral zones supported	Tidal signal may be important for recruitment	Distribution	Speed of resettlement & colonisation; limits of larval settlement
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	

Indicator species:	**Polychaete worm, *Simplisetia aequisetis***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Reduced survivorship in sulfidic soils; copper inhibits larval settlement	Distribution	Tolerance of acid & metals

7.17 Polychaete worm – *Capitella* spp.

Capitella spp. are included due to their large abundance throughout the estuarine and marine regions of the Coorong. However, this species is frequently indicative of organically-polluted environments and therefore caution must be used as it may not be prudent to include this species as indicative of a 'healthy' system. Yet it must also be highlighted that this species was certainly present in the system when the Ecological Character Description (Phillips & Muller 2006) for the site was written and was also likely present when the site was designated Ramsar status. *Capitella* spp. are known to provide food for juvenile mullet (Geddes & Francis 2008). Table 7.17 links *Capitella* spp. to individual ecological outcomes.

Table 7.17: List of ecological outcomes that would be indicated by *Capitella* spp. populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes. Rationale taken from Rolston & Dittmann (2009) unless otherwise indicated.

Indicator species:	**Polychaete worm, *Capitella* spp.**		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Able to recruit year-round within optimal marine-type conditions in Coorong	Recruitment events	Salinity & temperature limits for larval settlement; recruitment through Murray Mouth (MM)
Suitable habitat	Has wide range of salinity tolerance	Distribution; Recruitment events	Salinity & temperature limits for larval settlement
Suitable food resources	Detritus/deposit feeder	Feeding rates; Food web structure	Ingestion rates
Suitable water quality	Able to tolerate wide range of salinities	Distribution	Accurate salinity limits for larval & juvenile settlement & those that restrict recruitment
Species connectivity	Connectivity between Coorong & Lower Lakes may be important for spawning & recruitment events	Distribution	Freshwater signals for recruitment & spawning
Viable propagule bank	Able to reproduce year-round in the Coorong	Recruitment events	Salinity limits for larval settlement
No barriers to recruitment	Lack of hydraulic connectivity between Coorong & Lower Lakes may impede spawning & recruitment events	Distribution; Recruitment events	Freshwater signals for recruitment & spawning
Lateral hydraulic connectivity	Indicator of changing water levels & salinities; requires inundation but able to survive short periods of emersion	Distribution	Maximum periods of emersion
Water residence times finite	Tidal flushing possibly important for recruitment	Distribution	Recruitment through MM
Regional hydraulically connected	Hydraulic connectivity important for dispersal of larvae	Distribution	Salinity limits for larval settlement; need for a freshwater signal for recruitment
Longitudinal biological connectivity	Indicator of organically-enriched sediments (Tsutsumi 1990)	Distribution; Sediment organic content	
No accumulation of pollutants	Growth & ingestion rates affected by cadmium, lead & nickel (Horng *et al.* 2009)	Tissue composition	Bioaccumulation of metals
Lateral habitat diversity	Not an indicator: occupies mudflats only	NA	
Habitat variability	Not an indicator	NA	

Indicator species:	**Polychaete worm, *Capitella* spp.**		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Range of salinities with appropriate maxima	Able to tolerate a wide range of salinities	Distribution	Accurate thresholds for salinity for recruitment
Temporal variability in salinity	Able to tolerate a wide range of salinities; indicator of organically-enriched sediment	Distribution; Sediment organic content	Accurate thresholds for salinity for recruitment
Communities requiring varied salinities supported	Tidal signal would allow possible exchange of larvae with other estuaries; freshwater signal may be important for recruitment	Distribution; Recruitment events	Recruitment through MM
Temporal variability in flow	Not an indicator	NA	Upper flow tolerance
Seasonal variability in flows	Not an indicator	NA	Upper flow tolerance
Seasonal variability in water levels	Tidal signal may be important. Able to exist at various mudflat elevations but generally most abundant where frequently submersed; Able to withstand short periods of mudflat exposure	Distribution	Upper timeframe for survival out of water
Communities requiring varied hydrology supported	Generally requires permanent to frequent submersion but able to withstand short periods of exposure	Distribution	Upper timeframe for survival out of water
Communities requiring flooding supported	Generally requires permanent to frequent submersion but able to withstand short periods of exposure	Distribution	Upper timeframe for survival out of water
Tidal signal apparent	Tidal & freshwater signal may be important for recruitment	Distribution	Recruitment through MM
Complex food webs present	Detritus/deposit feeder (Tsutsumi 1990); prey species for larger fish, predatory polychaete worms & some wading birds	Distribution	Prey species; switch between feeding modes; predation rates
Functions performed by multiple species	Most abundant polychaete in the Coorong region	Distribution	Interspecific competition
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Wide salinity tolerance; growth & ingestion rates affected by cadmium, lead & nickel (Horng *et al.* 2009)	Distribution	Sensitivity to acidity
Wide riparian & littoral zones supported	Tidal signal may be important for recruitment	Distribution	Speed of resettlement & colonisation, limits of larval settlement
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange between	Not an indicator of energy cycles but indicator of organically-	Distribution;	

Indicator species:	**Polychaete worm, *Capitella* spp.**		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
aquatic & terrestrial systems	enriched sediments	Sediment organic content	
Regular oxidation of sulfidic material	Growth & ingestion rates affected by cadmium, lead & nickel (Horng *et al.* 2009)	Distribution	Tolerance levels of acid & metals

7.18 Brine shrimp – *Parartemia zietziana*

The mobile brine shrimp, *Parartemia zietziana* is the only macroinvertebrate species present in large abundance in the hypersaline environment of the South Lagoon during dry periods. It acts as a filter feeder and is an important food source for some bird and fish species. Brine shrimp is a species typical of salt lakes and its presence in large numbers in the Coorong was first noticed around 2006 (Brookes *et al.* 2009). Recent high abundances suggest a lack of fish predators to limit population numbers. Table 7.18 links *P. zietziana* to individual ecological outcomes.

Table 7.18: List of ecological outcomes that would be indicated by *Parartemia zietziana* populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Brine Shrimp, *Parartemia zietziana*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Tend to occur in large numbers when predators are unable to tolerate conditions, so can be considered indicative of a degraded habitat in some areas	Distribution; Abundance	Limitations on predators
Suitable habitat	Indicator of hypersaline environments (Timms 2009, Williams 1998)	Distribution	
Suitable food resources	Filter feeder	Feeding rates	Size selection may operate
Suitable water quality	Indicator of hypersaline environments (Timms 2009, Williams 1998)	Distribution	
Species connectivity	Connectivity not essential for this species	NA	
Viable propagule bank	Has a resistant propagule phase	Abundance - after adverse conditions	Viability after exposure to lower salinities
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Resident times may not be important for this species	NA	Impact of residence times
Regional hydraulically connected	Hydraulic connectivity not essential for this species	NA	
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Not an indicator	NA	
Lateral habitat diversity	Not an indicator	NA	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Indicator of hypersaline environments	Distribution; Abundance	
Temporal variability in salinity	Has a resistant propagule phase, so is able to tolerate times of adverse salinities	Distribution; Abundance	
Communities requiring varied salinities supported	Indicator of hypersaline environments	Distribution; Abundance	
Temporal variability in flow	Impact of flow on the taxon is unknown	NA	Impact of flow

Indicator species: **Brine Shrimp, *Parartemia zietziana***			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Seasonal variability in flows	Impact of flow on the taxon is unknown	NA	Impact of flow
Seasonal variability in water levels	Impact of water levels unknown, although has a resistant propagule phase so can probably survive adverse conditions	NA	Impact of water levels
Communities requiring varied hydrology supported	Impact of water levels unknown	NA	Impact of water levels
Communities requiring flooding supported	Impact of flooding unknown	NA	Impact of flooding
Tidal signal apparent	Tidal signal not important for this species	NA	
Complex food webs present	Secondary consumer of phytoplankton; prey for small-mouthed hardyhead (fish)	Distribution; Abundance	
Functions performed by multiple species	No other filter-feeder species other than brine shrimp able to tolerate such elevated salinities	Abundance	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	If large numbers spread, could potentially be considered an invasive species	Abundance	
Acid- & saline-tolerant & terrestrial species present	Very saline-tolerant, so increasing abundances could indicate changes in the proportion of saline-tolerant taxa (Timms 2009, Williams 1998)	Abundance	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

7.19 Goolwa Cockle – *Donax deltoides*

Goolwa cockles, *Donax deltoides* live in the sand near the shore of the ocean beach and are subject to ongoing substantive consumption and trade with other Indigenous people by Ngarrindjeri nation and commercial fishery. The dependence of *D. deltoides* on River Murray outflows (i.e. as a source of food, for example) is currently unknown but was being researched but for which the findings were not available at the time of writing. Table 7.19 links *D. deltoides* to individual ecological outcomes.

Table 7.19: List of ecological outcomes that would be indicated by *Donax deltoides* populations. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	Goolwa Cockle, *Donax deltoides*		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Sensitive to overfishing (Ward *et al.* 2010)	Fishing quotas	
Suitable habitat	Indicator of surf-zone habitat	Distribution	
Suitable food resources	Filter feeder – *Asterionella* (a diatom) is main food supply (King 1976); are a food item for some bird species	Feeding rates	Size selection
Suitable water quality	Indicator of marine salinities (can tolerate salinities of 20-45 ppt: Nell & Gibbs 1986)	Distribution	
Species connectivity	Connectivity essential to provide food supply through nutrient loading; Large outflows can lead to significant cockle mortalities (Murray-Jones & Johnson 2003)	Distribution; Abundance	Filtering rates, size selection
Viable propagule bank	Peak spawning occurs in September-October (King 1976), although year-round recruitment is likely (Murray-Jones 1999)	Recruitment events (& conditions)	Geographical distribution of recruitment
No barriers to recruitment	Recruitment possible year-round	Abundance - within size-classes	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Outflows deliver nutrients to create a phytoplankton food source; large decreases in salinity can be fatal	Distribution; Abundance	Filtering rates
Longitudinal biological connectivity	Nutrient outflow important for food supply	Distribution; Abundance; Feeding rates	
No accumulation of pollutants	Potential bioaccumulator of pollutants (Haynes *et al.* 1995, Haynes *et al.* 1998)	Tissue composition	Uptake rates; lethal doses
Lateral habitat diversity	Indicator of high-energy surf zones	Distribution	
Habitat variability	Indicator of high-energy surf zones	Distribution	
Range of salinities with appropriate maxima	Indicator of high-energy marine environments	Distribution	
Temporal variability in salinity	Recruitment possible throughout the year	Recruitment events (& conditions)	

Indicator species: **Goolwa Cockle, *Donax deltoides***			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Communities requiring varied salinities supported	Indicator of marine salinities	Distribution	
Temporal variability in flow	Flow important for delivery of nutrients to food supply; large flows can cause large mortalities due to salinity changes	Distribution; Abundance	
Seasonal variability in flows	Flow important for delivery of nutrients to food supply; large flows can cause large mortalities due to salinity changes	Distribution; Abundance	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Not an indicator	NA	
Communities requiring flooding supported	Indicator of high-energy marine environments (surf zone)	Distribution	
Tidal signal apparent	Not present on the Coorong side of the Murray Mouth, but tidal signal on ocean side of Younghusband Peninsula important for distribution & recruitment dynamics	Distribution; Abundance	
Complex food webs present	Secondary consumer of phytoplankton; prey for birds & fish	NA	Food web structure on ocean side of Younghusband Peninsula
Functions performed by multiple species	Most abundant filter feeder present on ocean side of Younghusband Peninsula	Abundance; Distribution	Abundance of other bivalves
Efficient nutrient cycling	Secondary consumer of phytoplankton	Feeding rates	Uptake rates
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Not an indicator	NA	
Wide riparian & littoral zones supported	Tidal signal important for dispersal & recruitment dynamics	Distribution; Abundance; Recruitment events	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Important fishery, most abundant marine bivalve on ocean side of Younghusband Peninsula	Fishing quotas; Distribution	
Exchange between aquatic & terrestrial systems	Important part of the food chain for birds who may transfer energy to terrestrial systems	Fishing quotas; Feeding rates – filtration rate	Food web dynamics, predation
Regular oxidation of sulfidic material	Not influenced by ASS on ocean side of Younghusband Peninsula	NA	

7.20 Evaluation of macroinvertebrate indicators as evidence for achieving specific outcomes for the site

In total, 19 macroinvertebrate taxa were selected (Table 7.20) across freshwater, estuarine, marine and hypersaline inhabitants. The indicator that provides evidence for the largest number of outcomes was one of the polychaete worms, *Capitella* spp., scoring against 25 out of a possible 33 outcomes (76%). *Capitella spp.* have been commonly used as indicators of organically-polluted environments and therefore may be more useful as an indicator of degraded conditions rather than a healthy state in some instances. However, they are abundant in estuarine and marine habitats within the CLLMM region, even during good ecological conditions.

Five taxa scored 24 out of the possible 33 outcomes: mayflies, stoneflies, caddisflies, the tubeworm and the Goolwa cockle. The mayflies, stoneflies and caddisflies, collectively known as the EPT taxa, are known for their sensitivity to poor water quality. These taxa, particularly the diversity within each of the orders, are useful indicators of healthy freshwater habitats but do not occur in estuarine, marine or hypersaline conditions, limiting their use as indicators. Tubeworms are sessile polychaetes which are able to exist in very large aggregations if the conditions are right, can recruit at any time of year, can tolerate a wide range of salinities and readily invade new habitats by colonising any hard substrate which is reflected in their metrics ability to providing evidence for so many outcomes. It should be noted though that their recent high abundance, with its detrimental impacts on other fauna (e.g. crabs and tortoises), and distribution in usually-freshwater habitats (e.g. Lake Alexandrina) has been indicative that the site was not healthy, productive and resilient (Table 19.3; Appendix D), so this species can be indicative of negative changes in ecological condition as well as positive changes. The Goolwa cockle is an important fisheries species and is limited to surf-zone habitats around the Murray Mouth. Although the Goolwa cockle may provide evidence for many outcomes, the limited distribution of this species must be acknowledged when considering its use as an indicator.

The indicators that scored the lowest number of outcomes were the segmented worms and marsh beetles (11 or 33% each). Segmented worms are relatively tolerant to pollutants and can thus withstand degraded environmental conditions, reducing their effectiveness as an indicator, although they are not tolerant of elevated salinity, so can be used in combination to indicate freshwater habitats. Marsh beetles have an aquatic larval phase and terrestrial adult phase. Although they indicate a relatively small number of outcomes, the quality and specificity of the evidence they provide is very high. The other macroinvertebrate indicators provide evidence for between 13 and 23 (40 to 70%) outcomes, and as a suite they offer capacity to assess achievement of outcomes at a variety of temporal and spatial scales as well as along a scale of tolerance to a given environmental stressor (e.g. predictable sequence of species tolerances to salinity).

There was only one outcome for which no macroinvertebrate indicator was found to show evidence for. Lateral connectivity of vegetation, which specifically relates to whether an interconnected mosaic of diverse vegetation from terrestrial to the extent of the euphotic zone exists, is easily assessed by specifically evaluating vegetation indicator metrics (Chapter 6) and only indirectly relates to macroinvertebrates. Suitable habitat and suitable food had the highest number of invertebrates able to indicate success. All 19 invertebrates were identified as potential indicators for both of these outcomes. Suitable water quality and all three of the salinity gradient outcomes had the second-highest number of macroinvertebrate indicators (18 out of possible 19). The marsh beetles did not score against suitable water quality because of having a terrestrial adult life stage and the blackfly larvae were not indicators of the salinity gradient outcomes.

For some of the outcomes, overall invertebrate community measures were deemed appropriate as supporting or primary evidence of successful outcomes. These have been listed in Appendix D in Table 19.3.

The current unevenness in the number of studies undertaken for various taxa (e.g. extensive information regarding the distribution of polychaete worms) compared to the lack of even basic information for species such as hydra, microbivalves, and freshwater limpets has led to uncertainty regarding the application of the listed indicator species. However, ongoing monitoring and research would redress this issue with time.

An individual macroinvertebrate taxon-based approach for indicating specific ecological objectives does not take into account entire invertebrate communities, which may be more appropriate for indicating outcomes rather than individual species. Without further research and development, the taxa listed here (see Table 19.3) may be incomplete or inadequate, and invertebrate taxa may not be the most appropriate indicator for set objectives. Thus, we have also suggested community-based metrics that should also be considered. Research in other regions suggests that there is significant potential that the suite of metrics outlined here will prove comprehensive and cost-effective indicators.

7.21 Summary

- **The macroinvertebrate taxa and metrics which provide indicators for the key outcomes are presented in detail, although the knowledge of macroinvertebrates in the CLLMM region is spatially and temporally variable and not all habitats in all regions have been surveyed.**
- **Macroinvertebrates are known to be important indicators of water quality, habitat quality and biodiversity and have many advantages for being used as indicators.**
- **A total of 19 macroinvertebrate taxa were selected as possible indicators, including 12 freshwater, six estuarine/marine and one hypersaline taxa.**
- **The polychaete *Capitella* spp. provides evidence for the highest number of outcomes, with 25 out of a possible 33 outcomes.**
- **Segmented worms and marsh beetles were the indicators that scored the lowest number of outcomes, although both these taxa are useful as indicators of specific outcomes.**
- **Some individual taxa can be useful for indicating specific ecological objectives but the entire invertebrate community may be more appropriate for indicating most outcomes.**

Table 7.20: Summary of outcomes represented by the macroinvertebrate indicators

Note: A tick denotes the taxa are an indicator for that outcome. All scientific names and further information can be found in the text above. Note that the quality and spatial extent of data available varied between taxa, as described in the individual sections above. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Objective	Outcome	Freshwater mussel	Freshwater crayfish	Mayfly larvae	Stonefly larvae	Caddisfly larvae	Amphipoda	Segmented worms	Hydra	Freshwater limpets	Brackish water crab	Marsh beetle	Blackfly larvae	Tubeworms	Microbivalve	Polychaete worm ***Nephtys***	Polychaete worm ***Simplisetia***	Polychaete worm ***Capitella***	Brine shrimp	Goolwa cockle	Count
Self-sustaining populations	Successful recruitment	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	**16**
	Suitable habitat	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	**19**
	Suitable food resources	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	**19**
	Suitable water quality	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	**18**
Population Connectivity	Species connectivity	✓		✓	✓	✓			✓			✓		✓	✓	✓	✓	✓		✓	**13**
	Viable propagule bank	✓	✓										✓	✓	✓	✓	✓	✓	✓	✓	**9**
	No barriers to recruitment	✓	✓	✓	✓	✓			✓	✓	✓			✓			✓	✓	✓	✓	**15**
Hydraulic Connectivity	Lateral hydraulic connectivity	✓		✓		✓									✓	✓	✓	✓			**7**
	Water residence times finite			✓	✓	✓		✓	✓	✓	✓		✓		✓	✓	✓	✓			**11**
	Regional hydraulically connected			✓		✓					✓		✓	✓	✓	✓	✓	✓		✓	**10**
	Longitudinal biological connectivity								✓				✓					✓		✓	**3**
	No accumulation of pollutants	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	**17**
Habitat	Lateral habitat diversity			✓	✓	✓	✓			✓		✓	✓							✓	**8**

Objective	Outcome	Freshwater mussel	Freshwater crayfish	Mayfly larvae	Stonefly larvae	Caddisfly larvae	Amphipoda	Segmented worms	Hydra	Freshwater limpets	Brackish water crab	Marsh beetle	Blackfly larvae	Tubeworms	Microbivalve	Polychaete worm ***Nephtys***	Polychaete worm ***Simplisetia***	Polychaete worm ***Capitella***	Brine shrimp	Goolwa cockle	Count
Complexity	Habitat variability																			✓	**1**
Salinity Gradients	Range of salinities with appropriate maxima	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	**18**
	Temporal variability in salinity	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	**18**
	Communities requiring varied salinities supported	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	**18**
Flow and Water level	Temporal variability in flow	✓	✓	✓	✓	✓	✓		✓		✓		✓	✓						✓	**13**
	Seasonal variability in flows	✓		✓	✓	✓		✓			✓									✓	**8**
	Seasonal variability in water levels	✓	✓	✓	✓	✓		✓			✓			✓	✓	✓	✓	✓			**12**
	Communities requiring varied hydrology supported	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			**14**
	Communities requiring flooding supported	✓	✓		✓	✓					✓			✓	✓	✓	✓	✓		✓	**9**
	Tidal signal apparent													✓	✓	✓	✓	✓		✓	**6**
Ecological function	Complex food webs present	✓	✓	✓	✓	✓	✓		✓	✓	✓		✓		✓	✓	✓	✓	✓		**17**

Objective	Outcome	Freshwater mussel	Freshwater crayfish	Mayfly larvae	Stonefly larvae	Caddisfly larvae	Amphipoda	Segmented worms	Hydra	Freshwater limpets	Brackish water crab	Marsh beetle	Blackfly larvae	Tubeworms	Microbivalve	Polychaete worm ***Nephtys***	Polychaete worm ***Simplisetia***	Polychaete worm ***Capitella***	Brine shrimp	Goolwa cockle	Count
Ecological function	Functions performed by multiple species	✓	✓	✓	✓	✓	✓			✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	**16**
	Efficient nutrient cycling													✓	✓					✓	**3**
	Control of invasive species	✓												✓					✓		**3**
	Acid- & saline-tolerant & terrestrial species present	✓	✓	✓	✓	✓	✓	✓		✓		✓		✓	✓	✓	✓	✓	✓		**15**
Aquatic-terrestrial connectivity	Wide riparian & littoral zones supported				✓									✓	✓	✓	✓	✓		✓	**7**
	Lateral connectivity of vegetation																				**0**
	Balance of aquatic & terrestrial species	✓	✓	✓	✓							✓								✓	**6**
	Exchange between aquatic & terrestrial systems		✓	✓	✓	✓								✓				✓		✓	**8**
	Regular oxidation of sulfidic material	✓	✓	✓	✓	✓								✓	✓	✓	✓	✓			**10**
	Count	**23**	**20**	**24**	**24**	**24**	**14**	**11**	**15**	**15**	**17**	**11**	**13**	**24**	**23**	**22**	**23**	**25**	**13**	**24**	

8. Fish indicators

Jason Higham & Kerri Muller

A number of ecological outcomes have been recognised as representing a healthy, productive and resilient wetland for the Coorong, Lower Lakes and Murray Mouth region. These have been summarised in Chapter 3 above. This section identifies in detail the fish species and metrics which provide indicators for these outcomes.

Fish have been shown to be excellent biological indicators for impact assessment (Grabarkiewicz & Davis 2008, *Gibson et al.* 2000). Based on this and the rationale specified below, fish could potentially be indicators of many of the ecological outcomes linked to a healthy, productive and resilient wetland of international importance because they:

- live in the water all of their life and integrate the chemical, physical, and biological histories of the waters;
- are relatively easy to collect (with the right equipment);
- are easy to identify in the field;
- differ in their tolerance to amount and types of degradation in water quality;
- live for a range of life-spans (one or two years to more than 30 years) and can reflect both long-term and current water resource quality;
- have a range of life-history strategies and habitat requirements;
- are important in the linkage between benthic and pelagic food webs;
- consume lower-order elements of food webs and are, in turn, prey for other species;
- may exhibit physiological, morphological, or behavioural responses to stresses;
- may exhibit obvious external anatomical pathology due to pollutants; and
- being mobile, sensitive fish species may avoid stressful environments, leading to measurable population patterns (distribution) reflecting that stress.

However, some limitations may restrict the use of fish as biological indicators because (as stated in Grabarkiewicz & Davis 2008, *Gibson et al.* 2000):

- fish represent a relatively high trophic level, and lower-level organisms may provide an earlier indication of water quality problems;
- some fish are resident species with a relatively limited life spans and spatial ranges. Others have relatively large ranges, making it difficult to isolate probable causes of degradation that could occur anywhere within their range. Thus, the spatial scale of sampling is important and, because of seasonal open-water migrations, temporal adjustments may also be necessary;
- mobile organisms such as fish may avoid stressful environments, reducing their exposure to toxic or other harmful conditions;
- fish surveys may be biased because of recreational and commercial fishing pressures on the same or related fish assemblages;
- some fish are very habitat selective and their habitats may not be easily sampled (e.g. reef-dwelling species); and
- since they are mobile, spatial variability can be very high, potentially requiring a large sampling effort to adequately characterize the fish assemblage.

While these issues require consideration, they do not prevent the use of fish as indicators of ecological outcomes being achieved. On the contrary, some of the limitations are easily dealt with, such as seasonal migration by targeting those events so as to collect samples effectively, while being relatively high in the trophic ecology means they integrate impacts at a whole range of levels. The targeting of particular species by recreational and commercial fishers provides opportunity to obtain samples at very little cost and to engage the community, especially given the abundance and health of the fish community is a primary indicator used by the public to discern the health of a waterbody (*Gibson et al.* 2000).

One of the key technical aspects of the use of fish as indicators is how much baseline information is already available regarding fish species of the Coorong and Lakes which increases their value as indicators of ecological outcomes and therefore the value of the identified requirements linked to environmental water that are ascertained.

Around 80 fish species have been recorded from the Coorong and Lower Lakes (Higham *et al.* 2002). The ECD identifies the site as being significant for 49 native species, which between them contribute to the site qualifying against five of Ramsar's nine criteria (with additional non-fish-related evidence qualifying the site against another three criteria; Phillips & Muller 2006). Three of these species are listed as vulnerable under the EPBC Act, including the Murray cod (*Maccullochella peelii peelii*), Murray hardyhead (*Craterocephalus fluviatilis*), and the Yarra pygmy perch (*Nannoperca obscura*) while five of the species are of protected under the *Fisheries Management Act* 2007 (Bice 2010a).

The extent of knowledge of the fish fauna present within the CLLMM region is both temporally and spatially variable (Eckert & Robinson 1990, Geddes & Hall 1990, 2002, Jennings *et al.* 2008a). The fish community within the Lower Lakes and Coorong have been studied over a number of years (e.g. early studies by Harris 1968, Hall 1984, 1986, to more recent investigations by Ye & Zampatti 2007), and more recently the migratory component of the fish community has received significant attention (Bice *et al.* 2007, Jennings *et al.* 2008a, 2008b, Zampatti *et al.* 2010a). However, significant knowledge gaps persist regarding habitat utilisation, recruitment and population dynamics (age and size structure) as well as migration that occurs within habitats both of the site and upstream of the site.

The majority of the species recorded in the region are primarily found in the Coorong, rather than the Lower Lakes, and many of these are of marine origin and thought to be only occasional visitors (Higham *et al.* 2002). Similarly, some obligate freshwater species are more common in the upper reaches of tributary streams or further upstream in the Murray-Darling Basin and are only encountered in this region following large floods (Eckert & Robinson 1990).

Bice (2009, 2010) identified three abiotic drivers, namely flow regime, physicochemical drivers and connectivity, which are important in structuring fish assemblages in the region. Of these, Bice (2010a) indicated that flow regime could be viewed as the overarching driver as it directly influences both physicochemical parameters and connectivity (hydraulic and population). Life-history models are presented for most species in Bice (2010a), with the exception of sandy sprat, Australian salmon and bronze-whaler sharks.

Bice (2009) developed a set of criteria for screening the species recorded in the region for relevance to site managers, which reduced the suite of species to 34, which we then further grouped based upon broad habitat requirements (e.g. freshwater, estuarine and marine), life-history strategies (e.g. diadromous), origin (i.e. native vs. alien) and conservation significance. This resulted in a list of 17 fish species that we considered representative of the various life-history strategies of fish found within the region and these form an initial suite of species acting as indicators of requirements for the site. The 17 species selected as indicators are:

Freshwater:

- Murray Cod – *Maccullochella peellii peellii*
- Golden perch – *Macquaria ambigua ambigua*
- Bony herring – *Nematolosa erebi*

- Australian smelt – *Retropinna semoni*
- Murray hardyhead – *Craterocephalus fluviatillis*
- Yarra pygmy perch – *Nannoperca obscura*
- Common carp – *Cyprinus carpio*

Diadromous:

- Congolli – *Pseuoaphritis urvillii*
- Common galaxias – *Galaxias maculatus*
- Short-headed lamprey – *Mordacia mordax*

Estuarine:

- Yellow-eyed mullet – *Aldichetta forsteri*
- Black bream – *Acanthopagrus butcheri*
- Small-mouthed hardyhead – *Atherinosoma microsoma*

Marine:

- Mulloway – *Argyrosomus japonicus*
- Sandy sprat – *Hyperlophus vittatus*
- Australian salmon – *Arripis truttacea*
- Bronze-whaler shark – *Carcharhinus brachyurus*

The level of information available regarding water quality tolerances for fish is limited for most parameters beyond salinity. The salinity tolerance of many freshwater fish examined is, as would be expected, quite low with LC50 values varying between species and even life-history stages of species with the rate of change in salinity also having a significant effect (see Bice 2010a for data or Clunie *et al.* 2002 for further discussion). Evidence on salinity tolerance summarised here, and in Bice (2010a) and Clunie *et al.* (2002), indicates that acclimated freshwater fish species are more tolerant of salinity than un-acclimated individuals. Salinity tolerance for marine species is difficult to verify, with information tending to be limited or general in nature, as it is mostly based on natural history observations or catch records. The quality of information will improve with further studies but arguably not without targeted research. Information from aquaculture studies may be an important source for this information in the future.

The information available on the sensitivity of critical life stages of fishes to salinity suggest that larval stages of both freshwater and estuarine species may be more sensitive than adult stages. For example golden perch, Murray cod and black bream have salinity tolerances for juvenile stages that is much lower than for adults (either directly transferred or acclimated). Fish eggs appear to be relatively tolerant of salinity increases however, once fertilised, they are much less tolerant (Hart *et. al.* 1991). Studies on the entire life cycle, or preferably on the most critical life stages, of important fish are needed as these may determine the critical salinity tolerance of a community if it is self sustaining through recruitment within the site.

Hart *et al.* (1991) indicate that sperm viability testing is rapid and simple, and may provide a conservative indication of a species' salinity tolerance and this is likely to be beneficial for the fish communities of the Lower Lakes and Coorong given the range of salinities present in the region. Limited recruitment as a result of salinities that are high enough to affecting sperm (or other sensitive stages of early life-history) could be significant for species that have very short life spans, especially if they are non-migratory (Clunie *et al.* 2002). Also, any impacts on prey items or sub-lethal effects are key areas to improve our understanding of the implications that water quality has on Coorong and Lakes fish communities. The reduction of freshwater inputs to the region may have indirect impacts on fish through reductions in productivity and decreased habitat diversity (Whitfield 2005, Flemer & Champ 2006). Freshwater inflows to estuaries are positively associated with phytoplankton and zooplankton biomass that may, in turn, support high densities of larval and juvenile fish

(Whitfield 1994), and could be expected to significantly impact on recruitment. Zooplankton are arguably the most important prey for larval and juvenile stages of freshwater fish, and play a key role in fish recruitment (Miller *et al.* 1990, Bremigan & Stein 1997). Predation and starvation of larval and juvenile fishes are the main regulators of recruitment (e.g. Houde 1987, Bremigan & Stein 1997).

Freshwater inflows and tidal regime determine estuarine salinities which may then affect fish population dynamics by influencing recruitment of marine, estuarine, freshwater and diadromous fish (Whitfield 1994, Staunton-Smith *et al.* 2004, Shoji *et al.* 2006, Halliday *et al.* 2008). Previous studies have demonstrated the deleterious effects that altered freshwater inflows and barriers to connectivity can have on estuarine fish (e.g. Gillanders & Kingsford 2002, Whitfield 2005, Kocovsky *et al.* 2009, Zampatti *et al.* 2010a). At a minimum, freshwater inflows to the Coorong have been shown to play a crucial role in structuring fish assemblages and facilitating the recruitment of catadromous congolli and common galaxias in the Coorong estuary (Zampatti *et al.* 2010a). Zampatti *et al.* (2010a) demonstrated that even small volumes of fresh water (e.g. 50 ML day^{-1}) appeared to produce a significant ecological response, promoting diversity in estuarine fish assemblages and recruitment of catadromous fish.

The following section briefly describes the biology of each indicator species whilst explaining the rationale behind its inclusion as an indicator of specific outcomes and the metrics to be monitored to indicate these outcomes. Metrics including abundance, population demographics, food web structure and distribution may be useful indicators of the habitat and food resources within the site. Also, population demographics can indicate whether recruitment has been successful while also raising concerns regarding the resilience of a species (short- or long-lived); if the age structure of a population is skewed such that >90% of that population is approaching its maximum age, then that species is at an increased risk of failing to be self-sustaining. Furthermore, age structure provides information on the historical recruitment success of the population & its ability to recover in the future during the occurrence of favourable conditions by the presence of older adult fish. Larger and/or older fish produce a disproportionately large numbers of eggs compared to smaller fish (Beamish *et al.* 2006).

Measuring fish kills may indicate a sudden loss of water quality, coupled with inadequate hydraulic connectivity in the region, preventing fish movement to escape adverse conditions. Tissue composition could potentially be useful in identifying whether pollutants are bioavailable and being accumulated through the food chain. Recruitment is dependent on availability of spawning, juvenile and adult habitat being present, as well as water quality within tolerances and appropriate food being available. Significant knowledge gaps that are relevant to the use of each species as an indicator are also listed.

8.1 Murray cod – *Maccullochella peelii peelii*

Murray cod (*Maccullochella peelii peelii*) is a large, iconic, long-lived (>40 years) and once-widespread native freshwater species in the Murray-Darling Basin (Lintermans 2007). Commercial fishing of this species started not long after European settlement (Sim & Muller 2004) and commercial records from both Lakes Alexandrina and Albert show catches up until recent years (Bice 2010a).

Murray cod is an apex predator, feeding primarily on fish, crustaceans and frogs (Ebner 2006), and throughout its life history prefers demersal (i.e. near the bottom of the waterbody) habitat with in-stream cover such as rocks and snags, as well as deeper holes (Lintermans 2007, Koehn 2009). In recent years, Murray cod have been shown to migrate considerable distances over river reaches (Lintermans 2007). Murray cod spawn annually throughout the MDB (Humphries *et al.* 2002, Humphries 2005) but no investigations have been conducted on Murray cod spawning in the Lower Lakes. Historical South Australian fisheries data suggested a strong correlation between recruitment of Murray cod and river flow (Ye *et al.* 2000) and there had not been a significant recruitment event recorded below Lock 1 since 1994 (Ye & Zampatti 2007) at the time of writing. There were low levels of recruitment in the South Australian Murray-Darling Basin (SA MDB) during 2000, which were correlated with daily flows to South Australia during the spawning season of between 20 to 60 GL (Ye & Zampatti 2007).

Adults have been documented as being able to tolerate moderate salinities (~13 200 mg L^{-1}[~13 ppt] LC50 direct transfer and 15 700 mg L^{-1}[~16 ppt] LC50 with acclimation) (Jackson & Pierce 1992 cited in Clunie *et al.* 2002) but larval and juvenile stages are less tolerant (~7000 mg L^{-1}[~7 ppt] LC50 direct transfer and ~14 100 mg L^{-1}[~14 ppt] LC50 with acclimation) (Chotipuntu *et al.* 2002. Tolerance to dissolved oxygen is unknown (Treadwell & Hardwick 2003). The Murray cod is EPBC-listed as a vulnerable species. Table 8.1 links Murray cod to individual ecological outcomes.

Table 8.1: List of ecological outcomes that would be indicated by Murray cod. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	Murray cod, *Maccullochella peelii peelii*		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Possible that local recruitment in this species occurs but has not been confirmed, being found only in Lower Murray (Bice 2010a), & as such may be dependent on recruitment occurring upstream so it is not currently an indicator	NA	Population age structures in the region; Confirmation of recruitment within the Lakes
Suitable habitat	Juveniles & adults should grow in the Lakes but require suitable habitats to do so. Prefers demersal habitat with in-stream cover (Lintermans 2007, Koehn 2009). The presence of juveniles in the region has not been confirmed although small numbers of large specimens have been collected (Bice 2010a). Not currently an indicator	NA	Distribution & abundance in Lower Lakes (LL); Reliance of the population on region as a breeding site, and use as juvenile & adult habitat
Suitable food resources	An apex predator (Ebner 2006) that depends on food resources being available for a range of species (via direct & indirect consumption) as diet changes through life-history (Bice 2010a). Abundance potentially related to that of food resources for itself & other species too	Food web structure – gut contents	Local diet & habitat use in LL

Indicator species: Murray cod, *Maccullochella peelii peelii*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Suitable water quality	Sensitive to elevated salinity (O'Brien and Ryan 1999, Chotipuntu *et al.* 2002), thus likely to indicate if water quality is declining to an unfavourable level	Abundance; Fisheries take – commercial fishery CPUE; Disease – increased occurrence or decreased health condition; Fish kills	Impacts of multiple water quality stressors in combination
Species connectivity	Migratory species that makes upstream movements prior to spawning (Koehn 2006, Lintermans 2007, Koehn *et al.* 2009). Unknown whether species recruits locally but population is possibly sustained through immigration of fish spawned upstream of the site	Population demographics – size & age structure; Movements – within & between local habitats	Reliance of the population on the LL as a juvenile & adult habitat; Location of spawning habitat within & upstream of site; Timing of movement of young fish into LL
Viable propagule bank	Not an indicator because no resting phase although species is long-lived & hence older adults in the population are still able to breed & enable temporal connectivity	NA	Population age structures in the region
No barriers to recruitment	Undertakes pre-spawning migrations (Koehn 2006, Koehn *et al.* 2009) & migrations more broadly of up to >100 km (Koehn 1996, Koehn & Nicol 1998, Humphries *et al.* 2002, King 2002)	Population demographics – size & age structure; Movements – between habitats	Movement between LL & River Murray (RM), & within the LL; use of site as a juvenile habitat
Lateral hydraulic connectivity	Not currently an indicator because adults prefer demersal habitats with in-stream cover (Lintermans 2007, Koehn 2009). While there is a strong correlation between recruitment & river flow (including floods) in the MDB (Rowland 1998, Ye *et al.* 2000, Ye & Zampatti 2007), the site is not thought to be a location for breeding or act as a juvenile habitats at this time	NA	Reliance of the population on region as a breeding site & juvenile habitat
Water residence times finite	Likely to respond to increased residence time because obligate aquatic species & sensitive to salinity & water quality which deteriorates with increased residence time	Disease – increased occurrence or decreased health condition; Fish kills; Distribution	Impacts of multiple water quality stressors in combination
Regional hydraulically connected	Adult cod make substantial movements of >100 km (Koehn 1996, Koehn & Nicol 1998, Humphries *et al.* 2002, King 2002)	Movements – within & between habitats	Movement between the LL & RM & movement within LL
Longitudinal biological connectivity	No currently an indicator because juveniles have not been demonstrated to occur within site	NA	Reliance of LL population on breeding upstream of site & use as a juvenile habitat
No accumulation of pollutants	Long-lived, apex predator (Ebner 2006), so may bioaccumulate toxins. Migratory behaviour may mean that the source of the toxins would be difficult to determine unless combined with otolith composition that demonstrates	Tissue composition – & otolith composition	Suitability as indicator given migratory nature

Indicator species:	Murray cod, *Maccullochella peelii peelii*		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
	residence		
Lateral habitat diversity	Not an indicator because only likely to be indirectly affected by diversity of habitats via prey items & is an obligate aquatic species	NA	Habitat association in LL
Habitat variability	Species prefers demersal habitat with in-stream cover throughout its life-history (Lintermans 2007, Koehn 2009) but the presence of all life history stages is unconfirmed so this sp. is not currently an indicator	NA	Presence of all life-history stages within site & the site's importance to the population
Range of salinities with appropriate maxima	Moderately salt tolerant for a freshwater fish (juveniles least tolerant with LC50 ~ 7000 mg L^{-1} [~7 ppt]; Chotipuntu *et al.*, 2002) (although sub-lethal effects are likely before 7 ppt) therefore indicative of fresh water salinities	Disease – occurrence of or decreased health condition; Fish kills; Population demographics – size & age structure; Distribution	Salinity preferences for optimal health. Salinity tolerance for eggs; Sub-lethal effects on growth & reproduction
Temporal variability in salinity	Indicative of freshwater salinities (Chotipuntu *et al.* 2002, O'Brien & Ryan 1999)	Distribution; Abundance; Fisheries take – CPUE; Disease – occurrence of or decreased health condition; Fish kills	Salinity preferences for optimal health. Salinity tolerance for eggs; Sub-lethal effects on growth & reproduction
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in flow	Although the level of recruitment within site is unknown, the population is dependent on lower-order trophic ecology through diet (Ebner 2006)	Abundance; Fisheries take – CPUE; Population demographics – size & age structure	Whether recruitment for this species occurs locally
Seasonal variability in flows	Not currently an indicator since only indirectly affected through lower-order trophic ecology & seasonality of flows has not been demonstrated to stimulate pre-spawning migrations	NA	Role of flow in stimulating spawning migrations
Seasonal variability in water levels	Not an indicator because seasonality of water levels unlikely to impact directly on species unless it results in hydraulic disconnection of preferred habitats	NA	
Communities requiring varied hydrology supported	Requires access to permanently-inundated habitat	Abundance; Distribution; Fisheries take – CPUE	Habitat use in LL
Communities requiring flooding supported	A strong correlation between recruitment & river flow (including floods) (Ye *et al.* 2000) indicates reliance on floods for successful recruitment, however recruitment in the LL is undocumented. Flooding & recruitment upstream with immigration into LL potentially important for sustaining the local population	Population demographics – size & age structure	Reliance of population on site & use of site by all life-history stages; reliance of LL population on upstream recruitment

Indicator species: Murray cod, *Maccullochella peelii peelii*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Tidal signal apparent	Not an indicator because primarily occurs in LL (Bice 2010a)	NA	
Complex food webs present	Apex predator that preys on fish, crustaceans & frogs (Ebner 2006) & thus depends on food resources being available for these species via complex & diverse food webs	Abundance; Fisheries take – CPUE; Population demographics – size & age structure; Movements – within & between local habitats; Food web structure – gut contents	Actual diet in site; Habitat use in site
Functions performed by multiple species	Not currently an indicator although sp. is an apex predator elsewhere (Ebner 2006). Other piscivores are also present (e.g. golden perch) & its relative importance is unknown	NA	Actual diet & habitat use at site; importance for trophic ecology
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator although is affected by invasive species (i.e. predation by redfin; Cadwallader & Backhouse 1983) & does consume invasive spp. (Kailola *et al.* 1993)	NA	
Acid- & saline-tolerant & terrestrial species present	Indicative of freshwater salinities only (Chotipuntu *et al.* 2002, O'Brien & Ryan 1999). Not known to be tolerant of low pH	Distribution	Acid tolerance
Wide riparian & littoral zones supported	Not an indicator although juveniles may depend on littoral vegetation	NA	Habitat associations in the LL; Presence of juveniles
Lateral connectivity of vegetation	Not an indicator although juveniles may depend on littoral vegetation	NA	Habitat associations in LL; Presence of juveniles
Balance of aquatic & terrestrial species	Indicative of aquatic habit only	Distribution; Abundance; Fisheries take – CPUE	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

8.2 Golden perch – *Macquaria ambigua ambigua*

Golden perch (*Macquaria ambigua ambigua*), also known as callop in South Australia, are a medium to large predatory native freshwater fish that are predominantly found in the lowland, warmer, turbid, slow-flowing rivers of the Murray-Darling Basin (Lintermans 2007). Golden perch are common in the Lower River Murray and Lakes. They are opportunistic carnivores as adults, feeding on fishes, crustaceans and aquatic and terrestrial insects, while juveniles feed on smaller prey items, such as aquatic insect larvae and microcrustaceans (Lintermans 2007). A commercial fishery is still operating in Lakes Alexandrina and Albert for this species (Sloan 2005). Golden perch complete their entire lifecycle in freshwater (Langdon 1987) and are often associated with physical in-stream structure (Crook *et al.* 2001, Boys & Thoms 2006, Lintermans 2007). In Lakes Alexandrina and Albert this possibly includes deeper holes and rocky areas (Bice 2010a). Spawning of golden perch typically occurs in spring and summer when water temperatures exceed 20 °C (Lintermans 2007). Whilst originally believed to be a flow-cued spawner (Lake 1967), evidence is growing that relatively modest prolonged increases of within-channel flow in the order of more than 15 000 ML day^{-1} may also stimulate spawning and successful recruitment (Mallen-Cooper & Stuart 2003, Leigh *et al.* 2008). Eggs are pelagic and both eggs and larvae may drift downstream (Ye 2005, Lintermans 2007, Cheshire & Ye 2008).

Adults are able to tolerate moderate rapid changes in salinities (~14 400 mg L^{-1} [~14 ppt] LC50 direct transfer and 31 000 mg L^{-1}[~31 ppt] LC50 with acclimation) (Jackson & Pierce 1992) while larval and juvenile stages are less tolerant (~8.3 g L^{-1} [~8 ppt] LC50 direct transfer) (O'Brien & Ryan 1999). Acclimatisation allows both adult and juveniles to survive salinities approximately twice these salinity values (Bice 2010a). Tolerance to low dissolved oxygen concentrations is significant with larvae able to withstand concentrations of 2.7 mg L^{-1} (Bice 2010a). Functional connectivity is highly important given that adults migrate within river reaches (potentially over 100s of kilometres; Reynolds 1983).

Golden perch is not presently listed as an endangered species under any legislation. Table 8.2 links golden perch to individual ecological outcomes.

Table 8.1: List of ecological outcomes that would be indicated by golden perch. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	Golden perch (Callop), *Macquaria ambigua ambigua*		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Spawning upstream appears to be flow dependent, therefore indicative of whether flow has been sufficient to support recruitment. However, there appears to have been recruitment in the Lakes between 1996 & 2006 despite low flows (Mayrhofer 2007, Bice 2010a)	Abundance; Fisheries take – CPUE; Population demographics – size & age structure; Recruitment events – YoY	Requirement of flow events for populations to successfully recruit & proportion recruiting locally
Suitable habitat	Juveniles & adults will grow in the Lakes but require suitable habitats to do so. Access to habitats containing physical in-stream structure by different life stages is likely to be important (Bice 2010a)	Abundance; Fisheries take – CPUE; Population demographics – size & age structure; Movements – within & between local habitats	Capacity to predict spawning events from flow events

Indicator species:	**Golden perch (Callop), *Macquaria ambigua ambigua***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Suitable food resources	High-level opportunistic predator that depends on food resources being available for a range of species (via direct & indirect consumption) as diet changes through life history (Lintermans 2007)	Food web structure – gut contents	Local diet & habitat use
Suitable water quality	Sensitive to significantly elevated salinity (Jackson & Pierce 1992) thus likely to indicate whether water quality is declining to a unfavourable level	Disease – occurrence or decreased health condition; Fish kills	Impacts of multiple water quality stressors
Species connectivity	Migratory species that has been shown to migrate over 100s of kilometres in other regions of the MDB (Reynolds 1983). Movement between local water bodies is likely although undocumented	Population demographics – size & age structure; Movements – within & between local habitats	The movement between Lower Lakes (LL) & River Murray (RM) & between Lake Alexandrina (Lx) & Lake Albert (Lb)
Viable propagule bank	Not an indicator because no resting phase although species is long-lived & hence older adults in the population are still able to breed & enable temporal connectivity	NA	
No barriers to recruitment	Migratory species that may be negatively impacted by the presence of physical barriers (Reynolds 1983)	Population demographics – size & age structure; Movements – within & between local habitats	The movement patterns between LL & RM & between Lx & Lb
Lateral hydraulic connectivity	Spawning is flow-related including within-channel rises & over-bank flows, while recruitment success possibly linked to the presence of increased food availability (Rowland *et al.* 1983 cited in Koehn & O'Connor 1990). Thus, floodplain inundation & connectivity may be important to recruitment in local populations	Population demographics – size & age structure; Recruitment events – YoY; Food web structure – gut contents	Local recruitment dynamics
Water residence times finite	Likely to respond to increased residence time because obligate aquatic species & sensitive to elevated salinity although larvae are tolerant of low dissolved oxygen (Bice 2010a)	Distribution; Fish kills; Disease – occurrence or decreased health condition	Impacts of multiple water quality stressors in combination
Regional hydraulically connected	Migratory species (Reynolds 1983) that may be negatively affected by disconnection	Movement within & between local habitats	The movement patterns between LL & RM & between Lx & Lb
Longitudinal biological connectivity	Indicator through lower order trophic ecology & availability of prey items for larvae from upstream of site	Food web structure – gut contents; Population demographics – size & age structure; Recruitment events – YoY	
No accumulation of pollutants	Relatively long-lived fish species that could be expected to bioaccumulate toxins. Migratory behaviour may make the source of the toxins difficult to determine	Tissue composition	Suitability as indicator given migratory nature
Lateral habitat	Not an indicator because only likely to be indirectly affected by diversity of	NA	Habitat association in LL

Indicator species: Golden perch (Callop), *Macquaria ambigua ambigua*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
diversity	habitat range via prey items & is an obligate aquatic species		
Habitat variability	Not an indicator	NA	Use of riparian, littoral & floodplain zones by different life stages
Range of salinities with appropriate maxima	Adults are able to tolerate moderately changes in salinities with larval & juvenile stages least tolerant (~8 ppt LC50 direct transfer; O'Brien & Ryan 1999) therefore likely to be indicative of freshwater salinities	Fish kills; Disease – occurrence or decreased health condition; Population demographics – size & age structure; Distribution	Salinity preferences for optimal health; Acclimation tolerances for eggs, larvae & juveniles; sub-lethal effects on growth & reproduction
Temporal variability in salinity	Indicative of freshwater salinities (Jackson & Pierce 1992, O'Brien & Ryan 1999)	Abundance; Fisheries take – CPUE; Population demographics – size & age structure; Distribution	Salinity preferences for optimal health; Acclimation tolerances for eggs, larvae & juveniles; sub-lethal effects on growth & reproduction
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in flow	Migration upstream by both immature & adult fish stimulated by small rises in stream flow (Reynolds 1983, Mallen-Cooper *et al.* 1996, Lintermans 2007). Spawning is flow- & temperature-dependent (Treadwell & Hardwick 2003)	Movements – within & between local habitats; Population demographics – size & age structure; Spawning events – timing of	Requirement of flow events for populations to successfully recruit & proportion recruiting locally
Seasonal variability in flows	Migration upstream by both immature & adult fish stimulated by small rises in stream flow (Reynolds 1983, Mallen-Cooper *et al.* 1996, Lintermans 2007). Spawning is flow- & temperature-dependent (Treadwell & Hardwick 2003)	Movements – within & between local habitats; Population demographics – size & age structure; Spawning events – timing of	
Seasonal variability in water levels	Not an indicator	NA	Whether successful recruitment occurs due to changes in water level independent of flows in LL region
Communities requiring varied hydrology supported	Requires access to permanently-inundated habitat	Distribution	Habitat use in LL

Indicator species: Golden perch (Callop), *Macquaria ambigua ambigua*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Communities requiring flooding supported	Not currently an indicator	NA	Whether successful recruitment occurs due to changes in water level independent of flows in LL region
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	High-level opportunistic predator (Lintermans 2007) that depends on food resources being available for a range of prey species via complex & diverse food webs	Abundance; Fisheries take – CPUE; Food web structure – gut contents	
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator although is affected by invasive species (i.e. predation by redfin; Cadwallader & Backhouse 1983, Welcomme 1988, Rowe *et al.* 2008) & does consume invasive spp. including carp (Kailola *et al.* 1993)	NA	
Acid- & saline-tolerant & terrestrial species present	Indicative of freshwater salinities (Jackson & Pearce 1992, O'Brien & Ryan 1999). Not known to be tolerant of low pH	Distribution; Disease – occurrence or decreased health condition; Fish kills	Acidity tolerance
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Indicative of aquatic habit only	Distribution; Abundance; Fisheries take – CPUE	
Exchange between aquatic & terrestrial systems	Gut contents should indicate whether terrestrial insects or other fauna are in abundance & are being consumed by this species	Food web structure – gut contents	
Regular oxidation of sulfidic material	Not an indicator	NA	

8.3 Bony herring – *Nematolosa erebi*

Bony herring (*Nematolosa erebi*), also known as bony bream, are a medium-sized, laterally-compressed native freshwater fish that is a very common widespread species in the River Murray (Lintermans 2007) and is abundant in the Lower Murray and Lakes (Bice 2010a). It is a pelagic species that is an algal detritivore eating mostly detritus, algae and microcrustaceans (Lintermans 2007, Sternberg *et al.* 2008). All life stages are found in a variety of habitats, with adults using open water habitat (Puckridge & Walker 1990, Zampatti *et al.* 2005).

Bony herring is consumed by other fish such as Murray cod and golden perch (Ebner 2006, Baumgartner 2007) and also forms a significant component of the diet for waterbirds such as cormorants and pelicans (McDowall 1996, Lintermans 2007). Spawning takes place in shallow bays in Lake Alexandrina in late spring and summer when water temperatures are greater than 20 °C (Puckridge & Walker 1990).

Bony herring is quite salt tolerant, withstanding salinities of up to 35 g L^{-1} (~35 ppt) (Bice 2010a) and able to resist very high water temperatures (up to 38 °C, Merrick & Schmida 1984). Specific tolerance to dissolved oxygen is unknown (Treadwell & Hardwick 2003), although they have been reported to be susceptible to low concentrations (Allen *et al.* 2002). Table 8.3 links bony herring to individual ecological outcomes.

Table 8.3: List of ecological outcomes that would be indicated by bony herring. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	**Bony herring, *Nematolosa erebi***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Very common species that completes its life cycle at the site (Puckridge & Walker 1990)	Abundance; Fisheries take – CPUE; Population demographics – size & age structure; Recruitment events – YoY	
Suitable habitat	Access to a variety of habitats is important (i.e. spawn in shallow bays in late spring/summer, live across all inundated habitats) (Puckridge &Walker 1990, Zampatti *et al.* 2005) & require access to habitats with freshwater salinities	Abundance; Fisheries take – CPUE; Population demographics – size & age structure	
Suitable food resources	Dependent on supply of algae, detritus & microcrustaceans (Lintermans 2007, Sternberg *et al.* 2008)	Abundance; Fisheries take – CPUE; Population demographics – size & age structure; Food web structure – gut contents	
Suitable water quality	Not an indicator because the sp. is quite tolerant of salinity (~35 ppt) for freshwater species (Bice 2010a) & specific tolerance to dissolved oxygen is unknown (Treadwell & Hardwick 2003) although likely to be susceptible to low concentrations (Allen *et al.* 2002)	NA	Impacts of multiple water quality stressors, tolerance to low dissolved oxygen
Species connectivity	Not currently an indicator because completes life cycle at the site &	NA	Movement patterns &

Indicator species: Bony herring, *Nematolosa erebi*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
	relationship to populations upstream unknown		relationship to upstream populations
Viable propagule bank	Not an indicator because sp. relies on availability of fresh eggs for recruitment & does not have resting phases. Is relatively short-lived although highly fecund	NA	
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic connectivity	Prey items may be linked to the inundation of lateral habitats	Food web structure – gut contents	
Water residence times finite	Obligate aquatic species tolerant of elevated salinity (Bice 2010a). Specific sensitivity to dissolved oxygen is unknown but likely to be susceptible (Allen *et al.* 2002)	Distribution; Fish kills; Disease – occurrence or decreased health condition	
Regional hydraulically connected	Not an indicator because completes its life cycle at the site & relationship to populations upstream unknown	NA	Movement patterns & relationship to upstream populations
Longitudinal biological connectivity	Indicator through availability of food items from upstream of site	Food web structure – gut contents	
No accumulation of pollutants	Relatively short-lived fish species that may be a good indicator assuming it completes life cycle at the site & because it consumes detritus	Tissue composition	Confirm sp. completes life cycle within site
Lateral habitat diversity	Access to a variety of habitats is important (spawn in shallows, lives across all inundated habitats; Puckridge & Walker 1990)	Population demographics – size & age structure	Dependence on riparian, littoral & floodplain zones for recruitment
Habitat variability	Pelagic sp. & all life stages are found in a variety of habitats	Distribution	
Range of salinities with appropriate maxima	Not an indicator because highly salt tolerant for a freshwater fish (35 000 mg L^{-1} [~ 35 ppt]; Bice 2010a) therefore unlikely to indicate whether a range of salinities are present	NA	Salinity preferences for optimal health. Salinity tolerance for eggs; sub-lethal effects on growth & reproduction
Temporal variability in salinity	Not an indicator due to high salinity tolerance of adults for freshwater spp. (Bice 2010a) & lack of information for other life-history stages	NA	Salinity preferences for optimal health. Salinity tolerance for eggs; sub-lethal effects on growth & reproduction
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in	Not an indicator because life history strategies are not directly flow-related	NA	

Indicator species: Bony herring, *Nematolosa erebi*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
flow			
Seasonal variability in flows	Not an indicator because life history strategies are not directly flow-related	NA	
Seasonal variability in water levels	Spawning is known to occur in the shallows around Lake Alexandrina (Puckridge & Walker 1990) therefore recruitment events may indicate whether the littoral zone was inundated in late spring & summer when spawning (Puckridge & Walker 1990)	Population demographics – size & age structure	
Communities requiring varied hydrology supported	Requires access to permanently-inundated habitat	Abundance; distribution; Fisheries take – CPUE	Habitat use in Lakes
Communities requiring flooding supported	Not currently an indicator because not dependent on occasional flooding, however, the use of floodplain habitats by juveniles has been observed in the Cooper Creek (Geddes & Puckridge 1988)	NA	
Tidal signal apparent	Not an indicator because typically only in the Lakes. Found in estuary during & immediately following barrage discharge	NA	
Complex food webs present	Sp. eats mostly detritus, algae & microcrustaceans (Lintermans 2007, Sternberg *et al.* 2008). Potentially important food resource for Murray cod & golden perch (Ebner 2006, Baumgartner 2007) & McDowall (1996) suggests it is also important food for pelicans & cormorants	Food web structure – gut contents	
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator although sp. is affected by alien species (i.e. predation by redfin perch; Cadwallader & Backhouse 1983, Rowe *et al.* 2008)	NA	
Acid- & saline-tolerant & terrestrial species present	Highly salt tolerant for a freshwater fish (35 000 mg L^{-1} [~ 35 ppt]; Bice 2010a) therefore its relative proportions to other freshwater fish may indicate a shift towards more saline tolerant species. Tolerant of a wide range of pH (Allen *et al.* 2002)	Changes in ratio of two groups – abundance relative to salt-sensitive taxa; Distribution; Abundance; Fisheries take – CPUE	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Indicative of aquatic habit only	Distribution	

Indicator species: Bony herring, *Nematolosa erebi*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Exchange between aquatic & terrestrial systems	Not an indicator because consumes detritus & algae & is not dependent on aquatic-terrestrial connectivity	NA	
Regular oxidation of sulfidic material	Not an indicator because occurs independently of water level variation	NA	

8.4 Australian smelt – *Retropinna semoni*

Australian smelt (*Retropinna semoni*) is a small-bodied native freshwater fish species that is very widespread and common in the Lower River Murray and Lakes (Lintermans 2007). Smelt is a pelagic species that is usually found in large numbers in a variety of habitats, preferring slow-moving or still-water habitats such as the main River Murray channel, shallow ponds, weir pools, and wetlands (Wedderburn & Hammer 2003, Bice & Ye 2007, Lintermans 2007).

Once considered to be non-migratory, it has now been observed to be highly mobile (Baumgartner *et al.* 2008). Adults can live for up to two years or more although most only live for a year (Lintermans 2007) and spawn multiple times during spring and summer when water temperatures exceed 15 °C (Allen *et al.* 2002, Lintermans 2007) depositing eggs amongst aquatic vegetation (Allen *et al.* 2002).

Australian smelt is an opportunistic carnivore, feeding mostly on zooplankton as well as aquatic and terrestrial insects (Allen *et al.* 2002) and has a relatively high tolerance to elevated salinity, with juveniles tolerating 28 g L^{-1} (~28 ppt) (Bice 2010a) and adults withstanding 58.7 g L^{-1} (~59 ppt) LC50 direct transfer (Williams & Williams 1991). Australian smelt is moderately tolerant to low dissolved oxygen concentrations (<2 mg L^{-1}; Bice 2010a). Table 8.4 links Australian smelt to individual ecological outcomes.

Table 8.4: List of ecological outcomes that would be indicated by Australian smelt. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	**Australian smelt, *Retropinna semoni***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Recruitment depends on access to aquatic vegetation (Allen *et al.* 2002) as well as freshwater salinities in the lakes & zooplankton, as well as aquatic & terrestrial insects (Allen *et al.* 2002) being available	Abundance; Population demographics – size & age structure; Recruitment events – YoY	Level of migration between populations within & outside of site
Suitable habitat	Recruitment depends on access to aquatic vegetation (Allen *et al.* 2002)	Population demographics – size & age structure; Recruitment events – YoY	
Suitable food resources	Although an opportunistic feeder & therefore will feed on terrestrial substitutes (e.g. terrestrial insects), aquatic food resources (e.g. zooplankton) are still probably most important (Allen *et al.* 2002)	Food web structure – gut contents	Reliance on non-aquatic food sources
Suitable water quality	Sensitive to dissolved oxygen, pH & other water quality variables thus likely to indicate whether water quality is declining	Abundance; Population demographics – size & age structure; Disease – occurrence or decreased health; Fish kills	Impacts of multiple water quality stressors
Species connectivity	Not an indicator because completes life cycle at the site	NA	
Viable propagule bank	Not an indicator because the species does not have a resting phase, relies on availability of 'fresh' eggs for recruitment& has a very short lifespan 1-2 years (Lintermans 2007)	NA	

Indicator species: Australian smelt, *Retropinna semoni*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
No barriers to recruitment	Temporal connectivity is reliant on fecund adults being available at the right time & place	Abundance; Population demographics – size & age structure	
Lateral hydraulic connectivity	Not an indicator because able to complete life cycle independent of floodplain inundation provided that it has access to vegetated littoral zone, although also likely to use floodplain habitats if accessible	NA	
Water residence times finite	Are highly saline-tolerant (Williams & Williams 1991, Bice 2010a) & moderately tolerant of low dissolved oxygen (Bice 2010a)	Fish kills; Disease – occurrence or decreased health	
Regional hydraulically connected	Species is omnivorous & hence dietary analysis may indicate consumption of items from upstream or laterally- connected sites	Food web structure – gut contents	
Longitudinal biological connectivity	Indicator through lower order trophic ecology & availability of prey items from upstream of site	Food web structure – gut contents; Abundance; Population demographics – size & age structure	
No accumulation of pollutants	Relatively short-lived fish species but may be a good indicator because it completes its life cycle locally & is carnivorous, although migratory movements may limit utility	Tissue composition	Level of migration within & out of site
Lateral habitat diversity	Not an indicator due to generalist habitat preferences	NA	
Habitat variability	Not an indicator because pelagic & all life stages are found in a variety of habitats	NA	
Range of salinities with appropriate maxima	Not an indicator because highly salt-tolerant for a freshwater fish (juveniles tolerating 28 g L^{-1} [~28 ppt] [Bice 2010a] & adults withstanding 58.7 g L^{-1} [~59 ppt] LC50 direct transfer [Williams & Williams 1991]) therefore unlikely to indicate whether a range of salinities are present	NA	Sub-lethal effects of salinity on growth & reproduction
Temporal variability in salinity	Not an indicator	NA	Sub-lethal effects of salinity on growth & reproduction
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in flow	Not an indicator because life history strategy is not directly flow-related	NA	
Seasonal variability in flows	Not an indicator because life history strategy is not directly flow-related	NA	
Seasonal variability in water levels	Not an indicator because all life stages can use a variety of habitats & thus not restricted by water level variations	NA	
Communities	Requires access to permanently-inundated habitat	Abundance; Population	Habitat use in Lakes

Indicator species:	**Australian smelt, *Retropinna semoni***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
requiring varied hydrology supported		demographics – age structure	
Communities requiring flooding supported	Not an indicator because not dependent on flooding	NA	
Tidal signal apparent	Not an indicator because typically only in Lakes. Found in estuary during freshes but likely to be washed in rather than dependent on tidal signal	NA	
Complex food webs present	Opportunistic carnivore which would make it potentially a poor indicator of complex & diverse food webs, however, likely to be an important prey species for a range of piscivorous fish, birds & other fauna	Abundance; Population demographics – size & age structure	Local diet & diversity of prey items
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator but may be affected through predation by alien species (i.e. redfin perch)	NA	
Acid- & saline-tolerant & terrestrial species present	Highly salt tolerant for a freshwater fish (juveniles tolerating 28 g L^{-1} [~28 ppt] [Bice 2010a] & adults withstanding 58.7 g L^{-1} [~59 ppt] LC50 direct transfer [Williams & Williams 1991]) therefore its relative proportions to other small-bodied native fish may indicate a shift towards more saline tolerant species. Not known to be tolerant of low pH	Abundance; Population demographics – size & age structure; Changes in ratio of two groups – abundance relative to small bodied native fish	Acid tolerance
Wide riparian & littoral zones supported	Dependent on submerged vegetation for recruitment (Allen *et al.* 2002)	Population demographics – age structure	
Lateral connectivity of vegetation	Not an indicator because all life stages use a variety of habitats (Wedderburn & Hammer 2003, Bice & Ye 2007, Lintermans 2007)	NA	
Balance of aquatic & terrestrial species	Indicative of aquatic habit only	Distribution; Abundance	
Exchange between aquatic & terrestrial systems	Opportunistic carnivore that will consume terrestrial insects	Food web structure – gut contents	
Regular oxidation of sulfidic material	Not an indicator	NA	

8.5 Murray hardyhead – *Craterocephalus fluviatilis*

Murray hardyhead (*Craterocephalus fluviatilis*) is an omnivorous small-bodied native freshwater species that is believed to be have formerly been abundant but is now declining and considered critically-endangered nationally (under the EPBC Act) (Lintermans 2007). Its distribution throughout the Basin is patchy (Treadwell & Hardwick 2003). The species is considered to be broadly associated with off-channel habitats and submerged aquatic vegetation (Wedderburn *et al.* 2007). Prior to the sustained drawdown of water levels in Lakes Alexandrina and Albert that began in 2006 and ended recently, Murray hardyhead habitats included off-channel wetlands in Lower Murray (i.e. Rocky Gully, Riverglades); primary wetland and irrigation channel habitats of Hindmarsh Island and sheltered lake-edge habitats of Goolwa Channel, Clayton, Milang Bay and Lake Albert (Wedderburn & Hammer 2003).

Adults are considered highly salt tolerant (Wedderburn & Walker 2008) for a predominantly freshwater fish, and are often found in habitats with elevated salinity and have been observed in Murray-Darling Basin waters with greater than 85 000 mg L^{-1} [~85 ppt] salinity (Wedderburn *et al.* 2008). The species is considered to be predominantly annual, although some survive into their second year (Lintermans 2007) and the species spawns serially during spring and summer (Bice 2010a).

Murray hardyhead is omnivorous, primarily eating microcrustaceans (rotifers, copepods and cladocerans) but also some aquatic insects and algae (Ellis 2006, Wedderburn *et al.* 2010), while little is known of its movements (Lintermans 2007). Table 8.5 links Murray hardyhead to individual ecological outcomes.

Table 8.5: List of ecological outcomes that would be indicated by Murray hardyhead. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species:	**Murray hardyhead, *Craterocephalus fluviatilis***		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Once locally-abundant species that completes its life cycle at the site. Sp. is short-lived & likely reliant on annual recruitment. Recruitment is dependent on availability of submerged aquatic vegetation (Wedderburn *et al.* 2007) & microcrustaceans (rotifers, copepods & cladocerans) aquatic insects & algae (Ellis 2006, Wedderburn *et al.* 2010)	Abundance; Population demographics – size & age structure; Recruitment events – YoY	
Suitable habitat	Key habitats are fringing wetlands & channel habitats in the Lower Lakes, largely on & around Hindmarsh Island (usually permanent) (Wedderburn & Hammer 2003). Recruitment is dependent on availability of submerged aquatic vegetation (Wedderburn *et al.* 2007)	Abundance; Population demographics – size & age structure	
Suitable food resources	Although omnivorous & therefore able to replace particular foods if not available, primarily consumes microcrustaceans (rotifers, copepods & cladocerans) but also some aquatic insects & algae (Ellis 2006, Wedderburn *et al.* 2010)	Food web structure – gut contents	Local diet (currently being studied)
Suitable water quality	Sensitivity to dissolved oxygen, pH & other water quality variables unknown but	Abundance; Disease –	Impacts of multiple water

Indicator species: Murray hardyhead, *Craterocephalus fluviatilis*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
	likely to indicate whether water quality is declining to an unfavourable level for a range of other species as well. Highly salt tolerant (Wedderburn *et al.* 2008) therefore a poor indicator for rising salinity	occurrence or decreased health condition; Fish kills	quality stressors
Species connectivity	Not an indicator because completes life cycle at the site & interaction with populations upstream is unknown	NA	
Viable propagule bank	Not an indicator because the species does not have a resting phase, relies on availability of 'fresh' eggs for recruitment& has a very short lifespan 1-2 years (Lintermans 2007)	NA	
No barriers to recruitment	Temporal connectivity is reliant on fecund adults being available at the right time & place	Population demographics – size & age structure; Recruitment events – YoY	
Lateral hydraulic connectivity	Indicator through lower-order trophic ecology & availability of prey items from upstream of site	Food web structure – gut contents	
Water residence times finite	Not an indicator because species is not sensitive to high salinity (Wedderburn *et al.* 2008) that may come with infinite residence time	NA	
Regional hydraulically connected	Indicator through lower-order trophic ecology & availability of prey items from upstream of site	Food web structure – gut contents	
Longitudinal biological connectivity	Indicator through lower-order trophic ecology & availability of prey items from upstream of site	Food web structure – gut contents	
No accumulation of pollutants	Relatively short-lived fish species that may act as a good indicator of accumulation of toxins, given that it completes its life cycle at the site & is carnivorous	Tissue composition	
Lateral habitat diversity	Strongly associated with off-channel drains & wetlands & submerged vegetation (Wedderburn & Hammer 2003, Wedderburn *et al.* 2007).	Distribution	
Habitat variability	Strongly associated with off-channel drains & wetlands & submerged vegetation (Wedderburn & Hammer 2003, Wedderburn *et al.* 2007)	Distribution	
Range of salinities with appropriate maxima	Not an indicator because highly salt-tolerant for a freshwater fish (>85 000 mg L^{-1} [~85 ppt] (Wedderburn *et al.* 2008)	NA	
Temporal variability in salinity	Recent observations suggest that spawning can occur with temporary declines in salinity below tolerances (A. Hall pers. comm.)	Recruitment events	Specific temporal requirements for salinity to allow spawning
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in flow	Not currently an indicator because life history strategies are not directly flow-related, however a variable flow regime will result in temporal variation in	NA	Whether recruitment & abundance are linked to

Indicator species: Murray hardyhead, *Craterocephalus fluviatilis*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
	inundation & salinity which may benefit species		availability of inundated habitat
Seasonal variability in flows	Not an indicator because life history strategy is not directly flow-related	NA	
Seasonal variability in water levels	Not an indicator, however appears to be locally dependent upon access to fringing wetlands & off-channel habitats (Wedderburn & Hammer 2003, Wedderburn *et al.* 2007) & varying water levels could increase available habitat (via wider bands of submerged vegetation & inundation of emergent vegetation)	NA	
Communities requiring varied hydrology supported	Requires access to permanently-inundated habitat	Abundance; Population demographics – age structure; Recruitment events – YoY	
Communities requiring flooding supported	Not directly dependent upon flooding although occasional flooding is likely to result in greater habitat availability (i.e. vegetated off-channel habitats)	Abundance; Population demographics – size & age structure; Recruitment events – YoY	
Tidal signal apparent	Not an indicator because only found in freshwater habitats	NA	
Complex food webs present	Omnivorous (Lintermans 2007) which indicates it could substitute prey items. Likely to be an important prey species for piscivorous fish, birds & other fauna	Food web structure – gut contents	Diet of species
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator although may be affected by invasive species (e.g. via predation by redfin or vegetation destruction by carp)	NA	
Acid- & saline-tolerant & terrestrial species present	Highly salt tolerant for a freshwater fish (>85 000 mg L^{-1} [~85 ppt]; Wedderburn *et al.* 2008) therefore its relative proportion to other small-bodied native fish may indicate a shift towards more saline tolerant species. Not known to be tolerant of low pH	Abundance; Population demographics – size & age structure; Changes in ratio of two groups – abundance relative to other small-bodied native fish; Recruitment events – YoY	Acid tolerance
Wide riparian & littoral zones supported	Locally sp. is dependent on off-channel & sheltered habitats with submerged vegetation for recruitment & growth (Wedderburn & Hammer 2003, Wedderburn *et al.* 2007)	Abundance; Population demographics – size & age structure; Recruitment events – YoY	
Lateral connectivity of	Locally sp. is associated with complex habitats (Wedderburn & Hammer 2003,	Abundance; Population	

Indicator species: Murray hardyhead, *Craterocephalus fluviatilis*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
vegetation	Wedderburn *et al.* 2007) , thus diverse fringing vegetation is likely to be important for this species	demographics – size & age structure; Recruitment events – YoY	
Balance of aquatic & terrestrial species	Indicative of aquatic habit only	Distribution; Abundance	
Exchange between aquatic & terrestrial systems	Consumes aquatic prey species, some of which are derived from inundation of floodplain habitats (i.e. zooplankton)	Food web structure – gut contents	
Regular oxidation of sulfidic material	Not an indicator	NA	

8.6 Yarra pygmy perch – *Nannoperca obscura*

Yarra pygmy perch (*Nannoperca obscura*)is a small-bodied native freshwater fish restricted in distribution to parts of Lake Alexandrina, specifically to key habitats such as wetlands and irrigation channels on Hindmarsh Island, the lower Finniss River and the edge of Goolwa Channel (Higham *et al.* 2005a, Bice & Ye 2007, Hammer 2007). This species is strongly associated with submerged and other in-stream aquatic vegetation (Allen *et al.* 2002, Woodward & Malone 2002, Wedderburn & Hammer 2003) and is potentially dependent upon aquatic vegetation for recruitment. *Nannoperca obscura* is a relatively poor disperser with no apparent gene flow between most populations (Hammer *et al.* 2009). Key habitats in the Lower Lakes were largely desiccated and disconnected from the open water during the recent drought and thus this species may now be locally extinct, not having been collected from Lower Lakes since 2007 to our knowledge (Hammer unpub. data). Some fish were removed from the Lakes once rapid declines were evident and were being bred in captivity for re-introduction when conditions improved.

Yarra pygmy perch breeds in spring when water temperatures are between 16 and 24 °C (Lintermans 2007). Salinity tolerance is relatively modest with larvae able to withstand 6300 mg L^{-1}[~6 ppt] LC50 direct transfer) and adults being observed in the field at lower salinities (3010 mg L^{-1}[~3 ppt]; McNeil & Hammer 2007). Diet includes microcrustaceans, molluscs and aquatic insects such as mosquito larvae (Allen *et al.* 2002, Hammer 2004, Lintermans 2007) and the species is relatively short-lived (*c.* 4-5 years; Hammer 2004). Table 8.6 links Yarra pygmy perch to individual ecological outcomes.

Table 8.6: List of ecological outcomes that would be indicated by Yarra pygmy perch. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Yarra pygmy perch, *Nannoperca obscura*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Species completes its life cycle wholly within the site in freshwater habitats in populations isolated from EMLR based on genetic studies (Hammer *et al.* 2009. Recruitment is dependent on submerged & other aquatic vegetation (Woodward & Malone 2002, Wedderburn & Hammer 2003) & availability of microcrustaceans, molluscs & aquatic insects (Hammer 2004)	Abundance; Population demographics – size & age structure; Recruitment events – YoY	
Suitable habitat	Key habitats are fringing wetlands & channel habitats, primarily within channels with extensive submerged aquatic vegetation (Wedderburn & Hammer 2003)	Abundance; Population demographics – size & age structure; Recruitment events – YoY	
Suitable food resources	Consumes microcrustaceans, rotifers & aquatic insects (Hammer 2004) so indicative of whether these resources are available for other species	Food web structure – gut contents	Local diet
Suitable water quality	Sensitive to increased salinity (McNeil & Hammer 2007). Based on southern pygmy perch tolerances (McNeil 2004) the species is probably not sensitive to very low dissolved oxygen concentrations	Abundance; Population demographics – size & age structure; Disease – occurrence or decreased health condition;	Impacts of multiple water quality stressors

Indicator species: Yarra pygmy perch, *Nannoperca obscura*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
		Fish kills	
Species connectivity	Not an indicator because completes life cycle wholly within the site in freshwater habitats (Hammer *et al.* 2009)	NA	
Viable propagule bank	Not an indicator because it does not have a resting stage, relies on availability of 'fresh' eggs & has a short lifespan (<5 years; Hammer 2004)	NA	
No barriers to recruitment	Fecund adults rely on access to submerged vegetation in littoral habitats (Woodward & Malone 2002, Wedderburn & Hammer 2003)	Distribution; Population demographics – size & age structure; Recruitment events – YoY	
Lateral hydraulic connectivity	Inundation of littoral vegetation & ephemeral wetlands providing more habitat & potentially greater extent of submerged vegetation, upon which the sp. relies (Woodward & Malone 2002, Wedderburn & Hammer 2003)	Abundance; Population demographics – size & age structure; Recruitment events – YoY	Whether species utilises floodplain habitat around Lakes
Water residence times finite	Relatively sensitive to poor water quality in freshwater elements (e.g. high salinity). Mortality already occurring at salinity >6.3 g L^{-1}[~6 ppt] (McNeil & Hammer 2007)	Disease – occurrence or decreased health condition; Fish kills	Salinity preferences for optimal health; tolerance for eggs; sub-lethal effects on growth & reproduction
Regional hydraulically connected	Not an indicator except perhaps of connectivity between Eastern Mount Lofty Ranges tributaries & Lakes	NA	Linkages between tributaries & Lakes populations
Longitudinal biological connectivity	Indicator through lower-order trophic ecology & availability of prey items from upstream of site	Food web structure – gut contents	Prey species & linkages to productivity upstream & longitudinal exchange
No accumulation of pollutants	Short-lived fish species that may be a good indicator given that it completes its life cycle at the site & is carnivorous	Tissue composition	Diet in local environment & susceptibility to toxins
Lateral habitat diversity	Strongly associated with submerged vegetation, wetland & channel habitats (Woodward & Malone 2002, Wedderburn & Hammer 2003)	Abundance; Distribution	
Habitat variability	Requires access to submerged & other in-stream aquatic vegetation (Woodward & Malone 2002)	Distribution	
Range of salinities with appropriate maxima	Relatively sensitive to increased salinity (>6.3 g L^{-1}[~ 6 ppt]; McNeil & Hammer 2007) therefore indicative of fresh waters only	Disease – occurrence or decreased health condition; Fish kills; Distribution	Salinity preferences for optimal health; tolerance for eggs; sub-lethal effects on growth & reproduction
Temporal variability in salinity	Sensitive to increasing salinity (>6.3 g L^{-1}[~ 6 ppt]; McNeil & Hammer 2007)	Disease – occurrence or decreased health condition; Fish kills; Distribution	Salinity preferences for optimal health; tolerance for eggs; sub-lethal effects

Indicator species: Yarra pygmy perch, *Nannoperca obscura*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
			on growth & reproduction
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in flow	Not an indicator although it may be dependent on variable flows as it is dependent on the associated vegetated habitats	NA	
Seasonal variability in flows	Not currently an indicator although it may be dependent on variable flows as it is dependent on the associated vegetated habitats	NA	Relationship with seasonality of flows
Seasonal variability in water levels	Tends to associate strongly with vegetation assemblages that require permanent inundation but may benefit from variable water levels & inundation of riparian vegetation & floodplains	Abundance; Population demographics – size & age structure; Recruitment events – YoY	Requirement for elevated & stable lake levels during spawning & recruitment
Communities requiring varied hydrology supported	Requires access to permanently-inundated flowing habitats that contain submerged vegetation (Woodward & Malone 2002, Wedderburn & Hammer 2003) but may benefit from variable water levels & inundation of riparian vegetation & floodplains	Abundance; Population demographics – size & age structure; Recruitment events – YoY	Requirement for elevated & stable lake levels during spawning & recruitment
Communities requiring flooding supported	Extent of available habitat may be greater if occasional flooding occurs	Distribution	Requirement for elevated &stable lake levels during spawning & recruitment
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Carnivorous small-bodied fish therefore indicative of whether food resources such as microcrustaceans, rotifers & aquatic insects are available (Hammer 2004)	Food web structure – gut contents	
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator although is affected by invasive species (predation by redfin; Cadwallader & Backhouse 1983, Wager & Jackson 1993, Rowe *et al*. 2008)	NA	
Acid- & saline-tolerant & terrestrial species present	Sensitive to salinity (>6.3 g L^{-1}[~ 6 ppt]; McNeil & Hammer 2007) although tolerance to acidity is unknown	Disease – occurrence or decreased health condition; Fish kills; Distribution	Acidity tolerance
Wide riparian & littoral zones supported	Yarra pygmy perch is dependent on submerged vegetation as a habitat (Woodward & Malone 2002, Wedderburn & Hammer 2003)	Abundance; Population demographics – size & age structure; Recruitment events – YoY	
Lateral connectivity of	Although sp. depend on submerged aquatic vegetation being permanently	Abundance; Population	Value of diverse

Indicator species: Yarra pygmy perch, *Nannoperca obscura*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
vegetation	available, diversity of plant community & continuity along the elevation gradient is likely to be important	demographics – size & age structure; Recruitment events – YoY	submerged aquatic vegetation species as opposed to a monoculture
Balance of aquatic & terrestrial species	Indicative of aquatic habit only	Distribution; Abundance	
Exchange between aquatic & terrestrial systems	Consumes aquatic prey species, some of which are derived from inundation of floodplain habitats (i.e. zooplankton)	Food web structure – gut contents	
Regular oxidation of sulfidic material	Not an indicator	NA	

8.7 Common carp – *Cyprinus carpio*

Common carp (*Cyprinus carpio*) is an introduced omnivorous large-bodied freshwater species, native to central Asia that has rapidly colonised watercourses throughout Australia since the 1960s when it is thought to have escaped from a fish farm near Mildura in Victoria (Koehn *et al.* 2000). Large floods in 1974 and 1975 facilitated its rapid expansion throughout the Murray-Darling Basin such that it was recorded in the Lower Lakes in 1976-77 (Koehn *et al.* 2000). It is now a very common and widespread pest species in the Murray-Darling Basin (Lintermans 2007), including the Lower Murray and Lakes where it forms a large proportion of the biomass (Bice 2010a,b).

Adult carp can live for more than 15-17 years (Sarig 1966) with the oldest carp aged at 32 years (Brown *et al.* 2003). Carp spawning may occur whenever mean water temperature and photoperiod exceed 15-16 °C and 10 h light, respectively, and where there is access to submerged vegetation in shallow, lentic (i.e. slow or no movement of water) habitat (Smith 2005). Larvae and juvenile carp prefer habitats with submerged vegetation (Smith 2005) whilst adults use various habitats, including open water and vegetated areas in the Lakes and fringing wetlands (SARDI unpub. data, cited in Bice 2010a). Carp are known to spawn and use floodplains following inundation (King *et al.* 2002), and while they will also spawn and recruit within-channel (Humphries *et al.* 2002), this appears to be less favourable to substantive recruitment. Carp have been found to aggregate around key access points to off-channel spawning habitat elsewhere (Stuart & Jones 2002) and in the Lower Murray (B. Smith pers. comm.).

Carp feed mostly by filtering small food particles from the water or substratum and using a pharyngeal sieve formed by the gill rakers with small sediment and particles being expelled through the operculum (Koehn *et al.* 2000). Carp diet varies between locations and seasons depending on food availability (Koehn *et al.* 2004). In Lake Alexandrina, Hall (1981) found zooplankton formed a large proportion of the diet of small carp while cladocerans and detritus were common food items for most size classes. Adults are omnivores and their diet includes molluscs, cladocerans, copepods, amphipods, chironomids, aquatic and terrestrial insects, detritus, seeds, fragments of dead aquatic plants and filamentous algae (Hall 1981). Carp have been documented to be prey for mulloway (Marais 1984), golden perch, Murray cod and seabirds (Kailola *et al.* 1993) as well as pelicans, pied cormorants and darters (Smith 2005).

Carp is highly tolerant of low dissolved oxygen levels, tolerating concentrations of <1 mg L^{-1} for short periods, by employing air-surface respiration to survive hypoxic and anoxic conditions (McNeil 2004). Mature fish from Lakes Alexandrina and Albert survived direct transfer to salinities of 12.5 g L-1 [~13 ppt] at 16-21 °C, while LC50 was 15 g L^{-1} [~15 ppt] with acclimation (Geddes 1979). Juvenile carp exhibited similar tolerance (11.7 g L^{-1}[~12 ppt] LC50 direct transfer and 13.1 g L^{-1}[~13 ppt] LC50 slow acclimation; Whiterod 2001). Carp are considered an indicator of poor wetland health due to their wide physicochemical tolerances and often high abundance in degraded habitats (Koehn 2004). Koehn *et al.* (2000) indicated that pH tolerance range for this species is from below 5.0 up to above 10.5.

Carp is capable of moving large distances at any time during its life-history, with larvae drifting downstream and young-of-year, juveniles and adults migrating either up- or downstream (I. Stuart pers. comm.). Adult carp can move hundreds of kilometres along the Murray and use fishways or boat locks to pass weirs (Stuart & Jones 2006). Carp has a strong urge to migrate laterally to floodplains through connecting channels and creeks as the floodplains start to fill (Jones & Stuart 2008). In winter, carp form schools, usually in deeper areas of permanent or temporary water and often among cover, with fish appearing almost dormant (Cadwallader & Backhouse 1983, Jones & Stuart 2008).

Carp is considered an ecologically-destructive species given its potential to disturb and re-suspend benthos through feeding, ability to compete with native species for food and habitat as well as potentially alter foodwebs (Gehrke & Harris 1994, Koehn *et al.* 2000, Smith 2005). It can also carry the parasitic copepod anchorworm (*Lernaea* sp.), which infests a range of native and alien fish species (MDBC 2008). Table 8.7 links carp to individual ecological outcomes.

Table 8.7: List of ecological outcomes that would be indicated by common carp. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Common carp, *Cyprinus carpio*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Species is believed to breed locally in Lakes (SARDI unpub. data). Requires submerged vegetation in shallow, lentic habitat (Smith 2005) being present, as well as small crustaceans, aquatic insect larvae, seeds, zooplankton & detritus (Hall 1981)	Abundance; Fisheries take – CPUE; Population demographics – size & age structure; Recruitment events – YoY	
Suitable habitat	Will breed in wetlands & fringing vegetation using submerged & emergent aquatic vegetation (Smith 2005)	Abundance; Fisheries take – CPUE; Population demographics – size & age structure; Recruitment events – YoY	
Suitable food resources	Carp is omnivorous & diet varies between locations & from season depending on food availability (Koehn *et al.* 2004)	Food web structure – gut contents	Recent information on local diet
Suitable water quality	Not an indicator because highly tolerant of poor water quality (i.e. low dissolved oxygen & elevated salinity) in freshwater habitats (McNeil 2004, Geddes 1979, Whiterod 2001)	NA	
Species connectivity	Not currently an indicator because prevalent throughout the MDB, but local movement patterns currently unknown although likely that species migrates between the Lower Lakes (LL) & Lower River Murray (RM) based on observations elsewhere (e.g. Stuart & Jones 2006)	NA	Movement of common carp between Lakes Alexandrina (Lx)& Albert (Lb)& between LL)& RM
Viable propagule bank	Not an indicator because it does not have a resting stage & relies on availability of 'fresh' eggs but has a lifespan of up to 32 years (Brown *et al.* 2003)	NA	
No barriers to recruitment	Recruitment linked to access to floodplain habitats or emergent & submerged vegetation (Smith 2005). Older adults are able to breed & enable temporal connectivity as larger fish produce disproportionately large numbers of eggs compared to smaller fish (Beamish *et al.* 2006)	Population demographics – size & age structure; Recruitment events – YoY	
Lateral hydraulic	Known to spawn & use floodplain following inundation (King *et al.* 2002). Carp	Abundance – presence of	

Indicator species: Common carp, *Cyprinus carpio*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
connectivity	aggregates at key access points to off-channel spawning habitat (Stuart & Jones 2002, Jones & Stuart 2008)	aggregations; Fisheries take – CPUE; Population demographics – size & age structure; Recruitment events – YoY	
Water residence times finite	Not an indicator since tolerant of a wide-range of physicochemical conditions including toxicants (Koehn *et al.* 2000)	NA	
Regional hydraulically connected	Not currently an indicator because local movement patterns unknown although migration between LL & upstream habitats likely based on observations elsewhere (e.g. Stuart & Jones 2006)	NA	Movement between Lx & Lb & between LL & RM
Longitudinal biological connectivity	Indicator through lower-order trophic ecology & availability of prey items from upstream of site	Food web structure – gut contents	Recent information on local diet & source of insects & other prey items
No accumulation of pollutants	Species may be a good indicator given feeding habit (Smith 2005) & ability to persist in degraded environments(Geddes 1979, Whiterod 2001, McNeil 2004)	Tissue composition	
Lateral habitat diversity	The provision of floodplain habitats or emergent & submerged vegetation is likely to facilitate spawning & recruitment in this species	Population demographics – size & age structure; Recruitment events – YoY	
Habitat variability	Requires access to a range of habitats over life-history (Smith 2005, Koehn *et al.* 2000)	Distribution	Local inter- & intra-annual habitat use
Range of salinities with appropriate maxima	Not an indicator for LL given relatively tolerant of moderate salinity for a freshwater species (12-15 ppt; Geddes 1979, Whiterod 2001)	NA	Salinity preferences for optimal health; tolerance for eggs; sub-lethal effects on growth & reproduction
Temporal variability in salinity	Not an indicator because relatively tolerant of moderate salinity for a freshwater species (12-15 ppt; Geddes 1979, Whiterod 2001)	NA	Salinity preferences for optimal health; tolerance for eggs; sub-lethal effects on growth & reproduction
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in flow	Not an indicator because it tolerates a wide range of flow conditions, spawning is not linked to flow cues & is likely to only be indirectly affected through water quality & habitat access	NA	
Seasonal variability in flows	Not an indicator because indirectly affected by seasonality of flows	NA	
Seasonal variability in	Seasonality of water levels & inundation of vegetation linked to recruitment	Population demographics –	Habitat use in LL

Indicator species: Common carp, *Cyprinus carpio*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
water levels	(Smith 2005)	age structure; Recruitment events – YoY	
Communities requiring varied hydrology supported	Requires access to permanently-inundated & ephemeral vegetated habitats to complete lifecycle (Smith 2005)	Population demographics – size & age structure; Recruitment events – YoY	Habitat use in LL
Communities requiring flooding supported	Inundation of floodplain & vegetation increases habitat availability & conditions favourable to spawning & recruitment	Distribution; Population demographics – size &age structure; Recruitment events – YoY	Habitat use in LL
Tidal signal apparent	Not an indicator because only occurs in freshwater habitats	NA	
Complex food webs present	Not an indicator because omnivorous & able to thrive without complex, diverse food webs. Juveniles likely to be important prey for a range of piscivorous fish, birds & other fauna (Marais 1984, Kailola *et al.* 1993)	NA	
Functions performed by multiple species	Species is omnivorous, being a detritivore as well as feeding on insects & it may provide redundancy of function for native fish species less tolerant of degraded water quality	Abundance; Changes in ratio of two groups – carp to native species abundance; Fisheries take – CPUE; Distribution	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Invasive species that is already present	Abundance; Fisheries take – CPUE; Population demographics – size &age structure; Recruitment events – YoY; Changes in ratio of two groups – carp to native species abundance	
Acid & saline-tolerant & terrestrial species present	Highly tolerant of a range of pH & other typically-adverse environmental conditions (Koehn *et al.* 2000) hence increasing abundance may indicate a shift towards tolerant species	Abundance; Fisheries take – CPUE	Acid tolerance
Wide riparian & littoral zones supported	Carp is dependent on submerged vegetation for recruitment & growth (Smith 2005)	Population demographics – size &age structure; Recruitment events – YoY	Recruitment in region linked to width of riparian zone
Lateral connectivity of vegetation	Not currently an indicator because level of historical recruitment unknown & changes may not be as a result of wider riparian zones but due to improved access to submerged habitat instead	NA	Historical recruitment in region
Balance of aquatic & terrestrial species	Indicative of aquatic habit only	Abundance; Fisheries take – CPUE; Distribution	

Indicator species: Common carp, *Cyprinus carpio*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Exchange between aquatic & terrestrial systems	Consumes aquatic prey species, some of which are derived from inundation of floodplain habitats (i.e. zooplankton)	Food web structure – gut contents	Recent information on local diet; source of insect prey
Regular oxidation of sulfidic material	Not an indicator	NA	

8.8 Congolli – *Pseudaphritis urvillii*

Congolli (*Pseudaphritis urvillii*) is a small- to medium-sized diadromous native fish species that inhabits the coastal catchments of south-eastern Australia. (Lintermans 2007). Until recently, little was known of its biology in the region but it was formerly very common in the Coorong and Lower Lakes (Lintermans 2007). Being a diadromous (catadromous) species, it is an ideal indicator of the maintenance of effective hydraulic connection between the Lakes and Coorong because it requires access to freshwater and estuarine/marine habitats to complete its life cycle. Adults primarily inhabit freshwater including wetlands, streams, off-channel and main channel habitats but spawn in the estuary/marine environment (Jennings *et al.* 2008a) and thus require free movement between fresh and estuarine habitats. According to Jennings *et al.* (2008b) and Zampatti *et al.* (2010b), movement between these different environments occurs at different times of year for different ecological functions, specifically:

- downstream adult migration in winter;
- estuarine/marine spawning and larval development in winter/spring (eggs likely to be pelagic); and
- corresponding upstream juvenile migrations in spring/summer.

Interstate studies have shown spawning migrations out of estuaries & into the sea (Crook *et al.* 2008) while recent studies indicated that a proportion of breeding congolli exit the Murray mouth (SARDI unpub. data). Congolli is predominantly an opportunistic benthic carnivore (Lintermans 2007). Research in Tasmanian streams indicated that its diet mostly composed small prey items such as aquatic insect larvae (chironomids, caddisflies, mayflies), small crustaceans (shrimp and amphipods), snails and worms with some plant material also consumed (Hortle and White 1980) as well as consuming live fish in aquaria (J. Higham pers. obs.). Congolli tends to inhabit benthic areas of slow-flowing, littoral habitats that have some cover such as clumps of *Typha* spp., beds of *Myriophyllum* spp., fallen wood and undercut banks (Hortle 1979, Lloyd 1987). Congolli has been noted to use floodplain habitats (Sim *et al.* 2000) and narrow channels in the region (Higham *et al.* 2005a). Congolli has a wide salinity tolerance range being able to move freely between freshwater and saltwater environments (Hortle 1979)

Congolli is believed to have declined considerably since the construction of the barrages due to reduced connectivity between freshwater and estuarine/marine habitats. In 2006/07, thousands of juveniles migrated into the Lakes when the barrages were open and freshwater was being discharged to the Coorong. The loss of connectivity in recent years from lack of barrage releases has been accompanied by major reductions in the numbers of juvenile upstream migrants in 2007/08 and 2008/09 (Jennings *et al.* 2008b, Zampatti 2010a).

Preliminary data suggested that this species may also exhibit spatial sexual segregation with adult females residing further upstream in freshwater habitats (Jennings *et al.* 2008b). A recent movement study (using acoustic tracking) demonstrated that adult female congolli were congregating at the barrages during winter/autumn in an attempt to access the estuary and the sea (Zampatti *et al.* 2010b). Previous research in the region and interstate indicated their maximum age was about five years (Zampatti *et al*. 2010b).

Congolli is not presently listed as an endangered species under any legislation. Table 8.8 links congolli to individual ecological outcomes.

Table 8.8: List of ecological outcomes that would be indicated by congolli. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Congolli, *Pseudaphritis urvillii*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Requires free movement between fresh, estuarine & marine water to complete its life cycle (Higham *et al.* 2002, Lintermans 2007, Jennings *et al.* 2008a, Zampatti *et al.* 2010b). Requires aquatic insects larvae, small crustaceans, snails & worms (Hortle & White 1980) to be available	Abundance – general & of upstream migrants; Population demographics – size & age structure; Recruitment events – YoY	Capacity for migration & recolonisation from nearby estuaries
Suitable habitat	Dependent on fresh, estuarine & marine habitats for different life-history stages (Higham *et al.* 2002, Lintermans 2007, Jennings *et al.* 2008a, Zampatti *et al.* 2010b)	Abundance – general & of upstream migrants; Population demographics – size & age structure; Recruitment events – YoY; Distribution – general & within different habitats	Microhabitat requirements & use in the Lower Lakes (LL) & Coorong
Suitable food resources	Benthic carnivore that feeds on fish, crustaceans & aquatic insects (Hortle & White 1980). Zooplankton are important prey for larvae & juveniles (Bremigan & Stein 1997, Miller *et al.* 1990)	Food web structure – gut contents; Abundance – general & of upstream migrants; Recruitment events – YoY	Local dietary information(i.e. whether diet naturally includes fish)
Suitable water quality	Obligate aquatic species therefore sensitive to degradation in water quality conditions (e.g. pH, dissolved oxygen). Broad range of tolerance to changes in salinity mean sp. is not able to indicate if salinity in freshwater habitats is suitable	Abundance; Population demographics – size & age structure; Recruitment events – YoY; Distribution; Disease – occurrence or decreased health condition	Impacts of multiple water quality stressors
Species connectivity	Not an indicator because the LL & Coorong is the primary region within the MDB that congolli occur (Lintermans 2007) & there is no known relationship with populations in nearby estuaries	NA	Relationship with & capacity for migration/recolonisation from nearby estuaries
Viable propagule bank	Not an indicator because it does not have a resting stage, but relies on availability of 'fresh' eggs & has a short lifespan (maximum age is 5 years)	NA	
No barriers to recruitment	Diadromous sp. that has a lifespan of 4-5 years (Zampatti *et al*. 2010b). Requires free access to fresh, estuarine & marine habitats to complete its life cycle (Higham *et al.* 2002, Lintermans 2007, Jennings *et al.* 2008a, Zampatti *et al.* 2010b)	Abundance – general & of upstream migrants (moving through fishways); Population demographics – size & age structure; Recruitment events – YoY; Distribution	Capacity for migration of new populations from nearby estuaries

Indicator species: Congolli, *Pseudaphritis urvillii*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Lateral hydraulic connectivity	Indicator through lower-order trophic ecology & availability of prey items from lateral inundation. Zooplankton are important prey for larvae & juveniles (Miller *et al.* 1990, Bremigan & Stein 1997).	Food web structure – gut contents; Abundance Population demographics – size & age structure; Recruitment events – YoY	
Water residence times finite	Congolli is not an indicator as it is highly tolerant of salinity (Hortle 1979) & tolerance to dissolved oxygen is unknown (Bice 2010a)	NA	Tolerance for DO
Regional hydraulically connected	Diadromous sp. needing free access to fresh, estuarine & marine habitats to complete its life cycle (Higham *et al.* 2002, Lintermans 2007, Jennings *et al.* 2008a, Zampatti *et al.* 2010b).	Abundance – within different habitats & of upstream migrants (moving through fishways); Population demographics – size & age structure & sex ratios above and below barrages; Recruitment events – YoY; Distribution – within different habitats	Migration from nearby estuaries(i.e. adults) Whether there is an influx of larvae/juveniles from sea & whether larvae are retained in the Coorong or develop in ocean & then migrate
Longitudinal biological connectivity	Indicator through lower-order trophic ecology & availability of prey items from upstream of site. Zooplankton are important prey for larvae & juveniles (Bremigan & Stein 1997, Miller *et al.* 1990)	Food web structure – gut contents; Population demographics – size & age structure; Recruitment events – YoY	
No accumulation of pollutants	Being a resident, omnivorous species, congolli could be an indicator for bioaccumulation	Tissue composition	
Lateral habitat diversity	Range of habitats in LL (e.g. slow-flowing, littoral habitats; Lloyd 1987) including floodplain habitats (Sim *et al.* 2000). Required habitats in estuarine & marine areas not documented so currently only an indicator in LL	Abundance – within different habitats	Habitats requirements in estuarine & marine areas
Habitat variability	Requires free access to fresh, estuarine & marine habitats to complete its life cycles & uses different habitats within the LL (SARDI unpub. data). Abundance & sex ratios of adults in LL and estuary will change seasonally due to downstream migration for spawning	Abundance – within different habitats & of upstream migrants (moving through fishways); Population demographics – size & age structure & sex ratios above and below barrages; Recruitment events – YoY	
Range of salinities with appropriate maxima	Requires free access to fresh, estuarine & marine habitats to complete its life cycles	Population demographics – size & age structure;	

Indicator species: Congolli, *Pseudaphritis urvillii*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Temporal variability in salinity	Sp. requires access to a range of salinities within its lifetime	Recruitment events – YoY; Distribution Abundance; Population demographics – sex ratios above & below barrages; Distribution	
Communities requiring varied salinities supported	Reliant on access to fresh, estuarine & marine habitats	Abundance; general & of upstream migrants; Population demographics – size & age structure; Recruitment events – YoY; Distribution	
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Seasonal barrage flows provide hydrological connectivity between the LL & the Coorong. Flows from the Eastern Mount Lofty Ranges may be a cue for downstream movement (C. Bice pers. comm.)	Population Demographics – size & age structure; Recruitment events – YoY; Distribution	Role of flow in stimulating migratory behaviour
Seasonal variability in water levels	Not an indicator provided that water-level variation does not prevent functional connectivity	NA	
Communities requiring varied hydrology supported	Requires access to permanently-inundated habitat	Abundance; Population demographics – size & age structure; Recruitment events – YoY	
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Interstate studies show spawning migrations out of estuaries and into the sea (Crook *et al.* 2008) recent studies indicate a proportion of breeding congolli exit the Murray Mouth (SARDI unpub. data), thus may be reliant on a tidal signal	Movement	Whether larvae are retained in the Coorong or develop in ocean and then migrate into Coorong
Complex food webs present	Sp. requires a changing diet through its life-history (Hortle & White 1980) so requires a complex food web as it completes its life cycle within the site. Sp. is likely to be eaten by larger fish (e.g. mulloway; Evans 1991) & possibly piscivorous birds although this has not been demonstrated	Abundance; Population demographics – size & age structure & sex ratios above & below barrages; Recruitment events – YoY; Food web structure – gut contents; Distribution	Whether species is consumed by piscivorous birds
Functions performed	Not an indicator	NA	

Indicator species: Congolli, *Pseudaphritis urvillii*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
by multiple species			
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Not an indicator	NA	Acid tolerance
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Indicative of aquatic habit only	Distribution	
Exchange between aquatic & terrestrial systems	Consumes aquatic prey species, some of which are derived from inundation of floodplain habitats (i.e. zooplankton)	Food web structure – gut contents	
Regular oxidation of sulfidic material	Not an indicator	NA	

8.9 Common galaxias – *Galaxias maculatus*

Common galaxias (*Galaxias maculatus*) is a small-bodied diadromous (i.e. catadromous) native species that is common in the Lower Lakes (Higham *et al.* 2002, Wedderburn & Hammer 2003, Bice & Ye 2007). Common galaxias is found at low elevations in rivers, streams and estuaries from Queensland to South Australia, Tasmania and in south-eastern Western Australia. It is also found in the lower reaches of the River Murray in South Australia (McDowall & Fulton 1996, Treadwell & Hardwick 2003, Lintermans 2007). Common galaxias is an opportunistic carnivore, consuming aquatic and terrestrial insects, microcrustaceans and amphipods (Pollard 1973). In the region, adult fish typically reside in a variety of freshwater habitats including slow-flowing or still waters, streams, irrigation drains and lake margins (Wedderburn & Hammer 2003, Higham *et al.* 2005a, Bice & Ye 2007) before migrating into estuaries to spawn (Koehn & O'Connor 1990, Ye *et al.* 2002) although it can also complete its life cycle in landlocked lakes (McDowall 1996). Eggs are deposited on riparian vegetation and develop out of the water (Allen *et al.* 2002, Bice 2010a). Larvae develop in the estuary or marine environment before migrating up into freshwater in what is known as a 'whitebait' phase (McDowall 1996). Downstream migrations typically occur in winter with subsequent juvenile upstream migration in spring and summer (Jennings *et al.* 2008a). Many adults perish after spawning although some survive another year (Allen *et al.* 2002).

Common galaxias is a powerful osmoregulator (Chessman & Williams 1975) and larvae have a salinity tolerance (LC50)of 6000 mg L^{-1}(~6 ppt) (Bacher & Garnham 1992 cited in Treadwell & Hardwick 2003). In laboratory studies, fish had mortality between 27 and 80% at dissolved oxygen concentrations of 1 mg L^{-1} (Dean & Richardson 1999). Salinity tolerance for adults ranged from less than 1 to 30 ppt (Chessman & Williams 1974). LD50 values of 62 ppt after gradual acclimatisation and 45 ppt after direct transference have been recorded (Chessman & Williams 1975), but *Galaxias maculatus* has also been observed in the Coorong at salinities greater than 25 000 mg L^{-1} (~25 ppt) (Bice 2010a) while Chessman & Williams (1975) observed the species in the field at salinities less than 10 ppt and as high as 49 ppt. Table 8.9 links common galaxias to individual ecological outcomes.

Table 8.9: List of ecological outcomes that would be indicated by common galaxias. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes. LL = Lower Lakes, C = Coorong.

Indicator species: Common galaxias, *Galaxias maculatus*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Usually requires free movement between freshwater, estuarine & marine habitats to complete its life cycle but can also exist as an isolated population (McDowall 1996). Recruitment is dependent upon access to riparian vegetation (Bice 2010a), the presence of aquatic & terrestrial insects, microcrustaceans & amphipods (Pollard 1973)	Abundance – in general & of upstream migrants; Population demographics – size & age structure; Recruitment events – YoY; Distribution	Capacity for migration of juveniles from nearby estuaries or to recruit within the LL without migration
Suitable habitat	Primarily dependent on access to freshwater, estuarine & marine habitats for different life history stages (McDowall 1996). Typically resides in a variety of freshwater habitats (Wedderburn & Hammer 2003, Higham *et al.* 2005a, Bice & Ye 2007) before migrating into estuaries to spawn (Koehn & O'Connor 1990, Ye *et al.* 2002)	Abundance – in general & of upstream migrants; Population demographics – size & age structure; Recruitment events – YoY; Distribution	
Suitable food resources	Pelagic & mid-water carnivore that feeds on amphipods, chironomids &	Abundance; Food web	

Indicator species: Common galaxias, *Galaxias maculatus*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
	microcrustaceans (Pollard 1973). Also is prey for larger fish (e.g. mulloway; Evans 1991) & probably piscivorous birds	structure – gut contents	
Suitable water quality	Not currently an indicator. Sp. appears to be highly tolerant to salinity (Chessman & Williams 1975) & dissolved oxygen (Dean & Richardson 1999) & other tolerances are unknown	NA	Impacts of multiple water quality stressors; response to pH & other water quality variables
Species connectivity	Not an indicator because believed to be a single population & the LL & C is the main location for the sp. within the MDB. Sp. has been recorded in the Lower Murray River (Lintermans 2007) & relationship to the main MDB population is currently unknown	NA	Presence in & capacity for migration of from nearby estuaries; relationship to populations in lower RM
Viable propagule bank	Not an indicator because the species does not have a resting phase, relies on availability of 'fresh' eggs for recruitment & has a very short lifespan 1-2 years (Allen *et al.* 2002)	NA	
No barriers to recruitment	Thought to be a short-lived species (1-2 years of age; Allen *et al.* 2002), it is critical that it recruits annually or every second year. Dependant on access to marine habitats & riparian vegetation for recruitment to occur (Allen *et al.* 2002, Bice 2010a)	Abundance –upstream migrants, Population demographics – size & age structure; Recruitment events – YoY	Capacity to recruit in LL without migration, Presence in & capacity for migration of from nearby estuaries
Lateral hydraulic connectivity	Species requires access to riparian vegetation to deposit its eggs on which then develop out of the water (Allen *et al.* 2002, Bice 2010a)	Abundance – in general; Population demographics – size & age structure; Recruitment events – YoY	Use of lateral habitats within LL & C
Water residence times finite	Not likely to be an indicator as it is highly tolerant of physicochemical parameters, particularly salinity (Chessman & Williams 1975) & dissolved oxygen (Dean & Richardson 1999)	NA	
Regional hydraulically connected	Requires free access to freshwater, estuarine & marine habitats to complete its life cycle (McDowall 1996)	Abundance – in general & of upstream migrants; Population demographics – size & age structure; Recruitment events – YoY	Migration from nearby estuaries or from the marine environment
Longitudinal biological connectivity	Indicator through lower-order trophic ecology & availability of prey items from upstream of sites	Food web structure – gut content	Migration within & upstream of site
No accumulation of pollutants	Short-lived species that could be used to determine whether recent contamination events had bioaccumulated within prey items (Pollard 1973)	Tissue composition	
Lateral habitat diversity	Uses a variety of freshwater habitats (Wedderburn & Hammer 2003, Higham *et al.* 2005a, Bice & Ye 2007)	Distribution	Habitat requirements & use in C
Habitat variability	Requires free access to fresh, estuarine & marine habitats as well as riparian	Distribution	

Indicator species: Common galaxias, *Galaxias maculatus*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
	vegetation (Allen *et al.* 2002, Bice 2010a) & uses a variety of freshwater habitats (Wedderburn & Hammer 2003, Higham *et al.* 2005a, Bice & Ye 2007)		
Range of salinities with appropriate maxima	Not an indicator given species is an excellent osmoregulator (Chessman & Williams 1975) with 50% of individuals being able to tolerate 62 ppt after gradual acclimatisation (Chessman & Williams 1975)	NA	
Temporal variability in salinity	Not an indicator although it does need free access to habitats of differing salinities for spawning & recruitment	NA	
Communities requiring varied salinities supported	Reliant on free access to fresh, estuarine & marine habitats (McDowall 1996)	Abundance – in general & of upstream migrants; Population demographics – size & age structure; Recruitment events – YoY	
Temporal variability in flow	Not an indicator assuming that temporal variability in flows does not preventing functional connectivity between habitats when needed	NA	
Seasonal variability in flows	Seasonal flows provide connectivity from LL to C & *vice versa*	Abundance – in general & of upstream migrants; Population demographics – size & age structure; Recruitment events – YoY	
Seasonal variability in water levels	Not an indicator provided that water level variation does not prevent functional connectivity when required	NA	
Communities requiring varied hydrology supported	Requires access to permanently-inundated habitat	Abundance; Distribution	Habitat requirements & use in LL & C
Communities requiring flooding supported	Not an indicator since there is no record of use of floodplain habitats	NA	Habitat use in LL & C
Tidal signal apparent	Juveniles potentially migrate into C & subsequently LL from the sea on rising tide (Cadwallader & Backhouse 1983) so tidal signatures important for recruitment	Population demographics – size & age structure; Recruitment events – YoY; Distribution – presence of larvae in near-shore coastal areas	Whether larvae develop within C or the ocean; whether freshwater discharge into ocean is an important location/migration cue
Complex food webs present	Preys on aquatic & terrestrial insects, microcrustaceans & amphipods (Pollard 1973). Likely to be important prey for a range of piscivorous fish, birds & other fauna	Food web structure – gut content; Abundance	Ontogenetic differences in diet, presence in diet of higher-order organisms
Functions performed by multiple species	Not an indicator	NA	

Indicator species: Common galaxias, *Galaxias maculatus*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Indicative of saline-tolerant freshwater species due to relatively high salinity tolerance (Chessman & Williams 1975). pH tolerance unknown	Abundance; Distribution	pH tolerance
Wide riparian & littoral zones supported	Utilises riparian habitat to lay eggs (Allen *et al.* 2002, Bice 2010a)	Abundance; Population demographics – size & age structure; Recruitment events – YoY	
Lateral connectivity of vegetation	Utilises riparian habitat to lay eggs (Allen *et al.* 2002, Bice 2010a)	Abundance; Population demographics – size & age structure; Recruitment events – YoY	
Balance of aquatic & terrestrial species	Indicative of aquatic habit only	Distribution; Abundance	
Exchange between aquatic & terrestrial systems	Consumes terrestrial & aquatic insects	Food web structure – gut contents	
Regular oxidation of sulfidic material	Not an indicator	NA	

8.10 Short-headed lamprey – *Mordacia mordax*

Short-headed lamprey (*Mordacia mordax*) is a primitive, native, medium-sized diadromous (anadromous) species (Lintermans 2007). This species exhibits marine residence as an adult, spending the majority of its adulthood in estuaries or at sea (Allen *et al.* 2002). Juveniles are parasitic on fishes such as trout, barracuda, black bream, and mullet for one to two years, and migrate upstream into rivers to spawn during spring (August to November; Koehn & O'Connor 1990, Allen *et al.* 2002). It is unknown whether the species spawns locally within the Lower Lakes or Eastern Mount Lofty tributaries (Bice 2010a) but it is known to spawn in small, shallow, gravel-bottomed tributaries elsewhere in its range (Allen *et al.* 2002).

Ammocetes prefer soft substrates (i.e. mud, sand and silt) in slow flowing water near the stream edge (Hortle 1979 cited in Koehn & O'Connor 1990, McDowall 1996, Lintermans 2007). Juveniles, or ammocetes, are filter feeders (using predominantly detritus, algae and other microorganisms) and live burrowed in sediment for several years before metamorphosing into adults and migrating downstream during spring (Allen *et al*, 2002, Lintermans 2007).

This species formerly undertook mass upstream migrations in the lower River Murray, however it has been substantially affected by in-stream barriers to movement (Lintermans 2007). Individuals were last collected migrating upstream in the Coorong in 2006/07 and have not been recorded since (Jennings *et al.* 2008b) to our knowledge. Table 8.10 links short-headed lamprey to individual ecological outcomes.

Table 8.10: List of ecological outcomes that would be indicated by short-headed lamprey. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Short-headed lamprey, *Mordacia mordax*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Requires free access between freshwater, estuarine &marine habitats (both within & outside the site) to complete its life cycle (Koehn & O'Connor 1990, Allen *et al* 2002) therefore dependent on connectivity between habitats via site	Abundance – upstream migrants; Distribution – presence of ammocoetes further upstream	Capacity for migration of new populations from nearby estuaries
Suitable habitat	Requires free access between freshwater, estuarine and marine habitats (both within & outside the site) to complete its life cycle (Koehn & O'Connor 1990, Allen *et al.* 2002)	Abundance – upstream migrants; Recruitment events – YoY; Distribution – presence of ammocoetes further upstream	Use of habitats within the site including spawning & larval habitat
Suitable food resources	Not an indicator because local feeding has not been demonstrated	NA	Adult or juvenile use of site for feeding
Suitable water quality	Being an obligate aquatic species it is likely to be sensitive to degradation in water quality conditions (e.g. pH, dissolved oxygen). But because tolerances are largely unknown (except for limited information on salinity) & its transient use of the site, it is not currently an indicator	NA	Water quality tolerances; Impacts of multiple water quality stressors
Species connectivity	Newly-metamorphosed adults migrate from upstream habitat to reach the	Abundance – upstream	Exchange between

Indicator species: Short-headed lamprey, *Mordacia mordax*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
	estuary or ocean (Allen *et al.* 2002). Spawning adults migrate through the site to upstream freshwater tributary habitat (Allen *et al.* 2002)	migrants, & newly-metaorphosed adult migrants	different estuaries is unknown; natal homing behaviour assumed
Viable propagule bank	Not an indicator because it does not have a resting stage, & relies on availability of 'fresh' eggs although ammocoetes remain burrowed in sediment for 3-4 years before metamorphosing into adults & migrating downstream (Lintermans 2007)	NA	
No barriers to recruitment	Requires free access between freshwater, estuarine and marine habitats (both within & outside the site) to complete its life cycle (Koehn & O'Connor 1990, Allen *et al.* 2002)	Abundance – ammocoetes in upstream habitats, & upstream migrants; Distribution	Capacity for migration of new populations from nearby estuaries
Lateral hydraulic connectivity	Not an indicator because independent of floodplain hydraulic connection	NA	
Water residence times finite	Not an indicator assuming connectivity is maintained	NA	
Regional hydraulically connected	Requires free access between freshwater, estuarine and marine habitats (both within & outside the site) to complete its life cycle (Koehn & O'Connor 1990, Allen *et al.* 2002)	Abundance – ammocoetes in upstream habitats, & upstream migrants; Distribution	Exchange between different estuaries is unknown. Natal homing behaviour assumed
Longitudinal biological connectivity	Not an indicator because local feeding has not been demonstrated	NA	Adult or juvenile use of site for feeding
No accumulation of pollutants	Not an indicator	NA	
Lateral habitat diversity	Not an indicator	NA	
Habitat variability	Not an indicator	NA	Use of local habitats
Range of salinities with appropriate maxima	Not an indicator	NA	Water quality tolerances, requirements for local freshwater habitats
Temporal variability in salinity	Not an indicator	NA	
Communities requiring varied salinities supported	Although sp. requires varying salinities, it is not an indicator because this is achieved by movement between habitats	NA	
Temporal variability in flow	Ammocetes induced to move downstream in response to marked increases in freshwater discharge (Potter *et al.* 1980). Conversely, main adult movement occurred in Tasmania in response to increased water temperatures & an	Abundance – upstream migrants, & newly-metamorphosed adult	Cues to locate estuary

Indicator species: Short-headed lamprey, *Mordacia mordax*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
	associated reduction in river flow (Sloane 1984)	migrants	
Seasonal variability in flows	Ammocetes induced to move downstream in response to marked increases in freshwater discharge (Potter *et al.* 1980). Conversely, main adult movement occurred in Tasmania in response to increased water temperatures & an associated reduction in river flow (Sloane 1984)	Abundance – upstream migrants, & newly-metamorphosed adult migrants	Cues to locate estuary
Seasonal variability in water levels	Not an indicator provided that water level variation does not prevent functional connectivity between habitats	NA	
Communities requiring varied hydrology supported	Requires access to permanently-inundated habitat	Abundance	Habitat use in freshwater habitats
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator because mechanism for locating estuary is unknown but is thought to rely on freshwater cues reaching the marine environment to locate desired upstream spawning habitats, as opposed to a tidal signal	NA	Cues to locate estuary
Complex food webs present	Not an indicator	NA	
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Not an indicator	NA	
Wide riparian & littoral zones supported	Not an indicator because not dependent on riparian or littoral vegetation	NA	
Lateral connectivity of vegetation	Not an indicator because not dependent on vegetation	NA	
Balance of aquatic & terrestrial species	Indicative of aquatic habit only	Distribution; Abundance	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

8.11 Yellow-eyed mullet – *Aldrichetta forsteri*

Yellow-eyed mullet (*Aldrichetta forsteri*) is an omnivorous, medium-sized estuarine fish that is common in the North Lagoon of the Coorong and the Murray Mouth region with rare records from the Lower Lakes (Higham *et al.* 2005b, Bice 2010a). Also known simply as Coorong mullet, yellow-eyed mullet adults typically feed on detritus, seagrass, algae, polychaetes, molluscs and crustaceans (Thomson 1957, Webb 1973a, Kailola *et al.* 1993, Edgar & Shaw 1995). Mulloway has been shown to feed on yellow-eyed mullet (Kailola *et al.* 1993).

Harris (1968) described yellow-eyed mullet as spawning within the Coorong estuary although other researchers have suggested that spawning occurs outside of estuaries in embayments (Chubb *et al.* 1981) and as such, spawning is likely to be also be occurring outside of the Coorong (Higham *et al.* 2005b). Spawning occurs from summer to early autumn (January to March) (Harris 1968). The species may live for up to five years based on historical ageing studies (Higham *et al.* 2005b).

Larval stages are found in estuarine and marine habitats with the species able to complete its life cycle independent of access to estuaries, instead potentially only requiring sheltered embayments to recruit (Higham *et al.* 2005b). Juvenile and adult fish are pelagic, using estuarine habitats with adults showing a preference for deeper channels and juveniles showing a preference for structured habitat and shallow beaches (Webb *et al.* 1973b). Juvenile yellow-eyed mullet are very tolerant of elevated salinities (86 000 mg L^{-1} [~86 ppt] LC50 with acclimation at 23 ^{o}C; Bice 2010a) while adults have only been observed at salinities up to 35 ppt (Chubb *et al.* 1981).

Yellow-eyed mullet is one of the major species targeted by the commercial fishery within the Lakes and Coorong region (Sloan 2005). Table 8.11 links yellow-eyed mullet to individual ecological outcomes.

Table 8.11: List of ecological outcomes that would be indicated by yellow-eyed mullet (Coorong mullet). See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Yellow-eyed mullet (Coorong mullet), *Aldrichetta forsteri*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Recruitment to the Coorong (C) population is dependent on the provision of suitable estuarine habitat (including access to the ocean via an open Murray Mouth; Higham *et al.* 2005b), estuarine to marine salinities & detritus, seagrass, algae, polychaetes, molluscs & crustaceans (Thomson 1957, Webb 1973a, Kailola *et al.* 1993)	Abundance; Fisheries take – CPUE; Population demographics – size & age structure	Confirmation of whether spawning occurs outside of, or within C
Suitable habitat	Completes its life cycle across a range of different physical structures within estuarine habitats (NB: larvae can also enter the site & use the estuarine habitats for growth)	Abundance; Fisheries take – CPUE; Distribution	Habitat use within estuary
Suitable food resources	Being omnivorous (Thomson 1957, Webb 1973a, Kailola *et al.* 1993, Edgar & Shaw 1995), diet could be used to determine whether a range of estuarine food resources exist such as detritus, seagrass, algae, polychaetes, molluscs & crustaceans	Food web structure – gut contents	Local dietary analysis

Indicator species: Yellow-eyed mullet (Coorong mullet), *Aldrichetta forsteri*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Suitable water quality	Not an indicator although an obligate aquatic species therefore sensitive to degradation in water quality conditions (e.g. pH, dissolved oxygen) because tolerances are unknown, except for salinity (Bice 2010a)	NA	Impacts of multiple water quality stressors, lower salinity tolerance; tolerance to degraded DO & pH
Species connectivity	Not currently an indicator because it can spawn inside C (Harris 1968) but the importance of migration for the local population is unknown. Immigrant larvae from the ocean may be important to provide new cohorts to this population (Higham *et al.* 2005b)	NA	Migration to & from C
Viable propagule bank	Not an indicator because it can spawn in C (although fresh eggs & larvae may enter from the ocean) & does not have resting phases. Adults live for up to 5 years (Higham *et al.* 2005b)	NA	
No barriers to recruitment	Not an indicator because intraspecific connectivity with populations outside of C depends on an open Murray Mouth and relationships to other populations is unknown	NA	Movement between C & ocean; gene flow between C & other populations
Lateral hydraulic connectivity	Likely to use mudflat habitat for feeding based on studies elsewhere (Webb 1973a)	Distribution; Abundance; Fisheries take – CPUE	Habitat use in C
Water residence times finite	Not an indicator given tolerance to elevated salinities that could occur in Coorong (juveniles: 86 000 mg L^{-1}[~86 ppt] LC50 with acclimation at 23 °C; Bice 2010a)	NA	
Regional hydraulically connected	Not currently an indicator given lack of information on migration & its importance to the local population	NA	Migration to & from C
Longitudinal biological connectivity	Feeds upon the lowest trophic levels & thus may be dependent upon longitudinal transport of energy, nutrients, carbon & zooplankton to drive estuarine productivity	Abundance; Fisheries take – CPUE; Food web structure – gut contents	
No accumulation of pollutants	Sp. feeds on a range of items that may have accumulated pollutants including detritus & algae	Tissue composition	Local dietary information
Lateral habitat diversity	Likely to use mudflat habitat for feeding based on studies elsewhere (Webb, 1973a)	Distribution; Abundance; Fisheries take – CPUE	Habitat use in C
Habitat variability	Adults & juveniles prefer different habitats (Webb 1973b)	Distribution; Abundance; Fisheries take – CPUE	Habitat use in C
Range of salinities with appropriate maxima	Sp. has a broad distribution in C & is highly salt tolerant (juveniles: 86 000 mg L^{-1}[~86 ppt] LC50 with acclimation at 23 °C; Bice 2010a) so is indicative of marine to hypersaline salinities	Abundance; Fisheries take – CPUE; Distribution	
Temporal variability in salinity	Sp. has a broad distribution in Coorong, & is highly salt tolerant (juveniles: 86 000 mg L^{-1}[~86 ppt] LC50 with acclimation at 23 °C; Bice 2010a)	Abundance Fisheries take - CPUE; Distribution	
Communities requiring varied	Not an indicator	NA	

Indicator species: Yellow-eyed mullet (Coorong mullet), *Aldrichetta forsteri*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
salinities supported			
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Requires access to permanently-inundated habitat	Abundance; Distribution	
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not currently an indicator although it will potentially respond to tidal signal	NA	Whether feeding, migration & habitat use respond to tidal signal
Complex food webs present	Omnivorous estuarine fish therefore indicative of whether food resources such as microcrustaceans, detritus, algae, seagrasses & molluscs are available (Webb 1973a). Prey species for mulloway (Kailola *et al.* 1993) & probably other piscivorous fauna	Abundance; Fisheries take – CPUE; Food web structure – gut contents	Whether consumed by predators
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Not an indicator	NA	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Indicative of aquatic habit only	Distribution; Abundance; Fisheries take – CPUE	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

8.12 Black bream – *Acanthopagrus butcheri*

Black bream (*Acanthopagrus butcheri*) is a long-lived (potentially greater than 20 years) medium-bodied estuarine fish that feeds on a variety of items including crustaceans, fish, polychaetes and various plant matter (Sarre *et al.* 2000, Norriss *et al.* 2002). Black bream supports a commercial fishery but annual catches have declined significantly in recent years (Ferguson & Ye 2008).

Black bream has been observed moving into fishways but is considered rare in the Lower lakes (Jennings *et al.* 2008a). Spawning occurs between spring and summer in lower salinity water, located around the halocline (Nicholson & Gunthorpe 2006, 2008). Nicholson & Gunthorpe (2008) suggested that salinity profile and dissolved oxygen were important for larval survival and that vegetated habitat was important for settlement, however this has not been confirmed in the Coorong. In the Hopkins River, Newton (1996) found peak concentrations of larvae and eggs in salinities ranging from 13 to 28 ppt, while successful recruitment appeared to be linked to food availability following barrage outflows and the timing of river flows was critical to recruitment success for this species in Victorian estuaries (Newton 1996). In Western Australia and Victoria, adults use estuaries and the lower reaches of rivers and lakes, preferring deeper water with hard substrates and complex structure (Ferguson & Ye 2008). Juveniles are similar to adults but probably prefer shallower habitats with complex structure (e.g. reefs) (Bice 2010a) and are thought to be more tolerant of varying salinity (Nicholson & Gunthorpe 2008). Adult bream have been observed in salinities ranging from 0.3 to greater than 40 g L^{-1} (Harbison 1973, Lenanton 1977 cited in Ferguson & Ye 2008) and dissolved oxygen concentrations of between 5.18 to 8.64 mg L^{-1} (Lenanton 1977 cited in Ferguson & Ye 2008, Bice 2010a). In the Gippsland Lakes, bream has been identified to live for up to 29 years (Morrison *et al.* 1998).

Black bream is not presently listed as an endangered species under any legislation. Table 8.12 links black bream to individual ecological outcomes.

Table 8.12: List of ecological outcomes that would be indicated by black bream. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Black bream, *Acanthopagrus butcheri*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Recruitment is dependent on provision of accessible estuarine habitat including littoral zones & salinities between 13-28 ppt (Newton 1996)	Abundance; Fisheries take – CPUE; Population demographics – size & age structure	Juvenile habitat requirements in the Coorong (C), diet of in C
Suitable habitat	Completes its life cycle within estuaries in Western Australia & Victoria (Ferguson & Ye 2008)	Abundance; Fisheries take – CPUE; Population demographics – size & age structure	
Suitable food resources	Sp. is omnivorous & feeds on crustaceans, fish, polychaetes & plant matter (Sarre *et al.* 2000, Norriss *et al.* 2002) in WA estuaries	Food web structure – gut contents	Diet in C
Suitable water quality	Not an indicator because tolerance levels unknown except for salinity. Generally	NA	Impacts of multiple water

Indicator species: Black bream, *Acanthopagrus butcheri*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
	tolerant of changes in salinity (Bice, 2010) so unlikely to indicate whether freshwater or estuarine water quality is suitable		quality stressors; lower salinity tolerance; tolerance to degraded DO & pH
Species connectivity	Not currently an indicator because any interaction with other populations unknown. Sp. seems to move to ocean from C (SARDI unpub. data), which may indicate corresponding emigration & potentially exchange between populations in other estuaries	NA	Exchange with nearby estuaries & population connectivity
Viable propagule bank	Not an indicator because it does not have a resting stage, relying on availability of 'fresh' eggs, although it has a long lifespan of up to 29 yrs (Morrison *et al.* 1998)	NA	
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic connectivity	Not an indicator	NA	Interactions between lateral hydraulic connectivity & diet
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Freshwater flows through the barrages are important for spawning	Abundance Fisheries take - CPUE; Population demographics - size & age structure; Distribution – fresh/estuarine	
Longitudinal biological connectivity	Indicator through lower-order trophic ecology & availability of prey items from upstream of site	Food web structure - gut contents	
No accumulation of pollutants	Likely to be a good indicator of bioaccumulation because it is long-lived (up to 29 years; Morrison *et al.* 1998) & omnivorous, although movement out of the system to other estuaries may limit its applicability without otolith studies to determine residence	Tissue composition	Exchange with nearby estuaries & population connectivity
Lateral habitat diversity	Not an indicator	NA	
Habitat variability	Dependent on estuarine or brackish conditions & a range of different habitats (vegetation, deeper water with hard substrates & complex structure; Ferguson & Ye 2008). In WA & Vic, adults use estuaries, lower reaches of rivers & lakes (Ferguson & Ye, 2008)	Distribution; Abundance	
Range of salinities with appropriate	Sp. generally prefers brackish or marine salinities, although also found in lower reaches of rivers & lakes (Ferguson & Ye, 2008). Sp. will tolerate a range of 0.3 to	Abundance; Distribution; Population demographics – size	

Indicator species: Black bream, *Acanthopagrus butcheri*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
maxima	>40 g L^{-1}, (Harbison 1973, Lenanton 1977)	& age structure	
Temporal variability in salinity	Flows through the barrages are important for establishing estuarine conditions & a halocline to trigger spawning (Nicholson & Gunthorpe 2006, 2008)	Abundance; Fisheries take – CPUE; Population demographics – size & age structure; Recruitment events – YoY; Distribution	
Communities requiring varied salinities supported	Requires estuarine salinities & a halocline for spawning & recruitment (Nicholson & Gunthorpe 2006, 2008)	Abundance; Fisheries take – CPUE; Population demographics – size & age structure; Recruitment events – YoY; Distribution	
Temporal variability in flow	Variation in flows through time interacts with C salinity	Abundance; Fisheries take – CPUE; Distribution	
Seasonal variability in flows	Flows through the barrages are important for establishing estuarine conditions & a halocline during breeding season to trigger spawning (Nicholson & Gunthorpe 2006, 2008)	Abundance; Fisheries take – CPUE; Population demographics – size & age structure; Recruitment events – YoY; Distribution	The influence of timing of fresh water on spawning & recruitment success
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Requires access to permanently-inundated habitat	Abundance; Fisheries take - CPUE; Distribution	Habitat use in Lakes & C
Communities requiring flooding supported	Not an indicator except through lower-order trophic ecology	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Omnivorous estuarine fish therefore indicative of whether food resources such as crustaceans, molluscs, fish, plant material & algae are present (Sarre *et al.* 2000, Norriss *et al.* 2002)	Abundance; Fisheries take – CPUE; Population demographics – size & age structure; Food web structure – gut contents	Local diet
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive	Not an indicator	NA	

Indicator species: Black bream, *Acanthopagrus butcheri*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
species			
Acid- & saline-tolerant & terrestrial species present	Tolerant of a wide range of salinities but has a lower upper tolerance than small-mouthed hardyhead therefore changes in the ratio of the two species may indicate whether salt-tolerant species are proportionally increasing	Changes in ratio of two groups – abundance vs. small-mouthed hardyhead; Distribution; Population demographics – size & age structure	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Indicative of aquatic habit only	Distribution; Abundance; Fisheries take – CPUE	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

8.13 Small-mouthed hardyhead – *Atherinosoma microstoma*

Small-mouthed hardyhead (*Atherinosoma microstoma*) is a highly-abundant, small-bodied euryhaline native fish species which occurs in the Coorong (including the Murray estuary, North Lagoon and South Lagoon), as well as in the Lower Lakes (Molsher *et al.* 1994, Wedderburn & Hammer 2003, Bice & Ye 2007, Jennings *et al.* 2008). It is widely tolerant of both low and elevated salinities; being able to tolerate low salinities (~3300 mg L^{-1} [3.3 g L^{-1}] LC50 direct transfer) & very high salinities (~108 000 mg L^{-1} [108 g L^{-1}] LC50 direct transfer; Lui 1969). During periods of elevated salinity in the Coorong, the species is able to persist, having been observed in salinities ranging as high as 100-130 g L^{-1} (Geddes 1987, Noell *et al.* 2009). The species is often referred to as a 'keystone' species (although this has not been formally demonstrated using the scientific definition of 'keystone') since it consumes zooplankton, in particular ostracods and copepods (Geddes 1987) as well as insects (Lintermans 2007) and is major food item for selected piscivorous birds (Paton 1982) and thus is a critical part of trophic structure in the Coorong.

Small-mouthed hardyhead is largely an annual species that spawns in multiple batches during spring (August to December) each year (Molsher *et al.* 1994). A reduction in salinity may be one of the environmental cues involved in triggering spawning (Molsher *et al.* 1994). Whilst adults and juveniles are typically estuarine and associated with submerged aquatic vegetation such as *Ruppia* spp., they are also found in edge habitats of the Lower Lakes or those with aquatic vegetation (Lintermans 2007). This suggests they are more likely to be generalists in terms of habitat usage. Small-mouthed hardyhead appears to be able to complete its life cycle on either side of the barrage so connectivity does not appear to be obligatory for this species (C. Bice pers. comm.). Table 8.13 links small-mouthed hardyhead to individual ecological outcomes.

Table 8.13: List of ecological outcomes that would be indicated by small-mouthed hardyhead. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Small-mouthed hardyhead, *Atherinosoma microstoma*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Euryhaline species that is able to withstand a broad range of salinities (Molsher *et al.* 1994). Recruitment is possibly dependent on availability of submerged aquatic vegetation (e.g. *Ruppia* spp) or edge habitats (Lintermans 2007) & ostracods, copepods (Geddes 1987) & insects (Lintermans 2007)	Abundance; Population demographics – size & age structure; Recruitment events – YoY; Distribution	
Suitable habitat	Sp. completes its life cycle in estuarine habitats (associated with submerged aquatic vegetation. It is also found in edge habitats & vegetated habitats in the Lower Lakes (LL)	Abundance; Population demographics – size & age structure; Distribution	
Suitable food resources	Important carnivorous species in the Coorong (C) since it consumes zooplankton, including ostracods & copepods (Geddes 1987) & insects (Lintermans 2007) & is consumed by piscivorous birds (Paton 1982)	Food web structure – gut contents; Abundance	
Suitable water quality	The only fish sp. the South Lagoon when salinities >80 ppt (Higham *et al.* 2002). If it is not recruiting then conditions are unlikely to be favourable for other estuarine fish	Abundance; Population demographics – size & age structure; Recruitment events – YoY; Disease – occurrence of decreased health condition;	Impacts of multiple water quality stressors; pH & DO tolerance

Indicator species: Small-mouthed hardyhead, *Atherinosoma microstoma*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
		Fish kills; Distribution	
Species connectivity	Not an indicator given species completes its life cycle on either side of the barrage so species connectivity does not appear to be obligatory (C. Bice pers. comm.)	Abundance; Population demographics – size & age structure; Distribution	
Viable propagule bank	Not an indicator because the species does not have a resting phase, relies on availability of 'fresh' eggs for recruitment & has a very short lifespan 1-2 years (Molsher *et al.* 1994)	NA	
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic connectivity	Uses flooded estuarine margins in Surrey River, Victoria in high numbers to forage (Becker & Laurenson, 2007) & possibly does the same in C & LL habitats	Abundance; Distribution	Confirmation species uses riparian & flooded habitat
Water residence times finite	The only fish sp. the South Lagoon when salinities >80 ppt (Higham *et al.* 2002). If it is not recruiting then conditions are unlikely to be favourable for other estuarine fish	Abundance; Population demographics – size & age structure; Recruitment events – YoY; Distribution	
Regional hydraulically connected	Not an indicator given sp. can recruit on either side of the barrages	NA	
Longitudinal biological connectivity	Indicator through lower-order trophic ecology & availability of prey items from upstream of site	Food web structure – gut contents; Abundance; Population demographics – size & age structure	
No accumulation of pollutants	Likely to be a good indicator of bioaccumulation of pollutants because it is carnivorous, thus given its tolerance to poor water quality, is likely to be exposed to a range of pollutants	Tissue composition	
Lateral habitat diversity	Uses flooded estuarine margins in Surrey River, Victoria in high numbers to forage (Becker & Laurenson 2007) & possibly does the same in C & LL habitats	Abundance; Distribution	Confirmation species uses riparian & flooded habitat
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	The only fish sp. the South Lagoon when salinities >80 ppt (Higham *et al.* 2002). If it is not recruiting then conditions are unlikely to be favourable for other estuarine fish	Abundance; Population demographics – size & age structure; Recruitment events – YoY; Distribution	
Temporal variability in salinity	Species requires a reduction in salinity to trigger spawning (Molser *et al.* 1994)	Population demographics – size & age structure; Recruitment events – YoY	
Communities requiring varied salinities supported	Species requires a reduction in salinity to trigger spawning (Molser *et al.* 1994)	Population demographics – size & age structure; Recruitment events – YoY	

Indicator species: Small-mouthed hardyhead, *Atherinosoma microstoma*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Requires access to permanently-inundated habitat	Abundance; Population demographics – size & age structure	
Communities requiring flooding supported	Not an indicator although likely to benefit from increased habitat extent & abundance of food when flooding occurs	NA	Foraging success in flooded habitats of C & LL
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Carnivorous fish that opportunistically uses a range of fresh & estuarine habitats, therefore likely to indicate whether microcrustaceans are present Sp. is also an important food source for piscivorous birds (Paton 1982)	Abundance; Food web structure – gut contents	
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	The only fish sp. the South Lagoon when salinities >80 ppt (Higham *et al.* 2002). If it is not recruiting then conditions are unlikely to be favourable for other estuarine fish	Abundance; Distribution; Population demographics – size & age structure compared to other species	
Wide riparian & littoral zones supported	Uses flooded habitat in Surrey River, Victoria in high numbers to forage (Becker & Laurenson 2007) & possibly does the same in C & LL habitats	Distribution; Abundance	Confirmation species uses riparian & flooded habitat
Lateral connectivity of vegetation	Uses flooded habitat in Surrey River, Victoria in high numbers to forage (Becker & Laurenson 2007) & possibly does the same in C & LL habitats	Distribution; Abundance	Confirmation species uses riparian & flooded habitat
Balance of aquatic & terrestrial species	Indicative of aquatic habit only	Distribution; Abundance	
Exchange between aquatic & terrestrial systems	Carnivore that will consume terrestrial insects (Lintermans 2007)	Food web structure – gut contents	
Regular oxidation of sulfidic material	Not an indicator	NA	

8.14 Mulloway – *Argyrosomus japonicus*

Mulloway (*Argyrosomus japonicus*) is large, long-lived predator feeding primarily on fish (e.g. bony bream, sea mullet, yellow-eyed mullet) but also on crabs, prawns and worms (Kailola *et al.* 1993). The species may live for up to 41 years (Ferguson 2011). Adults are typically found in the near-shore ocean environment (surf zone) and enter the Coorong whilst juveniles (2-6 years of age) where they are common (Ferguson 2011). The Coorong is believed to be an important juvenile habitat (Hall 1984, Ferguson 2011) that provides some protection from conspecific predation similar to estuaries in South Africa (Ferguson 2011). The species is still moderately common in the Murray Mouth estuary despite recent low barrage flows, but is likely to be rare in Lower Lakes as only an occasional visitor (SARDI unpub. data). Mulloway still supports a commercial fishery in the Coorong (Sloan 2005).

Spawning areas in South Australia are unknown, although spent and spawning fish have been observed at the Murray Mouth (during October to January with a peak in November; Ferguson 2011). Hall (1984 cited in Ferguson & Ward 2003) and recreational fishermen have observed aggregations of large mulloway at the Murray Mouth in spring/early summer during times of freshwater discharge (Ferguson 2011). Ferguson *et al.* (2008) correlated commercial catch data with flow years indicting that recruitment is linked to periods of barrage outflow. Although the causal mechanism remains unconfirmed, spawning and recruitment probably occur annually but flow seasonality is likely to affect the success of a given recruitment event (i.e. cohort strength; Ferguson *et al.* 2008). Larval development is likely to occur in the marine environment before juveniles enter and subsequently reside in the Coorong (Hall 1986). Salinity preferences range from 5 to 35 ppt (PIRSA 2001).

Table 8.14 links Mulloway to individual ecological outcomes.

Table 8.14: List of ecological outcomes that would be indicated by mulloway. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Mulloway, *Argyrosomus japonicus*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Not an indicator because thought to spawn in the ocean although the Coorong (C) is believed to be an important juvenile habitat (Ferguson 2011)	NA	
Suitable habitat	Juveniles use C as a nursery site (Ferguson 2011)	Abundance Fisheries take – CPUE; Population demographics – size & age structure; Distribution	The proportion of the adult population outside C that is comprised of C-related fish
Suitable food resources	Is a carnivorous fish that feeds on crabs, prawns & worms (Kailola *et. al.* 1993)	Food web structure – gut contents	
Suitable water quality	Obligate aquatic species therefore sensitive to degradation in water quality conditions (e.g. pH, dissolved oxygen). Sp. preference is for salinity between 5 – 35 ppt (PIRSA 2001)	Abundance; Fisheries take – CPUE; Distribution; Disease – occurrence of decreased health condition; Fish kills	Impacts of multiple water quality stressors

Indicator species: Mulloway, *Argyrosomus japonicus*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Species connectivity	Larvae develop in the ocean & enter C where they grow to adults & leave for the ocean again, thus the sp. indicates exchange of individuals between the ocean & C. If sp. were to be found in the Lower Lakes (LL) then would also indicate exchange between C & LL	Abundance; Fisheries take – CPUE; Population demographics – size & age structure; Distribution	
Viable propagule bank	Not an indicator because sp. relies on availability of fresh eggs & incoming larvae for recruitment & does not have resting phase but does live for an extended period (up to 41 years; Ferguson 2011)	NA	
No barriers to recruitment	Sp. depends on connectivity with the ocean for new larvae to enter the site	Abundance; Fisheries take – CPUE; Population demographics – size & age structure	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Fish kills are possible if insufficient connectivity does not allow escape to the ocean during any deterioration in water quality	Abundance; Fisheries take – CPUE; Fish kills	
Regional hydraulically connected	Larvae develop in the ocean & enter C where they grow to adults & leave for the ocean again, thus the sp. indicates exchange of individuals between the ocean & C. If sp. were to be found in LL then would also indicate exchange between C & LL	Abundance; Fisheries take – CPUE; Population demographics – size & age structure; Distribution	
Longitudinal biological connectivity	Indicator through lower-order trophic ecology	Food web structure – gut contents	
No accumulation of pollutants	May be a good indicator of bioaccumulation of pollutants because it is carnivorous (Kailola *et al.* 1993)	Tissue composition	
Lateral habitat diversity	Not an indicator	NA	
Habitat variability	Not currently an indicator because habitat requirements in C unknown	NA	Habitat requirements in C
Range of salinities with appropriate maxima	Indicative of marine salinities up to 35 ppt (PIRSA 2001)	Abundance; Fisheries take - CPUE; Distribution; Disease - occurrence of decreased health condition	
Temporal variability in salinity	Able to tolerate a range of salinities (5-35 ppt; PIRSA 2001)	Abundance; Fisheries take – CPUE; Population demographics – size & age structure; Distribution	
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Aggregations of large mulloway have been observed at the Murray	Abundance - aggregations;	May use freshwater flows

Indicator species: Mulloway, *Argyrosomus japonicus*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
	Mouth in spring/early summer during freshwater discharges (Ferguson & Ward 2003)	Fisheries take - CPUE, Population demographics - size & age structure	through Mouth as a cue
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Requires access to permanently-inundated habitat	Abundance; Fisheries take – CPUE; Population demographics – size & age structure	
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator	NA	May use freshwater flows through Mouth as a cue
Complex food webs present	Carnivorous estuarine fish (Kailola *et al.* 1993) & an apex predator therefore indicative of whether food resources such as crustaceans, fish, crabs & worms are available	Abundance; Fisheries take – CPUE; Population demographics – size & age structure; Food web structure – gut contents	
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Not an indicator	NA	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Indicative of aquatic habit only	Distribution; Abundance; Fisheries take – CPUE	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

8.15 Sandy sprat – *Hyperlophus vittatus*

Sandy sprat (*Hyperlophus vittatus*) is a small-bodied marine clupeoid (i.e. a soft-rayed, bony fish of the Order Clupeiformes) fish species (maximum length ~10 cm) found in shallow bays, estuaries and along coastal beaches from southern Queensland, around the southern coastline of Australia to south-western Western Australia (Rogers & Ward 2007). Common in gulf waters of South Australia and the Coorong, at times sandy sprat is highly abundant in the Coorong (Jennings *et al.* 2008) with some records from the Lower Lakes (SARDI unpub. data cited in Bice 2010a). Pelagic spawning occurs in the South Australian gulfs in spring-summer and the Coorong may be used as a nursery area, although spawning within Coorong is unlikely (Rogers & Ward 2007). The oldest fish found in the Coorong was approximately four years old (Rogers & Ward 2007). The species supports a commercial fishery outside of the Coorong.

Sandy sprat is an important prey item for small coastal seabirds and inshore pelagic fish (Klomp & Wooler 1988, Hoedt & Dimmlich 1994, Edgar & Shaw 1995, Hoedt *et al.* 1995) although this has not been documented in the Coorong. Sandy sprat is not presently listed as an endangered species under any legislation. Table 8.15 links sandy sprat to individual ecological outcomes.

Table 8.15: List of ecological outcomes that would be indicated by sandy sprat. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Sandy sprat, *Hyperlophus vittatus*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Not an indicator because only known to spawn in the SA Gulfs (Rogers & Ward 2007)	NA	
Suitable habitat	Use the Coorong (C) embayment as a juvenile habitat (Rogers & Ward 2007) although habitat requirements in C & Lower Lakes (LL) are presently unknown	Abundance	Habitat requirements in the LL & C
Suitable food resources	Being planktivorous, (D'Souza *et al.* 2009), sp. relies on zooplankton, phytoplankton & floating insect food resources. An important prey item for small coastal seabirds & inshore pelagic fish (Klomp & Wooler 1988, Hoedt & Dimmlich 1994, Edgar & Shaw 1995, Hoedt *et al*. 1995)	Food web structure – gut contents; Abundance, Population demographics – size & age structure	
Suitable water quality	Although an obligate aquatic species & therefore sensitive to degradation in water quality conditions (e.g. pH, dissolved oxygen), no information on water quality tolerances is available & hence sp. is not currently an indicator	NA	Water quality tolerances; Impacts of multiple water quality stressors
Species connectivity	Larvae develop in the ocean & enter the Murray Mouth & so require exchange between the ocean & C. If sp. was found in LL, then would also indicate exchange between C & LL	Abundance; Population demographics – size & age structure; Distribution	
Viable propagule bank	Not an indicator because the species does not have a resting phase, relies on availability of 'fresh' eggs & larvae for recruitment & has a very short lifespan of 1-2 years	NA	
No barriers to recruitment	Local populations depend on connectivity with the ocean for new larvae to enter the site given spawning locations (Rogers & Ward 2007)	Abundance; Population demographics – size & age structure	

Indicator species: Sandy sprat, *Hyperlophus vittatus*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Lateral hydraulic connectivity	Indicator through lower order trophic dynamics given species is planktivorous (D'Souza *et al.* 2009)	Food web structure – gut content	
Water residence times finite	Fish kills may occur if water quality deteriorates & connectivity is insufficient to allow escape	Abundance; Population demographics – size & age structure; Fish kills	
Regional hydraulically connected	Spawns in the ocean (Rogers & Ward 2007) & enters C & so indicative of hydraulic connections between the Murray Mouth, C & the ocean. If sp. is found in LL then would also indicate hydraulic connection between C & LL	Abundance; Population demographics – size & age structure; Distribution	
Longitudinal biological connectivity	Indicator through lower-order trophic dynamics given the sp. is planktivorous (D'Souza *et al.* 2009)	Food web structure – gut contents; Abundance; Population demographics – size & age structure	
No accumulation of pollutants	Not an indicator	NA	
Lateral habitat diversity	Not currently an indicator because habitat use is not known	NA	Habitat use in the site
Habitat variability	Not currently an indicator because habitat use is not known	NA	Habitat use in the site
Range of salinities with appropriate maxima	Indicative of marine salinities	Abundance; Population demographics – size & age structure	Water quality tolerances
Temporal variability in salinity	Whilst primarily a marine species, individuals have been caught upstream of Goolwa Barrage & attempting to enter LL during freshwater discharge (SARDI unpub. data). Sp. is likely to prefer salinities of marine concentrations or less	Abundance; Population demographics – size & age structure; Distribution	Salinity tolerance
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Requires access to permanently-inundated habitat	Abundance; Population demographics – size & age structure	Habitat use in site
Communities requiring flooding supported	Not an indicator	NA	

Indicator species: Sandy sprat, *Hyperlophus vittatus*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Tidal signal apparent	Not presently an indicator because cues for attracting individuals to C unknown	Abundance; Population demographics – size & age structure; Distribution	Cues that attract individuals into C
Complex food webs present	Planktivorous fish therefore indicative of whether food resources such as microcrustaceans & algae are available. Also an important prey species for piscivores (e.g. Australian salmon) (Chubb *et al.* 1981)	Abundance; Population demographics – size & age structure; Food web structure – gut contents	
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Not an indicator	NA	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Indicative of aquatic habit only	Distribution; Abundance	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

8.16 Australian Salmon – *Arripis truttacea*

Australian Salmon (*Arripis truttacea*) is a medium-sized piscivorous, schooling marine species that inhabits exposed surf beaches and surge zones around rocky reefs as an adult and shallow bays and estuaries as a juvenile (Kailola *et al.* 1993). *A. truttacea* are distributed from south-western Western Australia, east along the southern coastline to western Victoria and Tasmania (Paulin 1993). The species is common in coastal South Australia, with juveniles common within the Coorong (Eckert & Robinson 1990, Noell *et al.* 2009). It is able to tolerate temperature and salinity extremes, including those found in the Coorong which acts as a nursery site (Kailola *et al.* 1993) but is not typically found in areas with salinities greater than marine, preferring estuarine to marine salinities (Kailola *et al.* 1993). Eastern Australian salmon (*A. trutta*) has been identified also within the site from the Coorong beach and Lagoons and the coastal SE waters of SA (Jones 2008a) and its diet is very different from that of *A. truttacea* but is not described here. Australian salmon migrate from South Australia to spawn in Western Australia in autumn (Cappo 1987). The Leeuwin current and predominant westerly winds distribute post-larval individuals eastwards toward South Australia (Cappo 1987, Lenanton *et al.* 1991, Cappo*et al.* 2000). Some adults also undertake return easterly migrations after spawning in WA, although there is no evidence of mature spawning fish occurring in SA waters (i.e. SA appears to be a maturing ground and fish that are ready to spawn appear to migrate back to WA; Cappo 1987, Fairclough *et al.* 2000). Juvenile Australian salmon, between 50 and 80 mm, can be found from July to September each year (Malcolm 1966) entering the Coorong with specimens any greater than 250 mm in length being uncommon, probably having departed the Coorong for the nearshore coastal zone (Eckert & Robinson 1990). *A. truttacea* have been observed to consume fish (Scott *et al.* 1974, Cappo 1987, Hoedt & Dimmlich 1994) and be consumed themselves by sharks and dolphins (Kailola *et al.* 1993). Records in the Coorong show a diet including gobies and juvenile flounder (Eckert & Robinson 1990).

Australian salmon mature between three and six years, when they are around 700 mm in length and 5 kg in weight (Cappo 1987). They reach a maximum age of about nine years and can grow as long as 900 mm and as heavy as 10.5 kg (Cappo 1987). Australian salmon support a commercial fishery largely outside of the Coorong (Jones 2008a). Table 8.16 links Australian salmon to individual ecological outcomes.

Table 8.16: List of ecological outcomes that would be indicated by Australian salmon. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Australian salmon, *Arripis truttacea*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Not an indicator because species spawns in Western Australia (Kailola *et al.* 1993)	NA	
Suitable habitat	Juveniles use the Coorong (C) embayment as a nursery habitat (Kailola *et al.* 1993), so likely to indicate whether suitable habitat exists for development to sub-adult fish	Abundance – in general &CPUE; Population demographics – size & age structure	Specific water quality tolerance information
Suitable food resources	Species is piscivorous (Scott *et al.* 1974, Eckert & Robinson 1990, Hoedt & Dimmlich 1994)	Food web structure – gut contents	Updated information on diet in C
Suitable water quality	Able to tolerate brackish to marine waters (Kailola *et al.* 1993)	Abundance – in general & CPUE; Population	Salinity range necessary to support growth & survival

Indicator species: Australian salmon, *Arripis truttacea*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
		demographics – size & age structure; Disease – occurrence, decreased health condition; Fish kills	
Species connectivity	Juveniles enter C where they grow to adults & subsequently leave for the ocean (Eckert & Robinson 1990) thus require exchange between the ocean & C	Abundance; Population demographics – size & age structure; Distribution	
Viable propagule bank	Not an indicator because it relies on availability of fresh eggs & incoming juveniles for recruitment & does not have resting phases. Sp. has a life span of 9 years (Cappo 1987)	NA	
No barriers to recruitment	Depend on connectivity with the ocean for juveniles to enter the site since it spawns outside of the site (Kailola *et al.* 1993) & is thus susceptible to barriers to connectivity	Abundance – in general & CPUE; Population demographics – size & age structure	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Estuarine/marine conditions which juveniles use are not likely to persist if residence times increase & water quality deteriorates	Distribution	
Regional hydraulically connected	Juveniles enter C where they grow to sub-adults & then leave again for the ocean (Eckert & Robinson 1990), thus rely on connection between C & the ocean	Abundance – in general & CPUE; Population demographics – size & age structure; Distribution	
Longitudinal biological connectivity	Indicator through lower-order trophic ecology & availability of prey items, some of which would be from LL	Food web structure – gut contents	
No accumulation of pollutants	May be a good indicator because is piscivorous (Scott *et al.* 1974, Eckert & Robinson 1990, Hoedt & Dimmlich 1994) & thus may accumulate pollutants via food chain. Sp. is used for human consumption	Tissue composition	
Lateral habitat diversity	Not an indicator	NA	
Habitat variability	Not currently an indicator because detailed information on habitat use is not available	NA	Habitat use & requirements within the site
Range of salinities with appropriate maxima	Indicative of estuarine to marine salinities (Kailola *et al.* 1993)	Abundance – in general & CPUE; Distribution	Preferred salinities & tolerance
Temporal variability in salinity	Indicative of estuarine to marine salinities (Kailola *et al.* 1993)	Abundance – in general & CPUE; Distribution	
Communities requiring varied salinities	Indicative of estuarine to marine salinities (Kailola *et al.* 1993)	Abundance – in general & CPUE; Distribution	

Indicator species: Australian salmon, *Arripis truttacea*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
supported			
Temporal variability in flow	Not an indicator assuming that salinity remains within tolerances	NA	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	Water levels & access to preferred habitats
Communities requiring varied hydrology supported	Requires access to permanently-inundated habitats	Abundance – in general & CPUE; Distribution; Population demographics – age structure;	Habitat use in C
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Piscivorous species therefore indicates whether smaller fish (e.g. sandy sprat) are available & are supporting complex, diverse food webs (Eckert & Robinson 1990). Also an important prey species for higher-order predators such as sharks & dolphins (Kailola *et al.* 1993)	Abundance; Population demographics – size & age structure; Food web structure – gut contents	
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Juveniles are found in estuarine to marine habitats (Kailola *et al.* 1993), therefore changes in distribution may indicate a shift towards species more tolerant of salinity	Abundance; Distribution	
Wide riparian & littoral zones supported	Not an indicator because not associated with littoral or riparian vegetation	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Indicative of aquatic habit only	Distribution; Abundance – in general & CPUE	
Exchange between aquatic & terrestrial systems	Not an indicator because piscivorous	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

8.17 Bronze-whaler shark – *Carcharhinus brachyurus*

The bronze-whaler shark (*Caracharinus brachyurus*)is a large shark (maximum length >3 m) with a global distribution found in temperate and sub-tropical waters around all continents but Antarctica (Kailola *et al.* 1993). It is considered a nearshore species, commonly found in the surf zone to depths of 100 m, occasionally entering large coastal bays, estuaries and inshore (including freshwater) areas (Kailola *et al.* 1993). It is viviparous, giving birth to litters of 7 to 20 pups (Kailola *et al.* 1993) and can live for up to 30 years (Walter & Ebert 1991). Its diet consists primarily of benthic and pelagic bony fishes such as mullet, Australian salmon, smaller sharks and rays, but also cephalopods (Compagno *et al.* 1989, Cappo 1992). The species is relatively common in coastal waters of South Australia and along the ocean beach outside of the Murray Mouth and Coorong (Cappo 1992, Jones 2008b). Bronze-whalers are rarely found in the Coorong, although there are some records from the Lakes and Coorong commercial-fishery returns (PIRSA unpub. data), and the vast majority are caught on the Ocean Beach (Jones 2008b). This finding could also be due to the gear types used inside the Coorong rather than the abundance of bronze-whaler sharks. Table 8.17 links Bronze whaler sharks to individual ecological outcomes.

Table 8.17: List of ecological outcomes that would be indicated by bronze-whaler shark. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Indicator species: Bronze-whaler shark, *Carcharhinus brachyurus*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Not an indicator because predominantly lives along Coorong ocean (O) beach & rarely enters the Coorong (C)	NA	Links between recruitment & feeding in & C & O; Location of 'pupping' areas
Suitable habitat	Not an indicator because it completes its life cycle in O & is primarily independent of habitats that exist in the site	NA	
Suitable food resources	Not an indicator because opportunistic predator that will hunt available prey of suitable sizes	NA	
Suitable water quality	Not an indicator because opportunistic inhabitant rather than resident species	NA	
Species connectivity	Not an indicator	NA	
Viable propagule bank	Not an indicator because it completes its life cycles in the ocean & has no resting stage although it is long-lived (Walter & Ebert 1991)	NA	
No barriers to recruitment	Not currently an indicator	NA	Location of 'pupping' areas
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Not an indicator because it is only present in C when the MM is functionally open, so residence times must be finite	NA	
Regional hydraulically connected	Bronze-whaler sharks is most common along the Coorong O beach & occasionally enter C thus require exchange of between O & C to be present in C	Distribution; Abundance in C	Frequency of time present in C

Indicator species: Bronze-whaler shark, *Carcharhinus brachyurus*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Longitudinal biological connectivity	Indicator through lower-order trophic ecology & availability of prey items from upstream of site	Food web structure – gut contents	
No accumulation of pollutants	Not an indicator because it would not be easy to link tissue composition to pollution from the site	NA	
Lateral habitat diversity	Not an indicator	NA	
Habitat variability	Not currently an indicator because habitat use in the site is unknown	NA	Habitat use within C
Range of salinities with appropriate maxima	Species not observed in salinities greater than marine (Kailola *et al.* 1993), thus indicative of marine species only	Abundance; Distribution	Preferred salinities
Temporal variability in salinity	An indicator for estuarine to marine salinities	Abundance; Distribution	
Communities requiring varied salinities supported	An indicator for estuarine to marine salinities	Abundance; Distribution	
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Not currently an indicator, although flow may be what attracts this sp. to the region as a signal for food, but this mechanism is not currently well-understood	NA	Cues attracting sp. to C
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Requires access to permanently-inundated habitat	Abundance – in general & CPUE	
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Not an indicator	NA	
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Increases in abundance could indicate a shift towards residence as opposed to current status as rare opportunistic forager in C	Abundance – In general & CPUE	
Acid- & saline-tolerant & terrestrial species	Increases in abundance may indicate a shift towards marine species inside the C	Abundance – In general & CPUE	

Indicator species: Bronze-whaler shark, *Carcharhinus brachyurus*			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
present			
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Indicative of aquatic habit only	Distribution; Abundance – In general & CPUE	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

8.18 Discussion

In total 17 fish species were selected as indicators of achievement of the ecological outcomes detailed in Chapter 3, including species with a range of habitat preferences from freshwater to estuarine and marine (see Table 8.18). The highest number of outcomes against which a fish indicator scored was 22 out of a possible 33 outcomes by Yarra pygmy perch and the lowest was nine out of 33 (18%) by the bronze-whaler shark and short-headed lamprey.

Yarra pygmy perch is a small-bodied native freshwater fish restricted in distribution to parts of Lake Alexandrina, associated with very specific habitats that support submerged and other in-stream aquatic vegetation. Its diet includes microcrustaceans, molluscs and aquatic insects, and the species can only tolerate very modest salinities (~3 ppt; McNeil & Hammer 2007). These very specific requirements mean that the species can be applied as an indicator of many outcomes. Five other species (golden perch, Murray hardyhead, congolli, common galaxias and small-mouthed hardyhead) were indicators for 20 out of a possible 33 outcomes. Yarra pygmy perch is believed locally extinct in the wild and recovery will depend on environmental recovery and returning captured fish to the wild – a process that was underway at the time of writing (A. Hall pers. comm.). Its use as an indicator is predicated on the success of this process or its use as an indicator would need to be re-evaluated.

The bronze-whaler shark is a vagrant marine visitor to the site that would only be observed rarely if the Coorong were a healthy, productive and resilient wetland. As such, bronze-whaler sharks are only indicative of the relatively few outcomes being achieved that relate to exchange between the ocean and the Coorong and increased relative proportions of marine species. Similarly, short-headed lamprey, a primitive, native, medium-sized diadromous (anadromous) species that spends the majority of its adulthood in estuaries or at sea and migrates upstream into rivers to spawn is an indicator for a narrow band of outcomes focussed on flow and functional connectivity. Interestingly it was one of only three species that acted as an indicator for a tidal signal being apparent, so may give specific information that other indicators may not provide.

Murray cod scored against 15 outcomes (48%) even though significant knowledge gaps exist surrounding the use of the site by juveniles of this species. Furthermore, the local populations are considered to be in poor condition with a significant recruitment event below Lock I not being observed since 1994 (Ye *et al.* 2000). If populations recover, or if spawning is detected in the Lower Lakes, the outcomes that Murray cod are considered to provide evidence for should be re-evaluated because it was assumed that Murray cod are unlikely to be spawning below Lock 1 or in the Lakes.

Across the 17 fish indicator species, evidence can be found for all but three of the possible 33 outcomes (9%). Those three outcomes (Viable propagule banks, Efficient nutrient cycling and Regular oxidation of sulfidic material) relate primarily to other biotic groups (e.g. microbes and vegetation) so, although fish may indirectly respond to the achievement of these outcomes, there are other indicators that would be better suited to act as indicators for those outcomes. For some outcomes, such as Suitable food resources and Suitable water quality, it will be necessary to look at evidence from a range of fish species to determine whether or not the overall outcome has been achieved. The process indicator suite goes some way to providing indicators that involve multiple species, but a specific suite of fish may also be needed. Evidence for outcomes such as those relating to salinity gradients (e.g. Range of salinities with appropriate maxima) can be based on fish that are more or less tolerant of salinity (e.g. small-mouthed hardyhead are more tolerant than yellow-eyed mullet and black bream). An assessment of the need to include additional taxa not listed here to improve assessment of redundancy (i.e. inclusion of benthic small bodied euryhaline/estuarine species such as gobies, or the inclusion of invasive predatory species such as redfin) should be undertaken as a part of future work, but redundancy is also potentially better covered by other indicators suites, such as ecological processes.

The key outcomes representing a healthy, productive and resilient wetland for the Coorong, Lower Lakes and Murray Mouth region incorporate all major factors (i.e. flow regime, connectivity, tolerance limits, habitat availability and resource needs) that may influence the distribution and abundance of fish species within this site. Thus, the fish species used here are expected to provide good evidence of that the ecological objectives and outcomes are going likely to be met for the region.

Table 8.18 Summary of outcomes represented by the fish indicators

Note: A tick denotes the taxa are an indicator for that outcome. All scientific names and further information can be found in the text above. Note that the quality and spatial extent of data available varied between taxa, as prescribed in the individual sections above. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

	Outcome / Fish	Murray cod	Golden perch	Bony herring	Australian smelt	Murray hardyhead	Yarra pygmy perch	Common carp	Congolli	Common galaxias	Short-headed lamprey	Yellow-eyed mullet	Black bream	Small-mouthed hardyhead	Mulloway	Sandy sprat	Australian salmon	Bronze-whaler shark	**Count**
Self-sustaining populations	Successful recruitment		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					**12**
	Suitable habitat		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		**15**
	Suitable food resources	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		**15**
	Suitable water quality	✓	✓		✓	✓	✓		✓					✓	✓		✓		**9**
Population Connectivity	Species connectivity	✓	✓								✓			✓	✓	✓	✓		**7**
	Viable propagule bank																		**0**
	No barriers to recruitment	✓	✓		✓	✓	✓	✓	✓	✓	✓				✓	✓	✓		**12**
Hydraulic Connectivity	Lateral hydraulic connectivity		✓	✓		✓	✓	✓	✓	✓	✓	✓		✓		✓			**10**
	Water residence times finite	✓	✓	✓	✓		✓							✓	✓	✓	✓		**9**
	Regional hydraulically connected	✓	✓		✓	✓			✓	✓	✓		✓		✓	✓	✓	✓	**12**
	Longitudinal biological connectivity		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	**15**
	No accumulation of pollutants	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓		**14**
Habitat Complexity	Lateral habitat diversity			✓		✓	✓	✓	✓	✓	✓		✓						**8**

	Outcome / Fish	Murray cod	Golden perch	Bony herring	Australian smelt	Murray hardyhead	Yarra pygmy perch	Common carp	Congolli	Common galaxias	Short-headed lamprey	Yellow-eyed mullet	Black bream	Small-mouthed hardyhead	Mulloway	Sandy sprat	Australian salmon	Bronze-whaler shark	**Count**
	Habitat variability			✓		✓	✓	✓	✓	✓	✓	✓							**8**
Salinity Gradients	Range of salinities with appropriate maxima	✓	✓				✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	**11**
	Temporal variability in salinity	✓	✓			✓	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	**12**
	Communities requiring varied salinities supported								✓	✓			✓	✓			✓	✓	**6**
Flow and Water level	Temporal variability in flow	✓	✓								✓		✓						**4**
	Seasonal variability in flows		✓						✓	✓	✓		✓		✓				**6**
	Seasonal variability in water levels			✓			✓	✓											**3**
	Communities requiring varied hydrology supported	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	**17**
	Communities requiring flooding supported	✓				✓	✓	✓											**4**
	Tidal signal apparent								✓	✓						✓			**3**
Ecological function	Complex food webs present	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓		**14**
	Functions performed by multiple species							✓											**1**
	Efficient nutrient cycling																		**0**
	Control of invasive species							✓										✓	**2**
	Acid- & saline-tolerant & terrestrial species present	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓			✓	✓	**12**

	Outcome / Fish	Murray cod	Golden perch	Bony herring	Australian smelt	Murray hardyhead	Yarra pygmy perch	Common carp	Congolli	Common galaxias	Short-headed lamprey	Yellow-eyed mullet	Black bream	Small-mouthed hardyhead	Mulloway	Sandy sprat	Australian salmon	Bronze-whaler shark	**Count**
Aquatic-terrestrial connectivity	Wide riparian & littoral zones supported				✓	✓	✓	✓		✓				✓					**6**
	Lateral connectivity of vegetation					✓	✓	✓		✓				✓					**6**
	Balance of aquatic & terrestrial species	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	**17**
	Exchange between aquatic & terrestrial systems		✓		✓	✓	✓	✓	✓	✓				✓					**9**
	Regular oxidation of sulfidic material																		**0**
	Count	**15**	**20**	**14**	**15**	**20**	**22**	**19**	**20**	**20**	**9**	**13**	**16**	**20**	**15**	**14**	**16**	**9**	

9. Ecological process indicators

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This section follows Chapters 6, 7 and 8, which outlined the vegetation, macroinvertebrate and fish indicators of ecological condition in the CLLMM region. This section provides a detailed description of the ecological processes selected as indicators for the region and their links to each of the ecological outcomes (Chapter 3).

Ecological processes are those processes that naturally occur within an ecosystem, such as the Coorong and Lower Lakes ecosystems. Ecological processes differ from physical and chemical processes in that they involve a change or a response in the ecological functioning of the system, rather than simply a physicochemical response. Ecological processes thus occur between individual organisms, within populations or among communities. Counts of species or other taxa (or any other descriptive elements) within an ecosystem are static or structural descriptors of that ecosystem, whereas processes are more applicable to functions occurring within the system, and are best assessed by measuring rates of the processes. Focussing upon such rates at the ecosystem level is still reasonably novel (Fairweather 1999a). Where they do measure rates, most traditional indicators, on the other hand, tend to focus on physiological or biochemical (i.e. at sub-organism level) or physicochemical variables.

Using ecological processes as indicators is a relatively new concept, and is not frequently applied in the management of aquatic ecosystems. Despite this, there are many significant advantages to using processes as an alternative, or in addition, to more-traditional species- or assemblage-based indicators (as argued by Fairweather 1999a, 1999b). A major advantage is that process indicators tend to integrate responses across multiple species. This means that large-scale ecological function is easier to target and interpret for some processes than is the case for species- or assemblage-based indicators. Other advantages include that processes can be easy to measure, can more directly reflect the consequences of ecological change, and can provide an early warning of changes in ecological character, before long-lived organisms have died out from a particular ecosystem.

In attempting to relate process indicators to the ecological outcomes specified for the CLLMM region, as a part of the development of an EWR for the region, we have focused specifically on the outcomes, and have concentrated upon identifying which processes are relevant based on our current knowledge (Table 9.1). Thus, it is possible (or likely) that the processes listed may also be relevant to additional outcomes. However, in some instances, our understanding of the links between the process and the outcome is incomplete; in others ground-truthing is lacking or a protocol for measurement and interpretation has yet to be developed.

Finally, there are many instances where outcomes, as stated, refer to hydrological (or other) variables that can be more-easily measured directly (e.g. by flow loggers or mapping of flood waters), rather than via these process indicators. In these instances, the process indicators may still be relevant to provide further information regarding the ecological consequences of those variables (e.g. the ecological response to flow) but, as stated, the ecological process is considered to be a rather round-about manner of achieving the same answer as is provided by direct physical or chemical measurements.

Table 9.1: Summary of outcomes represented by the process indicators

Note: * denotes the process as a vital indicator for that outcome, ✓ denotes the process as an important indicator for that outcome, ? denotes that the process may be an indicator but there may be better or more-direct indicators (e.g. one for which adequate data are available) for that outcome and a blank cell denotes that the process is not an indicator for that outcome. Counts are the total number of outcomes represented (i.e.*, ✓ and ?) for each class of processes or within the process indicators. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

	Outcome	Process	Photosynthesis	Decomposition	Nutrient cycling	Functional connectivity	Salinity	Acid/base	Sediment	Water clarity	Terrestrialisation	Colonisation	Bioaccumulation	Food-web functionality	**Count**
Self-sustaining populations	Successful recruitment			✓		?						*			**3**
	Suitable habitat		?		?		?		?	✓	✓		?	✓	**8**
	Suitable food resources		*	✓	✓							?		*	**5**
	Suitable water quality			?			?	?		✓			?		**5**
Population Connectivity	Species connectivity			✓		*									**2**
	Viable propagule bank					?						*			**2**
	No barriers to recruitment				✓	?						✓			**3**
Hydraulic Connectivity	Lateral hydraulic connectivity			?		?					*				**3**
	Water residence times finite														**0**
	Regional hydraulically connected				?	?									**2**
	Longitudinal biological connectivity		✓	✓	*									*	**4**
	No accumulation of pollutants								✓		*		*		**3**
Habitat Complexity	Lateral habitat diversity			?					✓						**2**
	Habitat variability			?							?				**2**
Salinity Gradients	Range of salinities with appropriate maxima						*								**1**
	Temporal variability in salinity						✓								**1**
	Communities requiring varied salinities supported						✓								**1**
Flow and Water level	Temporal variability in flow				?										**1**
	Seasonal variability in flows										?				**1**
	Seasonal variability in water levels			?											**1**

	Outcome / Process	Photosynthesis	Decomposition	Nutrient cycling	Functional connectivity	Salinity	Acid/base	Sediment	Water clarity	Terrestrialisation	Colonisation	Bioaccumulation	Food-web functionality	**Count**
	Communities requiring varied hydrology supported		?							*				**2**
	Communities requiring flooding supported				?					*				**2**
	Tidal signal apparent													**0**
Ecological function	Complex food webs present	✓	*										*	**3**
	Functions performed by multiple species	*	*	*									*	**4**
	Efficient nutrient cycling	✓	*	*									✓	**4**
	Control of invasive species				?						✓			**2**
	Acid- & saline-tolerant & terrestrial species present					✓	✓	?	✓			✓		**5**
	Wide riparian & littoral zones supported													**0**
Aquatic-terrestrial connectivity	Lateral connectivity of vegetation													**0**
	Balance of aquatic & terrestrial species	?								*				**2**
	Exchange between aquatic & terrestrial systems		*	*	?								✓	**4**
	Regular oxidation of sulfidic material						✓			?		?		**3**
	Count	**7**	**14**	**9**	**9**	**6**	**3**	**4**	**3**	**9**	**5**	**5**	**7**	

9.1 Photosynthesis

Photosynthesis is actually two linked processes, each with multiple steps, where the two stages are light reactions and the Calvin cycle (Campbell *et al.* 1999). The light reactions are the steps of photosynthesis that convert energy from the sun to chemical energy in the form of two compounds NADPH (a source of energised electrons) and ATP (energy currency of cells) (Campbell *et al.* 1999). The Calvin cycle reduces fixed carbon (i.e. incorporating CO_2 from the air into organic molecules) to carbohydrate (in the form of sugar) by the addition of electrons (Campbell *et al.* 1999). It is the Calvin cycle that makes the sugar, but it does so with the help of the compounds (i.e. NADPH and ATP) produced by the light reactions (Campbell *et al.* 1999). Photosynthesis by macrophytic plants, phytoplankton and benthic algae is the pathway for carbon fixation from the atmosphere into aquatic ecosystems (i.e. including wetland ecosystems), the building of tissues by these photosynthetic organisms and the process by which conversion of nutrients from the water column and sediments become available for use by other trophic levels (via decomposition of detritus or consumption by herbivores; Begon *et al.* 1990).

Environmental variables affect the photosynthesis of aquatic plants by regulating the photosynthetic process directly and by modifying the pigment and enzyme concentrations which define the reaction kinetics of the process (Sand-Jensen 1989). The main environmental factors usually considered are light, temperature, dissolved inorganic nutrients (e.g. carbon and dissolved oxygen) and water movement (Sand-Jensen 1989). The regulation of photosynthesis by environmental resources and the fate of the resulting production in herbivore consumption, detrital conversion and organic carbon storage have been extensively studied (Cebrian & Duarte 1994, 1995, Sand-Jensen 1997). Measurements of photosynthesis are needed for comparing and understanding productivity (biomass accumulation) of vegetal systems at the leaf, plant or community level as well as their response to environmental issues (Millan-Almaraz *et al.* 2009). Measurements of photosynthesis are also important in understanding the fluxes of carbon and the mechanistic relationships between vegetation types (e.g. physiological activity or energy transfer) (Gamon *et al.* 1995).

Photosynthesis can be measured at two separate scales; the plant scale using Pulse-Amplitude-Modulated (PAM) Fluorometry, and at the larger scale (e.g. at a stand scale) using remote sensing techniques. PAM Fluorometry is a standard technique for directly measuring photosynthesis using a type of electromagnetic spectroscopy that uses light to excite electrons in the photosynthetic tissue to yield a measure of photosynthetic activity. Remote sensing techniques include the Normalised Difference Vegetation Index (NDVI), which is a numerical indicator derived from remote sensing measurements (typically from satellite) that can be used to determine whether the target image contains live green vegetation or not. NDVI has been shown to be directly related to the photosynthetic capacity of plant canopies (Sellers 1985; Myneni *et al.* 1995). Table 9.2 links photosynthesis to the specified ecological objectives.

Table 9.2: List of ecological outcomes that would be indicated by photosynthesis. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Process indicator: Photosynthesis			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Not an indicator	NA	
Suitable habitat	Photosynthetic pigment composition could be a major factor determining which species of aquatic plants grow where, potentially indicating whether suitable habitat exists, e.g. different major groups (like algae) are not mixed at random, domination of any type is not usually complete & progressive changes in proportions of different groups along a depth gradient can often be discerned (i.e. zonation is the variation of the light field with depth) (Kirk 1983)	Changes in photosynthetic activity in space & time – pigment composition	
Suitable food resources	The presence of photosynthesis would indicate food sources (such as terrestrial & aquatic vegetation) exist for a variety of herbivorous species	Changes in photosynthetic activity in space & time	
Suitable water quality	Not an indicator	NA	
Species connectivity	Not an indicator	NA	
Viable propagule bank	Not an indicator	NA	
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Not an indicator	NA	
Longitudinal biological connectivity	Photosynthesis is the fundamental pathway for carbon fixation & resultant plant growth cycles nutrients from inorganic to organic forms, which may indicate exchange of energy, nutrients & carbon	Changes in photosynthetic activity in space & time; Changes in the rate of an identified process - photosynthesis	
No accumulation of pollutants	Not an indicator	NA	
Lateral habitat diversity	Not an indicator	NA	

Process indicator:	**Photosynthesis**		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Not an indicator	NA	
Temporal variability in salinity	Not an indicator	NA	
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Not an indicator	NA	
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	The role of biodiversity in ecosystem processes (such as photosynthesis) is high (Duarte 2000), therefore, the presence of photosynthesis may be indicative of the composition (rather than the abundance) of the community present (Duarte 2000)	Changes in photosynthetic activity in space & time – pigment composition	Potential of photosynthesis to indicate community composition or diversity
Functions performed by multiple species	The presence of photosynthesis through space & time would indicate multiple vegetative species are present which can perform similar functions (e.g. acting as a food source for herbivores)	Changes in photosynthetic activity in space & time; Changes in the rate of an identified process - photosynthesis	Potential for photosynthesis (including rates & pigment composition) to act as an indicator for dependent species (e.g. shredders, herbivores)
Efficient nutrient cycling	Photosynthesis is the fundamental pathway for carbon fixation & resultant plant growth cycles nutrients from inorganic to organic forms	Changes in photosynthetic activity in space & time - PAM fluorometry & NDVI scores	
Control of invasive	Not an indicator	NA	

Process indicator: Photosynthesis			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
species			
Acid- & saline-tolerant & terrestrial species present	Not an indicator	NA	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Photosynthetic pigment composition could be a major factor determining which species of aquatic plants grow where, potentially indicating whether the ecosystem supports a balanced mix of terrestrial & aquatic plants through space & time	Changes in photosynthetic activity in space & time – pigment composition	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

9.2 Decomposition

Decomposition is a combination of three major processes, including leaching, saprophytic decay and fragmentation of dead organic matter (Robertson & Mann 1980; Harrison 1982; Boulton & Boon 1991). Leaching is often described as the first stage of the decomposition process, where the initial and rapid loss of mass due to the leaching of water-soluble compounds occurs. Gessner *et al.* (1999) describe the leaching process as the release of solutes as dissolved organic matter (DOM), which can be influenced by the timing of leaf fall, prevailing weather conditions, channel and bank morphologies and vegetation species composition. The next stage of decomposition is the 'conditioning' stage which promotes the enhancement of leaf palatability for detritivores by microbial colonisation (Gessner *et al.* 1999). This 'preparation' of leaf material for invertebrate consumers (i.e. shredder feeders) is influenced by the chemical-structural modification of leaf material by the activity of microbes, especially fungi and bacteria (e.g. promoting loss of mass) (Gessner *et al.* 1999). The final stage of the decomposition process is the fragmentation of the leaf litter. This can be a physical process, where fragmentation of leaf litter is a result of abrasion and shear stress which can be exerted by flowing water (Gessner *et al.* 1999). Biotic fragmentation also occurs, where the comminution (i.e. breakdown into finer particles) of leaves through the feeding and digestive activities of shredders resulting in the release of fine particulate organic matter (FPOM) (Gessner *et al.* 1999). The rate at which these processes occur depends, among other factors, on the type of detritus (Walker & McComb 1985; Mews *et al.* 2006), the initial condition of the detritus (Harrison & Mann 1975), meio- and macrofaunal activities (Rieper-Kirchner 1990; Jedrzejczak 2002) and environmental conditions (Jedrzejczak 2002). Many of these factors are likely to be influenced by changes associated with freshwater inflow and may result in variability in decomposition rates across different spatial and temporal scales (Duong 2008).

The advantage of using the process of decomposition as an indicator of ecological condition is that rates of decomposition tend to integrate across all the factors listed above. Thus, by measuring the rate at which organic matter is decomposed, information is gathered about the type and condition of detritus available (assuming that locally-occurring detritus is used), a broad range of organisms (including bacteria, fungi, meiofauna and macrofaunal invertebrates, amongst others) and the environmental conditions, particularly where they limit decompositional pathways (e.g. due to extreme salinity). Assessment of some of these taxa could be done individually but most methods are selective in relation to size or expensive (e.g. microbes). Therefore, measuring the rate of the decomposition process is a case of being both more inclusive as well as easier.

Various techniques relating to the measurement of the decomposition process are presented in the literature, including deploying *in situ* leaf packs or cotton strips (to measure mass loss), rates of degradation of individual fractions (i.e. chemical constituents) and microbial respiration and/or biomass (Boulton & Boon 1991; Tiegs *et al.* 2007). Such techniques may be simple, but consideration is seldom given to the aspect of decomposition that is to be studied (Boulton & Boon 1991). In addition, the constituents of microbial assemblages, which are centrally involved in decomposition, are rarely examined in sufficient detail (Boulton & Boon 1991). Therefore the aims of any study should be clearly defined, rates of mass loss should not just be equated to rates of decomposition and the importance of other factors (e.g. environmental conditions, rates of microbial activity and macroinvertebrate functional groups) should be carefully considered in the study design (Boulton & Boon 1991).

While understanding the precise nature of the microbial assemblages contributing to decomposition in the region is a key knowledge gap, it is not one that would prevent the use of decomposition as a process indicator of ecological condition. Instead, through the use of that indicator and further developmental work, filling that knowledge gap would simply contribute to our ability to interpret changes in decomposition rates to ecological outcomes and objectives.

Although the process of decomposition may be complex, appropriate techniques and approaches and consideration of other related ecological processes (e.g. nutrient cycling) could provide further insight into important ecological linkages (e.g. terrestrial-aquatic). In addition, the rates of decomposition for a range of organic matter, under conditions typical of the CLLMM region, are not well known as yet. Table 9.3 links decomposition to the specified ecological objectives.

Table 9.3: List of ecological outcomes that would be indicated by decomposition. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Process indicator:	Decomposition		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	The process of decomposition is enhanced by macroinvertebrates; fine fragments are colonised by bacteria & fungi; therefore an indicator of successful recruitment of decomposers/detritivores (Dye 2006)	Changes in the rate of an identified process – decomposition, colonisation of litter bags	Which taxa to expect across all habitats
Suitable habitat	Not an indicator	NA	
Suitable food resources	Crucial part of the nutrient cycling process, through the regeneration of nutrients into the system, providing nutrient regeneration for primary producers, primary energy for detritivores & microbial components of the benthos (Dye 2006)	Changes in the rate of an identified process – decomposition; Detritus composition & condition – DOM & POM fractions	Alternative food webs supported by plants & phytoplankton (i.e. other sources of nutrients)
Suitable water quality	Although poor water quality conditions are a possible reason for no or slow decomposition, the decomposition process is not the best/most direct indicator for this outcome (e.g. would measure water quality properties, including temperature, salinity etc. instead of decomposition, the ecological process)	NA	
Species connectivity	Increasing the number & diversity of taxa contributing matter (i.e. via spatial connectivity) to the detrital bank can enhance the rates of mass loss; also the variability & diversity of organic matter sources in the system may indicate spatial connectivity; therefore detrital dynamics & sourcing of detritus is an important indicator for the exchange of species within the system (Gartner & Cardon 2004)	Changes in the rate of an identified process – decomposition; Detritus composition & condition; Changes in assemblage abundance through space & time – decomposers; Changes in assemblage diversity through space & time - decomposers	Not all sources of organic matter will be indicative of connectivity & those that are need to be identified
Viable propagule bank	Not an indicator	NA	
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic connectivity	Although variability in the decomposition rates, diversity of organic matter sources & detrital accumulation may be influenced by freshwater inflows, wetting/drying by seasonal flows	Changes in the rate of an identified process – decomposition; Detritus composition & condition – variability &	Period until breakdown & loss as indicator (i.e. how long it lasts)

Process indicator:	Decomposition		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
	or tides (Walker & McComb 1985; Jedrzejczak 2002; Mews *et al.* 2006), the decomposition process is not the best/more direct indicator for this outcome (e.g. would measure flow values instead of the process)	diversity of OM sources	
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Not an indicator	NA	
Longitudinal biological connectivity	Crucial part of the nutrient cycling process, through the regeneration of nutrients into the system, providing primary energy for detritivores & microbial components of the benthos (Dye 2006)	Changes in the rate of an identified process – decomposition; Detritus composition & condition	How the exchange of nutrients occurs
No accumulation of pollutants	Not an indicator	NA	
Lateral habitat diversity	Although the diversity of detritus sources may indicate that a diversity of habitat units exist within the site, the decomposition process is not the best/most direct indicator of this outcome (e.g. may be better to measure vegetation metrics, including diversity, distribution and cover)	Changes in the rate of an identified process- decomposition; Detritus composition & condition; Changes in assemblage abundance through space & time – vegetation cover; Changes in assemblage diversity through space & time - vegetation	
Habitat variability	Although variability in the decomposition rates are expected across space & in time depending on the type & initial state of detritus (Harrison & Mann 1975; Walker & McComb 1985; Mews *et al.* 2006), the decomposition process is not the best/most direct indicator of temporal & spatial variability in available habitats (e.g. may be better to measure changes in vegetation community structure, including distribution & diversity)	Changes in the rate of an identified process – decomposition; Detritus composition & condition – variability	
Range of salinities with appropriate maxima	Not an indicator	NA	
Temporal variability in salinity	Not an indicator	NA	
Communities requiring varied salinities	Not an indicator	NA	

Process indicator: Decomposition			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
supported			
Temporal variability in flow	Not an indicator	NA	Flow responses
Seasonal variability in flows	Not an indicator	NA	Flow responses
Seasonal variability in water levels	Although decomposition rates may vary due to the wetting/drying by tides (i.e. water levels) (Jedrzejczak 2002), the decomposition process is not the best/most direct indicator of this outcome (e.g. may be better to measure water level changes across temporal scales)	NA	
Communities requiring varied hydrology supported	Not a primary indicator although redox potential profiles & decomposition dynamics might differ across a variety of hydrological conditions	NA	Redox potential profiles & decomposition dynamics under different hydrological conditions
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Increasing the number of species contributing matter (i.e. via spatial connectivity) to the detrital bank can enhance the rates of mass loss (Gartner & Cardon 2004); decomposition is enhanced by the activity of macroinvertebrates that shred & ingest litter, producing fine fragments that are colonised by bacteria & fungi (i.e. detritivory) (Rieper-Kirchner 1990, Jedrzejczak 2002); therefore supporting complex & diverse food webs	Changes in the rate of an identified process – decomposition; Detritus composition & condition; Changes in assemblage abundance through space & time – decomposers; Changes in assemblage diversity through space & time – decomposers	Relative importance of detritivory to other food web processes (e.g. how brown is the community?)
Functions performed by multiple species	Relative proportions of POM & DOM, as well as presence of leaf litter, would indicate whether multiple species performing similar decomposition processes were supported	Detritus composition & condition – POM vs. DOM concentrations & leaf litter; Changes in assemblage abundance through space & time – decomposers; Changes in assemblage diversity through space & time - decomposers	Which taxa to expect
Efficient nutrient cycling	Leaching & fragmentation as part of the decomposition process are important in the regeneration of nutrients; crucial to wider nutrient cycling e.g. breakdown of emergent & submerged macrophytes & riparian vegetation provide primary energy for detritivores & microbial components of the benthos (Boulton & Boon 1991, Gessner *et al.* 1999)	Changes in the rate of an identified process – decomposition; Detritus composition & condition; Changes in assemblage abundance through space & time – decomposers; Changes in assemblage diversity through space &	Best metrics for identifying biogeochemical cycles in the field

Process indicator:	Decomposition		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
		time - decomposers	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Not an indicator	NA	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange between aquatic & terrestrial systems	Crucial part of the nutrient cycling process, through the regeneration of nutrients into the system, providing primary energy for detritivores & microbial components of the benthos (Dye 2006)	Changes in the rate of an identified process – decomposition; Detritus composition & condition; Changes in assemblage abundance through space & time – decomposers; Changes in assemblage diversity through space & time - decomposers	
Regular oxidation of sulfidic material	Not an indicator	NA	

9.3 Nutrient cycling

Nutrients are the substances that are metabolised by organisms to give energy and build tissue (Aldridge *et al.* 2009a). Macronutrients include carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and phosphorus (P) and these are required in greater amounts than micronutrients, such as iron (Fe) and chloride (Cl), which are only needed in small amounts. Cycling of nutrients from organic to inorganic forms and back again between sediments, the water column, living tissue, food and detritus is complex (Howard-Williams 1985; Hooper & Vitousek 1998; Aldridge *et al.* 2009a). It is affected by the availability of oxygen (e.g. drying previously inundated soils leads to the oxidation of reduced mineral phases which can affect phosphorus availability; Baldwin & Mitchell 2000), salinity (see Section 9.5) and other physicochemical factors. Nutrient cycling can also be affected by wetting and drying cycles (see Section 9.9), with nutrient availability varying widely as wetlands dry and refill (de Groot & van Wijk 1993; Qiu & McComb 1994; Baldwin & Mitchell 2000).

In addition to environmental factors, nutrient cycling is influenced by the biological communities within the system. Heterotrophic microorganisms, for example, play direct and indirect roles in phosphorus adsorption and desorption from sediments (Aldridge *et al.* 2009a). Benthic macroinvertebrates can also promote phosphorus release and uptake into the sediments; burrowing, filtering, feeding and excreting activity at the sediment-water interface can increase the amount of phosphorus released from the oxic sediments by disturbing the oxic layer (i.e. bioturbation) (Aldridge *et al.* 2009a). Phytoplankton and macrophytes access nutrients from the water column, converting them to organic forms that may be transferred up the food chain and therefore competing for nutrients and increasing overall demand for nutrients (Aldridge *et al.* 2009a). For example, most recycling occurs via the detrital pathway rather than living food chains as a way of mobilising the nutrients in dead organic matter. Thus, processes like scavenging and decomposition are a first step in the breakdown of dead organic matter (see Section 9.2). Further breakdown of dead organic matter comes from saprotrophs, especially fungi and bacteria.

The advantage of using the process of nutrient cycling as an indicator of ecological condition is that the rates of change of nutrient concentrations (e.g. nitrification vs. denitrification, inorganic vs. organic) enables an understanding of how the system functions. An understanding of how internal nutrient dynamics change under different conditions is essential to the management of the system, particularly for the influence of salinity, water level and water regime and the interactions between them (Aldridge *et al.* 2009a). Thus, the process of nutrient cycling can indicate the resilience of the system, whereby the types of nutrients available (and rates of change), the broad range of organisms and the environmental conditions which may limit (and/or enhance the nutrient cycles) can be investigated.

Nutrient cycling pathways, and in some cases relative rates, can be inferred by the concentrations and changes in concentrations of key nutrients (e.g. of nitrogen and phosphorus). Other metrics include rates of nitrification, denitrification, sulfate reduction rates, as well as total Kjeldahl nitrogen (TKN) and total phosphorus (TP) retention rates.

Although there have been some studies investigating changes in nutrient concentrations within the system (e.g. see Cook *et al.* 2008; Aldridge *et al.* 2009b), there are still important knowledge gaps. For example, there is a lack of knowledge within the Lower Lakes on internal flux rates and factors (i.e. environmental or biological assemblages) controlling the flux rates and how nutrient dynamics change under different conditions (e.g. how each respond to salinity, water regime and levels) (Aldridge *et al.* 2009a). Addressing these knowledge gaps and implementing long-term monitoring will assist the management of the region by identifying the mechanisms responsible for observed changes, enabling predictions about likely responses to climate change and management actions (e.g. flow alterations) can be made (Aldridge *et al.* 2009a). Table 9.4 links nutrient cycling to the specified ecological objectives.

Table 9.4: List of ecological outcomes that would be indicated by nutrient cycling. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Process indicator:	**Nutrient cycling**		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Not an indicator	NA	
Suitable habitat	Nutrient cycling can potentially indicate suitable habitat, as terrestrial & aquatic vegetation can affect nutrient cycling (DeAngelis 1980, Howard-Williams 1985, Hooper & Vitousek 1998) & relative resource use (including nutrients) increases as plant diversity increases (DeAngelis 1980)	Changes in the rate of an identified process – nutrient cycling by terrestrial plants; Changes in nutrient dynamics within the region	Role of phytoplankton & macrophytes which may influence nutrient dynamics within the system
Suitable food resources	Nutrient cycling may indicate suitable food resources exist for a variety of species (e.g. numerous species are dependent on a complex cycling of nutrients occurring through various components of an aquatic ecosystem (Aldridge *et al.* 2009a)	Changes in nutrient dynamics within the region	
Suitable water quality	Not an indicator	NA	
Species connectivity	Not an indicator	NA	
Viable propagule bank	Not an indicator	NA	
No barriers to recruitment	Nutrient cycling may indicate hydraulic connectivity & conversely a lack of connectivity, as nutrient cycling is strongly linked to the hydrologic cycle (Bormann & Likens 1967), & nutrient input & output are directly related to the volume of water moving into & out of an ecosystem (Bormann & Likens 1967)	Changes in nutrient dynamics within the region - across the hydrologic cycle	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Nutrient cycling may indicate hydraulic connectivity, as it is strongly linked to the hydrologic cycle (Bormann & Likens 1967) & nutrient input & output are directly related to the volume of water moving into & out of the ecosystem (Bormann & Likens 1967)	Changes in nutrient dynamics within the region – across the hydrologic cycle	
Longitudinal biological connectivity	Nutrient cycling may indicate hydraulic connectivity, as it is strongly linked to the hydrologic cycle (Bormann & Likens 1967) & nutrient input & output are directly related to the volume of water moving	Changes in nutrient dynamics within the region – across the hydrologic cycle	Indicators of disconnection

Process indicator:	Nutrient cycling		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
	into & out of the ecosystem (Bormann & Likens 1967)		
No accumulation of pollutants	Not an indicator	NA	
Lateral habitat diversity	Not an indicator	NA	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Not an indicator	NA	
Temporal variability in salinity	Not an indicator	NA	
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in flow	Nutrient cycling may indicate hydraulic connectivity, as it is strongly linked to the hydrologic cycle (Bormann & Likens 1967) & nutrient input & output are directly related to the volume of water moving into & out of the ecosystem (Bormann & Likens 1967)	Changes in nutrient dynamics within the region – across the hydrologic cycle	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Not an indicator	NA	
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Not an indicator	NA	
Functions performed by multiple species	Cycling of nutrients through space & time would indicate multiple species are present that are capable of performing similar functions	Changes in nutrient dynamics within the region – throughout the ecosystem	Nutrient budgets throughout the system, including the exchange of nutrients through numerous physical processes & biological components of the system

Process indicator: Nutrient cycling			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Efficient nutrient cycling	Rates of nutrient cycling may indicate appropriate biogeochemical pathways for nutrient cycling throughout the system	Changes in the rate of an identified process – nutrient cycling; Changes in nutrient dynamics within the region – throughout the ecosystem	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Not an indicator	NA	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange between aquatic & terrestrial systems	The exchange of nutrients between terrestrial & aquatic ecosystems may be indicated by the exchange of nutrients through various physical (e.g. erosion, run-off) & biological components (e.g. decomposition, deposition) of the system, culminating in nutrient availability for species such as macrophytes & streamside vegetation. Nutrients are also linked to the hydrologic cycle & may enter the terrestrial ecosystem via meteorologic means (Bormann & Likens 1967)	Changes in nutrient dynamics within the region – throughout the ecosystem	Nutrient budgets (inc. input, uptake & loss) throughout the ecosystem, including the link between aquatic & terrestrial ecosystems
Regular oxidation of sulfidic material	Not an indicator	NA	

9.4 Functional connectivity

Functional connectivity can be defined as the movement of individuals (or populations) or materials (e.g. organic matter in detrital dynamics) through and within the landscape across space and time. Connectivity can affect population demographics; including genetic composition (Lambeets *et al.* 2009) and community structure (Gallardo *et al.* 2008). Functional connectivity differs from physical connectivity in that physical connectivity implies that a connection exists (e.g. a fishway), while functional connectivity further requires that that physical connection is able to be used by individuals in a manner that allows the population to persist within the region.

An organism's presence can be telling of habitat quality *per se* (e.g. macroinvertebrates; Gallardo *et al.* 2008); while movement across the landscape (active habitat selection for those species that can easily disperse) can indicate that suitable habitat and food resources exist. Lack of movement or changes in rates of movement can also indicate levels of pollution, adverse chemical conditions (e.g. salinity) and barriers to connectivity (e.g. hydraulic connectivity), all of which can limit functional connectivity within the region.

The reliance of some taxa on off-site factors (e.g. wetland condition elsewhere in the flyway for migratory bird species) may also affect immigration and/or emigration, making the process of functional connectivity within the site difficult for interpreting some outcomes for some taxa.

The distributions of mobile taxa (i.e. taxa with mobile propagules and those that physically move as juveniles or adults) are important when considering functional connectivity within the system. The movement of certain taxa may be easily measurable (e.g. fish, macroinvertebrates, birds) but determining the effect of that movement upon community composition and genetic structure may prove time consuming and costly, depending on the taxa targeted and the methods chosen. However, it may be possible to measure aspects of functional connectivity in conjunction with recruitment.

How biotic factors (e.g. predation, competition) influence functional connectivity is largely unknown and constitutes a key knowledge gap for how this process should be interpreted within the CLLMM region. Patterns of use may also vary between waterway types, but little has been done to compare these patterns (Able 2005), thus representing another knowledge gap relating to this indicator process.

Table 9.5 links functional connectivity to the specified ecological objectives.

Table 9.5: List of ecological outcomes that would be indicated by functional connectivity. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Process indicator: Functional connectivity			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Although the consistency of population demographics & their development through time indicates successful recruitment which is linked to functional connectivity (Gallardo *et al.* 2008, Lambeets *et al.* 2009), the ecological process of functional connectivity may not be the best/most direct indicator of this outcome (e.g. may be better to use colonisation metrics, including changes in recruitment patterns & population demographics)	NA	Sources of recruits
Suitable habitat	Not an indicator	NA	
Suitable food resources	Not currently an indicator	NA	Relative impact of CLLMM specific changes in food availability compared with off-site impacts along the migration route
Suitable water quality	Not an indicator	NA	
Species connectivity	Functional connectivity (the exchange of taxa throughout all wetland units) is vital for ecosystem function. Genetic & taxon diversity & population demographics would identify functional connectivity occurring between habitat units	Changes in assemblage composition through space & time - mobile taxa, including migratory species; Changes in assemblage distribution through space & time - mobile taxa, including migratory species	Distributions of taxa across multiple habitats
Viable propagule bank	Although propagules are one source of colonist which may indicate functional connectivity within the system, the ecological process of functional connectivity may not be the best/most direct indicator for this outcome (e.g. may be better to measure vegetation metrics, including propagule viability, diversity & distribution)	Changes in population demographics; Changes in recruitment patterns through space & time – arrival of 'new' individuals	Balance of recruitment vs. migration
No barriers to recruitment	Although a lack of functional connectivity may indicate spatial, temporal or physical barriers preventing taxa movement, functional connectivity may not be the best/most direct indicator for this outcome (e.g. may be better to use colonisation metrics, including changes in recruitment patterns, population demographics & individual taxa distributions)	NA	How much to expect (i.e. know when there are barriers to connectivity)
Lateral hydraulic connectivity	Functional connectivity of aquatic taxa between waterbodies may indicate the presence of hydraulic connectivity, but it is not the	NA	

Process indicator:	Functional connectivity		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
	best/most direct indicator for this outcome (e.g. may be better to measure water quantity properties, such as flow)		
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Although a physical connection between wetland units allows mobile taxa to utilise adjacent habitat & the composition of these assemblages & their development through time is linked to functional connectivity, functional connectivity may not be the best/most direct indicator of this outcome (e.g. may be better to measure flow & water levels properties or changes in recruitment patterns & distribution of individual taxa)	NA	
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Not an indicator	NA	
Lateral habitat diversity	Not an indicator	NA	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Not an indicator	NA	
Temporal variability in salinity	Not an indicator	NA	
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied	Not an indicator	NA	

Process indicator:	Functional connectivity		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
hydrology supported			
Communities requiring flooding supported	Although the opportunistic use of floods to connect habitats (e.g. permanently-inundated & floodplain habitats) allows mobile taxa to move between habitats & may indicate functional connectivity, it may not be the best/most direct indicator (e.g. may be better to measure changes in flow, water levels & also recruitment patterns & population demographics)	NA	How big of a flood is enough to connect the variety of habitats?
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Not an indicator	NA	
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Identifying rates of movement between management units & the composition of local communities can indicate the dominance/uncontrollable spread of invasive taxa (where predominance of invasive taxa would be bad). Functional connectivity may not be the best/most direct indictor of this, for example it may be better to measure changes in community structure over time (i.e. proportion and distribution of native vs. invasive taxa)	NA	How to limit metric to connected species
Acid- & saline-tolerant & terrestrial species present	Not an indicator	NA	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange	Functional connectivity between aquatic & riparian zones is	NA	

Process indicator: Functional connectivity			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
between aquatic & terrestrial systems	indicative of a transfer of carbon between those zones (at least). However, the process of functional connectivity may not be the best/most direct indicator of the exchange of energy, nutrients & carbon between aquatic & terrestrial ecosystems (e.g. may be better to measure processes such as decomposition or nutrient cycling)		
Regular oxidation of sulfidic material	Not an indicator	NA	

9.5 Response to salinity dynamics

Water can be classified into four broad categories, freshwater (i.e. <2 ppt), estuarine (i.e. 2-20 ppt), marine (i.e. 20-40 ppt), and hypersaline (>40 ppt), although in reality, a gradient exists between the four. Biotic assemblages can be indicative of either one of these four states. However, a change in salinity (not only increasing but also potentially decreasing) can influence biotic population dynamics, connectivity, habitat complexity and ecological processes (Hart *et al.* 2003, Nielsen *et al.* 2003a).

Changes in salinity can directly or indirectly affect biota, making salinity dynamics a good indicator for numerous ecological objectives, including self-sustaining populations, salinity gradients and ecological function. Direct impacts of changes in salinity can include reduced fitness, growth, reproduction, and survival of individual populations. Indirect effects include impacts to community structure and function (e.g. removing species that could provide habitat or food), modifying predation pressure, limiting recruitment success, and the depletion of propagules (e.g. microinvertebrate eggs and aquatic plant seeds) (Nielsen *et al.* 2003b).

Salinity may directly or indirectly impact biota (Nielsen *et al.* 2003a) but the rates of change in salinity may also be influential on the survivorship and tolerance of fish, macrophyte and macroinvertebrate populations (Lester *et al.* 2008). For example, the steady and slow selective pressure often associated with climate change enables most biota to adapt to changing conditions, compared to biota subjected to sudden and extreme changes in salinity levels (James *et al.* 2003). Salinity dynamics are not as useful for indicating connectivity, as highly mobile species tend to be poor indicators of salinity (e.g. birds), avoiding unsuitable conditions by moving to more-favourable refugia rather than adapting to changing conditions (Lester *et al.* 2008). However, the interaction of increasing salinity and altered hydrological regimes can also have detrimental effects; for example, the combined effect of salinity and waterlogging had a greater detrimental impact on growth and survival of young plants (e.g. *Eucalyptus* and *Melaleuca*) than either factor alone (James *et al.* 2003).

Responses to salinity may also be a useful indicator for ecological objectives such as habitat complexity and connectivity, as increasing salinity can affect the physical environment, reducing the exchange of oxygen and nutrients through the establishment of a salt gradient, influencing light climate, and altering the cycling of energy and nutrients (Nielsen *et al.* 2003a), again via altering the conditions that are present, and thus the organisms that are able to thrive.

Generally, biodiversity decreases with increasing hypersalinity, but at a community-level the relationship between salinity and biodiversity is not a simple negative correlation (James *et al.* 2003) as estuarine and marine biota replace freshwater biota as salinities increase. For example in many estuaries, species number may decrease while population size increases. This may be due to species intolerant of higher salinities being lost and more-tolerant species taking their place within the community (James *et al.* 2003). Therefore, it is important to consider responses to salinity at both the species level and at the wider community level. Measurements should then encompass factors including changes in abundance, diversity, distribution and also changes in community composition via changes in the ratio of salt-tolerant and salt-sensitive taxa. Studies should include a range of taxa and life stages to assess the impact of changes in salinity within the system.

The effects of salinity dynamics on ecosystem processes (such as primary production, metabolism, respiration and denitrification, for example) are often unknown, particularly in combination with other potential stressors (e.g. changes in pH), and provide knowledge gaps for further research and development (Hart *et al.* 2003). Tolerance to salt levels (salinity thresholds) are known mainly for adults, however, salinity thresholds and the effects of changing salinity regimes are poorly known for many species, including larval or juvenile fish and invertebrates (Lester *et al.* 2008). In addition, our understanding of the resilience of freshwater taxa to salinity levels is limited, based on relatively few taxa, predominately aquatic macrophytes, invertebrates and fish (James *et al.* 2003). Hence, there are large gaps in our understanding of saline water management requirements of microbes, microalgae, riparian vegetation, amphibians, reptiles, mammals and waterbirds (James *et al.* 2003). As well as the taxa themselves, there are large knowledge gaps in relation to the interaction of salinity and other stressors, and the effect of salinity on plant-animal interactions.

Table 9.6 links response to salinity dynamics to the specified ecological objectives.

Table 9.6: List of ecological outcomes that would be indicated by the response to salinity dynamics. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Process indicator:	**Response to salinity dynamics**		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Not an indicator	NA	
Suitable habitat	Although aquatic and terrestrial habitats show both positive & negative responses to salinity & shifts in habitat assemblages are reflected through responses to salinity, this process indicator may not be the best/most direct indicator for the existence of suitable habitat. It may be better to measure vegetation community composition, cover & population demographics directly rather than associated with responses to salinity	NA	
Suitable food resources	Not an indicator	NA	
Suitable water quality	A range of salinity-tolerant & sensitive taxa (i.e. freshwater, estuarine & marine) would indicate that water quality is within tolerances for a variety of taxa for all life-history stages. Although the ecological responses to salinity dynamics may be a useful indicator, the best/most direct method would be to measure the physicochemical values as an indicator of water quality. The use of the process as an indicator may be necessary for taxa where salinity tolerances are poorly understood	Changes in population demographics; Changes in the ratio of two groups of taxa through space & time - salinity tolerant vs. sensitive	Maximum rate of change in salinity that can be accommodated by various taxa
Species connectivity	Not an indicator	NA	
Viable propagule bank	Not an indicator	NA	Tolerances of terrestrial vegetation to salinity
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic	Not an indicator	NA	

Process indicator:	Response to salinity dynamics		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
connectivity			
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Not an indicator	NA	
Longitudinal biological connectivity	Not an indicator	NA	Salinity interactions with nutrient & carbon processing
No accumulation of pollutants	Not an indicator	NA	
Lateral habitat diversity	Not an indicator	NA	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	A range of salinity tolerant & sensitive taxa would indicate a range of salinities is represented across the site	Changes in the ratio of two groups of taxa through space & time - salinity tolerant vs. sensitive	Tolerances of all individual taxa at various life history stages
Temporal variability in salinity	Taxa require a range of salinities for successful recruitment & completion of life cycles (e.g. fish larval & juvenile life stages are more sensitive to salinity changes than adults) (Nielsen *et al.* 2003a); hence the persistence of all life history stages is indicative that these variations do not exceed tolerances	Changes in the ratio of two groups of taxa through space & time - salinity tolerant vs. sensitive	
Communities requiring varied salinities supported	The presence of community structures characteristic of a variety of salinity regimes (e.g. salt tolerant and salt sensitive) are indicative of a diverse community & associated requirements	Changes in the ratio of two groups of taxa through space & time - salinity tolerant vs. sensitive	
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Not an indicator	NA	

Process indicator:	Response to salinity dynamics		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Not an indicator	NA	
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not currently an indicator	NA	Salinity interactions with nutrient & carbon processing & biogeochemical pathways
Control of invasive species	Not an indicator	NA	Whether other marine taxa can/will invade
Acid- & saline-tolerant & terrestrial species present	Shifts in community structure can indicate responses to changes in salinities, where an increase in the number of salt-tolerant taxa & a decrease in the more salt-sensitive taxa occurring in the region could indicate increasing salinity. Gradual changes in salinity could be tolerated at medium to long time scales (Lester *et al.* 2008)	Changes in assemblage composition through space & time – proportion of salt-tolerant & sensitive species; Changes in assemblage abundance through space & time – numbers of salt-tolerant & sensitive individuals; Changes in the ratio of two groups of taxa through space & time - salinity tolerant vs. sensitive	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator of balanced mix of terrestrial & aquatic vegetation, although indicating the types of species present (e.g. salt-tolerant)	NA	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

9.6 Response to acid/base dynamics

A crude definition of acidification is the process of decreasing pH (<7) while alkalinisation is the process of increasing pH (>7), where pH is a measure of the hydrogen ions in concentration on a logarithmic scale from 0 to 14. Acid/base dynamics can directly impact population and community structures, the distribution of vegetation and submerged aquatic macrophytes, fish and invertebrates, making ecological response to those dynamics a useful indicator for populations, connectivity, habitat complexity, and ecological function.

A reduction in pH (i.e. acidification) can result in changes to the composition and abundance of biota throughout the aquatic food web (Havens *et al.* 1993), influencing the composition and variety of food resources (McNicol *et al.* 1987). Acidification or alkalinisation can result in the successional shift in macrophyte community structure, depending on their acidity tolerance (Arts 2002). Alkalinisation encourages an increase in species richness of soft-water macrophytes, which cannot tolerate acidic conditions, and have a well-defined minimum pH of 5-6 (Arts 2002). Acidification, on the other hand, favours macrophytes that can tolerate acidic conditions. Both processes occur naturally and regularly within aquatic ecosystems, as a part of the wetting and drying cycle. The degree of change in assemblages will depend on the extent and rate of acidification or alkalinisation.

pH is the major abiotic factor controlling pelagic food web structure (Havens *et al.* 1993) affecting entire fish populations (Bendell & McNicol 1987) and causing widespread changes in zooplankton community structure (Havens *et al.* 1993). Biological changes resulting from acidification may result from indirect rather than direct effects of varying pH. For example, predator-prey relationships are influenced when fish populations decrease as a result of acidification, allowing predatory insects to increase (Bendell & McNicol 1987). Appropriate ecological function may also be compromised with decreasing pH, when macroinvertebrate (e.g. mayflies and chironomids) abundance and associated algal consumption are strongly reduced (Ledger & Hildrew 2004), for example.

Acidification and alkalinisation can significantly change the riparian vegetation community, accounting for substantial variation in the terrestrial ecosystem (Reuss *et al.* 1987). Excessive alkalinisation can reduce productivity, quality and limit the diversity of some vegetation (Wang *et al.* 2009). As the amount if inorganic carbon present in the water layers increases (i.e. as bicarbonate in water column as a result of alkalinisation), soft macrophytes are unable to tolerate these conditions are replaced by species more tolerant of alkaline water (Roelofs *et al.* 2002). Excessive acidification can be the major factor reducing plant species diversity (Roem *et al.* 2002). On the other hand, alkalinisation can positively influence the germination of certain marsh vegetation species (Roem *et al.* 2002). Reproductive performance in numerous bird species can be negatively impacted by acidification, whereas moderate levels of alkalinisation can positively influence the number of broods produced in relation to the number of nesting pairs (McNicol *et al.* 1987).

Changes in community structure and function in response to acid/base dynamics can be used to indicate self-sustaining populations, appropriateness of ecological function and aquatic-terrestrial connectivity. Some macrophytes can survive temporarily in acidified water, however they have lower fertility, a reduced production to biomass ratio, and suffer from growth deformations (Arts 2002), affecting the sustainability of communities. Acidification can also increase the concentration of metals in solution, increasing their bioavailability and hence concentration within macrophytes (Sparling & Lowe 1998), indicating potentially abnormal levels of pollutants.

Multiple taxa that can perform similar ecological functions may not be present under different acid/base regimes due to the strong influence pH has on community structures. Whether the resulting acid-tolerant assemblage may resist re-invasion when conditions return to pre-acidic condition remains a significant knowledge gap (Ledger & Hildrew 2004) or *vice versa* under alkalinisation.

The effects of acid/base dynamics can be measured by changes in population and process demographics and composition, the proportion of acid-sensitive to acid-tolerant species, and the tolerance, growth, and performance of different organisms/propagules under different acidity/alkalinity regimes. Table 9.7 links response to acid/base dynamics to the specified ecological objectives.

Table 9.7: List of ecological outcomes that would be indicated by the response to acid/base dynamics. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Process indicator: Response to acid/base dynamics			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Not an indicator	NA	
Suitable habitat	Not an indicator	NA	
Suitable food resources	Not an indicator	NA	
Suitable water quality	A range of both acid-tolerant & sensitive taxa would indicate that water quality is within tolerances for a variety of taxa for all life history stages. Although this response may be an indicator of water quality tolerance, this only represents one aspect of water quality & the better/most direct approach would be to measure physicochemical properties. The use of the process as an indicator may be necessary for taxa where acidity/alkalinity tolerances are poorly understood	Changes in the ratio of two groups of taxa through space & time - acid tolerant vs. sensitive	Acidity/alkalinity tolerances of all life history stages
Species connectivity	Not an indicator	NA	
Viable propagule bank	Not an indicator	NA	
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Not an indicator	NA	
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Not an indicator	NA	
Lateral habitat diversity	Not an indicator	NA	

Process indicator: Response to acid/base dynamics			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Not an indicator	NA	
Temporal variability in salinity	Not an indicator	NA	
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Not an indicator	NA	
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Not an indicator	NA	
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Changes in composition, abundance & distribution can indicate responses to changes in acid/base dynamics, where proportions of acid-sensitive taxa disappear &/or become locally extinct in areas affected by acidification	Changes in assemblage composition through space & time – proportion of acid-tolerant & sensitive taxa; Changes in the ratio of two groups of taxa through space & time – acid-tolerant	Specific information on acid sensitivity

Process indicator: Response to acid/base dynamics			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
		vs. sensitive	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator of a balanced mix of terrestrial & aquatic vegetation, although indicating the types of taxa present (e.g. acid-tolerant)	NA	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	The oxidation of acid sulphate soils indicates acidification, particularly areas which have been dry & sediments are exposed to air (Reuss *et al.* 1987); hence lack of variability in water levels	Changes in assemblage composition through space & time - benthic infauna; Changes in the ratio of two groups of taxa through space & time – acid-tolerant vs. sensitive	

9.7 Response to sediment dynamics

Turbidity, defined as the volume of fine sediment suspended within water, is a part of all naturally occurring systems and different rates and volumes of turbidity can alter the penetration of light through the water column (Henley *et al.* 2000) affecting local aquatic and terrestrial habitat, primary productivity and community structure (Johnston 1981, Henley *et al.* 2000).

Reduced water clarity can negatively affect pelagic and benthic primary productivity, reducing macrophyte biomass, growth and diversity (Porter *et al.* 2007; see Section 9.8), whilst increased sedimentation (the settlement of fine particles out of suspension; Henley *et al.* 2000) can smother benthic habitat, preventing sustainable populations, reducing community connectivity, and decreasing habitat complexity.

Self-sustaining and complex communities of submerged aquatic vegetation can reduce turbidity by slowing water movement and thus increasing the rate of sediment settlement and preventing re-suspension of fine particles (Clarke 2002), further promoting sustainability and community complexity in a positive feedback loop (Scheffer 1999, Kosten *et al.* 2009).

Benthic macroinvertebrate population dynamics are negatively affected by increased rates of sedimentation and turbidity (Henley *et al.* 2000), experiencing declines in abundance, diversity and a change in taxonomic composition. Direct impacts include the burial of macroinvertebrates, whilst the accumulation of fine sediment particles can affect fish and invertebrate respiratory and feeding structures (Strand & Merritt 1997, Martin & Neely 2001, Connolly & Pearson 2007). Indirect impacts can include smothering of food resources (e.g. microalgae for fish), altering the decomposition of plant detritus (Martin & Neely 2001) and reducing the visual range of some organisms (e.g. fish) (Davies-Colley & Smith 2001). Such impacts can prevent recruitment, alter suitable habitat and food resources, influence habitat complexity, and reduce or alter rates of ecological function (e.g. decomposition; see Section 9.2).

Sedimentation within an estuary can also influence pollution accumulation. As pollutants discharge into turbid waters, they can become bound to fine sediment particles (Bryan & Langston 1992) through a process known as adsorption. Depending on flow variability, pollutants can either pass through the system or accumulate, depending on whether particles remain suspended or settle out, and the relative rates of each can indicate hydraulic connectivity and flow variability. Thus, sediment dynamics within an aquatic ecosystem can influence the relative abundance of aquatic plants, the amount of pelagic and benthic primary productivity and the benthic macroinvertebrate populations present. In addition, through the influence of accumulated (or transported) pollutants, sediment dynamics also have the ability to influence other taxonomic groups. Either measuring the properties of the water and sediment themselves, or measuring the response in aquatic ecosystems to changes in sedimentation, can provide important information regarding the ecological condition of an aquatic ecosystem.

A Secchi disk is commonly used in highly turbid waters, whereas a 'black disk' measure can be used to record *in situ* water clarity in less turbid waters (Davies-Colley & Smith 2001). Turbidity can also be measured in the field with a nephelometer (Davies-Colley & Smith 2001). Suspended particles (seston) including sediments are measured by passing a known volume of water through a glass-fibre filter, and subsequently measuring the filtrate (Davies-Colley & Smith 2001). In addition, sediment traps may be used for measuring sedimentation rates *per se*. These simple field-based methods would suggest suspended sediment, turbidity, and water clarity could be measured in combination. Acoustic measurements can also be undertaken to capture bottom morphology, flow regimes, and suspended sediments simultaneously (Thorne & Hanes 2002). Table 9.8 links response to sediment dynamics to the specified ecological objectives.

Table 9.8: List of ecological outcomes that would be indicated by the response to sediment dynamics. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Process indicator:	**Response to sediment dynamics**		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Not an indicator	NA	
Suitable habitat	Although higher levels of sedimentation may alter habitats (e.g. via smothering, reducing macrophyte biomass & diversity & altering chemical properties of the substratum; Johnston 1981, Henley *et al.* 2000), the process indicator of responses to sediment dynamics may not be the best/most direct indicator of the existence of suitable habitat. For example it may be better to directly measure vegetation community metrics including demographics, cover & distribution or sediment & water quality variables.	NA	
Suitable food resources	Not an indicator	NA	
Suitable water quality	Not an indicator	NA	
Species connectivity	Not an indicator	NA	
Viable propagule bank	Not an indicator	NA	
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Not an indicator	NA	
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Sediment transport is also accompanied by the movement of pollutant substances, since many are strongly adsorbed to particles (i.e. minimising accumulation) (Bryan & Langston 1992); sediment can also be	Toxins in environmental media – chemical properties in sediment	

Process indicator:	**Response to sediment dynamics**		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
	considered a detrimental aquatic pollutant in itself, so turbid waters may also indicate the presence &/or accumulation of pollutants, as discharged pollutants rapidly bind to particle surfaces & become buried in substrata when they settle (Henley *et al.* 2000)		
Lateral habitat diversity	Sediment dynamics (e.g. higher levels of sediment, turbidity & erosion) can indicate a reduction in the diversity of habitat units across the site, e.g. reduction of macrophyte biomass, growth & diversity, mudflat & shoreline erosion (Bryan & Langston 1992)	Changes in assemblage composition through space & time – vegetation; Changes in assemblage abundance through space & time – vegetation cover; Changes in assemblage diversity through space & time – vegetation	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Not an indicator	NA	
Temporal variability in salinity	Not an indicator	NA	
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Not an indicator	NA	
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Not an indicator	NA	
Functions performed by	Not an indicator	NA	

Process indicator:	Response to sediment dynamics		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
multiple species			
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Shifts in community structure can indicate responses to changes in sediment dynamics (e.g. turbidity & sedimentation levels), where an increase in the number of taxa with higher tolerances & a decrease in sensitive taxa occurring in the region could indicate increased sedimentation & more turbid waters	Changes in assemblage composition through space & time – proportions of tolerant & sensitive taxa (i.e. to turbidity & sedimentation levels)	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

9.8 Response to water clarity

Growth in phytoplankton, as a response to increased nutrient enrichment (Schwarz & Hawes 1997) can result in alternation between two water clarity states; a clear- and a turbid-water state (Jeppesen *et al.* 1999), although in some systems, intermediate states are also possible. A reduction in water clarity can have two main biological effects, reduced light penetration for photosynthesis, and reduced visual range of sighted organisms (Davies-Colley & Smith 2001). The two states are therefore characterised by markedly different trophic structures (Jeppesen *et al.* 1999). Physical and biological processes within the aquatic ecosystem are affected between the two states, with community composition (Jeppesen *et al.* 1999), primary productivity (Schwarz & Hawes 1997) and species abundance/distributions (Kemp *et al.* 2005) all influenced. Clear-water ecosystems are usually dominated by submerged macrophytes, which form a positive feedback loop with increasing water clarity, by numerous physical and biological pathways, including the competition for light and nutrients with phytoplankton, providing refuge for zooplankton (Genkai-Kato 2007) and excreting allelopathic substances (i.e. biochemicals produced by some plants, algae, bacteria and fungi which influence the growth and development of other organisms) that inhibit the growth of phytoplankton (Hanson & Butler 1994, Jeppesen *et al.* 1999, Kosten *et al.* 2009), whereas the turbid-water state can be characterised by an almost complete lack of macrophytes (Jeppesen *et al.* 1999).

The relative importance of macrophytes and their influence on water clarity may vary depending on climate, lake morphometry, and variation in plant community composition and density (Jeppesen *et al.* 1999), presenting a knowledge gap for the effect of submerged macrophytes in the CLLMM region specifically. Interactions, mechanisms and rates of water clearing (by chemical, physical, or biological means) for this system are still unclear (Kosten *et al.* 2009).

Light attenuation (a measure of water clarity) can be measured by an inexpensive hand-held device in the field (Chen *et al.* 2007), although for broader applications (avoiding single measurements), the use of satellite remote-sensing has been suggested (Chen *et al.* 2007, Duan *et al.* 2009). Studies relating to submerged macrophytes can be more intensive due to increased costs and logistical issues. Remote sensing has been suggested as a promising tool for regionally assessing macrophytes but still has limitations (Nelson *et al.* 2006).

Water clarity can be affected by sediment dynamics (as indicated above; see Section 9.7), but also by phytoplankton concentrations and primary productivity. As a result, we are have considered response to water clarity as a separate indicator from response to sediment dynamics, although the two are somewhat overlapping. Here, in assessing the response to water clarity, we have focussed on biological interactions, but as sedimentation also plays a critical role in light attenuation, it could potentially be measured in conjunction with water clarity.

Table 9.9 links response to water clarity to the specified ecological objectives.

Table 9.9: List of ecological outcomes that would be indicated by the response to water clarity. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Process indicator:	Response to water clarity		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Not an indicator	NA	
Suitable habitat	A decrease in water clarity (from increased biomass & production of phytoplankton in response to increased nutrients & inorganic suspended sediments) can reduce macrophyte, seagrass & benthic microalgae biomass, growth & primary production (Hanson & Butler 1994, Schwarz & Hawes 1997). Increased water clarity can increase biomass, growth & primary productivity in aquatic plants, however dramatic increases in water clarity may indicate that biomass of phytoplankton is low which could impact on filter-feeding taxa (Jeppesen *et al.* 1999; Kemp *et al.* 2005)	Changes in assemblage composition through space & time – vegetation & phytoplankton; Changes in population demographics – vegetation & phytoplankton; Changes in water quality – nutrients & suspended sediments; Changes in the structure or complexity of food webs through space & time – switching between clear- & turbid-water states	
Suitable food resources	Not an indicator	NA	
Suitable water quality	An increase in nutrient loads & suspended sediments can decrease water clarity, causing a reduction in light availability for benthic plants, affecting their growth, biomass & productivity (Hanson & Butler 1994; Kemp *et al.* 2005). The relationship between water clarity & chemical variables such as nutrient loads can be highly non-linear, so measuring the ecological response can be more informative than simply measuring the chemical properties directly	Changes in assemblage composition through space & time – vegetation & phytoplankton; Changes in population demographics – vegetation & phytoplankton; Changes in assemblage distribution through space & time – vegetation & phytoplankton; Changes in water quality	
Species connectivity	Not an indicator	NA	
Viable propagule bank	Not an indicator	NA	
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Not an indicator	NA	

Process indicator: Response to water clarity			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Not an indicator	NA	
Lateral habitat diversity	Not an indicator	NA	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Not an indicator	NA	
Temporal variability in salinity	Not an indicator	NA	
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Not an indicator	NA	
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Not an indicator	NA	
Functions performed by multiple species	Not an indicator	NA	

Process indicator: Response to water clarity			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Shifts in community structure can indicate responses to changes in water clarity (i.e. turbidity levels), where an increase in the number of taxa with higher tolerances & a decrease in sensitive taxa occurring in the region could indicate reduced water clarity	Changes in assemblage composition through space & time – proportions of turbidity-tolerant & turbidity-sensitive taxa	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

9.9 Response to terrestrialisation (or re-wetting)

Terrestrialisation is essentially the drying out of aquatic habitats, creating a shift in biological populations and communities (i.e. from terrestrial to aquatic), especially plants. For example, terrestrialisation can result in a sequence of plants changing from submerged and free-floating aquatic plants to emergent reeds and other plants, followed by trees and shrubs that advance from the outer littoral zone towards the water through time (Kvet *et al.* 2002). Linked to the disappearance of water is the lengthening of dry periods and decrease in aquatic habitat size (area and depth). Decreasing depth may increase insolation (i.e. energy from sun) which, through changes in primary productivity and wind-induced aeration, may change water quality properties (particularly dissolved oxygen concentrations) (Williams 1996). In addition to changing water quality properties, terrestrialisation of a site may affect sediment properties (e.g. bioavailability of nutrients and metals), causing the ecosystem that develops on it to adapt (Vandecasteele *et al.* 2007).

Adaptations to these conditions vary among individual taxa, but members of the same major taxonomic groups tend to employ similar strategies (Williams 1996). For example, aquatic insects such as mayflies and mosquitoes largely survive drought via their egg stages and many beetles and hemipterans (bugs) survive as adults (Williams 1996). The rate at which terrestrialisation occurs depends on the total area of the water body, its bottom configuration, duration of an ecocycle (i.e. an ecosystem cycle, including the material circulation and the energy flow in an aquatic ecosystem) and on the relative areas initially occupied by submerged and/or emergent vegetation (Kvet *et al.* 2002). Hence, an advantage of using the terrestrialisation process as an indicator of ecological condition is that successional changes in vegetation communities and observations of other population and communities (e.g. macroinvertebrate community structure and presence/absence of fish communities) may provide information about hydrology (i.e. connectivity), water quality and the rate of change within the system.

The re-wetting of habitats (i.e. the reverse of terrestrialisation) can also influence the biological communities within a site, as a result of stress to changing water conditions. For example soil microbes may become physiologically stressed by re-wetting, with altered substrate properties (e.g. decreased substrate diffusion) leading to changes in metabolism and altered soil water potential leading to resource competition and starvation of terrestrial microbes (i.e. from osmotic stress; Griffiths *et al.* 2003). Shifts in plant communities may also occur, for example woody plants, which are sensitive to higher levels of inundation, may be eliminated and replaced with herbaceous species (Keddy 2000) and eventually aquatic species. Different life stages of plants are also impacted by re-wetting differently, with seedlings being more vulnerable than mature individuals (Tiner 1999). In addition to changing biological communities, re-wetting can also cause changes in the soil environment. For example, soil temperature is lower in flooded soils, acidic soils attain higher pH when flooded while alkaline soils decrease in pH and creating hypoxic (i.e. low dissolved oxygen concentrations) soil conditions (Tiner 1999; Keddy 2000).

Re-wetting also provides an opportunity for aquatic species to colonise new areas within a site. Aquatic plants, invertebrates, amphibians and fish may all expand in range as a result of re-wetting. For example, the re-introduction of hydraulic connectivity (i.e. re-wetting) may enhance fish passage, potentially increasing the diversity of fish within the system. Thus, the process of re-wetting not only influences the structure of the biological communities (e.g. succession and structure) but also the physical environment and resources upon which these communities rely (e.g. water and sediment properties, flow).

Finally, the regime of re-wetting or terrestrialisation in a region will play a significant role in determining the mix of species that are present. Frequent changes in the availability of submerged habitats will tend to favour amphibious species (i.e. species that can tolerate either wet or dry conditions) while infrequent changes would lead to clear boundaries between aquatic and terrestrial habitats and ecosystems. Thus observing rates of terrestrialisation can provide information about how the ecosystems respond to wetting and drying cycles and whether ecosystems have the capacity to withstand future changes.

Table 9.10 links response to terrestrialisation (re-wetting) to the specified ecological objectives.

Table 9.10: List of ecological outcomes that would be indicated by response to terrestrialisation (re-wetting). See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Process indicator: Terrestrialisation (re-wetting)			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Not an indicator	NA	
Suitable habitat	A mixture of terrestrial & aquatic habitats is a result of appropriate drying & re-wetting cycles, therefore terrestrialisation rates can indicate habitat diversity (e.g. presence of aquatic macrophytes, riparian vegetation & terrestrial plants)	Changes in recruitment patterns through space & time; Changes in population demographics – mixture of terrestrial & aquatic taxa; Changes in ratio of two groups of taxa through space & time - terrestrial vs. aquatic	
Suitable food resources	Not an indicator	NA	
Suitable water quality	Not an indicator	NA	
Species connectivity	Not an indicator	NA	
Viable propagule bank	Not an indicator	NA	
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic connectivity	Siltation accelerates the progressive infilling & terrestrialisation of aquatic habitats (Coiacetto 1996) & could thus indicate that hydraulic connectivity is limited; persistence & presence of aquatic taxa & habitats (e.g. linked to water exchange) could indicate that hydraulic connectivity is maintained. Changes in the relative proportions of terrestrial & aquatic taxa on floodplains would be indicative of changes in the level of hydraulic connectivity between the floodplains & permanent water bodies	Changes in assemblage composition through space & time, changes in ratio of two groups of taxa through space & time – terrestrial vs. aquatic	
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Not an indicator	NA	
Longitudinal	Not an indicator	NA	

Process indicator: Terrestrialisation (re-wetting)			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
biological connectivity			
No accumulation of pollutants	Increasing metal concentrations (e.g. Zn & Cd) in leaves & stems of plants can be a result of the process of terrestrialisation within the system (Vandecasteele *et al.* 2007)	Changes in the level of toxins in tissues in space & through time – plant uptake of pollutants; Toxins in environmental media – heavy metal concentrations in sediment	
Lateral habitat diversity	Not an indicator	NA	
Habitat variability	Hydraulic connectivity & therefore degree of terrestrialisation or re-wetting may indicate spatial variability in available habitats & changes in community composition (e.g. succession, terrestrialisation of species through time) may indicate temporal variability. However, the processes of terrestrialisation or re-wetting are not the best/most direct indicator of temporal & spatial variability in available habitats (i.e. it may be better to measure habitats directly, including vegetation populations demographics).	NA	
Range of salinities with appropriate maxima	Not an indicator	NA	
Temporal variability in salinity	Not an indicator	NA	
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	The colonisation of terrestrial species of plants & animals during drier phases & their replacement with aquatic species during periods of inundation could indicate that seasonality of flows exists. Although an indicator, the processes of terrestrialisation & re-wetting are not the best/most direct indicator for this outcome (e.g. may be better to measure temporal changes in flows)	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology	Changes in community composition, e.g. terrestrialisation of taxa (or re-wetting) could indicate that a limited range of hydrological conditions & subsequent taxa are supported	Changes in population demographics; Changes in assemblage composition through space & time – proportion of terrestrial &	

Process indicator: Terrestrialisation (re-wetting)			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
supported		aquatic taxa; Changes in ratio of two groups of taxa through space & time – terrestrial vs. aquatic	
Communities requiring flooding supported	Presence &/or persistence of aquatic taxa (particularly floodplain-dependent taxa & riparian taxa requiring occasional flooding) (all life history stages) could indicate that re-wetting is occurring; e.g. aquatic insects can become dormant & resume growth when water is restored & survive dry periods as eggs (Williams 1996)	Changes in population demographics; Changes in ratio of two groups of taxa through space & time – taxa with differing flooding requirements	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Not an indicator	NA	
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Not an indicator	NA	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Changes in community composition, e.g. terrestrialisation of taxa (or re-wetting), could indicate an imbalance in the mix of terrestrial & aquatic taxa through space & time	Changes in ratio of two groups of taxa through space & time – terrestrial vs. aquatic; Changes in assemblage composition through space & time – proportion of terrestrial & aquatic taxa	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	

Process indicator: Terrestrialisation (re-wetting)			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Regular oxidation of sulfidic material	Re-wetting after prolonged dry periods could influence biogeochemistry, e.g. acidification may be irreversible upon rewetting (Zedler 2000). Changes balance between terrestrial & aquatic taxa over short timeframes (e.g. mobile taxa, indicating that conditions varied between wet and dry) would indicate that re-wetting cycles were likely to be sufficient to prevent the accumulation of acidic material in the long term. However, the processes of terrestrialisation or re-wetting are not the best/most direct indicator of the rate of oxidation of sulfidic material (i.e. it may be better to measure acid potential & other sediment properties directly)	Changes in ratio of two groups of taxa through space & time - acid-tolerant vs. sensitive, & mobile terrestrial vs. aquatic; Toxins in environmental media – sediment quality properties	

9.10 Colonisation (including invasion)

Colonisation is the process whereby propagules (a reproductive segment of larger individual, capable of independent growth giving rise to a new individual; e.g. a seed for many vegetation species) or mobile individuals move into an area and become established in areas currently unoccupied by that species (i.e. recruitment dynamics; Bullock *et al.* 2002).

Different organisms have different modes of colonisation, which influences their ability to recolonise habitat (e.g. macroinvertebrates; Wallace 1990). Macroinvertebrate colonisation can occur during many different life stages (but not necessarily for a single taxon), the rate of which can depend on life-history traits, dispersal abilities and position within the stream network. Plants, on the other hand, are usually only mobile during their recruitment stage (e.g. through seed dispersal), limiting their distributive capacity.

Some taxa possess a resistant propagule phase, designed to protect the propagule against unfavourable conditions, allowing it to re-emerge when conditions become favourable (e.g. buried seed banks of *Ruppia* spp., delay of development stages [i.e. diapausing] in crustaceans). Many taxa will also suspend reproduction under unfavourable conditions and thus colonisation of new areas is highly unlikely without a return to favourable conditions. Many species will, however, persist for some time in sub-optimal conditions, whilst early life stages tend to be more sensitive to environmental conditions. This makes colonisation and recruitment a better indicator of current ecosystem health (and rehabilitation), or conversely ecological degradation, when compared with the simple presence or absence of a species. That is, detecting changes in colonisation patterns and recruitment rates will provide earlier information that conditions are more or less favourable than previously, without needing to wait for the appearance or disappearance of potentially-long-lived species. However, recruitment is variable in any timeframe or spatial scale, so this limits its usefulness more generally.

The colonisation of potentially invasive species may be difficult to predict, although the degree of mobility of each species and inhabitants of nearby regions (e.g. River Murray channel) can provide insight into the possible organisms that may colonise the Lower Murray Lakes (Lester *et al.* 2008). For example, the mechanism by which the estuarine tubeworm, *Ficopomatus enigmaticus*, has spread so rapidly is largely unknown, with current theory suggesting that low water levels (reverse head between Coorong and Lower Lakes) have allowed larger numbers of larvae to enter (Lester *et al.* 2008). The presence and predominantly the distribution (i.e. potentially colonising new or sensitive areas) of invasive species are important considerations in relation to their impact on other species (e.g. natives) and the system function. Wallace (1990) suggests some main areas of knowledge gaps, including:

- how biotic interactions (e.g. competition, predation) influence recovery of later colonists;
- how similar recolonisation mechanisms are (e.g. drift, aerial and upstream movements in streams of varying morphometry [i.e. shape]); and
- the effect of early-colonising species on the modification of resources and recovery of later colonists.

Table 9.11 links colonisation to the specified ecological objectives.

Table 9.11: List of ecological outcomes that would be indicated by colonisation. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Process indicator:	Colonisation		
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	The presence of a range of colonizing taxa (i.e. terrestrial & aquatic) would indicate successful recruitment of local breeding species	Changes in recruitment patterns through space & time – number of taxa recruiting; Changes in population demographics – number of young of year, presence of seedlings, presence of tadpoles etc.; Changes in assemblage composition in time – terrestrial & aquatic taxa	Recruiting stages of all taxa (i.e. identification of some taxa is difficult at these stages)
Suitable habitat	Not an indicator	NA	
Suitable food resources	Colonisation by certain taxa will only occur if suitable resources are available (e.g. food). Although, colonisation as an ecological process, it is not the best/most direct measure of food availability, with more direct measures (e.g. nutrient levels, taxa diversity & distribution) available as better indicators	Changes in recruitment patterns through time; Changes in population demographics	
Suitable water quality	Not an indicator	NA	
Species connectivity	Not an indicator	NA	
Viable propagule bank	Rates of colonisation can be influenced by the presence of viable plant & insect propagule banks, if ruderal (or early colonising) organisms possess a life-stage containing a resistant propagule phase	Changes in assemblage distribution through time - propagules; Changes in assemblage abundance through time – number of viable propagules; Changes in assemblage diversity through time –viable insect & plant propagules	
No barriers to recruitment	The presence of a range of colonizing taxa would indicate a lack of barriers to connectivity. For example, the distribution of invertebrates depends on their life-history strategies, where distributions of solely-aquatic life stages likely to be limited by hydraulic connectivity	Changes in population demographics; Changes in recruitment patterns through time	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Not an indicator	NA	
Longitudinal	Not an indicator	NA	

Process indicator: Colonisation			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
biological connectivity			
No accumulation of pollutants	Not an indicator	NA	
Lateral habitat diversity	Not an indicator	NA	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Not an indicator	NA	
Temporal variability in salinity	Not an indicator	NA	
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Not an indicator	NA	
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Not an indicator	NA	
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	

Process indicator: Colonisation			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Control of invasive species	The distribution & abundance of colonising taxa can indicate dominance &/or spreading of invasive species through the region	Changes in the ratio of two groups of taxa through space & time - invasive vs. non-invasive; Changes in recruitment patterns through space & time – colonisation rates of known invasive taxa; Changes in assemblage distribution through space & time –areal extent of invasive taxa; Changes in assemblage composition through space & time – proportion of invasive vs. non-invasive	
Acid- & saline-tolerant & terrestrial species present	Not an indicator	NA	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	Not an indicator	NA	

9.11 Bioaccumulation

Bioaccumulation is a useful indicator of self-sustaining populations and ecological function, where, for example, the concentration of metals in sediments act jointly in preventing recruitment, thus forcing the exclusion of, or limiting the distribution of, numerous taxa (e.g. benthic organisms) (Bryan & Langston 1992) or the accumulation of biomass (or bioaccumulation of carbon). Thus alterations in the rate of accumulation of biomass may indicate growth or contraction of a population or community. A reduction in organic pollution can result in higher (or lower) densities of prey species (depending on the tolerances of the taxa involved), leading to an increase (or decrease) in dependent species (e.g. wading birds; Bryan & Langston 1992). Higher levels of metal or organic pollutants may cause a decline in community density, composition, and changed behaviour (e.g. due to a decline in food species) (Bryan & Langston 1992). Self-sustaining populations are indicated by the negative relationships observed between metal concentration and weight, age or size of numerous taxa, as well as the response of larval and embryonic life stages, which are much more susceptible to bioaccumulation than adults (Bryan & Langston 1992). However, for both, it is likely that there may also be more-direct indicators than the process of bioaccumulation which may be easier to measure.

More than 90% of heavy metal load is bound to particulates of suspended particles and sediments through the process of adsorption (Calmano *et al.* 1993). Therefore, the transformation of metal forms in sediment and the re-mobilization of micropollutants by natural or artificial means are useful for indicating periodical flooding and hydraulic connectivity. The rate of carbon sequestration is strongly linked to an increase in sediment accumulation (i.e. it is a product of soil organic carbon density and the rate of soil vertical accretion, where soil vertical accretion contributes to soil surface elevation and evolution) (Howe *et al.* 2009), where a decline in soil carbon stores can indicate the re-introduction of flows, and the release of dissolved carbon can indicate residence times are finite.

Plants can directly or indirectly take up, sequester and degrade metals and contaminants (Cunningham & Ow 1996, Weis & Weis 2004), thus providing an important ecosystem service. The interactions between wetland plants and soil microbes play an important role in phytoremediation, as well as plant and microbial physiology, colonisation and survival and rates of photosynthesis and transpiration (Williams 2002). Submerged aquatic macrophytes also actively and passively circulate elements (Weis & Weis 2004), whilst phytoplankton provides the only means of phytoremediation in open waters (Williams 2002). However, toxic heavy metal contaminants can also be released above the surface of the water via senescent/dead plant material, tending to increase heavy metal bioavailability (Weis & Weis 2004) and the extra surface area provided by macrophytes seems to aid microbial breakdown of organic pollutants. The acute toxicity, speciation, and uptake or bioavailability of metals may also be indicative of a range of different salinities (Bryan & Langston 1992, Weis & Weis 2004).

The effects of bioaccumulation can be measured by changes in community composition and population demographics, rates of growth, recruitment, photosynthesis and productivity, as well as the chemical composition of sediments and biota, and the transport rate of pollutants.

Table 9.12 links bioaccumulation to the specified ecological objectives.

Table 9.12: List of ecological outcomes that would be indicated by bioaccumulation. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Process indicator: Bioaccumulation			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Not an indicator	NA	
Suitable habitat	Significant uptake of contaminants (e.g. heavy metals) into plant tissues can reduce plant growth rates, in turn reducing available vegetated habitats, but increased uptake of carbon may lead to increased cover of vegetated habitats (Weis & Weis 2004, Howe *et al.* 2009). However, bioaccumulation, as an ecological process, may not be the best or most-direct indicator of habitat availability (e.g. vegetation community metrics, including cover, diversity & distribution may be better indicators)	Changes in population demographics – vegetation growth rates over time; Changes in assemblage distribution through space & time – vegetation cover; Changes in assemblage composition through time – diverse vegetation assemblage	
Suitable food resources	Not an indicator	NA	
Suitable water quality	Embryonic & larval stages of organisms are far more sensitive to metals than adults, with conditions for successful settlement & establishment are critical (Bryan & Langston 1992); negative relationships have been established between metal concentration & weight, age &/or size observed in adults of different taxa, including mussels (Geffard *et al.* 2002). Although this response may be an indicator of water quality tolerance, it only represents one aspect of water quality & the better/most direct approach would be to measure physicochemical properties, provided tolerances were understood for all relevant taxa	Changes in population demographics – age & size structure; Changes in recruitment patterns through space & time –number of eggs, young of year, tadpoles etc.	Tolerances of all life-history stages for taxa of interest
Species connectivity	Not an indicator	NA	
Viable propagule bank	Not an indicator	NA	
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Not an indicator	NA	
Regional hydraulically	Not an indicator	NA	

Process indicator: Bioaccumulation			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
connected			
Longitudinal biological connectivity	Not an indicator	NA	
No accumulation of pollutants	Concentrations of heavy metals in sediments usually exceed those of overlying water by 3-5 orders magnitude (Bryan & Langston 1992); re-introduction of flows can reverse decline in soil carbon stores (i.e. lost through oxidation & decomposition), increasing the rate of carbon sequestration (Howe *et al.* 2009); riparian wetlands enhance degradation of non-point source inputs (e.g. increase remediation) (Williams 2002)	Changes in the rate of an identified process - oxidation & decomposition; Changes in assemblage distribution through space& time – vegetation; Changes in the level of toxins in tissues in space & through time – heavy metal concentrations	
Lateral habitat diversity	Not an indicator	NA	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Not an indicator	NA	
Temporal variability in salinity	Not an indicator	NA	
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Not an indicator	NA	
Communities requiring flooding	Not an indicator	NA	

Process indicator: Bioaccumulation			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
supported			
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Not an indicator	NA	
Functions performed by multiple species	Not an indicator	NA	
Efficient nutrient cycling	Not an indicator	NA	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Changes in the rate of accumulation of biomass or of pollutants within tissues are likely to be correlated with changes in the relative proportions of species that are tolerant of chemical conditions like acidity or salinity. How changes in bioaccumulation link to the changing proportion of each type of taxa is currently a knowledge gap, but could constitute a useful indicator in the future	NA	Relationships between bioaccumulation *per se* & the proportions of acid-, saline- or other pollutant-tolerant taxa
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange between aquatic & terrestrial systems	Not an indicator	NA	
Regular oxidation of sulfidic material	The mobilisation of heavy metals is an indicator of sediment acidification (Calmano *et al.* 1993), but other chemical measures are better/more direct indicators	Changes in the level of toxins in tissues in space & through time – heavy metal concentrations; Toxins in environmental media – sediment quality properties	

9.12 Food-web functionality

One of the most fundamental ways in which organisms interact within the environment is via how they acquire nutrition, so-called trophic dynamics. Food webs have been described (Paine 1988) as the "road maps" to community interactions (Polis & Winemiller 1996) and thus are a core research area within ecology (Menge 2008). An ecosystem's food web is a pictorial and numerical representation of 'who eats whom' within defined habitats but trophic interactions can be measured in many ways. For example, we could describe a food web by the number of and/or different types of interactions between different trophic levels or functional feeding guilds (FFGs; the grouping of taxa according to their feeding strategy) (Vander Zanden *et al.* 1999). Food-web structure regulates a variety of ecological patterns and processes (Vander Zanden *et al.* 1999), including feeding interactions and the flow of nutrients, carbon and energy across the entire ecosystem (Jepsen & Winemiller 2002).

Functional food webs would be a useful indicator for self-sustaining populations, the appropriateness of ecological functions occurring within an ecosystem and, to a more limited extent, hydraulic and aquatic-terrestrial connectivity. A balanced trophic structure and functional food-web would indicate the presence of suitable habitat for the successful breeding, feeding, shelter, and development of individuals, and that suitable food resources exist for a variety of species.

One overall measure of the health of an ecosystem can be attained by determining if the relevant apex predator(s) (i.e. species at the top of any food chain) is present and thriving in that ecosystem. Demonstrating this is important for a number of reasons: first, it suggests that the flow of energy and other resources through the rest of the food web is sufficient to maintain the very top of the tree; second, many top predators are larger and tend to move further than other organisms, and so they are naturally sparser but are the first species to disappear if conditions are poor; and third, these taxa are more likely to act as 'keystone predators' (*sensu* Paine 1969), thereby having enormous influence over many other species lower in the food web. Thus, the loss of apex predators represents the likelihood of much broader changes, e.g. the potential for 'trophic cascades' of influence tumbling down food chains and changing their character in massive ways (Paine 1969; Boyd *et al.* 2006; Myers *et al.* 2007; Stolzenburg 2008).

Redundancy and appropriateness of ecological function is especially indicated by functional food webs, where complex and diverse feeding guilds of numerous species are indicative of an appropriately diverse and complex food web. The relative richness of each functional feeding group is also used to indicate whether multiple species are present that can perform similar functions, giving the desirable property of systemic redundancy. Food web functionality and the presence of multiple feeding groups illuminate the effective pathways of cycling carbon, energy, and nutrients within the site. Food web functionality will also indicate the propensity for some trophic interactions between terrestrial and aquatic taxa, if the predominant domain of each taxon can be identified (Polis *et al.* 2004).

The effects of food web functionality can be measured by the relative proportions and representativeness of taxa within different functional feeding groups, relative food chain lengths and the diversity in the source of nutrients and carbon being utilised, as revealed by gut content and stable isotopic analyses.

Stable isotope ratios are useful for looking at the processes, connections and energy flow within and between aquatic and terrestrial ecosystems (Michener & Schell 1994, Collier *et al.* 2002), providing an energy flow-based measure of food web structure (Vander Zanden *et al.* 1999) and identifying the dominant pathways of carbon and nutrient transfer (Jepsen & Winemiller 2002).

Other approaches to food web analysis include gut content analyses, direct observation (in the field or laboratory) and radiotracer techniques. Yet, the collection of stable isotopes (including carbon, nitrogen, sulphur and hydrogen) is relatively inexpensive with the prevalence of automation (Michener & Schell 1994).

Table 9.13 links food-web functionality to the specified ecological objectives.

Table 9.13: List of ecological outcomes that would be indicated by food-web functionality. See Chapter 3 & Appendix B for details of abbreviated ecological outcomes.

Process indicator: Food-web functionality			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
Successful recruitment	Not an indicator	NA	
Suitable habitat	Successfully reproducing, recruiting & growing representatives from a range of FFGs would indicate suitable habitat exists for a variety of types of organisms (e.g. the presence of apex predators would indicate a suitable trophic pyramid; Paine 1980, Boyd *et al.* 2006, Stolzenburg 2008)	Changes in assemblage composition through space & time - presence of apex predators; Changes in recruitment patterns through space & time – range of FFGs; Changes in assemblage diversity through space & time –range of FFGs	
Suitable food resources	A functional food web would indicate appropriate food resources exist (e.g. a decrease in primary productivity can have a negative cascade effect through depleted food availability for lower trophic organisms, including zooplankton, macroinvertebrates & fish; Henley *et al.* 2000)	Changes in assemblage composition through space & time – presence of apex predators; Changes in the structure or complexity of food webs through space & time - relative proportions of FFGs, number of trophic levels, relative food chain lengths	Which taxa are at each trophic level
Suitable water quality	Not an indicator	NA	
Species connectivity	Not an indicator	NA	
Viable propagule bank	Not an indicator	NA	
No barriers to recruitment	Not an indicator	NA	
Lateral hydraulic connectivity	Not an indicator	NA	
Water residence times finite	Not an indicator	NA	
Regional hydraulically connected	Not an indicator	NA	
Longitudinal biological	Food-web functionality can illuminate the source & pathway of carbon, energy & other nutrients within an ecosystem	Changes in the structure or complexity of food webs through space & time - diversity in the sources of	

Process indicator: Food-web functionality			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
connectivity		nutrients, microbial C determination via BIOLOG plates (Barton 2006)	
No accumulation of pollutants	Not an indicator	NA	
Lateral habitat diversity	Not an indicator	NA	
Habitat variability	Not an indicator	NA	
Range of salinities with appropriate maxima	Not an indicator	NA	
Temporal variability in salinity	Not an indicator	NA	
Communities requiring varied salinities supported	Not an indicator	NA	
Temporal variability in flow	Not an indicator	NA	
Seasonal variability in flows	Not an indicator	NA	
Seasonal variability in water levels	Not an indicator	NA	
Communities requiring varied hydrology supported	Not an indicator	NA	
Communities requiring flooding supported	Not an indicator	NA	
Tidal signal apparent	Not an indicator	NA	
Complex food webs present	Diversity of FFGs (& their component taxa) would indicate complex & diverse food-webs exist across the site	Changes in the structure or complexity of food webs through space & time - range of FFGs; Changes in assemblage distribution through space & time - FFGs; Changes in assemblage diversity through space & time –FFGs; Changes in assemblage composition through space & time - FFGs	
Functions	FFGs are a simple way to determine what species are	Changes in assemblage diversity through space & time	

Process indicator: Food-web functionality			
Outcome	**Rationale**	**Metric**	**Knowledge gaps**
performed by multiple species	performing each function. The relative richness within each of these guilds would provide good evidence for whether multiple species were present to perform each of the functions	– diversity within FFGs; Changes in the structure or complexity of food webs through space & time - multiple taxa in each trophic level	
Efficient nutrient cycling	Food-web functionality can illuminate the source & pathway of carbon, energy & other nutrients within an ecosystem. The presence of multiple feeding guilds (either via qualitative assignment of taxa into guilds or isotope analysis) would elucidate the pathway of nutrients & carbon flow	Changes in the structure or complexity of food webs through space & time - diversity in the sources of nutrients (e.g. identified via stable isotope analyses); Changes in assemblage diversity through space & time –FFGs	
Control of invasive species	Not an indicator	NA	
Acid- & saline-tolerant & terrestrial species present	Not an indicator	NA	
Wide riparian & littoral zones supported	Not an indicator	NA	
Lateral connectivity of vegetation	Not an indicator	NA	
Balance of aquatic & terrestrial species	Not an indicator	NA	
Exchange between aquatic & terrestrial systems	A mix of terrestrial & aquatic trophic groups show a propensity for trophic interactions to cross these domain (habitat) boundaries (e.g. predation on aquatic insects & fish by terrestrial mammals, birds & invertebrates) (Collier *et al.* 2002)	Changes in the ratio of two groups of taxa through space & time – terrestrial vs. aquatic for each FFG; Changes in the structure or complexity of food webs through space & time - proportions of terrestrial vs. aquatic taxa in gut content analyses	
Regular oxidation of sulfidic material	Not an indicator	NA	

9.13 Evaluation of ecological process indicators as evidence for achieving specific outcomes for the site

Ecological health and ecological condition are defined at an ecosystem scale (Fairweather 1999a). This scale encompasses both the living and non-living components of a landscape, and the interactions that occur between them. Thus, ecological processes are a key component of ecological condition, and ecological function (described by ecological processes) is as likely to affect ecological condition as ecological structure (described by biotic assemblages) (Fairweather 1999a). Thus, ecological processes provide an alternative method to species-based indicators to describe ecosystem health and address the common failing of many monitoring programs whereby the full complexity of ecosystems are underestimated (Dale & Beyeler 2001).

Processes have the advantage of providing information regarding the trajectory of an ecosystem. This means that individuals do not necessarily need to die or to emigrate from the system before a response is detected, as is often the case with species-based monitoring. Thus, the assessment of ecological health is more sensitive than is often the case with species-based monitoring, potentially providing advance warning of deterioration, which is a key attribute of a useful indicator (Boulton 1999). Another major advantage of process indicators is the relative ease of measurement of many, particularly as an addition to existing species- or assemblage-based monitoring that is already occurring in the CLLMM region. Ease of measurement is another key attribute for a useful indicator (Boulton 1999).

Ecological processes can be more useful than species-based indicators at large spatial and temporal scales. As processes tend to integrate across species and communities, the patterns that emerge are sometimes more easily interpreted at a whole-of-system scale, than shifts in the distributions of particular species, or the replacement of one species with another that may or may not be equally desirable. Simply mapping patterns of species distributions, even through time, is unlikely to assist our understanding of ecosystem functionality (Harris 1994) and ecosystem functionality is a core part of the goal for the CLLMM region, of having a healthy, productive and resilient wetland of international importance.

All of the ecological processes investigated were relevant for one or more of the defined ecological outcomes. Decomposition, response to terrestrialisation, and functional connectivity were the three that were the most general (as defined by the number of outcomes they were deemed relevant to); however, generality is not necessarily the most important criterion for selecting good indicators. There was a noticeable trend amongst process indicators to be relevant for outcomes associated with a particular objective. For example, functional connectivity was likely to be indicative of outcomes linked to the hydrological connectivity and population connectivity objectives, while colonisation tended to be linked to outcomes relating to self-sustaining populations and population connectivity. This suggests that, to achieve the maximum understanding of ecological functioning in the CLLMM region, a mix of process indicators is likely to be needed, forming an 'ecoassay' (*sensu* Fairweather 1999a).

One major limitation of process indicators to date has been their relative lack of research and development, including explicit testing of process as indicators, despite the scientific literature proposing their utility for over a decade (e.g. Boulton 1999, Fairweather 1999a,b). For example, many of the processes that have been suggested here may be relevant for additional ecological outcomes, but lack either the protocols for them or an understanding of the magnitude of change that should be considered significant. However, despite these limitations, the integrative nature of processes and the knowledge that we currently have make many worth pursuing in the short term. Using these processes in the region, in combination with specific development work to test the protocols employed, will fill these knowledge gaps through time and provide additional information from each of the indicators employed.

Given that the monitoring of indicators is designed to provide information on ecological condition more generally, it is important that our understanding of how each indicator works is robust (Fairweather & Napier 1998; Dale & Beyeler 2001). If not, our ability to interpret the implications of any changes observed in indicator metrics will be inadequate (Fairweather & Napier 1998). Thus, research and development are needed as core elements of monitoring programs, to ensure that the indicators being measured are well-understood and are the most efficient way to collect information about ecological condition. Development should focus in two areas: identifying the best approaches for monitoring, and developing the scientific basis underpinning each indicator, to ensure that the indicator can be interpreted accurately and efficiently (Fairweather & Napier 1998). This development does not necessarily need to occur independently from routine monitoring but could form part of the broader monitoring program (Lester *et al.* 2009a).

Development should focus on the level of change that is considered meaningful (e.g. levels of acceptable change as outlined by the Ramsar Convention) and aggregation across indicators and across spatial and temporal scales (Fairweather & Napier 1998). For some of the identified taxon- and assemblage-based indicators (see Chapters 6-8), levels of acceptable change exist and are currently being reviewed but this has not yet been undertaken for the process-based indicators described here. Validation of an indicator is also necessary, including determining the timeframe in which that indicator will respond for the spatial scales of interest (Boulton 1999) and reliable protocols need to be developed to allow for accurate and repeatable measurement of that indicator.

Many of the process indicators assessed here are not traditionally used in management-oriented monitoring programs. Thus, research and development will be needed to establish how best to implement monitoring of these indicators and exactly how values of each indicator relate to ecological condition. However, this does not mean that the indicators are of limited value in the short term. For those outcomes that have been identified here, sufficient knowledge currently exists in the literature to warrant the use of process indicators. In the short term, initial interpretations of results should be made cautiously, and ground-truthing of the indicators will need to occur while monitoring is undertaken, but the improved understanding of how ecological function affects ecological condition within the CLLMM is likely to more than re-pay this initial investment.

9.14 Summary

- **Ecological processes occur between individual organisms, within populations or among communities and are more applicable to functions occurring within the system than structural ecological measures.**
- **Process indicators tend to integrate responses across multiple species and can more directly reflect the consequences of ecological change.**
- **The assessment of ecological health via processes is more sensitive than is often the case with taxon-based monitoring, potentially providing advance warning of deterioration in ecological character.**
- **Decomposition, response to terrestrialisation and functional connectivity were the process indicators that were the most general indictors (i.e. indicator of greatest number of outcomes).**
- **Many of the process indicators were relevant to a particular objective, suggesting that multiple process indicators are likely to be needed to meet majority of the ecological outcomes in the form of an ‘ecoassay’.**
- **The major limitation with the use of process indicators is the relative lack of research and development although they are still useful because of the integrative nature of processes and the knowledge we currently have.**

10. Hydrodynamic impacts of environmental water allocation in the Coorong

Rebecca E. Lester, Ian T. Webster & Peter G. Fairweather

This assessment of the hydrodynamic impacts of environmental water allocations on the Coorong directly follows from work undertaken from Heneker (2010). The focus of Heneker (2010) was on achieving salinity targets within Lake Alexandrina, and the implications this had on water levels, flow volumes and the hydrology of both Lakes Albert and Alexandrina. Here, we move downstream to investigate the effect of meeting these salinity targets on Coorong hydrodynamics by investigating the same set of scenarios that were covered in Heneker (2010).

In undertaking this investigation, figures are presented that are consistent with those presented in Heneker (2010) wherever possible to enable readers to compare the impact of the same volumes of water throughout the region. In addition, this work also has outputs that are consistent with other reports that have investigated the hydrodynamic and ecological implications of management options of the Coorong (e.g. see Lester *et al.* 2009 b,c,d). These reports have focused on the hydrodynamic drivers of ecosystem states, which are outlined in the work focused on the ecological implications for the Coorong of achieving salinity targets in Lake Alexandrina (see Chapter 11).

10.1 Hydrodynamic model

The effect of environmental water allocations on the hydrodynamics of the Coorong were investigated a one-dimensional hydrodynamic model (Webster 2010). This model simulates water levels and salinities along the length of the Coorong, allowing the effect of varying barrage flows to be assessed and compared among scenarios.

10.1.1 Model description

Here we provide a brief description of the hydrodynamic model applied to investigate the impacts of management intervention on water levels and salinities within the North and South Lagoons of the Coorong. The model structure, calibration and validation have been described in more detail by Webster (2007, 2010).

The base hydrodynamic model simulates water motions and water levels along the Coorong from the Mouth to the southern end of the South Lagoon as these respond to the driving forces associated with water-level variations in Encounter Bay (including tidal, weather band and seasonal), the wind blowing over the water surface, barrage inflows, flows in Salt Creek (via the Upper South East Drainage scheme; USED) and evaporation from the water surface. The model domain extends from the Mouth to the southern end of the South Lagoon (~5 km past Salt Creek) and is shown in Figure 10.1 with the major inflows. This domain is divided into 102 cells each 1 km long in which a momentum equation and an equation describing conservation of mass are solved. Major channel constrictions occur at the Mouth and in the channel connecting the two lagoons past Parnka Point (Parnka channel).

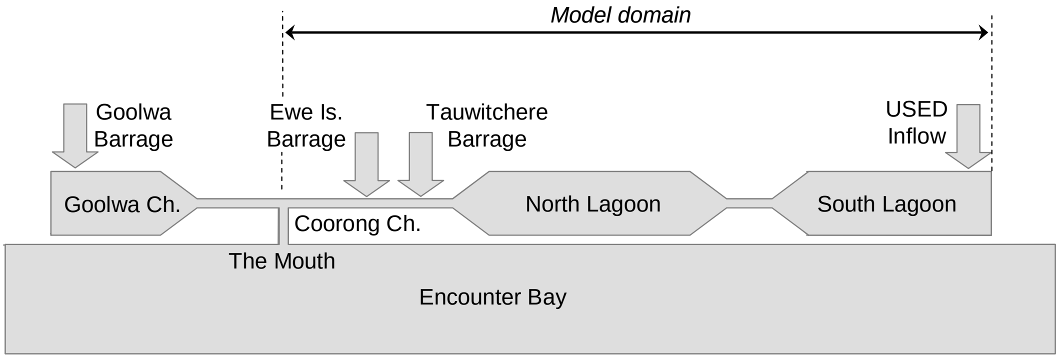

Figure 10.1: Coorong connectedness including major inflows and model domain

The depth of the Mouth is highly dynamic, increasing during times of significant outflows and tending to infill when flows are small or zero. The last six years (prior to late 2010) have experienced very small barrage flows, so it has been necessary to maintain the Mouth in an open condition by dredging, which ceased towards the end of 2010 with a return to larger barrage flows. In the model, the Mouth channel is assigned a width of 100 m and a length of 1500 m which approximate the dimensions seen in satellite imagery. Even though the bathymetry of the Mouth channel is highly complex, a single bed elevation is assigned as an approximation. Infilling, scouring by barrage flows, and dredging of the Mouth channel are represented as changes in the elevation of the channel bed.

The channel connecting the two lagoons is highly complicated and convoluted. Rather than attempting to resolve the details of the channel shape, the model assumes that the section of severely-constricted channel is 100 m wide and 1000 m long, dimensions approximately consistent with satellite images of the region. The optimal elevation of the Parnka channel was determined to be -0.19 m AHD through calibration.

The currents, water levels and mixing regimes simulated by the basic hydrodynamic model were used to drive a module representing the salinity dynamics. Salinity was modelled in the 14 cells shown in Figure 10.2 which extend across groups of cells used in the base hydrodynamic model. The salinity module solves equations for the conservation of the mass of salt in each cell and requires the prescription of the salinity of sea water and of the USED scheme. The salinity of the sea in Encounter Bay was set at 36.7 g L^{-1} and that of the USED to be 16.1 g L^{-1}. The latter is the calculated flow-weighted average of salinity in the Salt Creek discharge between 2001 and 2008.

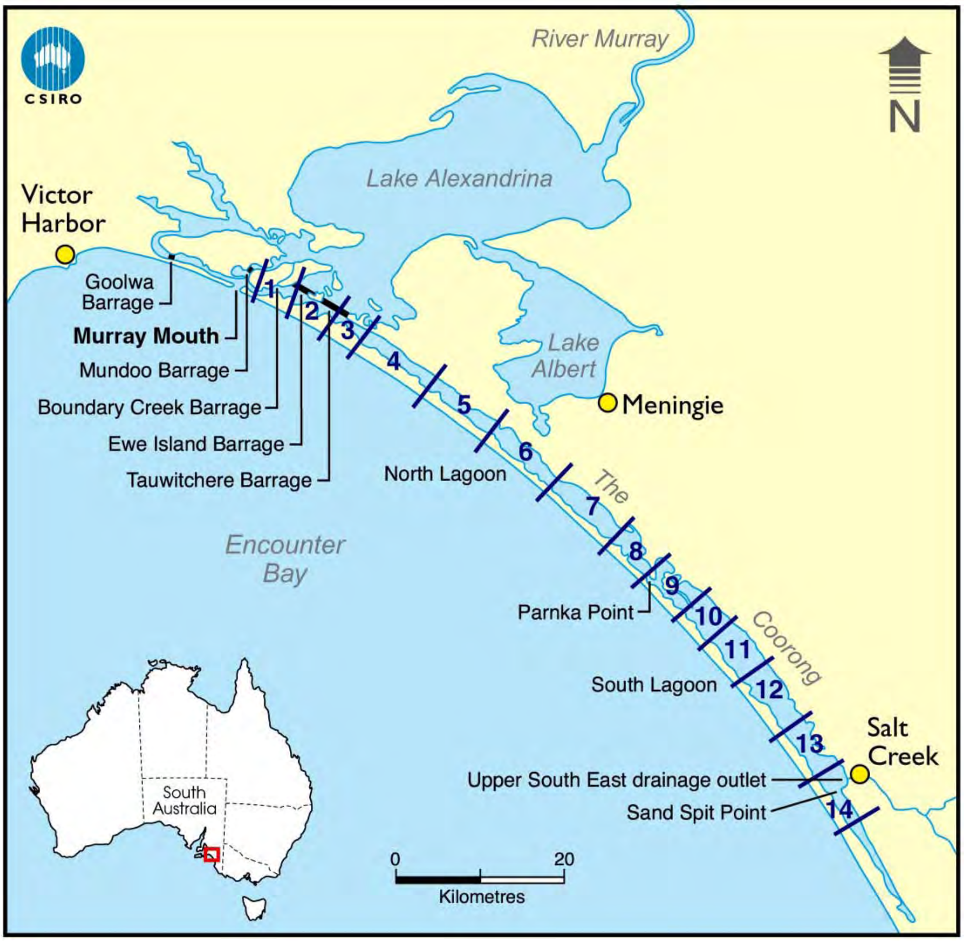

Figure 10.2: Map of the Coorong showing boundaries of cells used in the salinity module

10.1.2 Calibration

Calibration of the model required the specification of the continuously-changing elevation of the bed of the Mouth channel and of four fixed parameters. For its calibration, the elevation of the bed of the Mouth channel was continuously adjusted to achieve the best fit between modelled and measured diurnal water level variations measured at Tauwitchere Barrage. The time series of bed elevations of the Mouth channel obtained in this way for the calibration run is shown in Figure 10.3. Prior to 2001, one can see the annual cycle of Mouth deepening as a result of barrage flows, followed by Mouth infilling when barrage flows were small or zero. Note that Mouth flow in the figure is the calculated flow in through the Mouth and is effectively the negative of the barrage flow (i.e. flow tends to occur out of the Mouth). Dredging commenced in the Murray Mouth region in October 2002 and one can see the gradual decrease in Mouth elevations after that time. Annual variations in elevations result from seasonal variation in the dredging effort. One can also see that the Mouth elevation approached 0 m AHD following the periods of low flow in 1997-1998 and in 2001-2002.

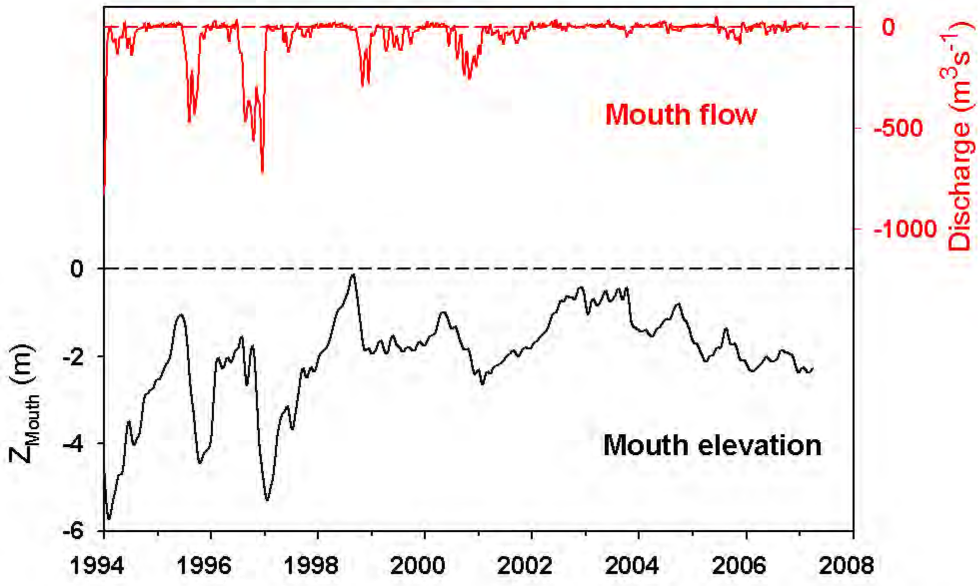

Figure 10.3: Mouth elevations and Mouth flows (see text for explanation of negative values)

The first fixed calibration parameter in the hydrodynamic model was a factor applied to the wind stress estimated from wind measurements made at Meningie on the south-eastern side of Lake Albert. This factor was adjusted so that the modelled water level spectra at Tauwitchere and at Sand Spit Point matched the measured spectra. The optimal factor was 1.6. Wind measurements at the Post Office in Meningie (Figure 10.2) were made twice a day so the value of the factor (i.e. above 1.0) was due to a number of reasons including the inability of the wind record to account for gustiness and the separation and terrain differences between Meningie and the Coorong. The second parameter was an evaporation correction factor applied to measured evaporation rates from a Class-A pan on Hindmarsh Island. The factor used in modelling had a value of 1.0. The third factor was the horizontal coefficient of mixing for the two lagoons (61 $m^2 s^{-1}$) and the fourth was the effective elevation of the bed of the Parnka channel (-0.19 m AHD). Parameters 2, 3 and 4 were adjusted to obtain the optimal fit using a least-squares approach between measured and modelled salinities in the North and South Lagoons and between measured and modelled water levels at Sand Spit Point in the South Lagoon. The calibration data used for salinity were obtained at 12 sites along both lagoons on 35 occasions by the South Australian Environment Protection Authority (SA EPA) and then South Australian Department for Environment and Heritage (DEH) between 1997 and 2005.

10.1.3 Model uncertainty and validity

All models are imperfect representations of reality (see Box 10.1 for a summary of the limitations of this model). It was necessary to know how credible hydrodynamic model simulations were and particularly how well they were able to represent variation in the system in response to changes in the drivers. An analysis of hydrodynamic model capability for simulating salinity and water level was undertaken (Webster 2010), but the main results are summarised here. Besides the salinity data used for calibration (1997-2005), additional data were obtained by various researchers for the periods 1963-1967, 1976-1979, 1981-1985, 1993, and 2005-2007 that were used to check the model response to conditions that were quite different from those encountered during the calibration period. In particular, barrage flows prior to 2002 tended to be substantially larger than those after this time.

When modelled and measured salinity values were plotted against one another for sections of each lagoon, the slope of the linear regression was ~0.9 for both the calibration and non-calibration periods. Average modelled salinity and measured salinity differ from one another by an average of 2 g L^{-1} in the North Lagoon and by less than 1 g L^{-1} in the South Lagoon. There was scatter around these regressions, which represented the limit of the model's ability to simulate the instantaneous salinity at a particular sample collection site. The root mean square (RMS) differences between modelled and measured salinity were 16 and 11 g L^{-1} in the North and South Lagoons, respectively.

We attributed much of this scatter to the incongruity of comparing salinities in cells that were effectively averaged over 5-10 km along the Coorong and across its width of several kilometres with spot measurements that are mostly obtained at the shore. There were certain to be heterogeneities in the salinity structure that were introduced by local evaporation or water input or by swirls in the current that were not resolved by the model. Other errors in the model were certain to be introduced through inaccuracies in prescribing the wind stress, barrage inflows, bathymetry, evaporation rates and by the neglect of groundwater inputs and losses that were unknown. Structural simplifications in the model would lead to further error including the simplified bathymetry and the assumption of constant mixing coefficients.

Overall, the model did a credible job of simulating the response of the system in both salinity and in water level. Water-level fluctuations for both the weather-band (less than 10-day period) and the longer-term seasonal fluctuations were modelled successfully in both lagoons. Due to limitations in the form of the meteorological data available, the response of the system to wind fluctuations having periods less than a day was not represented in the model, but for longer periods the measured and modelled water level variances differed by 10% or less. The model was capable of explaining ~90% of salinity changes in the system in a statistically-averaged sense, but it should be recognised that an individual modelled salinity value would be expected to differ from a related measurement due to a number of reasons, but that the bias of the modelled salinity was close to zero.

Box 10.1: Overview of the structure, assumptions and limitations of the hydrodynamic model

Function:

One-dimensional model which simulated water levels, salinity and mixing conditions in the Coorong as these respond to sea level variations, winds, barrage flows, flows from the Upper Southeast and dredging

Assumptions:

- Current infrastructure (dams, locks barrages) remained in place for whole model runs;
- Current operating and water-sharing rules as specified by the MDB Agreement continued to operate; and
- levels of diversions were applied across the full modelled period

Limitations:

- Accuracy of barrage flow information
- Wind measurements only available twice daily at one location
- Salinity modelled for larger cell sizes that would not resolve finer detail necessary for measurement comparison

10.2 The implementation of environmental water allocation scenarios

10.2.1 Conceptual basis of scenario effectiveness

In this chapter, we examine the impact of environmental water allocations on hydrodynamics of the Coorong. Flows into the Lower Lakes were altered to achieve various hydrological targets (e.g. a maximum salinity of 1000 µS cm^{-1} EC) for Lake Alexandrina. The effects of the various resultant barrage flows on the Coorong's physical responses are explored here with corresponding ecological responses investigated in Chapter 11. The conceptual basis for why these interventions should improve the condition of the Coorong is provided in the reports by Lester *et al.* (2009c,d) but is summarised here.

The Coorong is an inverse estuary; that is, its salinity tends to increase away from its Mouth. The conceptual model which underlies this estuary type is illustrated in Figure 10.4.

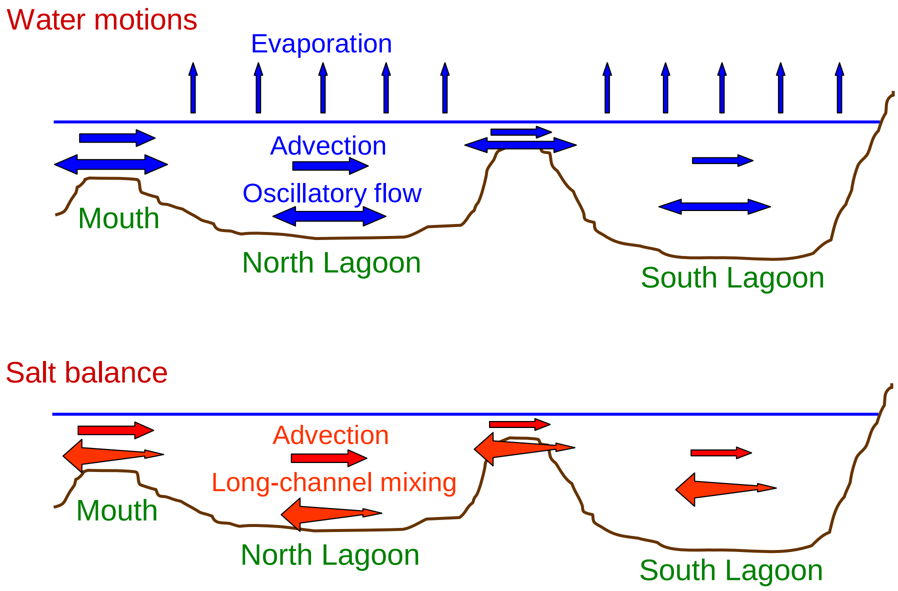

Figure 10.4: Conceptual model of the Coorong

Water is lost from along the length of the estuary through evaporation. To maintain the water level within the estuary, sea water flows in from the estuary mouth (Figure 10.4 top). The salt that is carried with the sea water tends to accumulate within the estuary. Back-and-forth water motions (oscillatory flows) within the estuary arise due to sea-level variations including the tides as well as seiching due to varying winds blowing over the water surface. These motions serve to mix the salt accumulating within the estuary back towards its mouth (long-channel mixing). Over the long term, the inflow of salt associated with evaporated water loss balances the transport of salt in the opposite direction due to oscillatory mixing. Super-imposed on this model of long-term salt transport within the Coorong are seasonal variations associated with the annual cycle of sea-level variation and of evaporation (and precipitation) rate, but fundamentally, this underlying salt balance pertains on an average basis. Inflows from the USED scheme have, in recent years, been too small to have a major influence on the hydrodynamics of the Coorong.

Flows over the barrages maintain water levels within the Coorong at a higher level than the sea level in Encounter Bay. This reduces seasonal disconnections between the lagoons and thus enhances long-channel mixing within the system, tending to result in higher water levels and lower salinities. In addition, the water that flows along the Coorong to replace evaporative loss has a lower salinity than sea water, so the overall input of salt into the system is lower, again reducing the salinity of Coorong waters. The exact reduction in salinity depends on the timing and amount of freshwater delivered to the Coorong, and is explored herein.

10.2.2 Model application

The hydrodynamic model was run for 19 scenarios. These scenarios involved combinations of flows to support different salinity targets in Lake Alexandrina coupled with different climate change scenarios (see Section 10.2.3 for details). Current water allocations were also modelled under an historical climate, along with under median and dry future climate scenarios, as was the so-called ‘natural’ (or ‘without development’) flow (i.e. with no extractions in the Murray-Darling Basin) under historical climate conditions.

The model was used to simulate water levels and salinity along both lagoons of the Coorong between 1895 and 2008. A 114-year time series was used as this was the period over which meteorological data were available for the region. Modelled daily barrage flows described above (see Section 10.2.1) obtained from the Murray-Darling Basin Authority (MDBA) were available for the 1891-2008 simulation period, but the other forcing data required were available only since 1982. The available forcing data were divided into 8-year segments starting in 1982, 1990 and 1998. As input to the model, these data sequences were repeated cyclically starting with the use of the 1990 segment to provide forcing time series from 1894-1902 (i.e. the first 8-year stretch of the model run). The 1998 segment was used to force the model from 1902 to 1910 followed by the 1982 segment being used to force the model during the period 1910-1918 and so on up to 2006. An additional segment of 4-year duration was used to start the model in 1890 and provide a spin-up time for the model of five years at the beginning of each simulation. Another 2-year forcing segment (2006-2008) was used to extend the model simulation from 2006-2008 at its end.

The barrage flows were provided as totals across all the barrages for each day. An analysis of the relative flows between the main barrages between 1982 and 2007 showed that an average of 58% of the total flow was released through Tauwitchere barrage and 19% through Ewe Island Barrage. These proportions were applied to the whole of the barrage flow time series to obtain the estimated daily flows through Tauwitchere and Ewe Island Barrages. The model did not simulate the flow interaction between Lake Alexandrina and the Coorong that would have occurred prior to the construction of the barrages. One of the scenarios considered had natural flow conditions with no extractions. For this scenario, the barrages were simply treated as if they remained open to allow all flows to pass through to the Coorong, but disallowed any flows from the Coorong to the Lakes. For all scenarios, the daily USED inflow was taken to be the average of measured flows on each day of the year between 2001 and 2008.

Evaporation within the model was calibrated using measured water levels and salinities in the South Lagoon for the period 1998-2005, giving the best estimates of evaporation rates for this period. During this period, salinities in the South Lagoon were approximately 100 g L^{-1}. Evaporation rate depends on thermodynamics as well as change in vapour pressure with salinity, so the heat balance associated with increasing salinity will affect the overall rate of evaporation. Basically, increasing salinity tends to decrease evaporation, but water temperatures then rise to compensate which in turn raises vapour pressure. Consequently, increasing salinity from 100 to 200 g L^{-1}, say, results in a decrease in evaporation of around 10%. As modelled salinities increase further, the evaporation rate will be less accurate, but given that few organisms can tolerate salinities of substantially more than 200 g L^{-1}, we believe that the model was calibrated in the right range, and we were able to describe the ecologically-relevant processes well.

The 19 scenarios considered in this report assumed one of three possible climates for considering river run-off and barrage discharge. These climates were historical climate, a median future climate, and a dry future climate. The latter two climates were based on the simulations of climate models used for estimating the median climate and a possible dry extreme climate for 2030. CSIRO and the Australian Bureau of Meteorology developed climate change projections for Australia that estimated changes in meteorological parameters as a result of climate change (Pearce *et al.* 2007). Temperature, evapo-transpiration, rainfall, wind speed, relative humidity and solar radiation were all expected to change to some degree. For the median future climate the temperature was expected to increase by 0.8 °C for the Coorong region, whereas, for the 10th percentile dry future climate, the temperature increase was expected to be 1.2 °C. These temperature increases were expected to increase the evaporation rate in the Coorong by 7% and 10%, respectively, so these increases were incorporated into the scenarios as appropriate. Model runs commenced on 1/7/1890 and water level and salinity output from 1/7/1895 following the 5-year spin-up period. Simulated time series were available at hourly intervals at 101 locations along the Coorong for water level and at 14 locations for salinity. These time series were then processed to provide suitable input to the ecological model.

It is important to note that while the scenarios ran for 114 years, they did not represent a sequence of evolving climate conditions. The entire model run was intended to give an idea of the variability inherent in a particular climate projection. For example, the Median Future climate scenario represented 114 years at a median 2030 future climate, rather than a progression from a current climate to a median future climate over the 114 years. This was due to limitations in the ability of climate models to predict how climate change will actually develop (Chiew *et al.* 2008).

10.2.3 Scenarios investigated

Scenario analyses were used to in order to assess the effect of environmental water allocations on the hydrodynamics of the Coorong and then on the ecological responses of the Coorong (see Chapter 11). This allowed the impact of water allocations to be objectively assessed under different climate change and delivery scenarios. Each scenario is outlined below and summarised in Table 10.1.

The scenarios investigating benchmark conditions were:

1. Benchmark conditions (hereafter called ‘Standard Historical’)

   This scenario included historical climate conditions, no interventions (including dredging), average daily discharge as per 2001-2008 for the USED scheme and actual flows over the barrages for a 114-year model run.

2. Natural flow conditions (‘Natural’)

   This scenario included historical climate conditions with no extractions from the Basin and none of the current infrastructure (with the exception of the barrages; see Section 10.2.2).

The scenarios investigating climate change were:

3. Median climate change with current extraction levels (‘Standard Median’)

   This scenario included a median 2030 climate (MDB SY Scenario C_{mid}; CSIRO 2008), current levels of extraction from the Basin and average inflows from the USED scheme. This scenario did not include dredging of the Murray Mouth.

4. Dry climate change with current extraction levels (‘Standard Dry’)

   This scenario included a dry 2030 climate (MDB SY Scenario C_{dry}; CSIRO 2008), current levels of extraction from the Basin and average inflows from the USED scheme. This scenario did not include dredging of the Murray Mouth.

Adjustments were required to the pattern of flow delivery to allow for objective comparison between years to occur for the hydrology of Lake Alexandrina (Heneker 2010). These scenarios are defined as:

5. Adjusted benchmark conditions ('Adjusted Historical')

This scenario used the same inputs as the Standard Historical scenario, but the pattern of flow allocation within each year was standardised so that each month had the same proportion of total flow from year to year.

6. Adjusted median climate change with current extraction levels ('Adjusted Median')

This scenario adjusted the Standard Median scenario in the same manner as occurred for the Standard Historical to produce the Adjusted Historical scenario.

7. Adjusted dry climate change with current extraction levels ('Adjusted Dry')

This scenario adjusted the Standard Dry scenario in the same manner as occurred for the Standard Historical to produce the Adjusted Historical scenario.

The effect of constant delivery of additional environmental water was assessed using the following scenarios:

8. Constant flow delivery to maintain a mean Lake Alexandrina salinity of 700 µS cm^{-1} EC ('Constant 700')

This scenario included historical climate conditions, no interventions (including dredging), average daily discharge as per 2001-2008 for the USED scheme and constant flows over the barrages to maintain a mean salinity in Lake Alexandrina of 700 µS cm^{-1} for a 114-year model run.

9. Constant flow delivery to maintain a maximum Lake Alexandrina salinity of 1000 µS cm^{-1} EC ('Constant 1000')

This scenario was as per Constant 700, but with constant flows to maintain a maximum salinity in Lake Alexandrina of 1000 µS cm^{-1}, rather than the mean of 700 µS cm^{-1} for the Constant 700 scenario.

10. Constant flow delivery to maintain a maximum Lake Alexandrina salinity of 1500 µS cm^{-1} EC ('Constant 1500')

This scenario was as per Constant 700, but with constant flows to maintain a maximum salinity in Lake Alexandrina of 1500 µS cm^{-1}, rather than the mean of 700 µS cm^{-1} for the Constant 700 scenario.

The effect of rules-based delivery of additional environmental water (as described in Heneker 2010) was assessed using the following scenarios:

11. Rules-based flow delivery to maintain a mean Lake Alexandrina salinity of 700 µS cm^{-1} EC ('Adjusted Historical 700')

This scenario included historical climate conditions, no interventions (including dredging), average daily discharge as per 2001-2008 for the USED scheme and rules-based flows over the barrages to maintain a mean salinity in Lake Alexandrina of 700 µS cm^{-1} for a 114-year model run using the adjusted flow delivery pattern.

12. Rules-based flow delivery to maintain a maximum Lake Alexandrina salinity of 1000 µS cm^{-1} EC ('Adjusted Historical 1000')

This scenario was as per Adjusted Historical 700, but with rules-based flows to maintain a maximum salinity in Lake Alexandrina of 1000 µS cm^{-1}, rather than the mean of 700 µS cm^{-1} for the Adjusted Historical 700 scenario.

13. Rules-based flow delivery to maintain a maximum Lake Alexandrina salinity of 1500 µS cm^{-1} EC ('Adjusted Historical 1500')

This scenario was as per Adjusted Historical 700, but with rules-based flows to maintain a maximum salinity in Lake Alexandrina of 1500 µS cm^{-1}, rather than the mean of 700 µS cm^{-1} for the Adjusted Historical 700 scenario.

The effect of rules-based delivery of additional environmental water under climate change was assessed using the following scenarios:

14. Rules-based flow delivery to maintain a mean Lake Alexandrina salinity of 700 µS cm^{-1} EC under a median future climate ('Adjusted Median 700')

This scenario included a median 2030 climate, no interventions (including dredging), average daily discharge as per 2001-2008 for the USED scheme and rules-based flows over the barrages to maintain a mean salinity in Lake Alexandrina of 700 µS cm^{-1} for a 114-year model run using the adjusted flow delivery pattern.

15. Rules-based flow delivery to maintain a maximum Lake Alexandrina salinity of 1000 µS cm^{-1} EC under a median future climate ('Adjusted Median 1000')

This scenario was as per Adjusted Median 700, but with rules-based flows to maintain a maximum salinity in Lake Alexandrina of 1000 µS cm^{-1}, rather than the mean of 700 µS cm^{-1} for the Adjusted Median 700 scenario.

16. Rules-based flow delivery to maintain a maximum Lake Alexandrina salinity of 1500 µS cm^{-1} EC under a median future climate ('Adjusted Median 1500')

This scenario was as per Adjusted Median 700, but with rules-based flows to maintain a maximum salinity in Lake Alexandrina of 1500 µS cm^{-1}, rather than the mean of 700 µS cm^{-1} for the Adjusted Median 700 scenario.

17. Rules-based flow delivery to maintain a mean Lake Alexandrina salinity of 700 µS cm^{-1} EC under a dry future climate ('Adjusted Dry 700')

This scenario included a dry 2030 climate, no interventions (including dredging), average daily discharge as per 2001-2008 for the USED scheme and rules-based flows over the barrages to maintain a mean salinity in Lake Alexandrina of 700 µS cm^{-1} for a 114-year model run using the adjusted flow delivery pattern.

18. Rules-based flow delivery to maintain a maximum Lake Alexandrina salinity of 1000 µS cm^{-1} EC under a dry future climate ('Adjusted Dry 1000')

This scenario was as per Adjusted Dry 700, but with rules-based flows to maintain a maximum salinity in Lake Alexandrina of 1000 µS cm^{-1}, rather than the mean of 700 µS cm^{-1} for the Adjusted Dry 700 scenario.

19. Rules-based flow delivery to maintain a maximum Lake Alexandrina salinity of 1500 µS cm^{-1} EC under a dry future climate ('Adjusted Dry 1500')

This scenario was as per Adjusted Dry 700, but with rules-based flows to maintain a maximum salinity in Lake Alexandrina of 1500 µS cm^{-1}, rather than the mean of 700 µS cm^{-1} for the Adjusted Dry 700 scenario.

This range of scenarios was investigated to provide an analysis across the range of possible future climates for which simulations were available (Pearce *et al.* 2007) and to explore a number of possible rules to determine an EWR for the region (i.e. to maintain salinities in Lake Alexandrina of an average of 700 µS cm^{-1}, or a maximum of 1000 or 1500 µS cm^{-1} EC). In order to objectively assess the impact of different EWR scenarios, it was necessary to adjust the hydrological record for inflows into Lake Alexandrina (Heneker 2010). One option was to add environmental water as a constant volume across the year (i.e. as per the constant flow scenarios), but a more realistic option was to adjust the flows to be proportional across the months each year (i.e. as per the adjusted flow scenarios) and these options were explored across the range of potential future climates to determine the impact of climate change on the range of options. The current conditions and a natural, or without-development, run provided benchmarks against which to measure improvements (or otherwise). This combination was explored for the Lower Lakes by Heneker (2010) and is consistent with other modelling undertaken for the region (e.g. see Lester *et al.* 2009 b,c,d).

Table 10.1: Summary of scenarios investigated in this chapter

Note: '✓' denotes present in the scenario and '×' indicates none or not present in the scenario. Numbers are targets for salinities in Lake Alexandrina in µS cm^{-1} EC.

No.	Scenario	Climate	Actual flow delivery pattern	Adjusted flow delivery pattern	Constant additional flow	Rules-based additional flow	Current extraction levels
1	Standard Historical	Historical	✓	×	×	×	✓
2	Natural	Historical	✓	×	×	×	×
3	Standard Median	Median	✓	×	×	×	✓
4	Standard Dry	Dry	✓	×	×	×	✓
5	Adjusted Historical	Historical	×	✓	×	×	✓
6	Adjusted Median	Median	×	✓	×	×	✓
7	Adjusted Dry	Dry	×	✓	×	×	✓
8	Constant 700	Historical	×	✓	Target 700	×	✓
9	Constant 1000	Historical	×	✓	Target 1000	×	✓
10	Constant 1500	Historical	×	✓	Target 1500	×	✓
11	Adjusted Historical 700	Historical	×	✓	×	Target 700	✓
12	Adjusted Historical 1000	Historical	×	✓	×	Target 1000	✓
13	Adjusted Historical 1500	Historical	×	✓	×	Target 1500	✓
14	Adjusted Median 700	Median	×	✓	×	Target 700	✓
15	Adjusted Median 1000	Median	×	✓	×	Target 1000	✓
16	Adjusted Median 1500	Median	×	✓	×	Target 1500	✓
17	Adjusted Dry 700	Dry	×	✓	×	Target 700	✓
18	Adjusted Dry 1000	Dry	×	✓	×	Target 1000	✓
19	Adjusted Dry 1500	Dry	×	✓	×	Target 1500	✓

10.3 Results

The results of the effect of environmental water allocation on the hydrodynamics of the Coorong have been presented in two sections. Firstly, results describing the general water level and salinity distributions throughout the Coorong were presented (as was done for the Lakes in Heneker 2010; Section 10.3.1). Then, the hydrodynamic drivers of ecosystem states were presented giving context to the findings regarding ecological impacts (see Chapter 11; Section 10.3.2).

Figure 10.5 shows an example of the results of the hydrodynamic simulations for scenarios simulating the adjusted baseline conditions (Adjusted Historical scenario) with the inclusion of a constant flow volume (Constant 700) or rules-based additional flow (Adjusted Historical 700) to maintain an average salinity in Lake Alexandrina of 700 in µS cm^{-1} EC. The time series shown were for average salinity in the South Lagoon and were obtained using the historical climate and represent scenarios 5, 8 and 11 (Table 10.1).

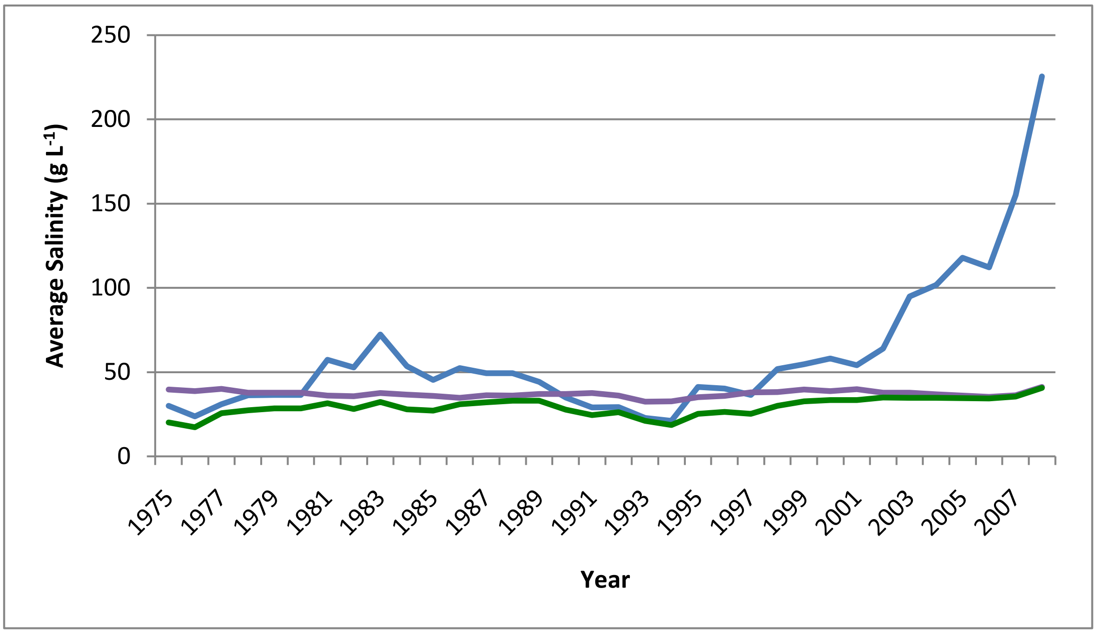

Figure 10.5: Average modelled salinity in the South Lagoon for the Adjusted Historical (blue line), Constant 700 (purple line) and Adjusted Historical 700 (green line) scenarios

Either the Constant 700 or the Adjusted Historical 700 scenario resulted in dramatically lower salinities in the South Lagoon of the Coorong. The Constant 700 scenario resulted in an extremely stable salinity in the South Lagoon, consistent with its constant flow through the barrages. The Adjusted Historical 700 scenario was more variable, with higher flow volumes in some wet years resulting in lower salinities in the South Lagoon those years. In low-flow years (e.g. 2005-2007), there was no difference in the predicted salinities between the Constant 700 and the Adjusted Historical 700 scenarios. The Adjusted Historical scenario, which did not include additional environmental water, resulted in salinities that were predominantly higher than either of the other scenarios, even in years where additional water would not have been required, likely due to an accumulation of salt during dry years. This was particularly evident at the end of the time series, where salinities were predicted to rise above 200 g L^{-1}.

10.3.1 Effect of additional environmental water on Coorong hydrodynamics

This section investigates the effect of the various scenarios on Coorong hydrodynamics in a manner similar to that explored for Lakes Alexandrina and Albert (Heneker 2010).

There were high levels of variability in the distribution of barrage flows in the Standard Historical scenario in the period of 1975 to 2007 (Figure 10.6). Flows ranged from greater than 120 000 ML day^{-1} to 0 ML day^{-1}, on average. Between 2007 and the end of the model run, annual average flows over the barrages were zero, which was longer than any other dry spell in this modelled sequence.

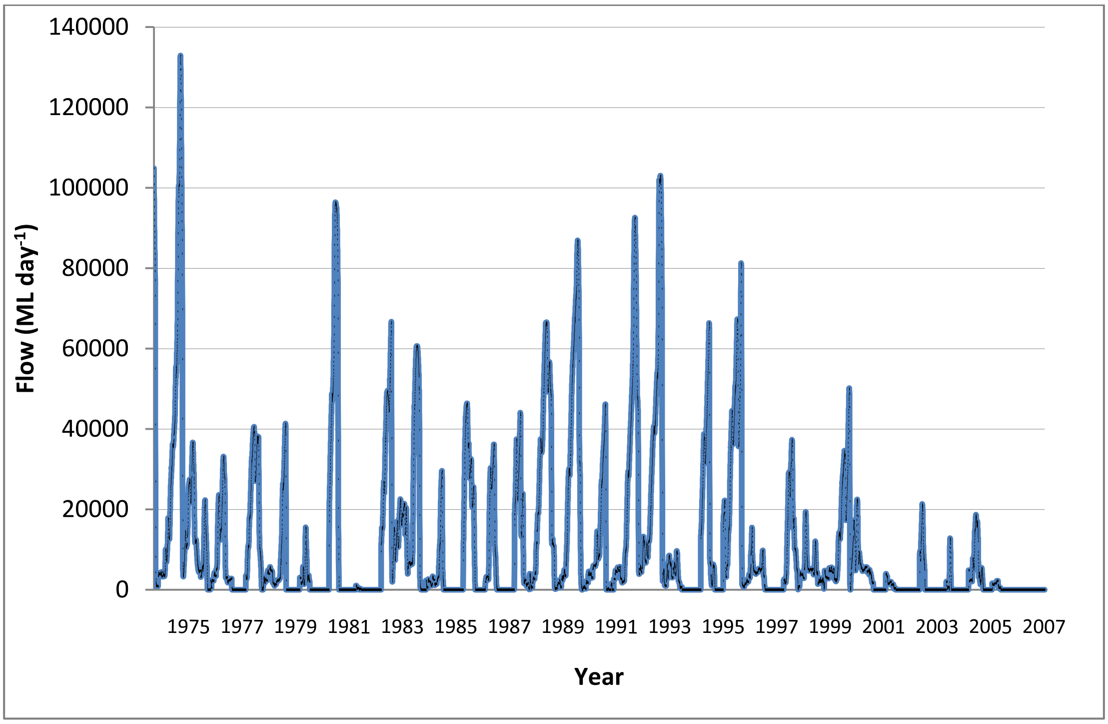

Figure 10.6: Daily flows over the barrages for the Standard Historical scenario

Average salinities in both the North and South Lagoons under the Standard Historical scenario also varied significantly after 1975 (Figure 10.7). For extended periods, salinities were estuarine in the North Lagoon across several periods, but tended to oscillate in the estuarine to marine range on a mostly-seasonal basis for the majority of the time sequence. South Lagoon salinities were higher than those observed in the North Lagoon throughout the sequence. Since 1975, no estuarine salinities were recorded in the South Lagoon and there were several periods of unusually high salinity (e.g. 1982/83). Since 2001, however, annual increases in salinity were observed in both Lagoons, with average salinities peaking at the end of the time series above 100 g L^{-1} in the North Lagoon and 250 g L^{-1} in the South Lagoon, as simulated by the Standard Historical scenario.

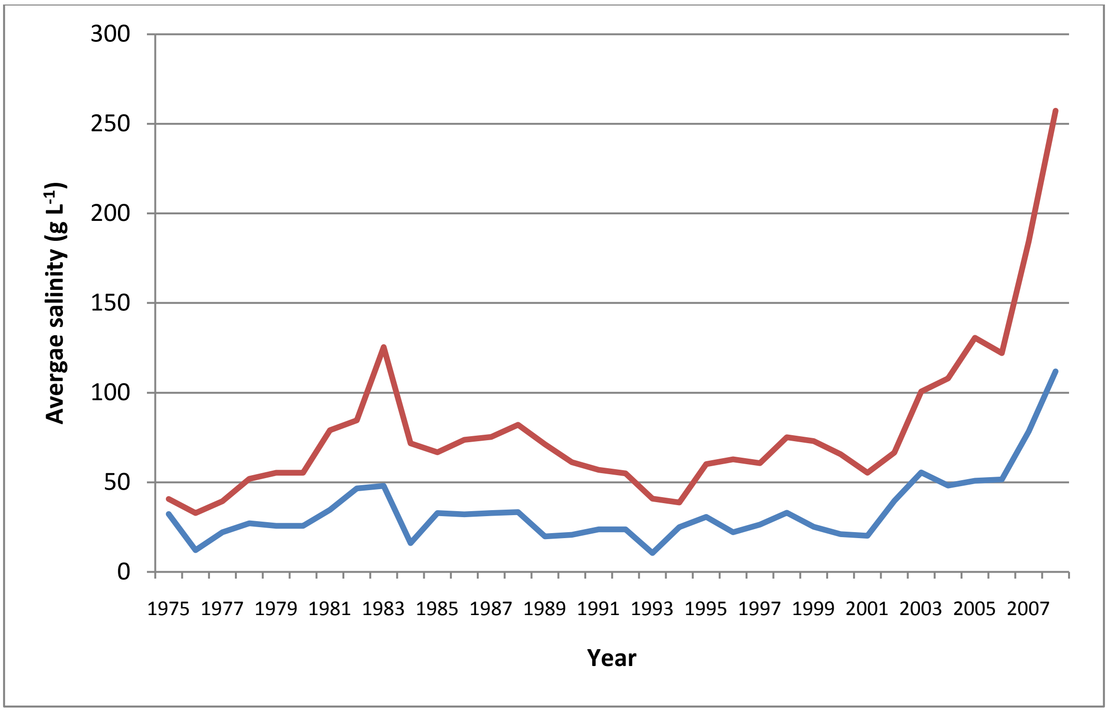

Figure 10.7: Average annual salinities in the North Lagoon (blue line) and the South Lagoon (red line) of the Coorong for the Standard Historical scenario

In order to add environmental water across the barrages according to the rules developed for the Lower Lakes, it was necessary to adjust the hydrological sequence to have standard proportions of flow occurring per month across all years within the model run. This meant that there was less variability in flow delivery within years in the adjusted sequence than in the historical record, which had the potential to affect the hydrodynamics of the Coorong.

Adjusting the distribution of flow throughout the year to facilitate comparisons between years for the Lakes, in the manner described above, did influence simulated salinities in both the North and South Lagoons. Substantial differences were apparent in the salinities predicted for the North Lagoon under the Standard Historical and Adjusted Historical scenarios (Figure 10.8). The Standard Historical scenario (as noted above) showed large inter-annual variability in salinities, with some short periods of unusually low salinities and two notable periods of unusually high salinity. The Adjusted Historical scenario matched the general trend of salinities observed under the Standard Historical scenario, but values were uniformly lower than the previous scenario. This suggested that the intra-annual variability in flows associated with the Standard Historical scenario was less effective at flushing salt from the system (or resulted in additional evaporative losses) than the consistent intra-annual patterns simulated by the Adjusted Historical scenario. Thus, any interpretation based on an adjusted flow sequence may underestimate peaks of salinity in the time series.

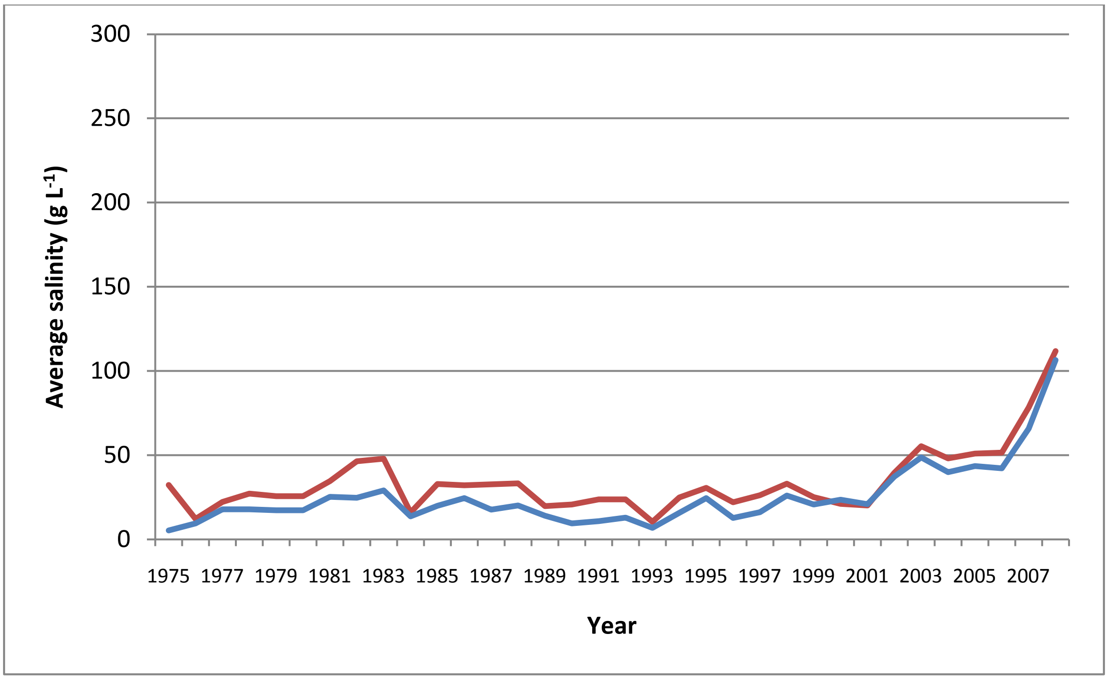

Figure 10.8: Average annual salinities in the North Lagoon for the Adjusted Historical (blue line) and the Standard Historical (red line) scenarios

In the South Lagoon, simulated salinities under the Adjusted Historical scenario were again consistently lower than those predicted for the Standard Historical scenario (Figure 10.9), as was the case under for North Lagoon salinities. The pattern of seasonal variability was similar, but the Adjusted Historical scenario did not show the same peaks of high salinity as were evident under the Standard Historical scenario. Again, this should be considered when interpreting the results of scenarios based on an adjusted flow sequence.

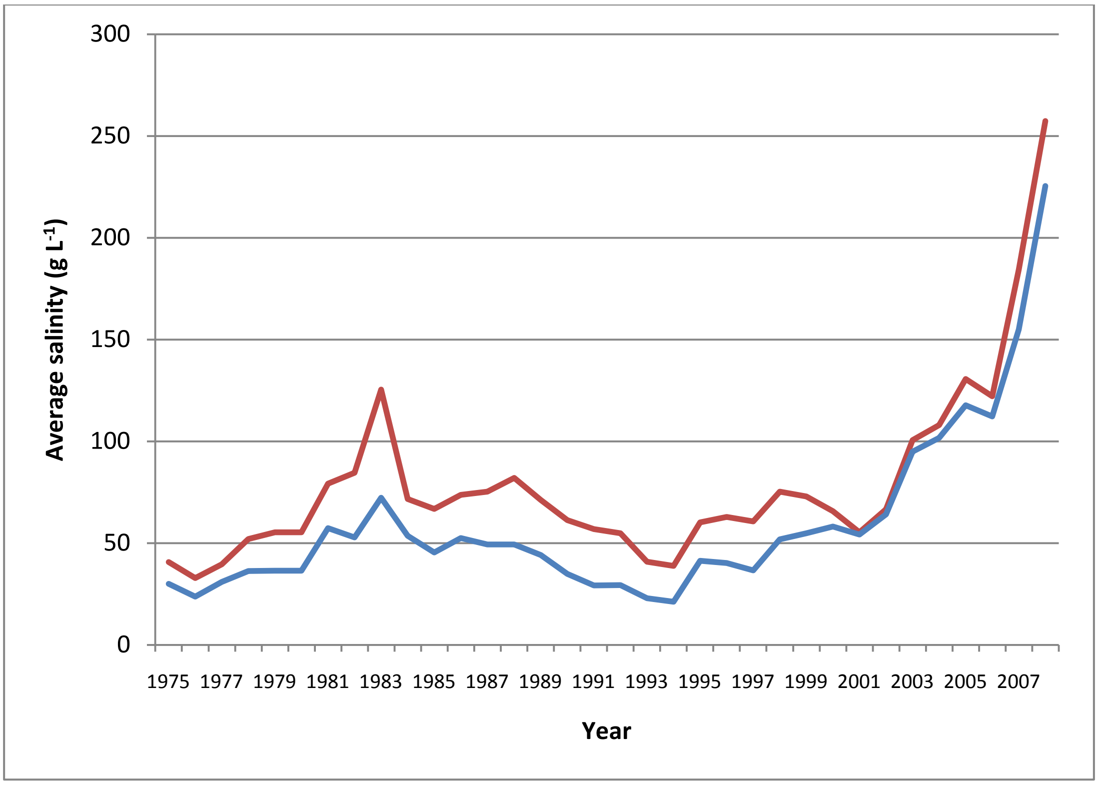

Figure 10.9: Average annual salinities in the South Lagoon for the Adjusted Historical (blue line) and the Standard Historical (red line) scenarios

The additional of environmental water was compared against the Adjusted Historical scenario, so that the mode of water delivery was consistent among scenarios. Figure 10.10 shows the effect of additional flows to maintain a salinity of 1000 µS cm^{-1} in Lake Alexandrina on simulated North Lagoon salinities. For the majority of the time series after 1975, there was no difference between the Adjusted Historical and Adjusted Historical 1000 scenarios, as no additional water was required. Two dry periods within the sequence (1981-1982 and 2001 onwards) illustrated that the additional water was sufficient to substantially reduce salinities in the North Lagoon. During both periods, salinities were maintained in an estuarine or marine range, in contrast to the increasing salinity observed for the Adjusted Historical scenario.

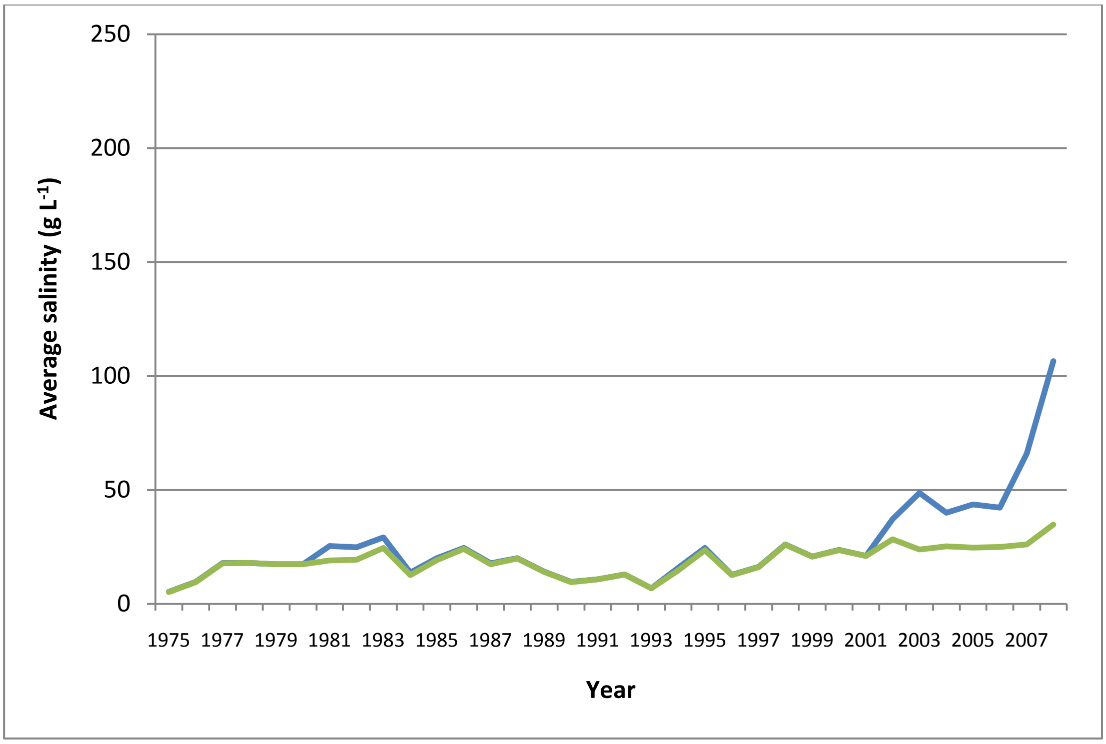

Figure 10.10: Average annual salinities in the North Lagoon for the Adjusted Historical (blue line) and the Adjusted Historical 1000 (green line) scenarios

This pattern was also observed for simulated South Lagoon salinities (Figure 10.11). The two main periods where additional water was required showed that the volumes included here were sufficient to maintain salinities below about 60 g L^{-1}.

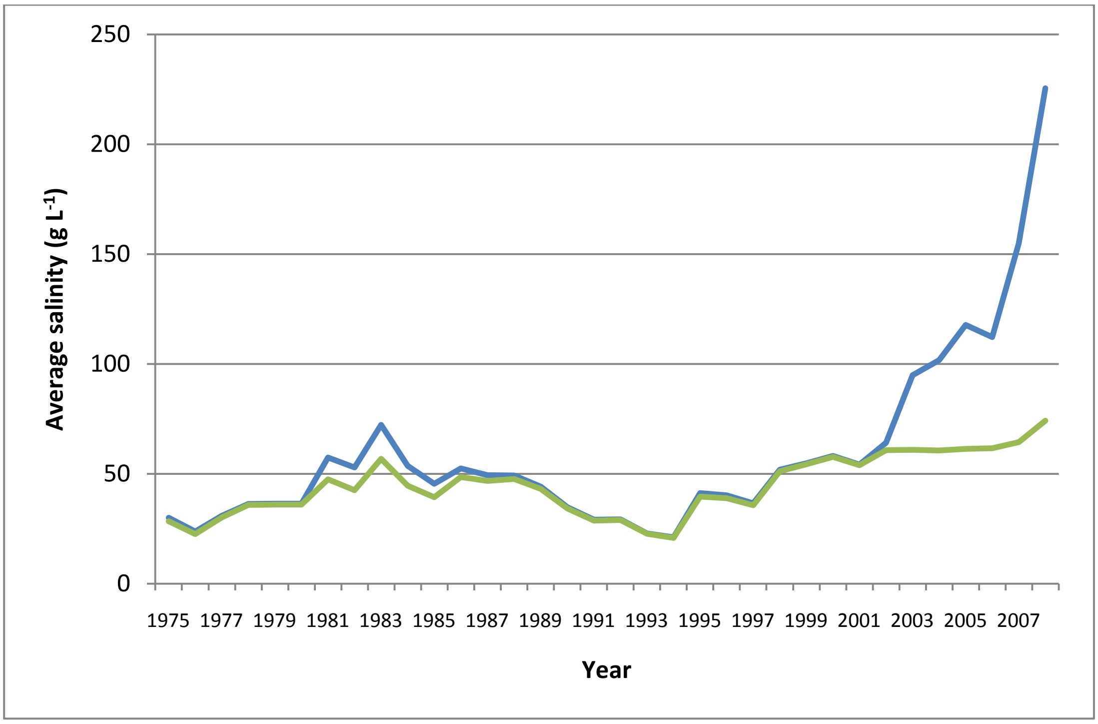

Figure 10.11: Average annual salinities in the South Lagoon for the Adjusted Historical (blue line) and the Adjusted Historical 1000 (green line) scenarios

10.3.2 Effect of additional environmental water under climate change

We also investigated the effect of additional environmental water on the hydrodynamics of the Coorong under two different climate changes scenarios: a median (C_{mid}) and a dry (C_{dry}) future climate. For this investigation, we focussed on the dry period of 1895 to 1916 to highlight the differences in hydrodynamics among the scenarios.

Under a median future climate (C_{mid}), a similar small difference was observed between the Standard Median and the Adjusted Median scenarios (Figures 10.12 and 10.13) as was observed under the scenarios using an historical climate. The Adjusted Median scenario resulted in slightly lower annual average salinities both in the North (Figure 10.12) and South (Figure 10.13) Lagoons. The differences in both Lagoons associated with adjusting the flow delivery pattern were small compared to the effect of the additional environmental water.

Under a median future climate, without the addition of environmental water, large fluctuations were observed in North Lagoon salinities (Figure 10.12). For wet periods, estuarine to marine salinities were predicted. However, for the majority of the sequence, average annual salinities under either the Standard Median or Adjusted Median scenarios were predicted to be at or greater than that of sea water, indicating that marine to hypersaline conditions would be the norm, rather than estuarine conditions. Additional environmental water to meet a salinity target of 700 µS cm^{-1} EC in Lake Alexandrina was sufficient to maintain estuarine salinities in the North Lagoon for the whole of the model sequence, despite a median future climate projection. Meeting a salinity target of 1000 µS cm^{-1} EC in Lake Alexandrina resulted in estuarine salinities for the majority of the model sequence, but there were times of higher salinity in dry periods, but these higher salinities approximately the concentration of sea water and very likely to be within the tolerances of the Ramsar-listed ecological character of the region. Additional environmental water associated with a salinity target of 1500 µS cm^{-1} EC in Lake Alexandrina resulted in somewhat higher salinities again, particularly during dry periods, but the extremes observed without the additional environmental water were effectively truncated.

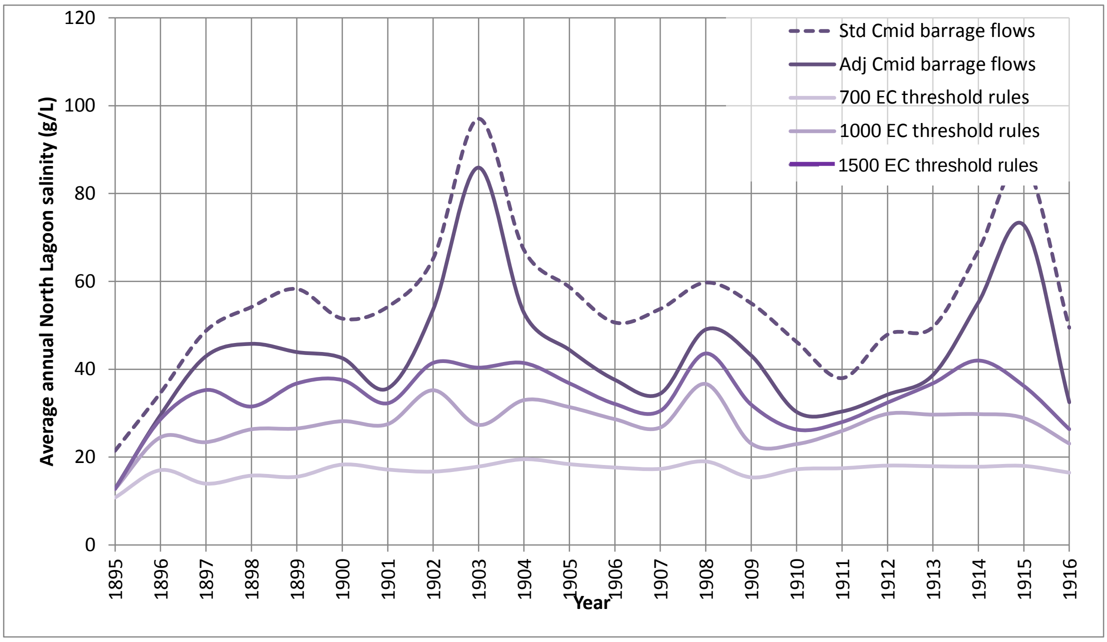

Figure 10.12: Average annual North Lagoon salinity with standard and adjusted C_{mid} barrage outflows showing the addition of environmental water to meet all thresholds ($StdC_{mid}$, $AdjC_{mid}$, 700 EC, 1000 EC, 1500 EC)

$StdC_{mid}$ is Standard Median, $AdjC_{mid}$ is Adjusted Median, 700 EC is Constant 700, 1000 EC is Constant 1000 and 1500 EC is Constant 1500.

In the South Lagoon, similar patterns were observed, although all salinities were higher than those predicted for the North Lagoon (Figure 8.15). All three scenarios investigating the addition of environmental water maintained salinities less than 100 g L^{-1}, which has been suggested in the past as an important threshold for biota in the region, despite the level of climate change modelled.

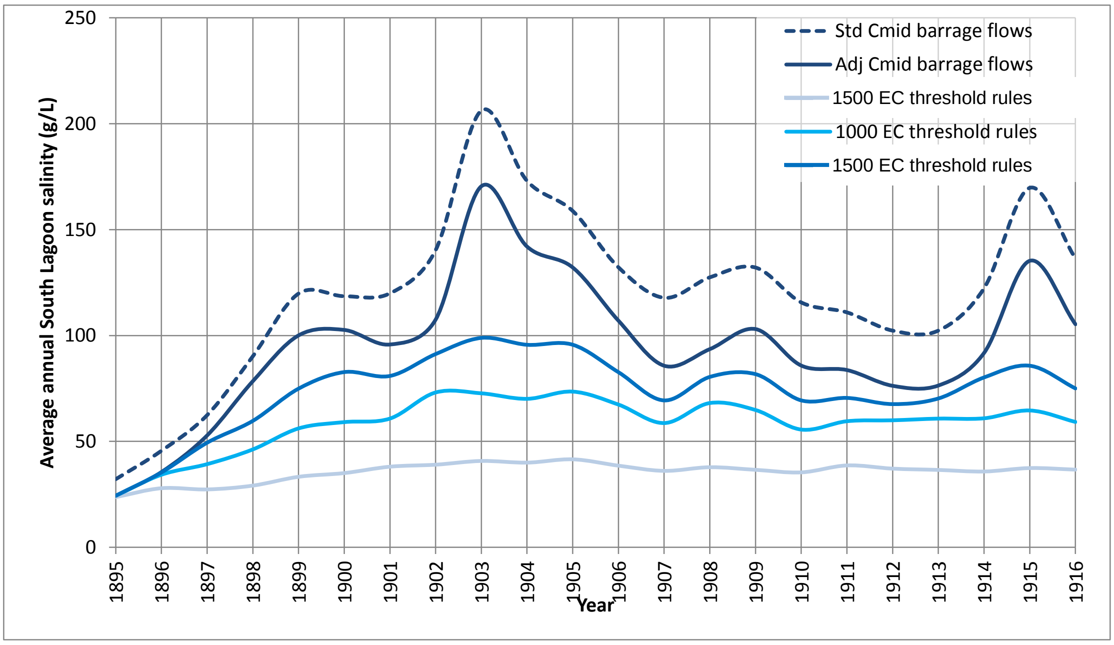

Figure 10.13: Average annual South Lagoon salinity with standard and adjusted C_{mid} barrage outflows showing the addition of environmental water to meet all thresholds ($StdC_{mid}$, $AdjC_{mid}$, 700 EC, 1000 EC, 1500 EC)

$StdC_{mid}$ is Standard Median, $AdjC_{mid}$ is Adjusted Median, 700 EC is Constant 700, 1000 EC is Constant 1000 and 1500 EC is Constant 1500.

Differences between the Standard Median and Adjusted Median scenarios were also apparent for water levels in both the North and South Lagoons (Figures 10.14 and 10.15). Adjusting the flow delivery pattern to standardise for intra-annual variability tended to remove the extremely low water levels from the predicted sequence for both the North and South Lagoons. This again highlighted the importance of flow delivery timing in the hydrodynamics of the Coorong.

In the North Lagoon, there was relatively little difference in the predicted water levels under any of three scenarios investigating the addition of environmental water under a median future climate (i.e. to meet any of the three salinity targets for Lake Alexandrina) (Figure 10.14). Each had similar patterns of variability; although the Adjusted Median 1500 scenario failed to address all of the falls in water levels during very dry periods.

The same patterns were observed for the South Lagoon (Figure 10.15), with the Adjusted Median 1500 scenario showing lower water levels under dry periods than the other two scenarios which included additional environmental water. In the South Lagoon, however, there was a noticeable difference in higher water levels among scenarios, with the Adjusted Median 700 scenario regularly resulting in much higher water levels than the other scenarios (except for occasional very wet periods that affected all scenarios).

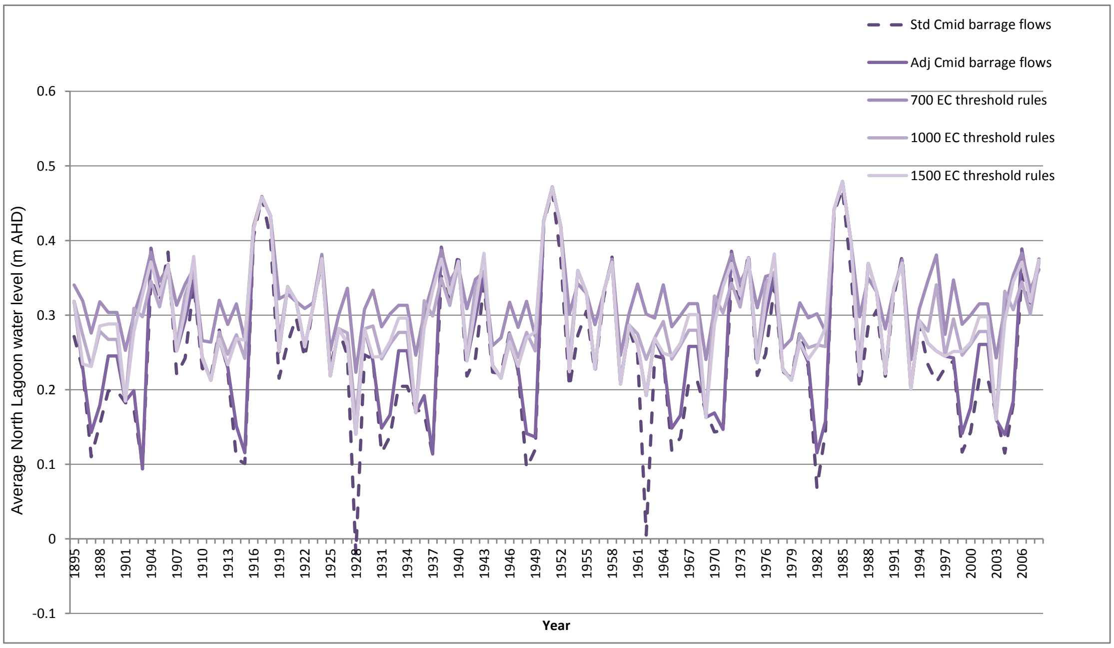

Figure 10.14: Average annual North Lagoon water level with standard and adjusted C_{mid} barrage outflows showing the addition of environmental water to meet all thresholds ($StdC_{mid}$, $AdjC_{mid}$, 700 EC, 1000 EC, 1500 EC)

$StdC_{mid}$ is Standard Median, $AdjC_{mid}$ is Adjusted Median, 700 EC is Adjusted Median 700, 1000 EC is Adjusted Median 1000 and 1500 EC is Adjusted Median 1500.

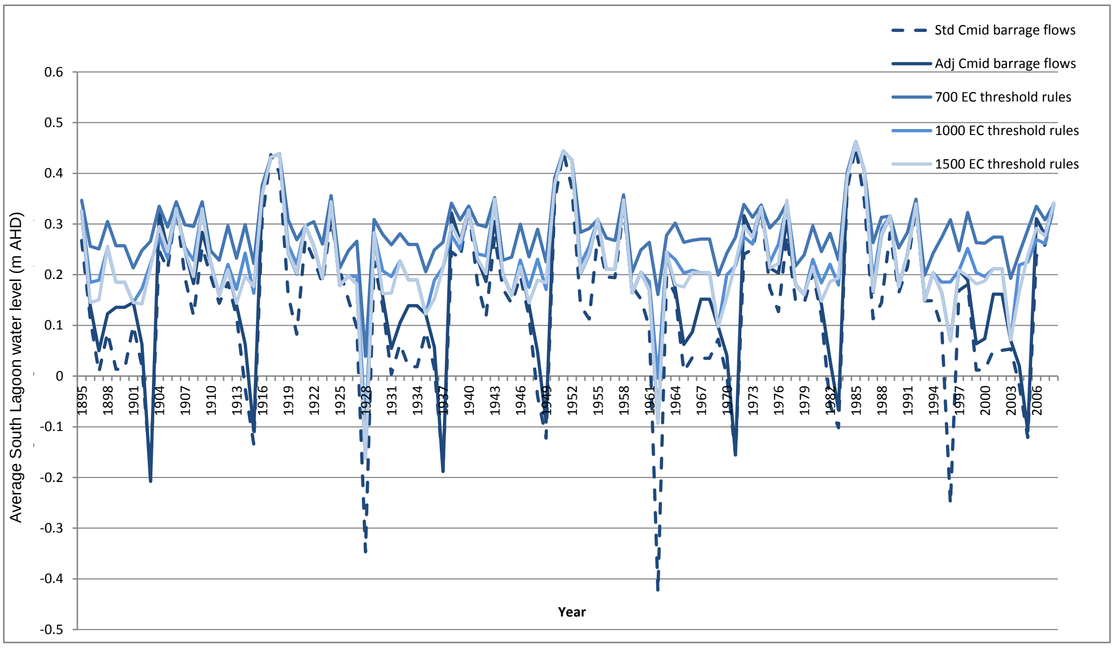

Figure 10.15: Average annual South Lagoon water level with standard and adjusted C_{mid} barrage outflows showing the addition of environmental water to meet all thresholds ($StdC_{mid}$, $AdjC_{mid}$, 700 EC, 1000 EC, 1500 EC)

$StdC_{mid}$ is Standard Median, $AdjC_{mid}$ is Adjusted Median, 700 EC is Adjusted Median 700, 1000 EC is Adjusted Median 1000 and 1500 EC is Adjusted Median 1500.

Under a dry future climate, the same patterns were observed for salinity in both the North and South Lagoons, although the extremes were much higher (Figures 10.16 and 10.17). The Standard Dry and Adjusted Dry scenarios resulted in very high salinity levels in both Lagoons and hypersaline conditions were the norm throughout the region under a dry future climate projection without additional environmental water. The salinities predicted under the three scenarios including additional environmental water resulted in very similar overall salinities under a dry future climate as occurred under a median future climate projection, which would be due to the additional water required under a dry future climate to meet the salinity targets in Lake Alexandrina compared to what would be required under median levels of climate change.

The same was also true for water levels in both Lagoons. Without additional environmental water, extremely low water levels were predicted frequently (Figures 10.18 and 10.19), while the scenarios including additional environmental water resulted in similar water level predictions as those described above under a median future climate.

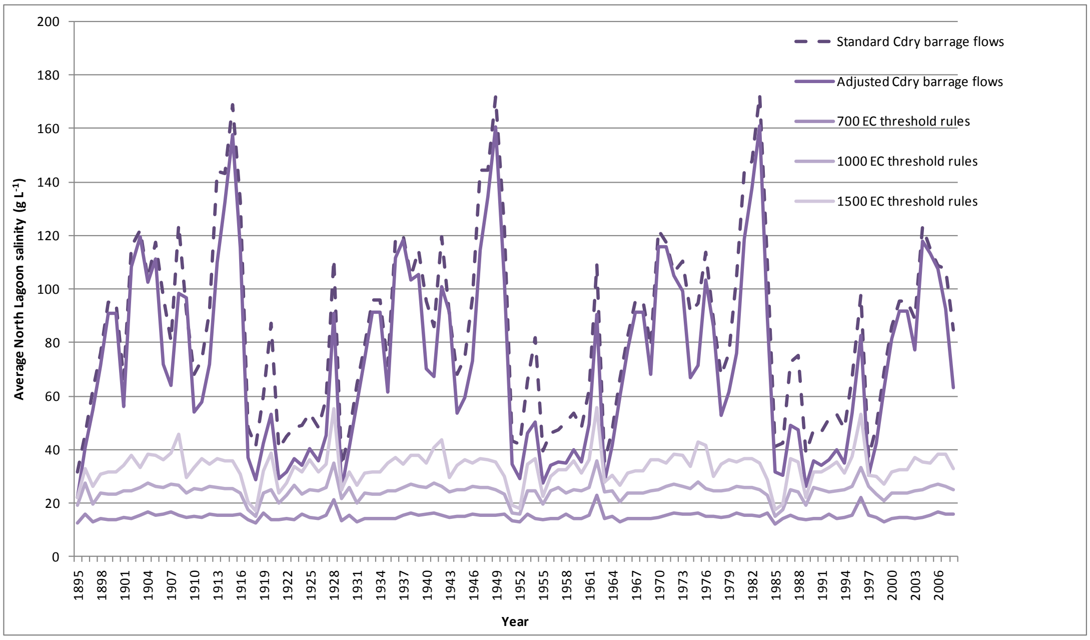

Figure 10.16: Average annual North Lagoon salinity with standard and adjusted C_{dry} barrage outflows showing the addition of environmental water to meet all thresholds (StdC_{dry}, AdjC_{dry}, 700 EC, 1000 EC, 1500 EC)

StdC_{dry} is Standard Dry, AdjC_{dry} is Adjusted Dry, 700 EC is Adjusted Dry 700, 1000 EC is Adjusted Dry 1000 and 1500 EC is Adjusted Dry 1500.

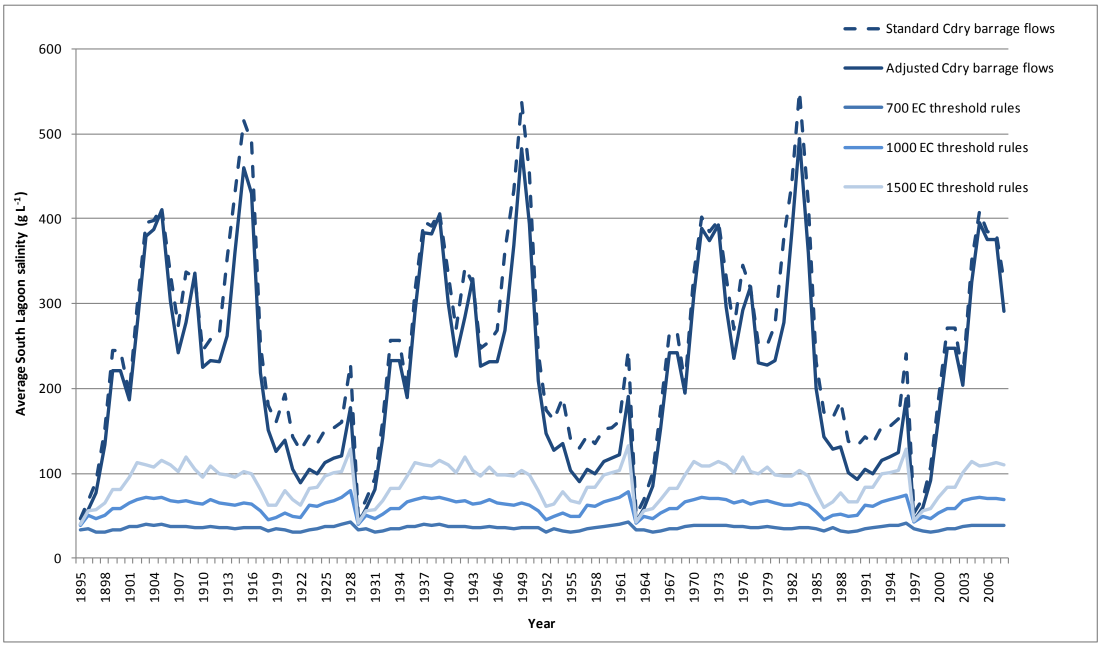

Figure 10.17: Average annual South Lagoon salinity with standard and adjusted C_{dry} barrage outflows showing the addition of environmental water to meet all thresholds ($StdC_{dry}$, $AdjC_{dry}$, 700 EC, 1000 EC, 1500 EC)

$StdC_{dry}$ is Standard Dry, $AdjC_{dry}$ is Adjusted Dry, 700 EC is Adjusted Dry 700, 1000 EC is Adjusted Dry 1000 and 1500 EC is Adjusted Dry 1500.

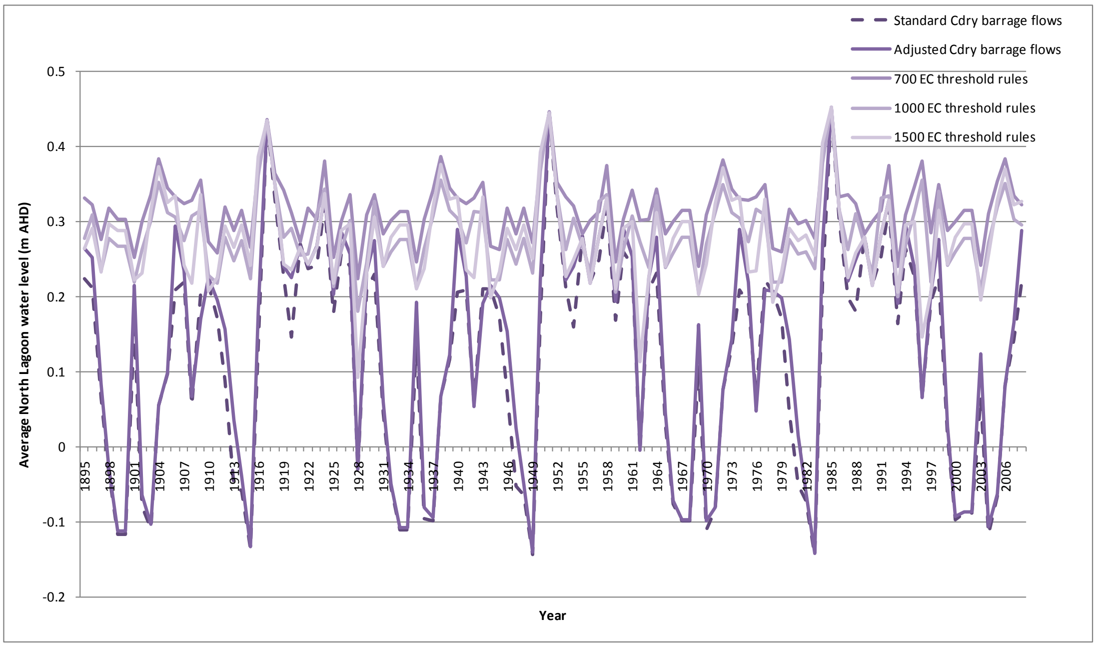

Figure 10.18: Average annual North Lagoon water levels with standard and adjusted C_{dry} barrage outflows showing the addition of environmental water to meet all thresholds ($StdC_{dry}$, $AdjC_{dry}$, 700 EC, 1000 EC, 1500 EC)

$StdC_{dry}$ is Standard Dry, $AdjC_{dry}$ is Adjusted Dry, 700 EC is Adjusted Dry 700, 1000 EC is Adjusted Dry 1000 and 1500 EC is Adjusted Dry 1500.

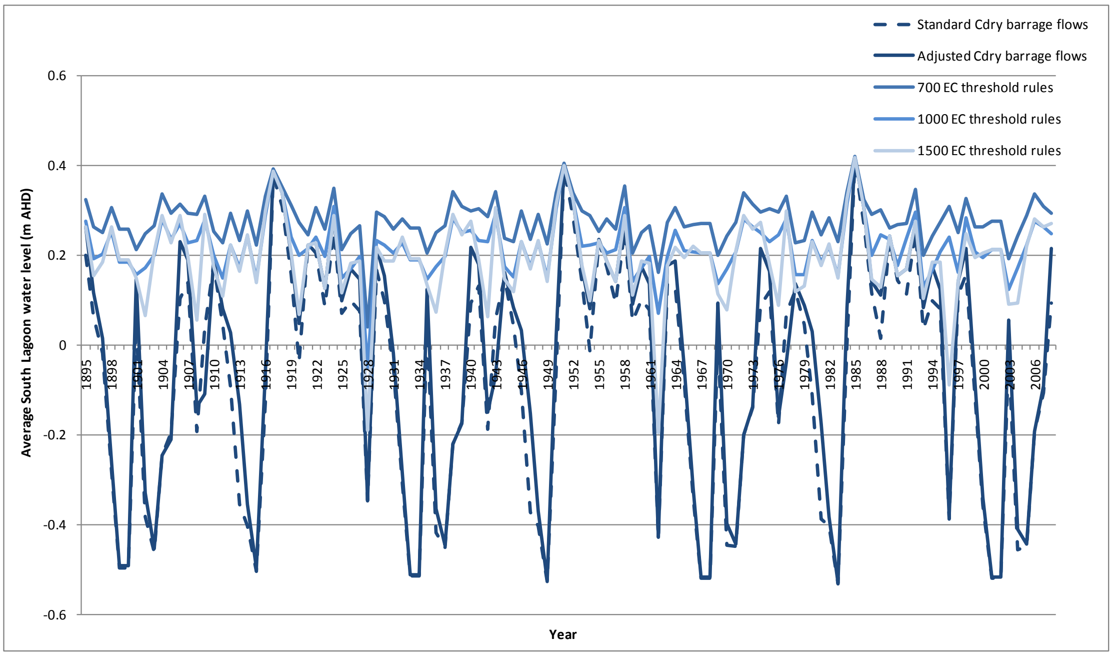

Figure 10.19: Average annual South Lagoon water levels with standard and adjusted C_{dry} barrage outflows showing the addition of environmental water to meet all thresholds ($StdC_{dry}$, $AdjC_{dry}$, 700 EC, 1000 EC, 1500 EC)

$StdC_{dry}$ is Standard Dry, $AdjC_{dry}$ is Adjusted Dry, 700 EC is Adjusted Dry 700, 1000 EC is Adjusted Dry 1000 and 1500 EC is Adjusted Dry 1500.

10.4 Hydrodynamic drivers of ecosystem states in the Coorong

Four hydrodynamic variables have been shown to drive the mix of ecosystem states that are present in the Coorong (see Chapter 11). These include the average water level, the maximum salinity, the average depth from two years previous and the annual range in water level (i.e. the maximum water level over the year minus the minimum water level from the year). For each of these variables, the effects of environmental water allocations have been explored in additional detail.

10.4.1 Effect of adjusting the timing of flow delivery and climate change

As mentioned above, adjusting the timing of flow delivery to facilitate comparison between years for the Lakes affected the simulated hydrodynamics of the Coorong. Here we compare the standard scenarios for each of the three climates investigated (the historical, median future and dry future climate projections) with their respective adjusted scenario (i.e. to have proportional flow delivery within each month, but no additional water), to assess the impact of that adjustment on the hydrodynamic drivers of ecosystem states (Figure 10.20).

The effect of adjusting the timing of flow delivery was not consistent across the different hydrodynamic variables investigated. There was relatively little change in water levels and depths from the previous two years between the standard scenario and its adjusted counterpart for each of the Historical, Median and Dry sets of scenarios. Median water levels and depths from two years previous were slightly higher (in the order of 2 cm) for each of the adjusted scenarios. The inter-annual variability in the annual range in water level, however, was substantially smaller under the adjusted scenarios, varying between 0.44 and 1.54 m for the Adjusted Historical scenario, compared with 0.25 and 2.05 m per annum under the Standard Historical, for example. This reflects the lower level of inter-annual variability in the pattern of flow delivery. Similar differences between the standard and adjusted scenarios were apparent for the maximum simulated salinities. Under the Standard Historical the median maximum salinity was 67.8 g L^{-1}, compared to 47.4 g L^{-1} for the Adjusted

Historical scenario, representing a substantial decline in salinities overall. Again, this pattern was consistent across the three climates investigated.

Despite this unevenness of effect, adjusting the pattern of flow delivery had a positive effect on water levels and depths in the North Lagoon (Figure 10.21), with higher overall water levels and water depths. It also had a positive effect on the simulated water levels and salinities in the South Lagoon (Figure 10.22). These differences are not true improvements as a result of changes in water allocation and should be borne in mind when the effects of other environmental water allocation scenarios are investigated.

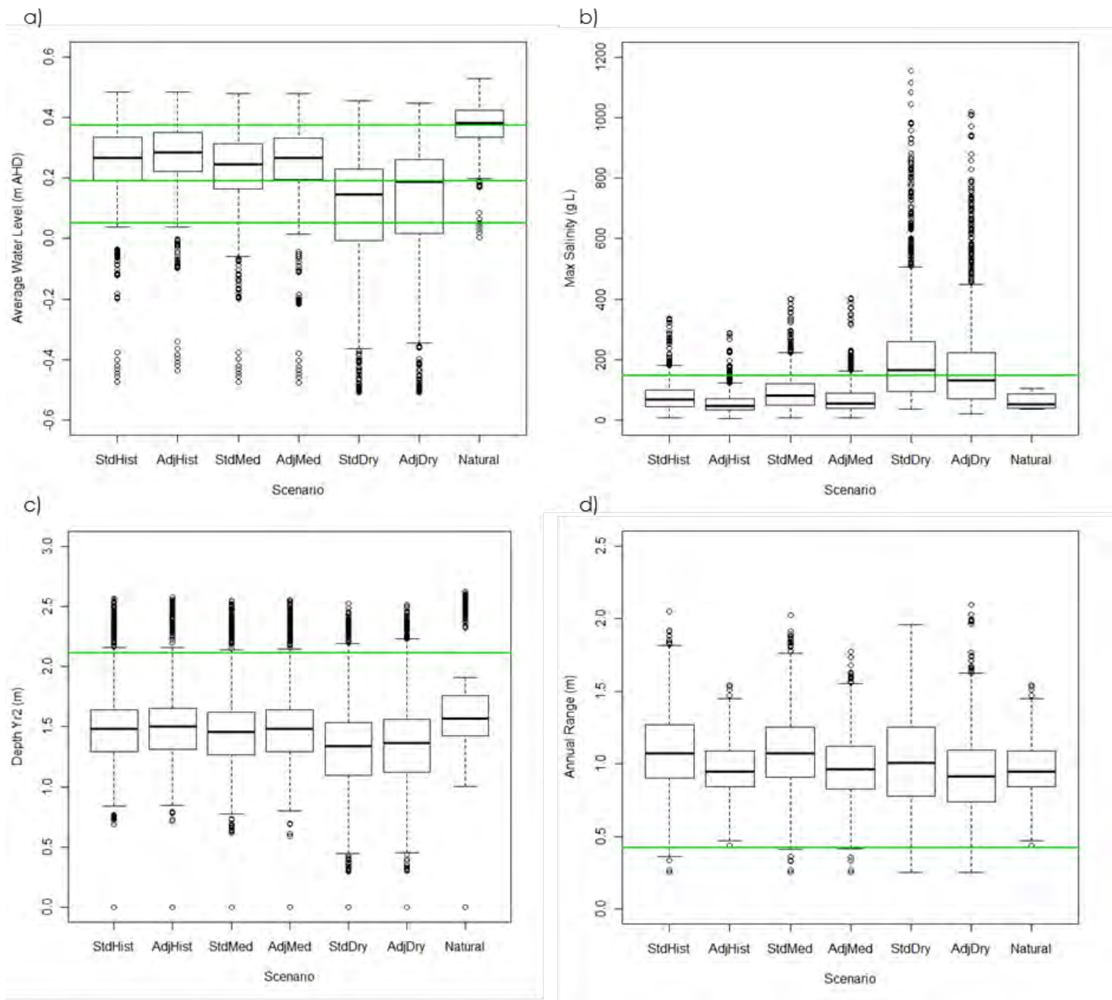

Figure 10.20: Boxplots showing the comparison between variables driving the ecosystem states of the Coorong for the timing of flow delivery and climate change scenarios. a) Average water level (m AHD), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Annual range in water level (m)

StdHist is Standard Historical scenario, AdjHist is the Adjusted Historical scenario, StdMed is the Standard Median scenario, AdjMed is Adjusted Median scenario, StdDry is Standard Dry scenario and AdjDry is Adjusted Dry scenario. Information on how to read the figure is presented in Appendix E.

A median climate change projection (Standard Median and Adjusted Median scenarios) had a relatively small impact on the hydrodynamic drivers of ecosystem states in the Coorong (Figure 10.20). Median water levels and median water depths were approximately 2 cm lower under either of the median future climate scenarios (Standard Median and Adjusted Median compared with the Standard Historical and Adjusted Historical scenarios, respectively). Annual ranges were virtually identical under either historical or median future climate scenarios. The largest simulated difference due to median future climate, was a median annual salinity under the

Standard Median scenario of 80.8 g L^{-1}, compared to 67.8 g L^{-1} under the Standard Historical scenario (and 56.2 g L^{-1} compared to 47.4 g L^{-1} for the equivalent adjusted scenarios).

This pattern was also evident when looking at the cumulative effect of a median future climate compared with the Standard Historical scenario in both the North and South Lagoon (Figures 10.21 and 10.22). A moderate future climate projection with no additional environmental water allocation (and without the adjustment to standardize flow distributions) resulted in a relatively small deterioration in both water levels and water depths from two years previous in the North Lagoon compared to the Standard Historical scenario (Figure 10.21) and a relatively small deterioration in water levels and salinities in the South Lagoon (Figure 10.22). In both lagoons, the Adjusted Median scenario was indistinguishable from the origin, indicating that hydrodynamic drivers were very similar to those of the Standard Historical scenario.

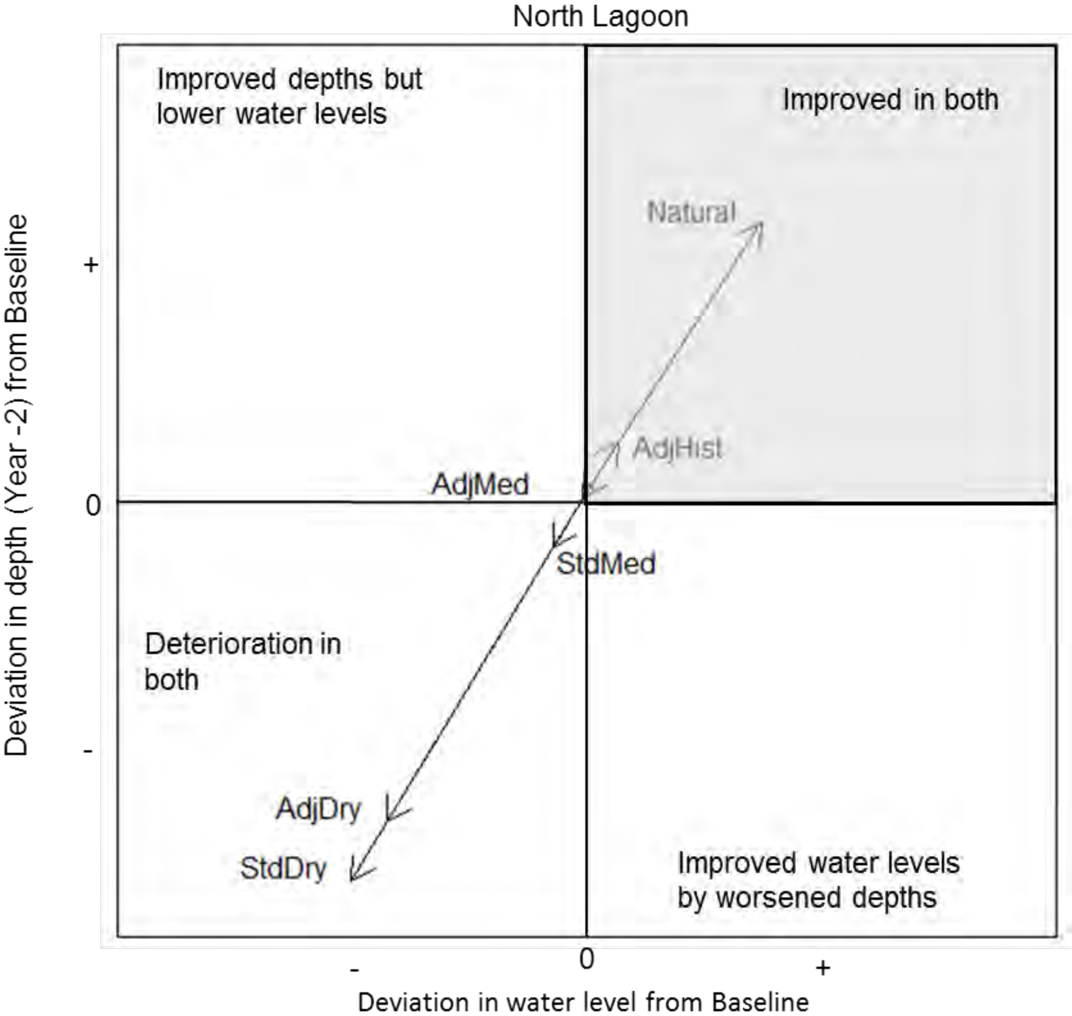

Figure 10.21: Comparison of the timing of flow delivery and climate change scenarios relative to the Standard Historical scenario for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Standard Historical scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Standard Historical condition (as shown by the 0,0 origin). Vectors in the upper-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and greater depths). AdjHist is Adjusted Historical scenario, AdjMed is Adjusted Median scenario, AdjDry is Adjusted Dry scenario, StdMed is Standard Median scenario and StdDry is Standard Dry scenario. Information on how to read the figure is presented in Appendix E.

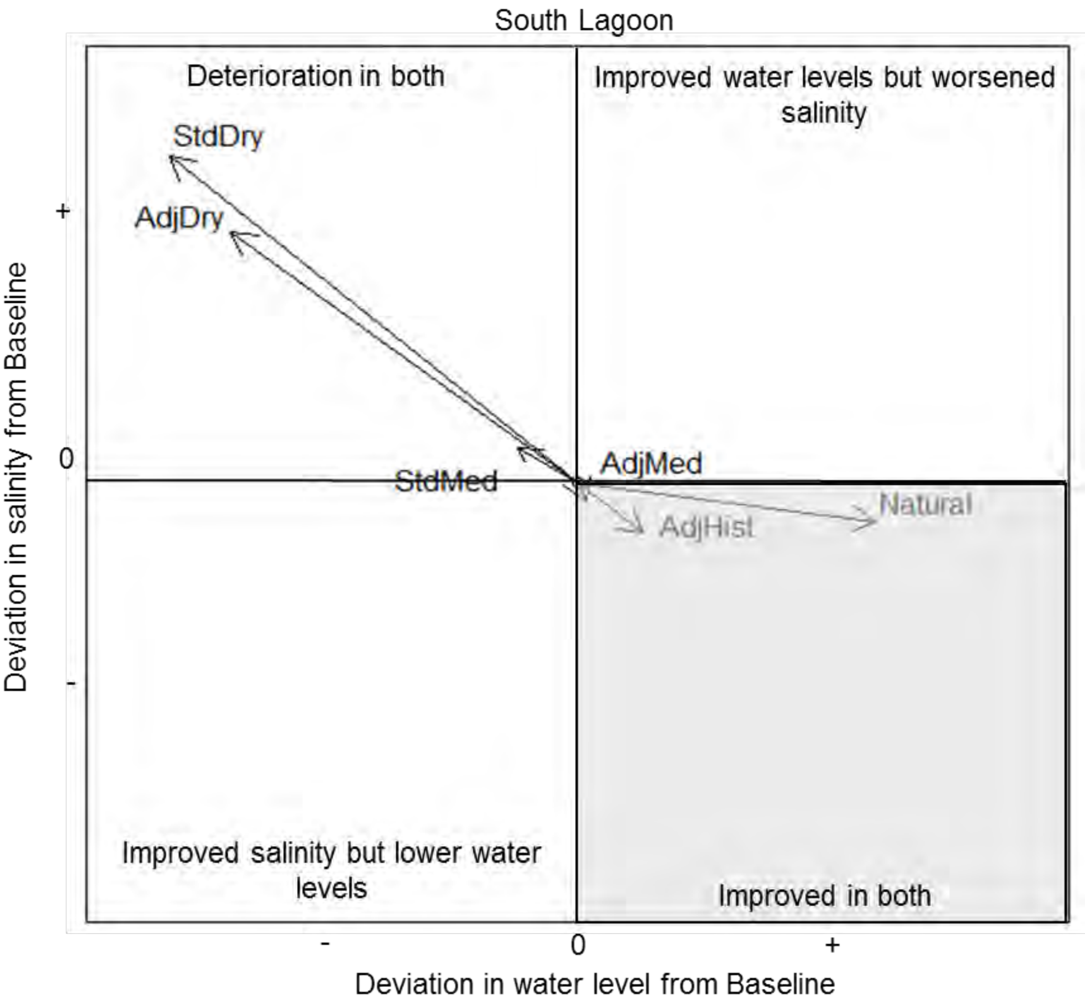

Figure 10.22: Comparison of the timing of flow delivery and climate change scenarios relative to the Standard Historical scenario for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Standard Historical scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Standard Historical condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and lower salinities). AdjHist is Adjusted Historical scenario, AdjMed is Adjusted Median scenario, AdjDry is Adjusted Dry scenario, StdMed is Standard Median scenario and StdDry is Standard Dry scenario. Information on how to read the figure is presented in Appendix E.

A more extreme future climate projection (Standard Dry and Adjusted Dry scenarios) had a larger negative impact on the hydrodynamic drivers of the Coorong (Figure 10.20), particularly on water levels and maximum salinities. Median water levels under a dry future climate were approximately 10-12 cm lower than under an historical climate and 8-10 cm lower than under a median future climate for both the standard and adjusted scenarios. Maximum salinities jumped dramatically under dry future climate projections, from a median of 66.8 g L^{-1} under the Standard Historical scenario to 166.8 g L^{-1} under the Standard Dry scenario (or 47.4 g L^{-1} to 132.9 g L^{-1} for the equivalent adjusted scenarios). This negative effect was also seen when the cumulative effect of a dry future climate projection was assessed relative to the Standard Historical scenario (Figures 10.21 and 10.22). For both the North Lagoon (Figure 10.21) and the South Lagoon (Figure 10.22), there were large deteriorations in all hydrodynamic drivers of ecosystem states for the both the Standard and Adjusted Dry scenarios.

The effect of current extraction levels can be seen by comparing the Standard Historical scenario to the Natural scenario. Current extraction levels within the Murray-Darling Basin were having an impact on the simulated values for all hydrodynamic drivers of ecosystems states within the Coorong (Figure 10.20). Median average water levels were substantially lower under the Standard Historical scenario (0.26 m AHD) than under the Natural scenario (0.38 m AHD), median depths were lower (1.48 m compared to 1.57 m) and median maximum salinities were higher (67.8 g L^{-1} compared to 52.1 g L^{-1}). Extraction levels also increased the median annual range in water level from 0.94 m under the Standard Historical Scenario to 1.07 m under the Natural scenario.

The cumulative effect of these changes could be seen for both the North and South Lagoons (Figures 10.21 and 10.22). The Natural scenario showed the greatest improvement in water levels and water depths in the North Lagoon of any scenario investigated (Figure 10.21), and in water levels and salinities in the South Lagoon (Figure 10.22), relative to the Standard Historical scenario.

10.4.2 Effect of constant environmental flow delivery

Constant flow delivery to maintain a particular salinity in Lake Alexandrina (i.e. 700, 1000 or 1500 µS cm^{-1} EC) had very little impact on the annual range in water level or the depth of water in the Coorong (Figure 10.23). However, it did affect both the water level and the maximum salinities simulated. Water levels were substantially less variable with the constant addition of flow to maintain Lake Alexandrina salinities, with a range of 0.43 m for the Adjusted Historical 700 scenario, 0.49 m for the Adjusted Historical 1000 scenario and 0.56 m for the Adjusted Historical 1500 scenario, compared with 0.92 m for the Adjusted Historical scenario. The effect of constant flow delivery on maximum salinities was interesting. Median maximum salinities for both the Constant 1000 and Constant 1500 scenarios were higher than that of the Adjusted Historical scenario (52.1 g L^{-1} and 94.5 g L^{-1} compared with 47.4 g L^{-1}, respectively), while the median maximum salinity under the Constant 700 scenario was lower (35.7 g L^{-1}). This suggests that Lake Alexandrina salinities have historically been lower than 1000 µS cm^{-1} EC, and thus that less water is delivered for the Constant 1000 and 1500 scenarios than in the Adjusted Historical scenario. However, the range of values for maximum salinities is lower for all constant flow scenarios, without the high salinity outliers that are evident in the Adjusted Historical scenario.

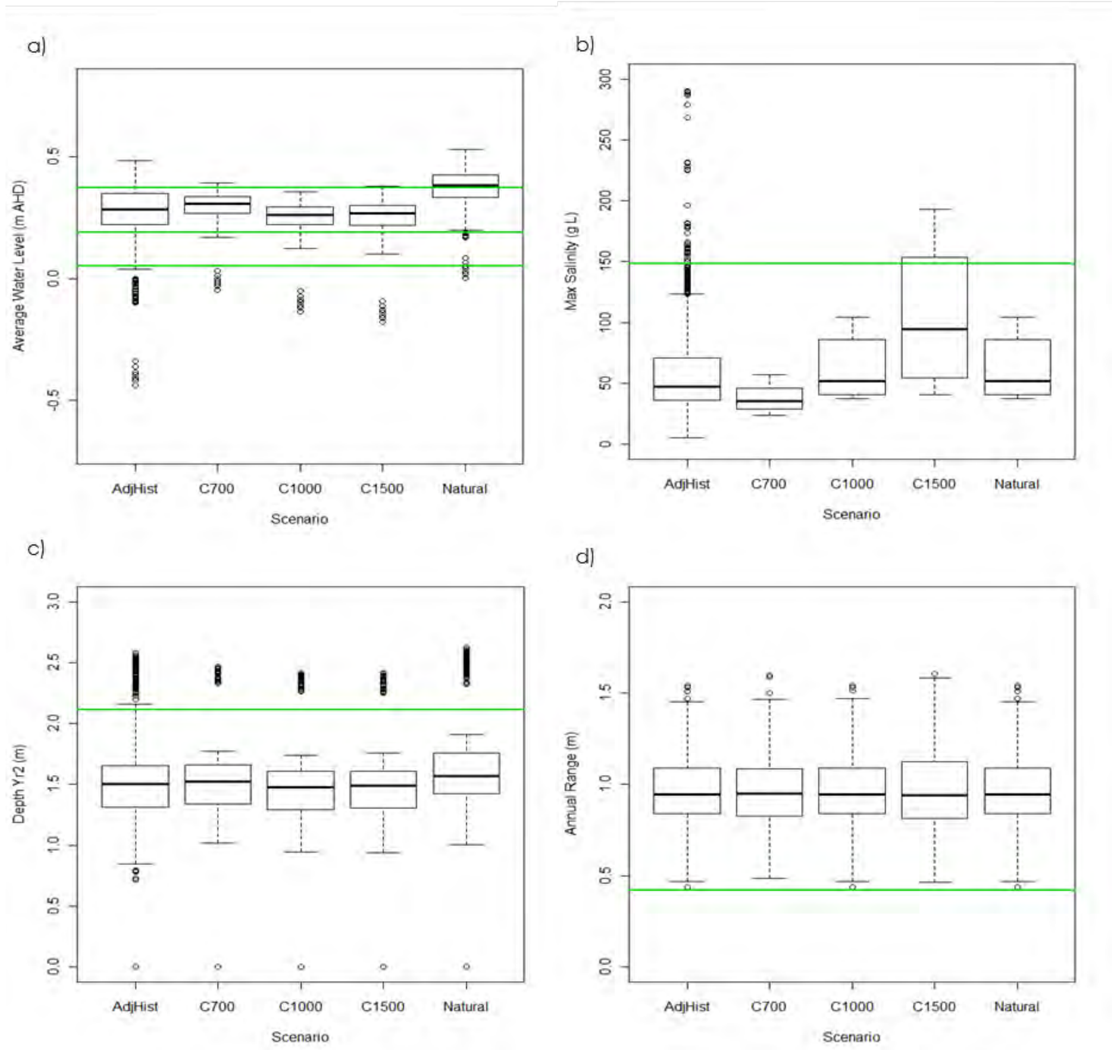

Figure 10.23: Boxplots showing the comparison between variables driving the ecosystem states of the Coorong for the constant flow scenarios. a) Average water level (m AHD), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Annual range in water level (m)

AdjHist is Adjusted Historical scenario, C700 is Constant 700 scenario, C1000 is Constant 1000 scenario, C1500 is Constant 1500 scenario. Information on how to read the figure is presented in Appendix E.

The cumulative effect of constant flow delivery was also somewhat unexpected when compared to the Standard Historical scenario (Figure 10.24). The Constant 1500 and Constant 700 scenarios showed an improvement in water levels and depths compared to the Standard Historical scenario (although the Constant 1500 scenario had a smaller positive effect than the Adjusted Historical scenario) in the North Lagoon. The Constant 1000 scenario, on the other hand, resulted in a relatively small deterioration in both water levels and water depths. This non-linear pattern of change as a result of constant flow delivery is mostly likely due to the dual effects of barrage flows to elevate water levels in the Coorong and to scour the Murray Mouth, changing the relative depth and thus the connectivity to Encounter Bay.

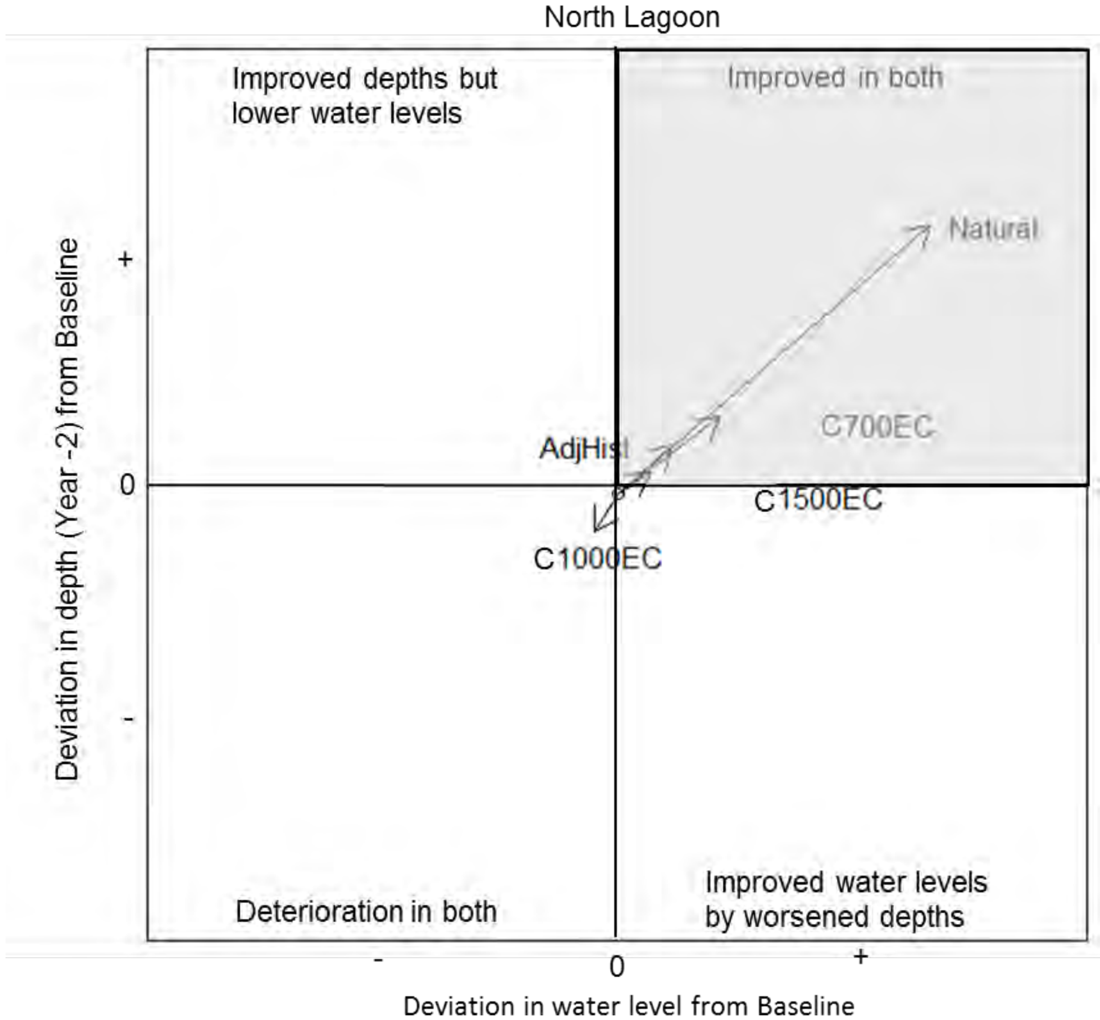

Figure 10.24: Comparison of constant flow scenarios relative to the Standard Historical scenario for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Standard Historical scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Standard Historical condition (as shown by the 0,0 origin). Vectors in the upper-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and greater depths). AdjHist is Adjusted Historical scenario, C700 is Constant 700 scenario, C1000 is Constant 1000 scenario, C1500 is Constant 1500 scenario. Information on how to read the figure is presented in Appendix E.

This non-linearity of effect of different constant flow scenarios was not evident in the South Lagoon (Figure 10.25). The Constant 1000 and Constant 1500 scenarios showed no net change in South Lagoon water levels compared to the Standard Historical scenario. The Constant 1000 scenario resulted in a slight improvement in South Lagoon salinities, while the Constant 1500 scenario resulted in a slight deterioration in salinity in the South Lagoon. The Constant 700 scenario was an improvement in both water levels and salinities in the South Lagoon when compared to the Standard Historical or the Adjusted Historical scenarios.

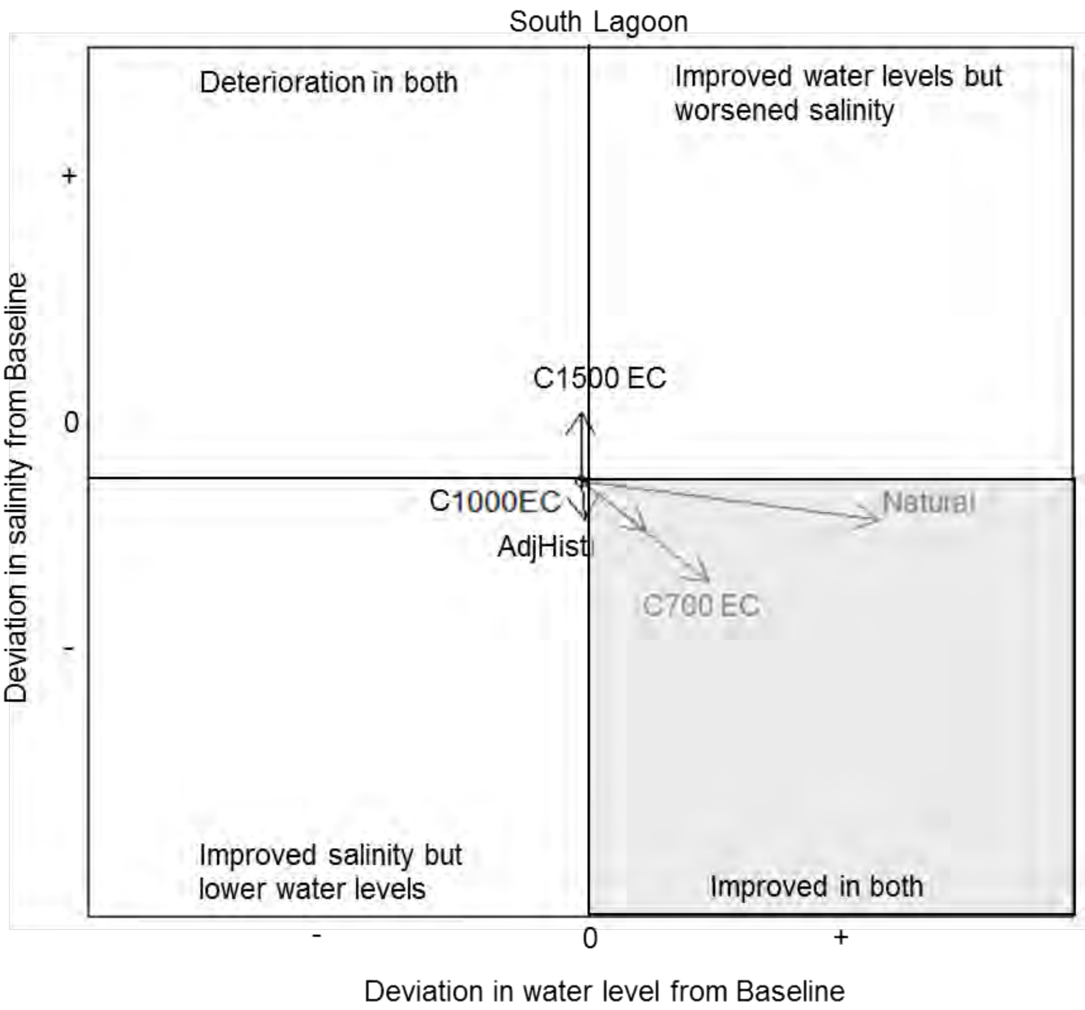

Figure 10.25: Comparison of the constant flow scenarios relative to the Standard Historical scenario for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Standard Historical scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Standard Historical condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and lower salinities). AdjHist is Adjusted Historical scenario, C700 is Constant 700 scenario, C1000 is Constant 1000 scenario, C1500 is Constant 1500 scenario. Information on how to read the figure is presented in Appendix E.

10.4.3 Effect of rules-based environmental flow delivery

When additional environmental water was allocated to the Coorong using the environmental watering rules described by Heneker (2010), the largest impact was seen on the maximum salinity for each scenario (Figure 10.28). Median maximum salinity for the Adjusted Historical 700 scenario was 31.6 g L^{-1}, compared with 40.5 g L^{-1} for the Adjusted Historical 1000 scenario, 44.7 g L^{-1} for the Adjusted Historical 1500 scenarios and 47.4 g L^{-1} for the Adjusted Historical scenario. Rules-based addition of environmental flows had little effect on median average water levels, but resulted in less variability in water levels across the model run. Water depths and the annual range in water levels were not greatly affected by the addition of rules-based environmental flow delivery.

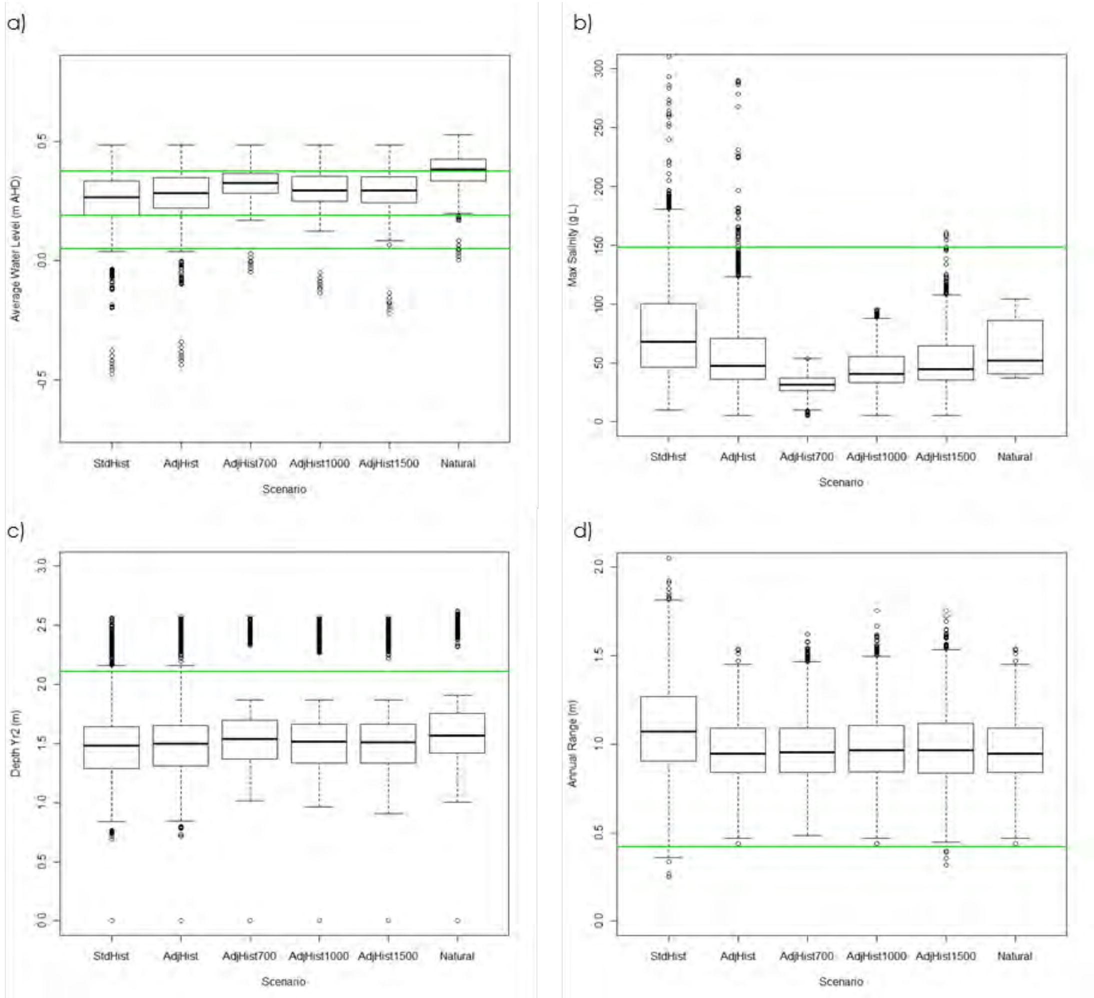

Figure 10.26: Boxplots showing the comparison between variables driving the ecosystem states of the Coorong for the rules-based flow scenarios. a) Average water level (m AHD), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Annual range in water level (m)

StdHist is Standard Historical scenario, AdjHist is Adjusted Historical scenario, AdjHist 700 is Adjusted Historical 700 scenario, AdjHist1000 is Adjusted Historical 1000 scenario and AdjHist1500 is Adjusted Historical 1500 scenario. Information on how to read the figure is presented in Appendix E.

All three scenarios investigating the effect of adding environmental water to the Coorong using rules to maintain salinities in Lake Alexandrina resulted in an improvement in both the water levels and depths in the North Lagoon, compared to both the Standard Historical and Adjusted Historical scenarios (Figure 10.27). Greater volumes of additional water (i.e. to achieve lower salinity targets in the Lakes) resulted in larger improvements in North Lagoon hydrodynamics. This pattern was also evident in the South Lagoon, where additional environmental water resulted in improvements in both water levels and salinities, with the degree of improvement correlating with the amount of extra water added (Figure 10.28). In both the North and South Lagoons, however, the volumes of additional water were insufficient to approximate the effect of natural flows (i.e. with no extractions in the Murray-Darling Basin).

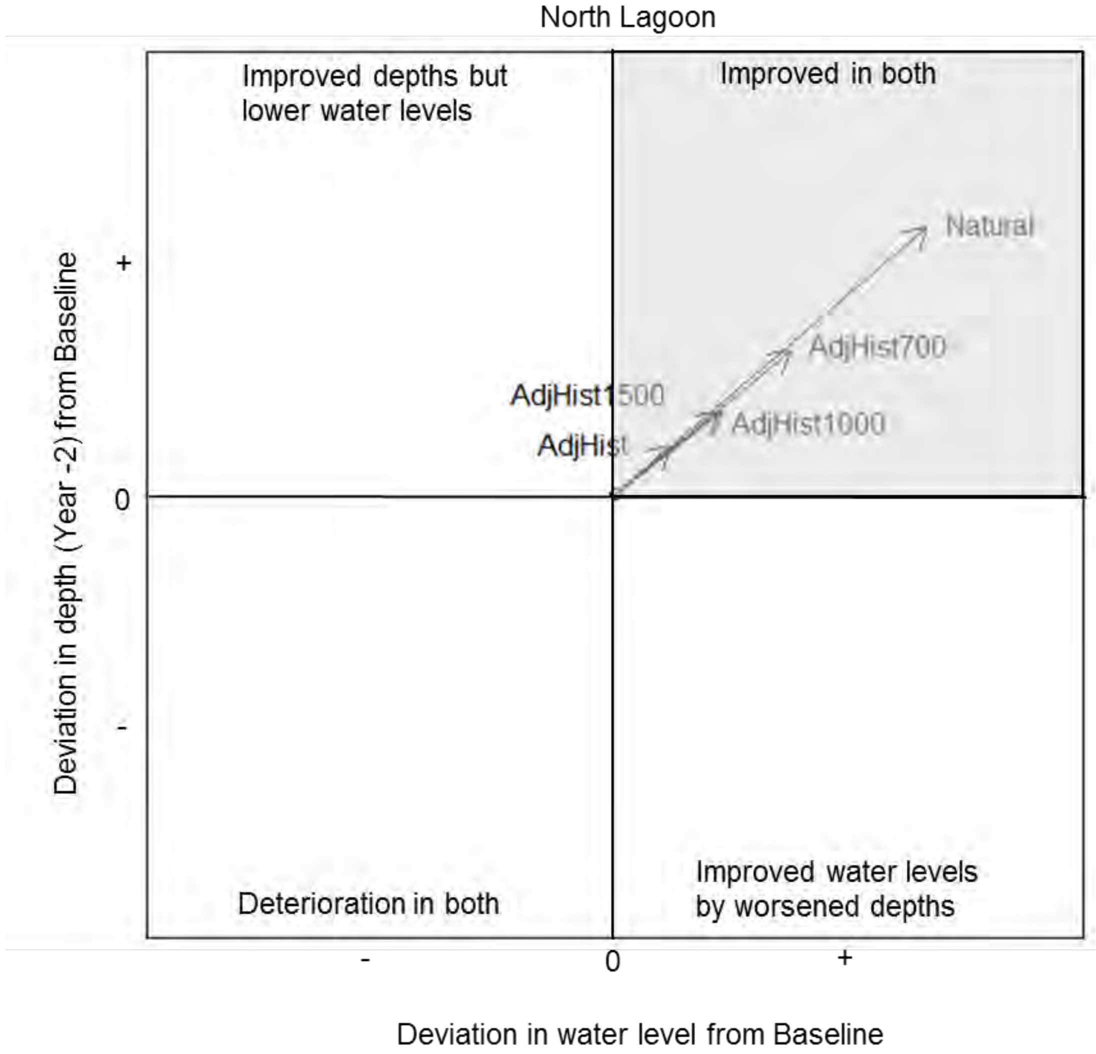

Figure 10.27: Comparison of the rules-based flow scenarios relative to the Standard Historical scenario for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Standard Historical scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Standard Historical condition (as shown by the 0,0 origin). Vectors in the upper-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and greater depths). AdjHist is Adjusted Historical scenario, AdjHist700 is Adjusted Historical 700 scenario, AdjHist 1000 is Adjusted Historical 1000 and AdjHist 1500 is Adjusted Historical 1500 scenario. Information on how to read the figure is presented in Appendix E.

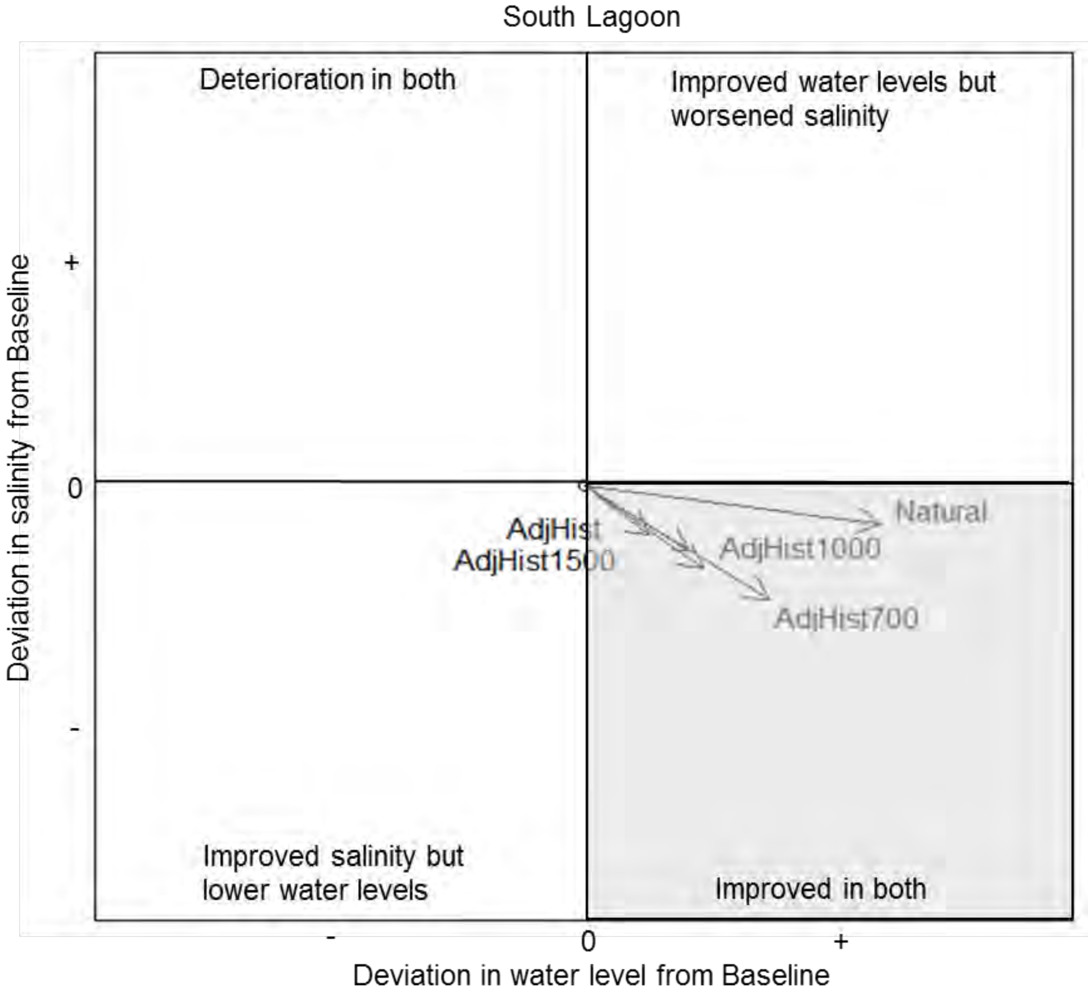

Figure 10.28: Comparison of the rules-based flow scenarios relative to the Standard Historical scenario for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Standard Historical scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Standard Historical condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and lower salinities). AdjHist is Adjusted Historical scenario, AdjHist700 is Adjusted Historical 700 scenario, AdjHist 1000 is Adjusted Historical 1000 scenario and AdjHist 1500 is Adjusted Historical 1500 scenario. Information on how to read the figure is presented in Appendix E.

10.4.4 Effect of rules-based environmental flow delivery under climate change

The effect of rules-based environmental flow delivery under median climate change was very similar to that under the historical climate (Figure 10.29). This is consistent with the relatively small impact of median future climate change described above. Median average water levels were higher, but also less variable, with increasing levels of additional environmental water. Median maximum salinities were much lower with the rules-based addition of environmental water, but were again much less variable (i.e. the range in values was 398.0 g L^{-1} for the Adjusted Median scenario compared to 47.3 g L^{-1} for the Adjusted Median 700 scenario, 91.7 g L^{-1} for the Adjusted Median 1000 scenario and 148.5 g L^{-1} for the Adjusted Median 1500 scenario). Very little difference was observed in water depths or the annual range in water level as a result of rules-based environmental flow delivery.

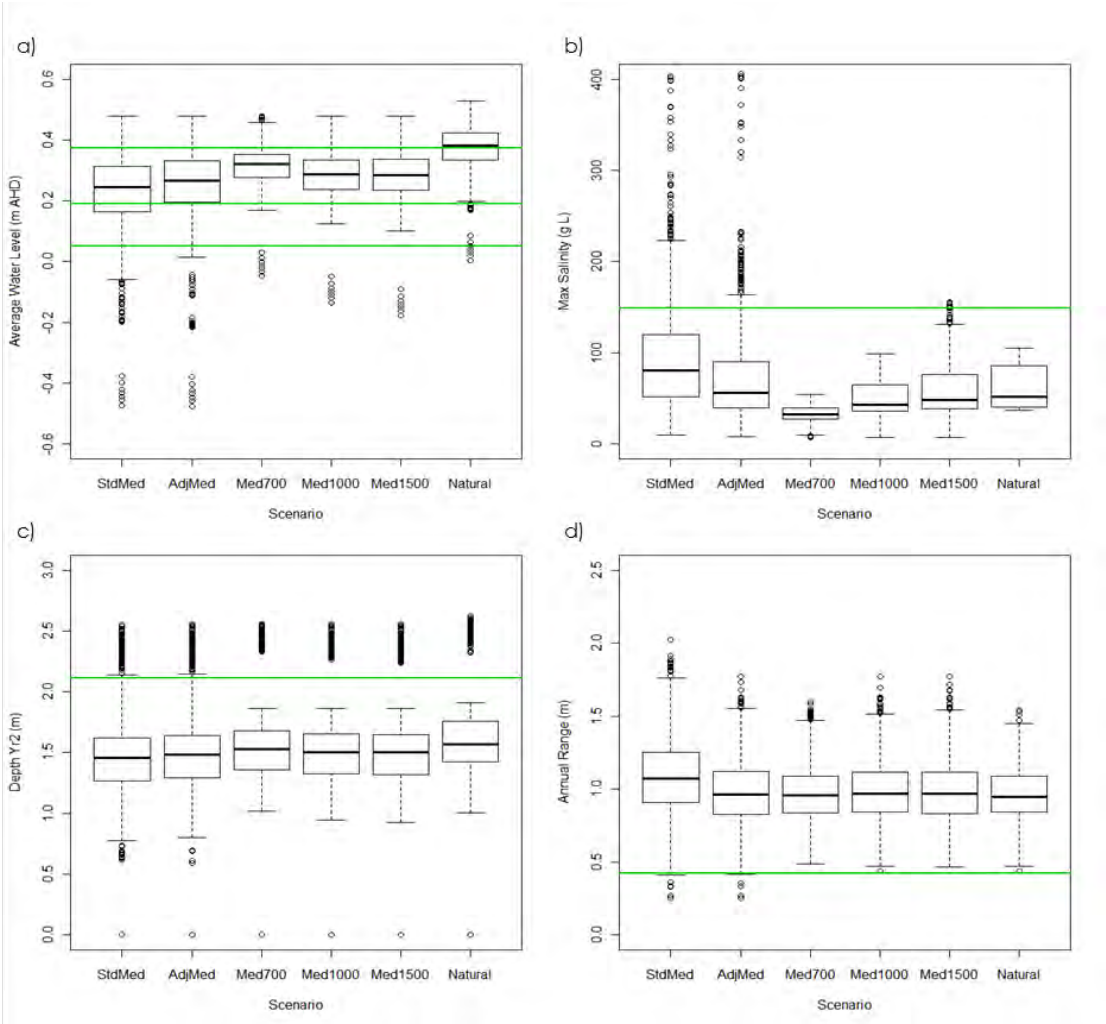

Figure 10.29: Boxplots showing the comparison between variables driving the ecosystem states of the Coorong for the rules-based flow scenarios under a median future climate. a) Average water level (m AHD), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Annual range in water level (m)

StdMed is Standard Median scenario, AdjMed is Adjusted Median scenario, Med700 is Adjusted Median 700 scenario, Med1000 is Adjusted Median 1000 scenario and Med1500 is Adjusted Median 1500 scenario. Information on how to read the figure is presented in Appendix E.

The addition of environmental water based on the specified rules resulted in improvements in both water levels and depths in the North Lagoon for all three Lake Alexandrina salinity targets investigated (Figure 10.30) compared to the Standard Historical or the Adjusted Median scenarios. There was little difference between the Adjusted Median 1000 and the Adjusted Median 1500 scenarios, and the Adjusted Median 700 scenario had the greatest impact. The cumulative effect of rules-based environmental flow delivery was similar for the hydrodynamic drivers of ecosystem states in the South Lagoon (Figure 10.31). All three scenarios resulted in improvements in South Lagoon water levels and salinities compared to both the Adjusted Median and Standard Historical scenarios, with the Adjusted Median 700 scenario showing the largest positive impact.

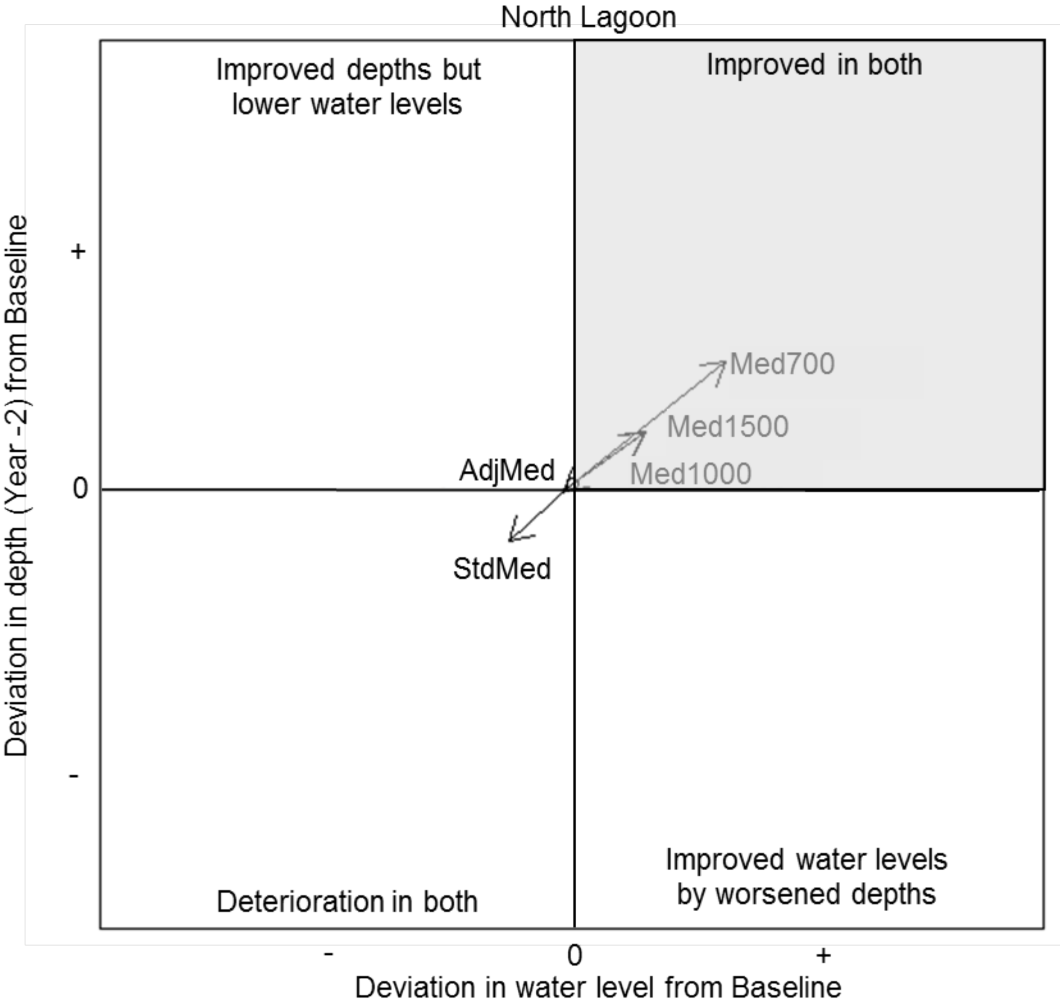

Figure 10.30: Comparison of the rules-based flow scenarios under a median future climate relative to the Standard Historical scenario for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Standard Historical scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Standard Historical condition (as shown by the 0,0 origin). Vectors in the upper-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and greater depths). StdMed is Standard Median scenario, AdjMed is Adjusted Median scenario, Med700 is Adjusted Median 700 scenario, Med1000 is Adjusted Median 1000 scenario and Med1500 is Adjusted Median 1500 scenario. Information on how to read the figure is presented in Appendix E.

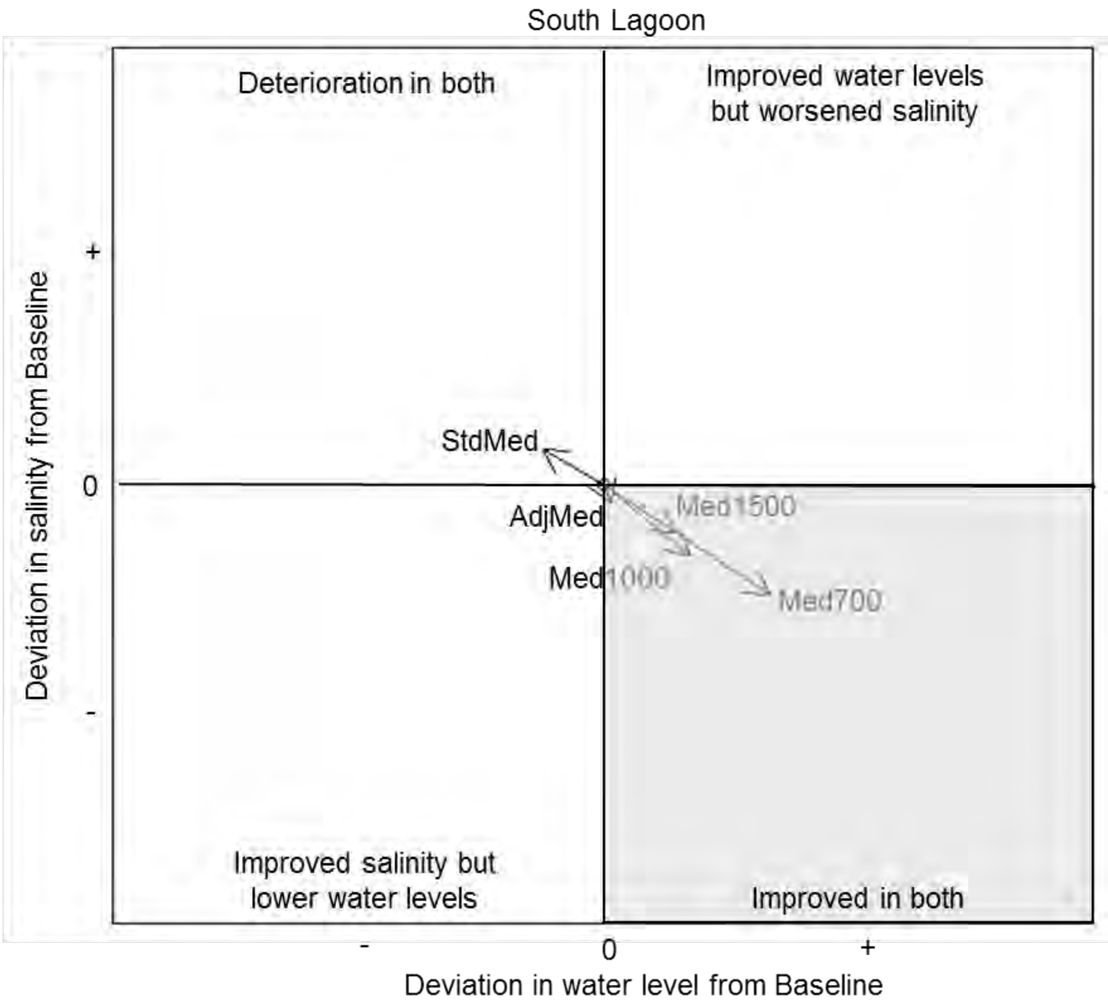

Figure 10.31: Comparison of the rules-based flow scenarios under a median future climate relative to the Standard Historical scenario for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Standard Historical scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Standard Historical condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and lower salinities). StdMed is Standard Median scenario, AdjMed is Adjusted Median scenario, Med700 is Adjusted Median 700 scenario, Med1000 is Adjusted Median 1000 scenario and Med1500 is Adjusted Median 1500 scenario. Information on how to read the figure is presented in Appendix E.

The effect of the rules-based addition of environmental water was greater under a dry future climate projection (Figure 10.32). All four hydrodynamic drivers of ecosystem states showed substantial change as a result of the additional water. Water levels were much higher when additional environmental water was added, and less variable with increasing amounts of that water (i.e. to maintain lower salinities in Lake Alexandrina). There was a smaller increase in the median average depth when environmental water was added using the described rules, but minimum depths were much higher than under a dry future climate without the additional water. There was also less variability in the annual range in water level. Maximum salinities were the most affected by the rules-based addition of environmental water. Median maximum salinities fell from 166.8 g L^{-1} under the Adjusted Dry scenario to 35.3 g L^{-1}, 48.2 g L^{-1} and 69.5 g L^{-1} under the Adjusted Dry 700, 1000 and 1500 scenarios, respectively. More importantly, the absolute maximum salinity over the model run dropped from an unrealistic 1154.0 g L^{-1} under the Adjusted Dry scenario to 54.7 g L^{-1}, 103.1 g L-1 and 177.6 g L-1 for the three Adjusted Dry rules-based additional flow scenarios, all of which are within the tolerances of at least some Coorong biota.

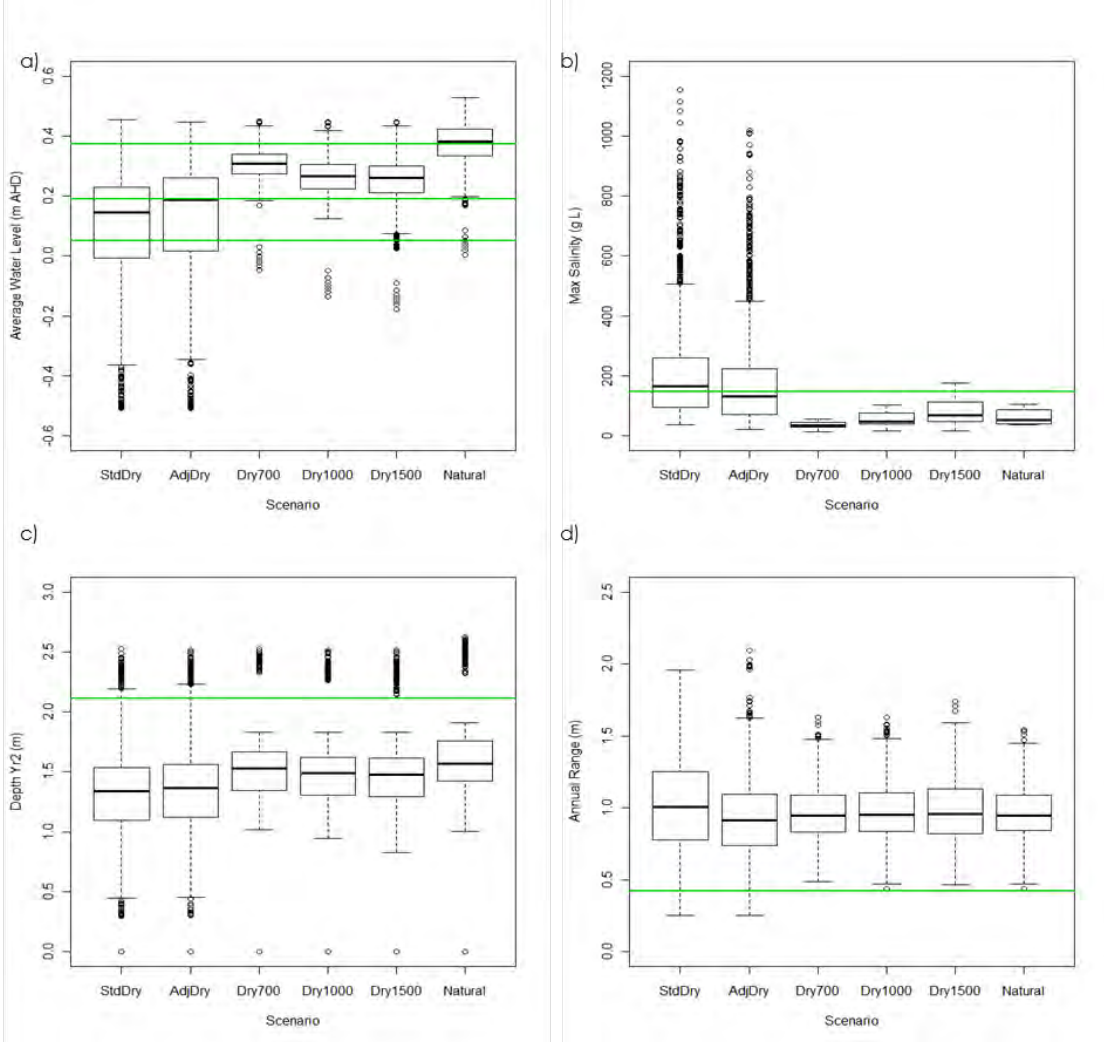

Figure 10.32: Boxplots showing the comparison between variables driving the ecosystem states of the Coorong for the rules-based flow scenarios under a dry future climate. a) Average water level (m AHD), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Annual range in water level (m)

StdDry is Standard Dry scenario, AdjDry is Adjusted Dry scenario, Dry700 is Adjusted Dry 700 scenario, Dry1000 is Adjusted Dry 1000 scenario and Dry1500 is Adjusted Dry 1500 scenario. Information on how to read the figure is presented in Appendix E.

The additional water needed to maintain salinities in Lake Alexandrina at either 1000 or 1500 µS cm^{-1} EC was sufficient to result in approximately no cumulative change in North Lagoon water levels and depths compared to the Standard Historical scenario (Figure 10.33) (as opposed to the Standard Dry and Adjusted Dry scenarios, both of which showed large deteriorations in both parameters). For the Adjusted Dry 1500 scenario, this was also true for South Lagoon water levels and salinities (Figure 10.34). Here, the Adjusted Dry 700 and the Adjusted Dry 1000 scenarios both showed improvements relative to the Standard Historical scenario, and very large improvements compared to either the Standard or Adjusted Dry scenarios.

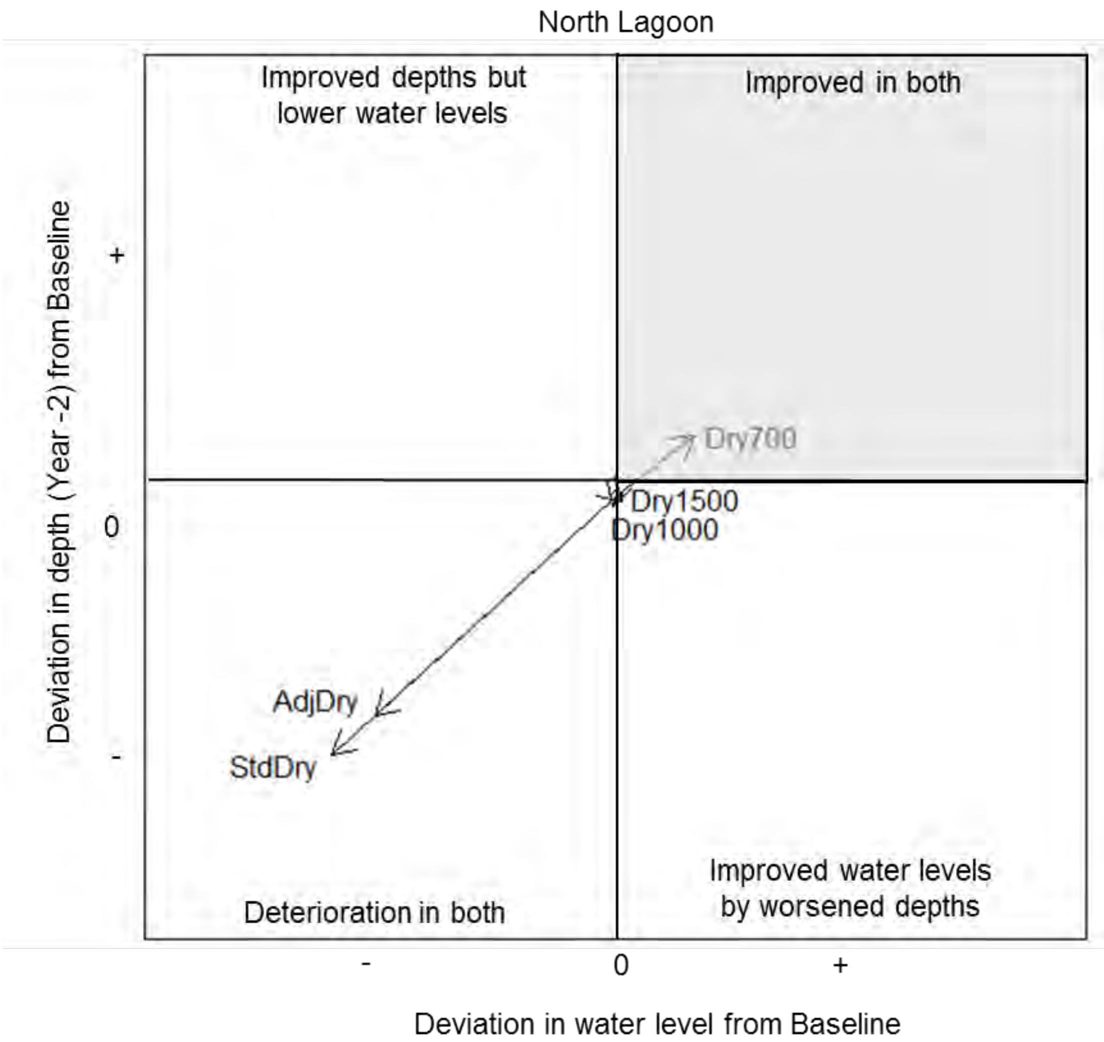

Figure 10.33: Comparison of the rules-based flow scenarios under a dry future climate relative to the Standard Historical scenario for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Standard Historical scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Standard Historical condition (as shown by the 0,0 origin). Vectors in the upper-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and greater depths). StdDry is Standard Dry scenario, AdjDry is Adjusted Dry scenario, Dry700 is Adjusted Dry 700 scenario, Dry1000 is Adjusted Dry 1000 scenario and Dry1500 is Adjuste Dry 1500 scenario. Information on how to read the figure is presented in Appendix E.

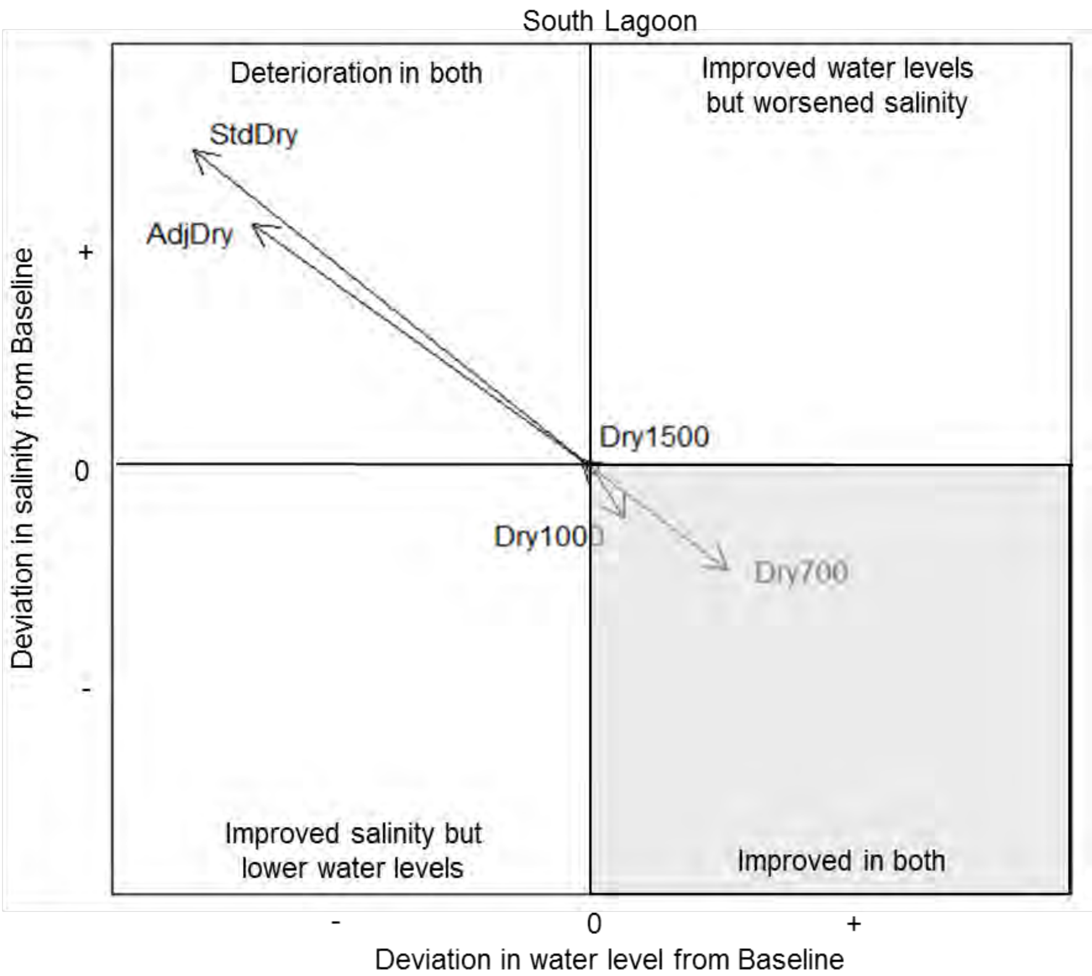

Figure 10.34: Comparison of the rules-based flow scenarios under a dry future climate relative to the Standard Historical scenario for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Standard Historical scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Standard Historical condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and lower salinities). StdDry is Standard Dry scenario, AdjDry is Adjusted Dry scenario, Dry700 is Adjusted Dry 700 scenario, Dry1000 is Adjusted Dry 1000 scenario and Dry1500 is Adjusted Dry 1500 scenario. Information on how to read the figure is presented in Appendix E.

10.5 Discussion

Adjusting the timing of flow delivery (here to a proportional allocation that did not vary between years) had an unexpectedly large impact on the hydrodynamics of the Coorong. Thus, the results of this modelling need to be interpreted with care. This does not mean that the simulated improvements in water levels, depths and salinities resulting from additional environmental water allocations cannot be relied upon. The trends that emerge with additional environmental flows are consistent across different climate scenarios, and tend to increase with larger volumes as would be expected, giving confidence that the findings are reliable overall. However, the absolute values that are predicted should be thought of as indicative. The inter-annual variability is substantially lower for the adjusted flow scenarios than occurs naturally, so it is likely that, in practice, there would be additional peaks and troughs that are not represented within this modelling. Thus, it is likely that there would be conditions that would be both better and worse than those that are captured here. The easiest way to resolve the magnitude of this effect would be via the collection of additional data.

Experimental releases of water would provide an opportunity to compare the predicted effects of environmental flows to observed effects, but comparing the predicted effect flows to observed normal flows would also be beneficial.

This unexpectedly large effect of adjusting the timing of flow delivery does highlight the importance of investigating the method of flow delivery (in terms of timing and duration) as well as simply considering the volume of water added. This is in contrast to the modelling undertaken for the Lakes, where explorations of the effect of the shape of the hydrograph suggested that volume was the primary determinant of salinity, in particular, and that skewness was relatively unimportant (Heneker 2010). In the Coorong, on the other hand, the shape of the hydrograph clearly had a large impact, in some instances as much of an effect as the volumes of additional water explored here, at least under historical climate conditions. Thus, the efficacy of environmental flow allocations will vary depending on how that flow is added, and additional modelling is required to determine when environmental flows should be added and how. Optimal flow delivery could mean that relatively small volumes of water could have a comparable effect to larger flow volumes with sub-optimal flow delivery and this should be understood to ensure that the maximum benefit per megalitre of environmental water added is achieved.

The natural flow scenario (that is, with no extractions in the Murray-Darling Basin) is shown on the majority of figures to provide a point of reference. The size of improvements and deteriorations are thus able to be benchmarked against the size of the impact of current extraction levels. None of the scenarios investigated here resulted in hydrodynamics that approximated the effect of natural flows under any climate projection. But, time series analysis did show that the volumes of water added to maintain salinities in Lake Alexandrina were sufficient to arrest the high salinities associated drought conditions in both the North and South Lagoons. This suggests that these salinity targets are potentially sufficient to limit the ecological decline associated with droughts in the region although not to reverse the effects of current extraction levels.

The constant addition of water to maintain one of three salinity targets for Lake Alexandrina highlighted the complexity of hydrodynamics within the Coorong. Barrage flows have multiple impacts on the hydrodynamics of the region, tending to both elevate water levels, and also scour the Murray Mouth. The rate of barrage flows, as well as the volume delivered, affects the relative impact on each. From this modelling, it appears that delivering a constant volume to maintain a salinity of 1500 $\mu S\ cm^{-1}$ in Lake Alexandrina was insufficient to result in much scour but did hold up water levels within the Coorong lagoons. The volume of water required to hold salinities in Lake Alexandrina below 1000 $\mu S\ cm^{-1}$ resulted in more Mouth scour, increasing the transmissivity of the Mouth, but was not a large enough volume to also hold up water levels. This means that additional water (compared to the Constant 1500 scenario) actually decreased water levels and depths in the North Lagoon (albeit slightly). The volume required to achieve a mean salinity of 700 $\mu S\ cm^{-1}$ in Lake Alexandrina had both effects, so resulted in improved hydrodynamics in both Lagoons. These complexities and non-linearities illustrate the value of tools such as well-calibrated hydrodynamic models in the determination of appropriate environmental flow allocations.

The result of rules-based flow additions was much more straightforward than those as a result of constant flows. Rules-based additional flows resulted in improvements in all of the hydrodynamic drivers of the Coorong in both the North and South Lagoons. These improvements were greater with greater flow volumes as would be expected. However, as mentioned above, none of the volumes investigated were sufficient to approximate natural flow conditions in the region.

The modelling undertaken here suggests that the hydrodynamics of the Coorong is not likely to be dramatically affected by median levels of climate change, provided that climate change acts in a manner consistent with that simulated here. The hydrodynamics under the standard and adjusted scenarios for the median future climate were very similar to those under the historical climate. This was also true of the scenarios investigating the rules-based addition of environmental water. A simulated dry future climate, on the other hand, had a dramatic effect on the hydrodynamics of the Coorong, with lower water levels, much higher salinities and much more variable conditions than occurred for either the historical or median future climate. It is likely that these conditions would have a large impact on the biota that could be supported within the region. The addition of environmental water using the described rules resulted in complete reversal of the impacts of the dry future climate. But, while the impact of rules-based addition of water to the Coorong was great under a dry future climate projection, it should be remembered that the larger amounts of water would be required to maintain salinities below the target levels in Lake Alexandrina than under historical or median future climate conditions. So, while this suggests that these targets may be appropriate, they will also be harder to achieve with increasing severity of climate change and more water (both in absolute terms and as a proportion of Basin inflows) will need to be available to meet those targets.

In considering the likely impact of climate change however, it is important to note that the effect of the timing of flow delivery on the hydrodynamics of the Coorong increases the uncertainty associated with the simulations here. One of the least well-understood aspects of climate change is the likely timing of future flows, as the variability of flows is expected to increase. If the flows are more (or less) uneven than has been simulated here for two future climate scenarios explored, the impact on the hydrodynamics of the Coorong may be very different (either better or worse, depending on the resultant flows) than has been predicted here. It is not currently possible to further explore this uncertainty, but may be in the future should simulations of the impact of climate change on River Murray flows improve.

10.6 Summary

- **This assessment of hydrodynamic impacts in the Coorong builds on work by Heneker (2010), which focussed on achieving salinity targets with Lake Alexandrina and the implications this had on water levels, flow volumes and the hydrology of Lakes Albert and Alexandrina.**
- **The hydrodynamic model used was a one-dimensional model that simulated water levels and salinities along the Coorong, allowing the effect of varying environmental flows to be assessed and compared among scenarios.**
- **Validation showed that the model did a credible job of simulating the response of the system in both salinity and in water level, although some inaccuracies exist when simulating instantaneous salinity measurements.**
- **Nineteen scenarios, involving combinations of environmental flows and three different climate change scenarios, were run. Current water allocations were also compared with 'natural' flow, simulating no development in the Murray-Darling Basin.**
- **Adjusting the pattern of flow delivery to be consistent each year (without adding additional environmental water) consistently predicted lower salinities and higher water levels than couple scenarios without adjustment, indicating that the pattern of flow delivery (i.e. timing and duration) was a critical driver of hydrodynamics in the Coorong.**
- **None of the scenarios investigated here resulted in comparable Coorong hydrodynamics to the natural flow scenario.**
- **The hydrodynamics of the Coorong would not be likely to be dramatically affected by median levels of climate change, as modelled here, particularly if environmental water were added. But, the simulated dry future climate had**

dramatic effects on the hydrodynamics of the Coorong, with lower water levels, much higher salinities and much more variable conditions than occurred for the historical or median future climate.

- **The addition of environmental water using the described rules resulted in a complete reversal of the impacts of the dry future climate but this would require larger amounts of water which may be harder to achieve with increasing severity of climate change.**
- **Constant delivery of environmental flows had complex effects on Coorong hydrodynamics, but tended to result in lower variability in hydrodynamics, which may not be advantageous. Constant delivery of flows to support a mean of 700 µS cm^{-1} in Lake Alexandrina showed the most consistent improvement in hydrodynamics, while effects of flows to meet the other two higher salinity targets were mixed.**
- **Environmental flows to support salinities of either a mean of 700 or a maximum of 1000 µS cm^{-1} in Lake Alexandrina resulted in substantial improvements in the hydrodynamics of the Coorong under any climate change scenario. Flows to support salinities of a maximum of 1500 µS cm^{-1} in Lake Alexandrina were also an improvement on corresponding scenarios without additional water, but did not prevent extreme conditions in very dry periods.**
- **If climate change occurred in a different manner to that simulated, the likely impact on Coorong hydrodynamics may differ substantially, given the importance of the timing and duration of barrage flows.**
- **This modelling indicated that providing rules-based environmental flows to support appropriate salinity targets in Lake Alexandrina could be an effective method of maintaining ecologically-appropriate hydrodynamic conditions in the Coorong as well, despite future climate change.**

11. Ecological impacts of environmental water allocation

Rebecca E. Lester & Peter G. Fairweather

This work follows directly from the investigation of the impact of additional work on the hydrodynamics of the Coorong (Chapter 10). The work described in this chapter focuses on identifying the likely mix of ecosystem states that would be supported by the recommended flow regimes, designed to support salinity targets in Lake Alexandrina (Heneker 2010). The same set of scenarios has been included (see Section 10 above for a detailed description of each) so as to evaluate the ecological impacts associated with the hydrodynamic impacts described previously.

In order to assess ecological impacts using the ecosystem state model, it was necessary to define some target conditions that could be assessed in this manner and were consistent with the overall objectives of the project. For all assessments made using the ecosystem states model, the following targets were used:

1. To avoid ecological degradation in the Coorong through the appearance of 'degraded' ecosystem states (with degraded ecosystem states defined as any of the Marine, Unhealthy Marine, Degraded Marine, Unhealthy Hypersaline or Degraded Hypersaline states).
2. To maintain the frequency of the Healthy Hypersaline state which is thought to be associated with high-flow conditions (which are likely to be of ecological importance to the region).

A secondary target of ensuring sufficient flow to maintain an open Murray Mouth without the need for dredging in 95% of years was also used, although there are issues associated with defining 'open' and, from an ecological perspective, it is highly likely that failure to maintain sufficient flow and connectivity in the system would result in degraded ecosystem states occurring (and so the first objective listed should also cover this secondary objective). The objective was retained, however, due to the stated objectives in DEH (2010).

By explicitly considering ecological impacts of environmental water allocations, we recognise that there are non-linearities in the response of biota to physicochemical conditions in the Coorong, and that increasing water levels and decreasing salinities do not necessarily lead to monotonic improvements in ecological condition. Results are presented in a manner consistent with previous reports that have investigated the hydrodynamic and ecological implications of management options of the Coorong (e.g. see Lester *et al.* 2009b,c,d).

11.1 Developing an ecosystem states model for the Coorong

Assessing ecological condition at an ecosystem scale is a difficult task. Typically, there are some aspects of an ecosystem that are well-studied and understood (e.g. birds and fish) and others that are less well understood (e.g. groundwater inputs and microbes). In order to assess ecological condition in the Coorong, we developed an ecosystem response model based on what we term 'ecosystem states'.

Unlike the hydrodynamic and hydrologic models that exist for the region (Chapter 10; Heneker 2010), the ecosystem states model is not based on a deterministic understanding of how ecosystems behave. That is, it is not based on equations describing the interactions between each species, their environments, and their competitors and predators, amongst other components. Instead, it is a statistical model, where existing data for the region has been statistically analysed and modelled to identify associations and relationships between the biota that occur within the system at any one point in time and the environmental conditions under which these biota occur. Our ability to construct a statistically-significant ecological model based on the hydrodynamics of the region re-enforces the notion that flows drive the ecology of the Coorong. In constructing the ecosystem states model, many non-hydrodynamic variables were included as potential drivers, so if flow were not the driving factor, the ecosystem states model should have reflected this (either by failing to satisfactorily explain the available ecological data or by including a range of non flow-related variables to distinguish among states). Thus, the concordance between the hydrodynamic model and the ecosystem states model suppors the underlying principle behind setting an environmental water requirement for the region: namely that influencing the flow coming to the region will influence the ecology of region.

The ecosystem state model developed for the Coorong under the CLLAMMecology Research Cluster identified eight distinct ecosystem states (see Box 11.1 for a description). These could be divided into two 'basins' of attraction, a marine basin and a hypersaline basin that are most often located within the North and South Lagoons respectively. Within each, there were four states, ranging from a broadly healthy state to a more degraded state. The biota and conditions characterizing each of these states are given in Appendix F. Additional information regarding the development and testing of the model is given in Lester & Fairweather (2009a,b, 2011).

One of the key driving parameters for the ecosystem model described in Lester & Fairweather (2011) was the occurrence of any freshwater flows over the barrages. Given that the scenarios investigated here are focussed on the effects of different flow volumes (rather than the presence versus absence of flows), we used a set of alterative models that had been developed to investigate the effect of alternatives to barrage flows such as dredging of the Murray Mouth (Lester & Fairweather 2009a). These models therefore describe the behaviour of the system without using flows over the barrages as a predictive variable.

In developing the alternative model, we retained the eight ecosystem states identified for the Coorong and related them to the salinities, water levels, depths and meteorological conditions in the Coorong. The best results were obtained when the two basins were modelled separately. The model for the marine basin (assumed to occur in the North Lagoon under the current conditions) is shown in Figure 11.1a. It describes the ecosystem state of the Coorong relative to the water level, the previous year's water level and depth from two years ago. This model correctly classified 72% of the training data set used and 70% of the test data set, indicating that it discriminated well between the marine ecosystem states.

a)

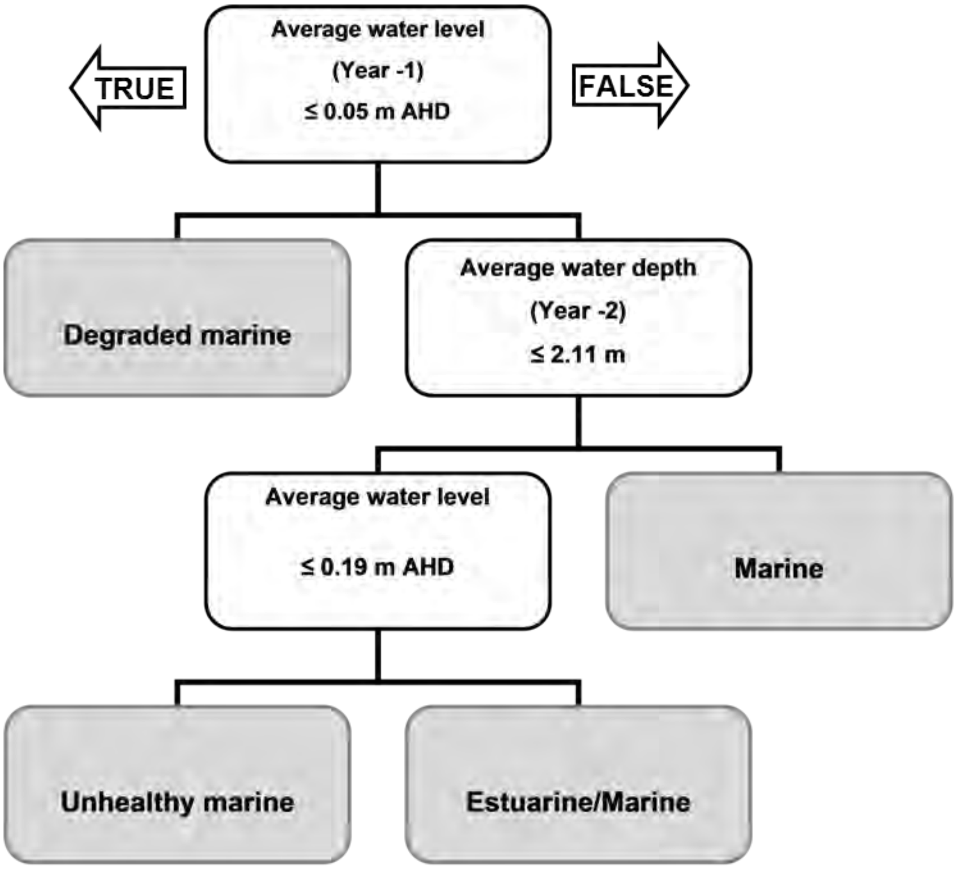

Figure 11.1a: Ecosystem state models for the Coorong (Marine or northern basin) excluding flow parameters as predictive variables

b)

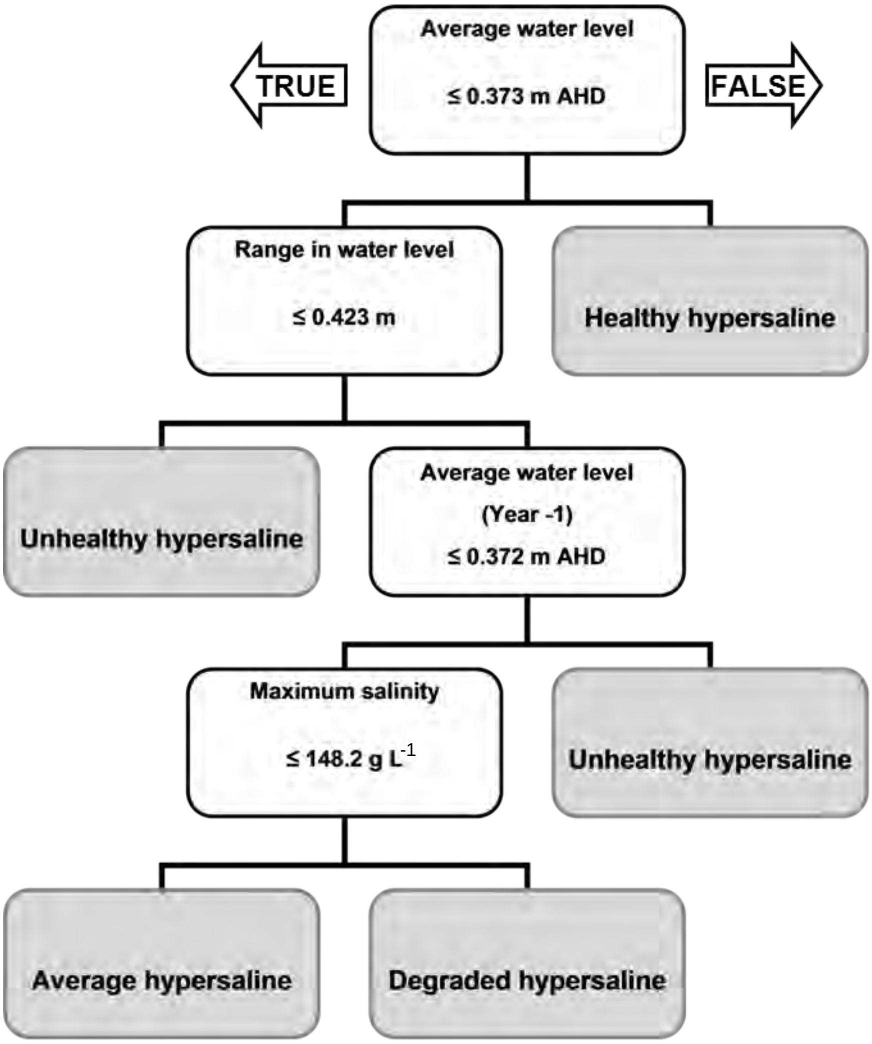

Figure 11.1b: Ecosystem state models for the Coorong (Hypersaline or southern basin) excluding flow parameters as predictive variables

This figure above presents logic trees which can be followed to identify the ecosystem state for a given location and time in the Coorong. Each white box contains a splitting parameter and a threshold value. Where the value for the parameter is less than or equal to the threshold value, then the tree should be followed to the left. Where it is higher, the tree should be followed to the right. When a grey terminal node box is reached, the state has been identified.

The hypersaline basin model (used to describe current South Lagoon states) identified a combination of average water level, water level from the previous year, the range in water levels over the year (i.e. change between the maximum and minimum water level over the year) and the maximum salinity for the year as driving the ecosystem state of the basin (Figure 11.1b). The hypersaline basin model correctly classified 87% of the training data set and 80% of the test data set under cross-validation. This is a high degree of predictive success given the variability inherent in ecological data sets.

Box 11.1: Characteristics of each of the eight ecosystem states

Marine Basin States

Estuarine/Marine

- Large numbers of marine and estuarine fish, a variety of birds dominated by piscivorous species, limited distribution of the aquatic macrophyte, *Ruppia tuberosa* and large numbers of invertebrates
- Lower average salinities, a shorter period since flow occurred over the barrages, highest average water depths and water levels and high variability in water levels across the both time periods than other states
- Low nutrient concentrations (e.g. ammonia and TKN [total Kjeldahl nitrogen]), low chlorophyll (*a* and *b*) concentrations, and low turbidity

Marine

- Dominated by marine and estuarine fish species, piscivorous birds and waterfowl species, with a reduced species richness but greater abundance of invertebrates
- Lowest average salinity of all the states, moderate average water levels, but had the highest variability in water levels across the time period, with greater time between water inputs, and more days since flow occurred over the barrages than the Estuarine/Marine state
- Lowest nutrient concentrations of total phosphate, TKN and turbidity of all other states

Unhealthy Marine

- Diverse fish population, bird species were dominated by piscivores, *Ruppia tuberosa* likely to be present and high abundances of adult and juvenile invertebrates
- Relatively low average salinities (but slightly higher than Estuarine/Marine), high average water levels but with greater variability in the average water levels across the time period for this state, greater average maximum number of days since flow occurred over the barrages and a lower average depths compared with other states in the marine basin
- Low nutrient concentrations

Degraded Marine

- Mix of piscivorous and wading birds, few fish species and chironomid larvae as the only characteristic benthic macroinvertebrates
- Appears to have higher average salinity with lower water levels and nutrient inputs than other marine-basin states
- Low water quality, with high concentrations of some nutrients (e.g. ammonia, TKN) and high turbidity
- Few predicted cases in the training data set, so care must be taken in characterising this state

Hypersaline Basin States

Healthy Hypersaline

- Few estuarine and marine fish species, large numbers of waders and waterfowl, lower numbers of invertebrates associated with this state but higher numbers of juvenile insects than for other ecosystem states
- Higher average salinity values than for the states of the marine basin, low average variability in water levels across the time period, high average water level, high average depths (only lower than the Estuarine/Marine and Marine states in the marine basin), with frequent freshwater flows
- Highest concentrations of nutrients (e.g. ammonia and TKN) and highest turbidity of all states, and high average chlorophyll concentrations

Average Hypersaline

- Very few fish species, only one characteristic piscivorous bird species (the Australian pelican *Pelecanus conspicillatus*), waders and waterfowl present, a high coverage of *Ruppia tuberosa* and very few invertebrate taxa but chironomid larvae and amphipods present in higher numbers.
- Higher average salinities than the marine-basin states, moderate changes in water levels, low average depths and few days between flows over the barrages
- High nutrient concentrations (e.g. TKN and ammonia) and turbidity, with the presence of algae and diatoms indicated by high concentrations of both chlorophyll *a* and *b*

Unhealthy Hypersaline

- Low numbers of fish present, except for high numbers of small-mouthed hardyhead (*Atherinosoma microstoma*) and piscivorous bird species, and a very small diversity of invertebrates but high numbers of chironomid larvae
- Higher average salinities than the Healthy or Average Hypersaline states, low average water levels and a high average maximum number of days since flow occurred over the barrage
- Like other hypersaline basin states, the water quality indicated high average nutrient concentrations (e.g. ammonia and total phosphate) and high turbidity

Degraded Hypersaline

- Relatively few fish species, a lack of invertebrate species, waders and waterfowl and lower numbers of piscivorous species
- Highest average salinity of all states, the lowest average water levels, a maximum water level of only -0.10 m AHD recorded. This state also had the lowest average change in water levels over the time period and the lowest average depths
- Highly variable water quality, with low average ammonia concentrations, but high average total phosphate concentrations and high turbidity (similar to the Average Hypersaline state) and higher average TKN than other hypersaline states
- Few predicted cases in the training data set, so care must be taken in characterising this state

All of the parameters identified as driving the ecosystem states of the Coorong could be calculated from output from the hydrodynamic model. The hydrodynamic model simulated hourly water levels and salinities along the length of the Coorong for each scenario (see Section 10). These data were then used to calculate the average water levels, depths and salinities as required by the ecosystem response models (i.e. Figure 11.1a,b). By using these parameters as input for the ecosystem response model, we were able to predict the mixture of ecosystem states present in the Coorong each year for the duration of the model run at each of the 14 salinity cells, which we have referred to as 'sites'. Each site could potentially support a different state in each subsequent year, so results have been presented by site, by year, which we refer to as 'site-years'.

The major area of uncertainty inherent in the ecosystem response model is in its ability to correctly predict the recovery of the system (Box 11.2). The model was developed using data from 1999 to 2007, which was a particularly dry period and one during which the ecological condition of the Coorong was deteriorating. Therefore, the model behaves as though the trajectory of decline is the same as the trajectory of recovery and that both occur over the same length of time. This is unlikely to be true, and represents a major uncertainty of the model but, until data describing the recovery of the system are available, there is no way to quantify the scale of the uncertainty. We are hoping to use data collected since higher barrage flows resumed to refine the model to address this uncertainty about recovery trajectories, once there are sufficient data to undertake this exercise.

Box 11.2: Overview of the ecosystems states function, assumptions and limitations

Function:

- Temporally- and spatially-explicit ecological response model intended to provide ecosystem-scale predictions of changes associated with management actions and climate change

Assumptions:

- Future changes in ecological character will mimic past changes
- Trajectories of decline are the same as trajectories of recovery, with no lag in the improvement of ecological condition
- The state located at each site-year is independent of previous or neighbouring states (although this is not the case for the hydrodynamic model from which input data are derived)
- No lag time is needed before ecological recovery occurs after degradation

Limitations:

- Does not necessarily capture casual relationships between environmental and biological aspects of the ecosystem
- Potentially biased towards describing declines in condition rather than any recovery (due to the available data upon which it was built)
- Inability to characterise additional ecosystem states for truly estuarine conditions using existing data
- Inability to build spatio-temporal links into the predictive model using existing data

Possible improvements:

- The recent break of drought is likely provide new data to quantify and potentially correct the bias to describing declines in condition, lags in ecological recovery and assumptions that the trajectory of decline is the same as that of recovery

11.2 Results

This section evaluates each scenario relative to the Standard Historical scenario and then relative to the other options explored. The scenarios are grouped according to the research categories outlined above (Section 10.2.3), as was done for the hydrodynamic results.

Figure 11.2 shows the distribution of ecosystem states at each site for each year of the model simulation that uses historical climate and current water extraction rules, with no other interventions (i.e. the Standard Historical scenario). It is presented as an example of the spatio-temporal output from the ecosystem state model and is used to illustrate features of the ecological response of the Coorong to environmental drivers over the 114-year model run.

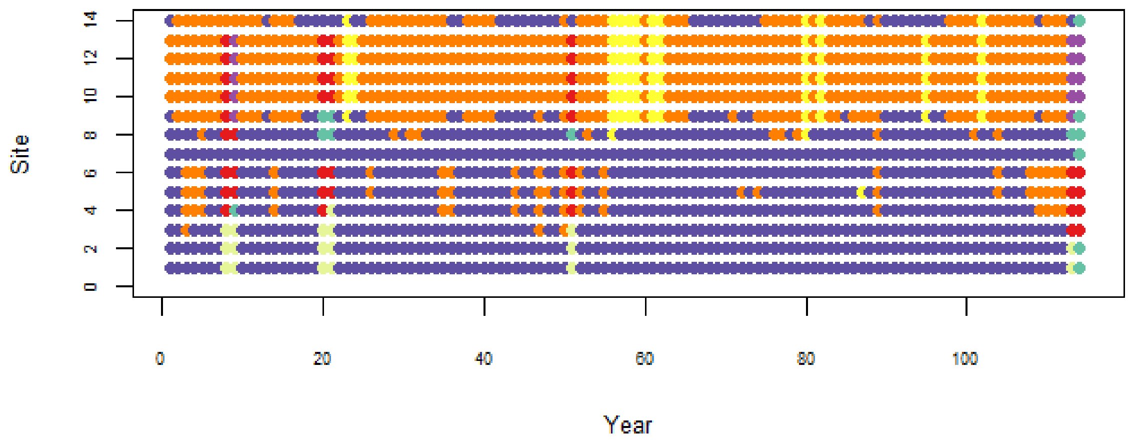

Figure 11.2: Distribution of ecosystem states for each site-year under the Standard Historical scenario

Each sequence of dots shows the distribution of the states for one site across the 114-year model run. The changes in the dot colours represent the transitions between states. For each dot, colours represent the following states: dark blue = Estuarine/Marine, light blue = Marine, light green = Unhealthy Marine, dark green = Degraded Marine, yellow = Healthy Hypersaline, orange =Average Hypersaline, red = Unhealthy Hypersaline and purple = Degraded Hypersaline. Information on how to read the figure is presented in Appendix E.

Over the 114-year model run, seven of the eight identified ecosystem states were present. The majority of site-years were either in the Estuarine/Marine state or the Average Hypersaline state. There were occasional departures from this typical condition, with North Lagoon sites occasionally changing to the Unhealthy Marine state for one or two years at a time and South Lagoon sites switching into the Degraded Hypersaline state predominantly, for up to eight-year stretches in times of drought.

In the following comparisons, the mix of ecosystem states illustrated for each scenario includes only years in which additional water was added. This emphasises the difference between the scenarios by excluding years in which there was no difference between the scenarios. Thus, each scenario as illustrated includes 1218 site-years (or 14 sites over 87 years).

11.2.1 Effect of adjusting the timing of flow delivery and climate change

The changes in the hydrodynamic parameters in the Coorong associated with adjusting the timing of flow delivery within the year affected the mix of ecosystem states simulated under each scenario (Figure 11.3). The loss of the extremes in water levels, salinities and other hydrodynamic parameters led to a more-uniform distribution of ecosystem states, despite using the same flow volumes and the same climatic simulations. The Standard Historical scenario had 21% of site-years predicted to be in degraded ecosystem states, compared with just 9% for the Adjusted Historical scenario. This was due to a decrease in the number of Degraded Hypersaline and Unhealthy Marine site-years in the latter, likely as a result of fewer prolonged dry periods. It should be emphasized that this difference was not due to an actual improvement in the system, but improvements which would have occurred had water delivery been more evenly distributed through time.

The differences in the proportion of site-years predicted to be in each ecosystem state is presented in Figure 11.4. This figure clearly shows where the differences between the Standard Historical and the Adjusted Historical scenarios lie. The alteration to the pattern of flow delivery resulted in a greater proportion of site-years predicted to be in the Estuarine/Marine and Average Hypersaline states than occurred in the Standard Historical scenario, with few site-years in the Unhealthy Marine and Degraded Hypersaline states, in particular.

Under current extraction levels, climate change had the potential to dramatically affect the mix of ecosystem states in the Coorong (Figure 11.3). The proportion of degraded site-years rose from 21% under the Standard Historical scenario (or 9% for the Adjusted Historical) to 34% under the Standard Median (17% for Adjusted Median) and 76% of site-years under the Standard Dry scenarios (64% for Adjusted Dry). The effect of this on the biota of the Coorong would be devastating and it is very unlikely that the described Ramsar ecological condition could be maintained.

Looking at the changes in the proportion of site-years in each ecosystem state (Figure 11.4), a median future climate projection (Standard Median and Adjusted Median scenarios) resulted in a relatively small decrease in the proportion of site-years in the Estuarine/Marine state, with a largely-comparable rise in the incidence of the Unhealthy Marine state (compared with the Standard Historical and Adjusted Historical scenarios, respectively). There was also a somewhat larger decline in the proportion of site-years predicted to be in the Average Hypersaline state, with the majority of those predicted to be in the Degraded Hypersaline state instead. The changes associated with a dry future climate projection (Standard Dry and Adjusted Dry scenarios) were consistent with those observed for the median future climate change scenarios, but were exacerbated. The major difference (other than the magnitude of change) between the two climate change projections was the appearance of the Degraded Marine state in the dry future climate scenarios.

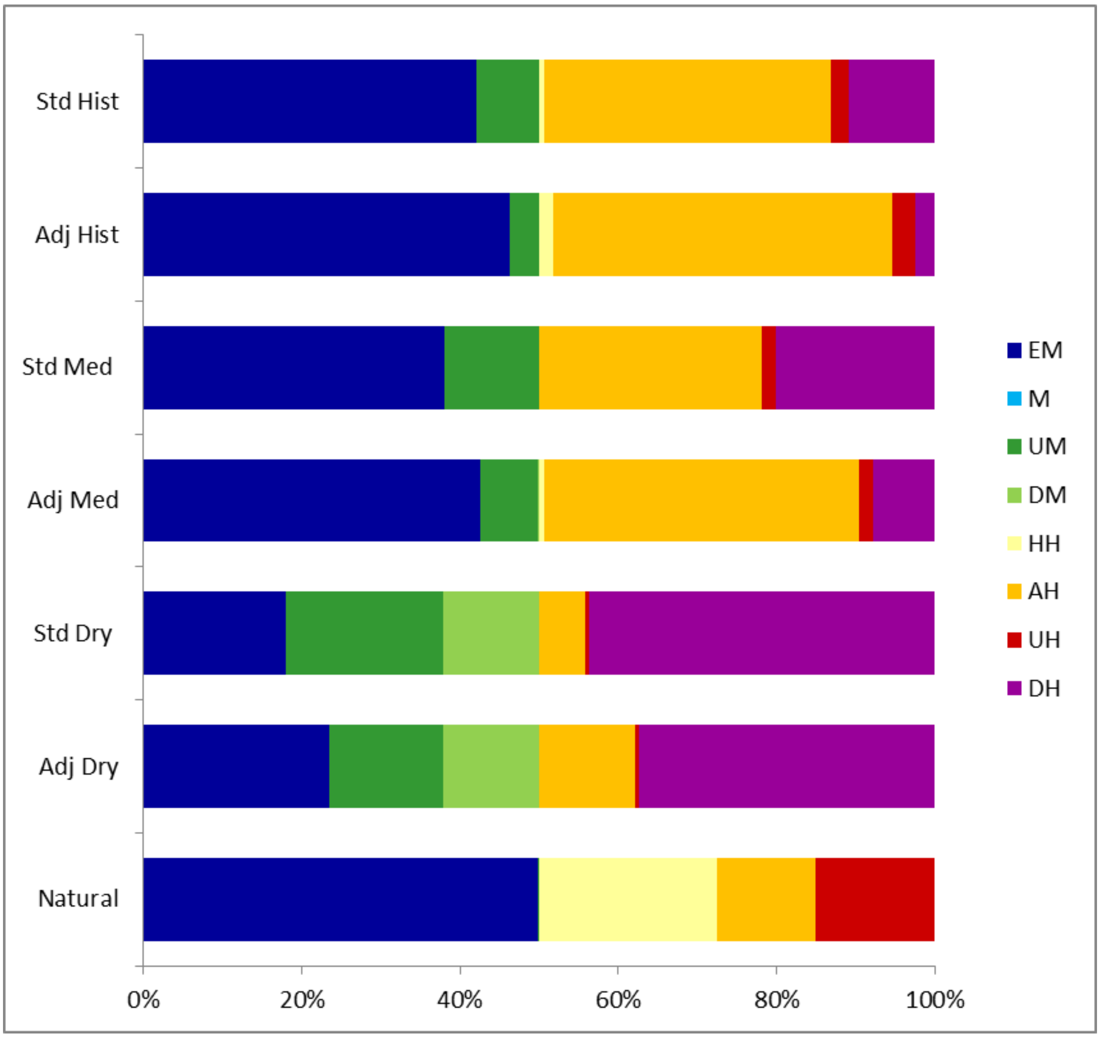

Figure 11.3: Comparing the proportion of site-years in each ecosystem state for the timing of flow and climate change scenarios

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Std Hist is Standard Historical scenario, Adj Hist is Adjusted Historical scenario, Std Med is Standard Median scenario, Adj Med is Adjusted Median scenario, Std Dry is Standard Dry scenario and Adj Dry is Adjusted Dry scenario. Information on how to read the figure is presented in Appendix E.

The Natural scenario (i.e. with an historical climate but no extractions within the Murray-Darling Basin) was included here to provide a point of comparison (Figure 11.3). By comparing the Natural scenario to the Standard Historical scenario, the effect of current extraction levels as simulated could be determined. All North Lagoon site-years were predicted to be in the Estuarine/Marine state under the Natural scenario, with no appearance of any degraded marine states. In the South Lagoon, however, 15% of site-years were predicted to be in the Unhealthy Hypersaline state. This was in contrast to predictions made using the original ecosystem states model for the Coorong (i.e. including the maximum number of days without flow as a predictive variable; see Lester & Fairweather 2009a, 2011, Lester *et al.* 2009b for further details), and thus may be an artefact of the model rather than an indication of truly degraded ecological condition. This finding is further explored in Appendix G.

However, none of the scenarios including current extraction levels approximated the mix of ecosystem states seen under the Natural scenario. In particular, the occurrence of degraded marine-basin states and the almost complete absence of the Healthy Hypersaline state were noteworthy. The Degraded Hypersaline state appeared in all scenarios except for the Natural scenario, indicating that current extraction levels were having a large impact on the ecology of the Coorong, particularly in the South Lagoon, according to model simulations.

The uniqueness of the Natural scenario amongst the scenarios presented here was also evident from Figure 11.4. The Natural scenario had a completely different pattern of deviations from the Standard Historical scenario compared with the other scenarios shown. The Natural scenario had higher proportions of site-years predicted to be in the healthiest ecosystem states (e.g. the Estuarine/Marine and Healthy Hypersaline states) and fewer in all other ecosystem states, except for the Unhealthy Hypersaline state as noted above.

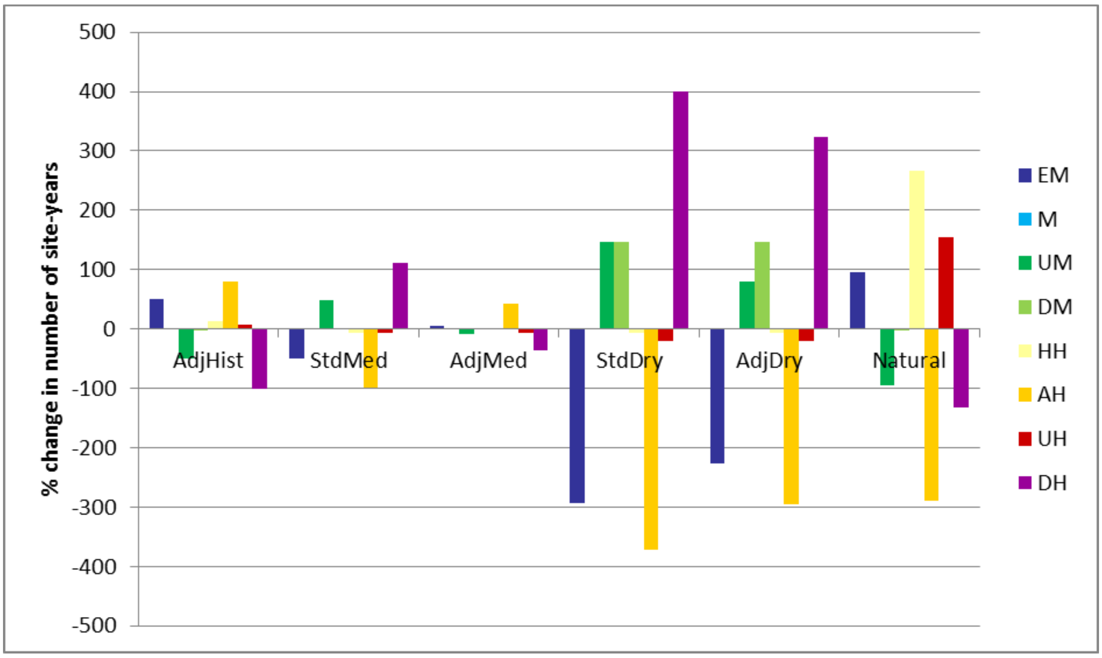

Figure 11.4: Deviations in the proportion of site-years in each ecosystem state compared to the Standard Historical scenario for the timing of flow and climate change scenarios

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Std Hist is Standard Historical scenario, Adj Hist is Adjusted Historical scenario, Std Med is Standard Median scenario, Adj Med is Adjusted Median scenario, Std Dry is Standard Dry scenario and Adj Dry is Adjusted Dry scenario. Information on how to read the figure is presented in Appendix E.

11.2.2 Effect of constant environmental flow delivery

Constant flow delivery to maintain a specified salinity in Lake Alexandrina (i.e. a mean of 700 or a maximum of either 1000 or 1500 µS cm^{-1} EC) under an historical climate, resulted in very little diversity in the mix of ecosystem states present (Figure 11.5). For a constant volume to maintain either a salinity of 700 or 1000 µS cm^{-1} EC in Lake Alexandrina, the vast majority of site-years were predicted to be in either the Estuarine/Marine state in the North Lagoon or the Average Hypersaline state in the South Lagoon. Constant additional flow delivery to maintain a salinity of 1500 µS cm^{-1} EC in Lake Alexandrina was not sufficient to maintain the mix of healthy ecosystem states, with 30% of site-years in the Degraded Hypersaline state (and less than 1% in the Unhealthy Marine state).

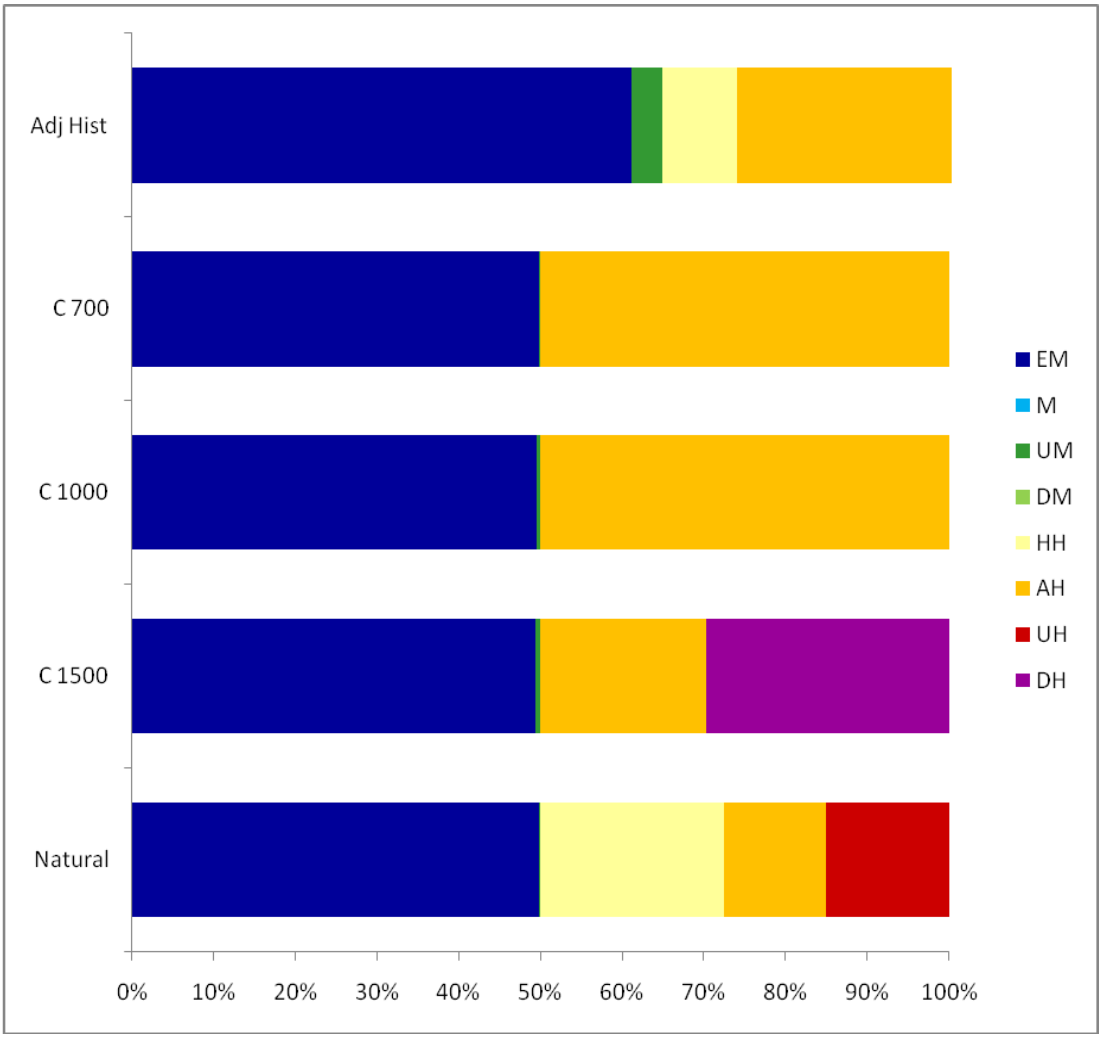

Figure 11.5: Comparing the proportion of site-years in each ecosystem state for the constant flow delivery scenarios

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Adj Hist is Adjusted Historical scenario, C 700 is Constant 700 scenario, C 1000 is Constant 1000 scenario, C 1500 is Constant 1500 scenario. Information on how to read the figure is presented in Appendix E.

The increase in the proportion of site-years in the Estuarine/Marine state and Average Hypersaline states for the Constant 700 and Constant 1000 scenarios is apparent in Figure 11.6. The Constant 1500 scenario had a very large decline in the proportion of site-years in the Average Hypersaline state and an even-larger increase in the proportion in the Degraded Hypersaline state. This supports the notion that the constant delivery of water to maintain a salinity of 1500 µS cm^{-1} EC in Lake Alexandrina was not sufficient to support South Lagoon ecosystems in a healthy condition.

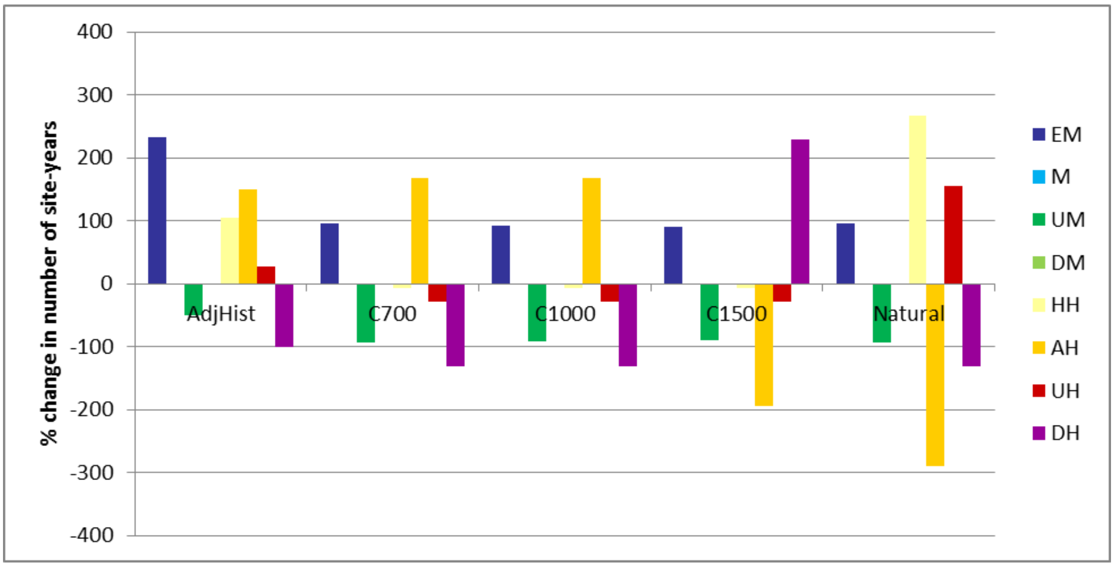

Figure 11.6: Deviations in the proportion of site-years in each ecosystem state compared to the Standard Historical scenario for the constant flow delivery scenarios

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Adj Hist is Adjusted Historical scenario, C 700 is Constant 700 scenario, C 1000 is Constant 1000 scenario, C 1500 is Constant 1500 scenario. Information on how to read the figure is presented in Appendix E.

11.2.3 Effect of rules-based environmental flow delivery

When additional environmental water was allocated to the Coorong using the environmental watering rules described above (Section 10.4.3), there was less difference in the mix of ecosystem states simulated for each scenario (Figure 11.7) than was apparent under constant delivery of environmental flows. Maintaining an average salinity of 700 µS cm^{-1} EC in Lake Alexandrina resulted in all North Lagoon site-years being classified as the Estuarine/Marine state and 46% of site-years predicted to be in either the Healthy Hypersaline or Average Hypersaline states. The remaining 4% of site-years were predicted to be in the Unhealthy Hypersaline state. The Adjusted Historical 1000 and Adjusted Historical 1500 scenarios resulted in a very similar mix of ecosystem states. There, 1% of site-years were predicted to be in the Unhealthy Marine state and 3% in the Unhealthy Hypersaline state for each scenario. Less than 1% of site-years were predicted to be in the Degraded Hypersaline state in the Adjusted Historical 1500 scenario (compared to none for the Adjusted Historical 700 or 1000 scenarios).

Figure 11.8 illustrates the similarity between the three flow scenarios. The pattern of deviations from the Standard Historical scenario was very similar across the three scenarios. There was a very small increase in the proportion of site-years in the Unhealthy Hypersaline state for the Adjusted Historical 700 scenario. It would be expected that this state would be less common due to the additional environmental water required to maintain the lower salinity target in Lake Alexandrina, so this may be related to the increased incidence of the Unhealthy Hypersaline state in the Natural scenario, which is discussed in Appendix G.

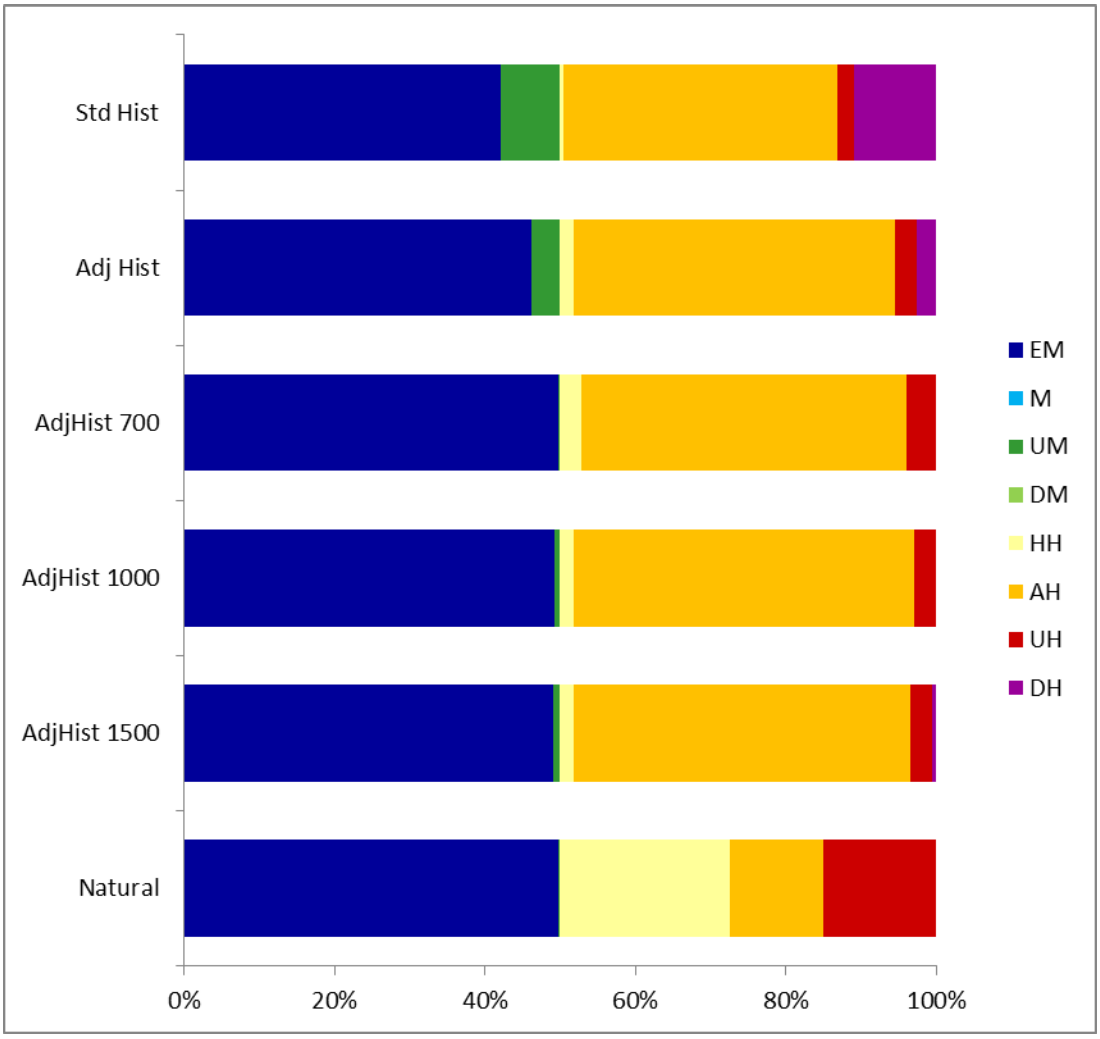

Figure 11.7: Comparing the proportion of site-years in each ecosystem state for the rules-based flow delivery scenarios

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Std Hist is Standard Historical scenario, Adj Hist is Adjusted Historical scenario, AdjHist 700 is Adjusted Historical 700 scenario, AdjHist 1000 is Adjusted Historical 1000 scenario, AdjHist 1500 is Adjusted Historical 1500 scenario. Information on how to read the figure is presented in Appendix E.

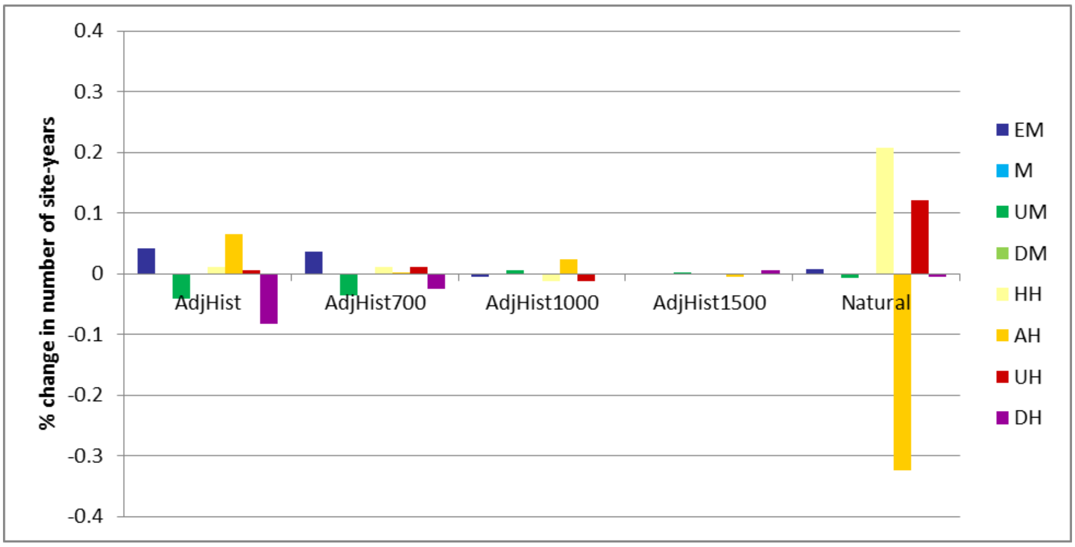

Figure 11.8: Deviations in the proportion of site-years in each ecosystem state compared to the Standard Historical scenario for the rules-based flow delivery scenarios

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Std Hist is Standard Historical scenario, Adj Hist is Adjusted Historical scenario, AdjHist 700 is Adjusted Historical 700 scenario, AdjHist 1000 is Adjusted Historical 1000 scenario, AdjHist 1500 is Adjusted Historical 1500 scenario. Information on how to read the figure is presented in Appendix E.

11.2.4 Effect of rules-based environmental flow delivery under climate change

The effect of additional environmental water delivered according to the rules described by Heneker (2010) under climate change resulted in dramatic improvements in the mix of ecosystem states in the Coorong under a median future climate (Figure 11.9). The addition of environmental water allocations to sustain salinity targets in Lake Alexandrina of either a mean of 700 or a maximum of 1000 µS cm^{-1} EC was sufficient to prevent the occurrence of the Degraded Hypersaline state, and the 1500 µS cm^{-1} EC target substantially reduced the frequency of that state. Delivery of additional environmental water to maintain the lowest salinity target was required to prevent the occurrence of degraded marine states (predominantly the Unhealthy Marine state), although the incidence of these states was also low for the scenarios maintaining higher salinity targets.

The deviation of incidence of ecosystem states compared to the Standard Historical scenario (Figure 11.10) demonstrated that maintaining target salinities in Lake Alexandrina resulted in an improved mix of ecosystem states despite the median climate change projection. There were sizeable declines in the prevalence of the Degraded Hypersaline and Unhealthy Marine states in all three rules-based flow delivery scenarios compared with the Standard Historical scenario. These were balanced by increases in the proportion of site-years predicted to be in the Estuarine/Marine and Average Hypersaline states. Despite this improvement, there was not a large increase in the proportion of Healthy Hypersaline states in any scenario, suggesting that the conditions provided by the rules-based flow addition were not yet optimal for South Lagoon ecosystems.

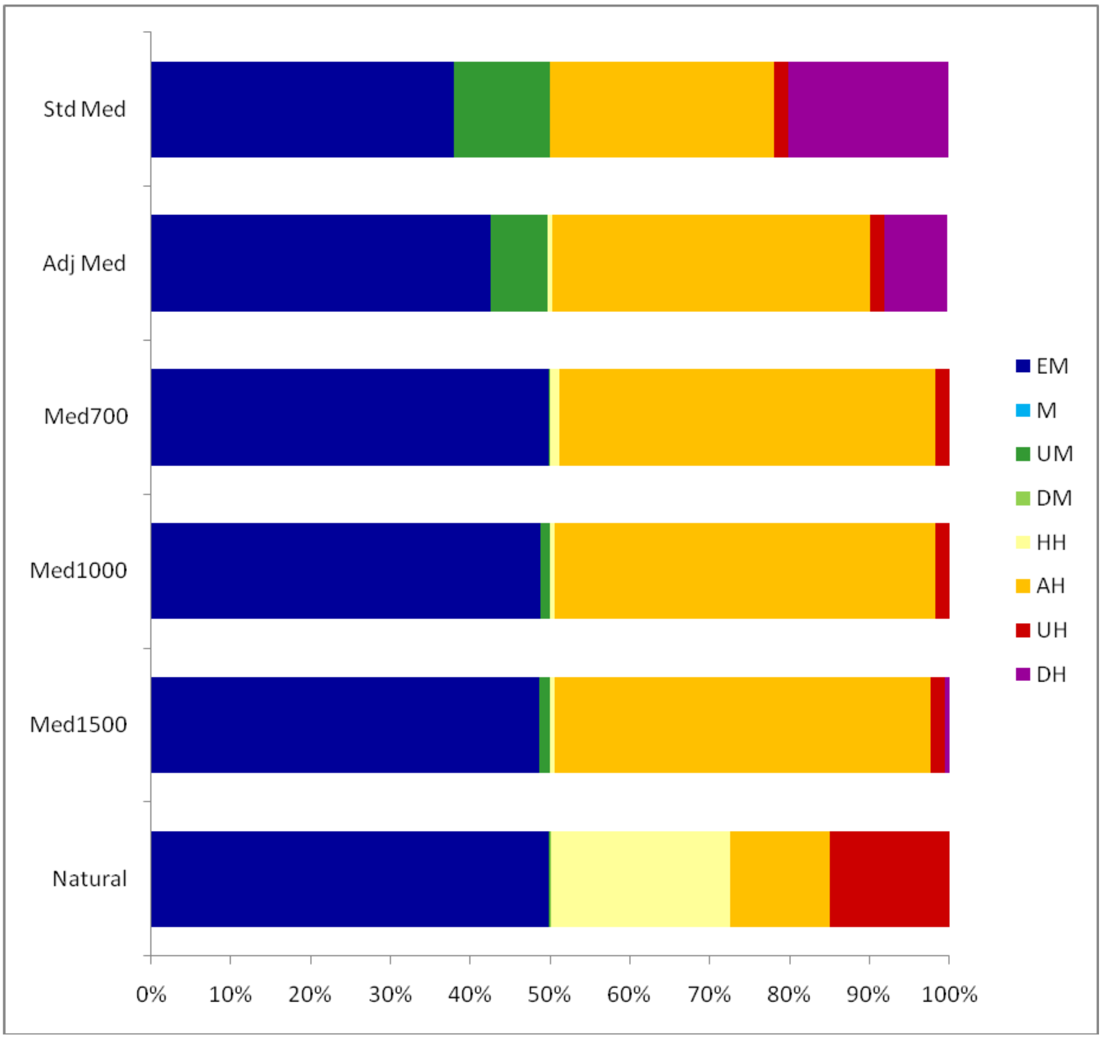

Figure 11.9: Comparing the proportion of site-years in each ecosystem state for the rules-based flow scenarios under a median future climate

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Std Med is Standard Median scenario, Adj Med is Adjusted Median scenario, Med700 is Adjusted Median 700 scenario, Med1000 is Adjusted Median 1000 scenario, Med1500 is Adjusted Median 1500 scenario. Information on how to read the figure is presented in Appendix E.

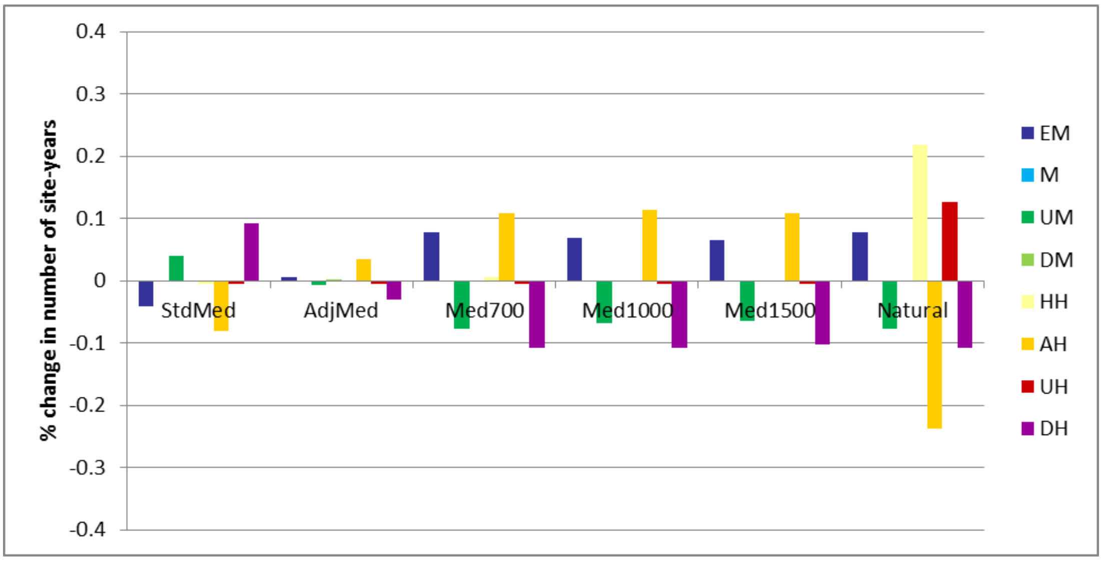

Figure 11.10: Deviations in the proportion of site-years in each ecosystem state compared to the Standard Historical scenario for the rules-based flow delivery scenarios under a median future climate

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Std Med is Standard Median scenario, Adj Med is Adjusted Median scenario, Med700 is Adjusted Median 700 scenario, Med1000 is Adjusted Median 1000 scenario, Med1500 is Adjusted Median 1500 scenario. Information on how to read the figure is presented in Appendix E.

Under a dry future climate projection, the improvement in the mix of ecosystem states associated with the rules-based addition of environmental flows was more marked (Figure 11.11). No matter which salinity target was maintained in Lake Alexandrina, there was a large decline in the proportion of site-years in degraded ecosystem states. The Adjusted Dry scenario had 64% of site-years predicted to be in degraded ecosystem states, compared with 1% under either of the Adjusted Dry 700 or 1000 scenarios and 9% under the Adjusted Dry 1500 scenario. The target of a maximum of 1500 µS cm^{-1} EC in Lake Alexandrina did not result in enough water being delivered to the Coorong to prevent the occurrence of the Degraded Hypersaline state, suggesting that this level of environmental flow allocation was insufficient to completely counteract the effects of more-severe climate change in the region. There was little difference between the mix of ecosystem states under the Adjusted Dry 700 and Adjusted Dry 1000 scenarios, although neither resulted in a similar mix of ecosystem states as the Natural scenario.

These patterns were highlighted when the deviation of occurrence of ecosystem states from the Standard Historical scenario was investigated (Figure 11.12). All of the rules-based flow scenarios under the dry future climate scenario resulted in small increases in the proportion of site-years in the Estuarine/Marine and Average Hypersaline states and decreases in the proportion of site-years in the Unhealthy Marine and Degraded Hypersaline states compared with the Standard Historical scenario. This suggested that environmental flows delivered in this fashion may be sufficient to maintain the ecological character of the Coorong, despite climate change in the region.

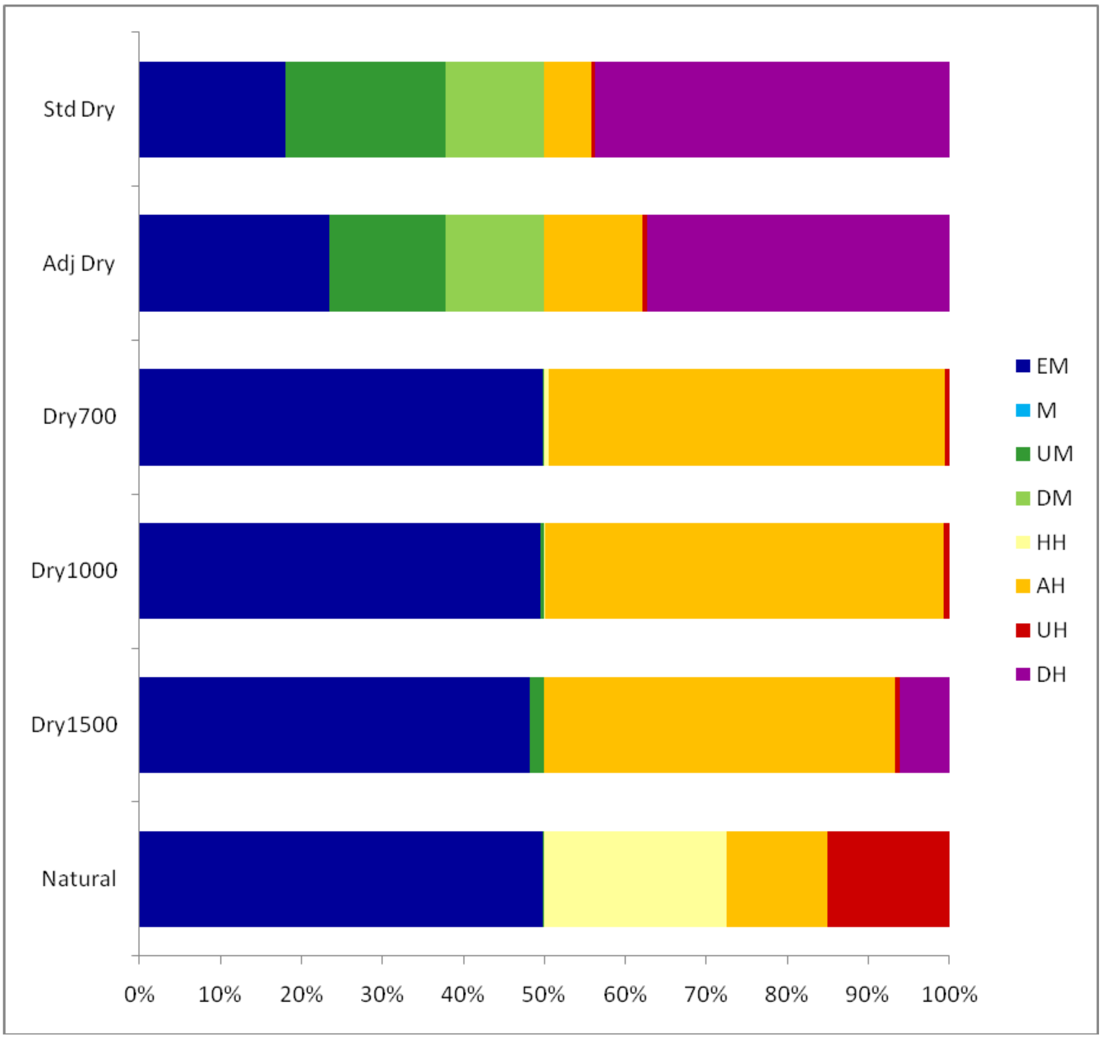

Figure 11.11: Comparing the proportion of site-years in each ecosystem state for the rules-based flow scenarios under a dry future climate

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Std Dry is Standard Dry scenario, Adj Dry is Adjusted Dry scenario, Dry700 is Adjusted Dry 700 scenario, Dry1000 is Adjusted Dry 1000 scenario, Dry1500 is Adjusted Dry 1500 scenario. Information on how to read the figure is presented in Appendix E.

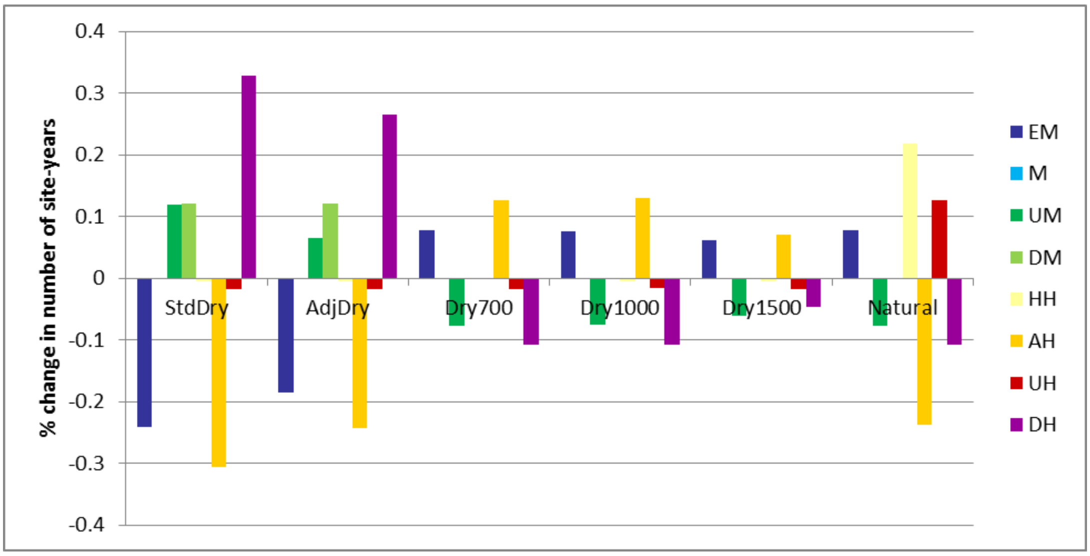

Figure 11.12: Deviations in the proportion of site-years in each ecosystem state compared to the Standard Historical scenario for the rules-based flow delivery scenarios under a dry future climate

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Std Dry is Standard Dry scenario, Adj Dry is Adjusted Dry scenario, Dry700 is Adjusted Dry 700 scenario, Dry1000 is Adjusted Dry 1000 scenario, Dry1500 is Adjusted Dry 1500 scenario. Information on how to read the figure is presented in Appendix E.

11.3 Discussion

The investigation of the ecological implications of environmental water requirements for the Coorong highlighted a similar effect of modifying the timing of flow delivery as was evident for the hydrodynamics of the Coorong. There were substantial differences in the predicted mix of ecosystem states between the standard scenarios for each of the three climate projections investigated (i.e. historical, median and dry) and their respective adjusted scenarios. This suggested that the timing and manner of flow delivery affected the ecology of the Coorong, as well as the hydrodynamics. Given that much of the ecology of the Coorong is linked to the hydrodynamics, this was not unexpected, but non-linearities in the response of the system may have complicated the ecological impacts. This finding indicated that a more-detailed exploration of the effects of the timing and mode of delivery of environmental flows is also needed to gain an understanding of the implications for ecological character, and to ensure that any additional water provided has the maximum possible impact.

The addition of constant flows to the Coorong, in order to maintain one of three salinity targets in Lake Alexandrina, resulted in very little variability in the mix of ecosystem states in the Coorong. Given that the diversity of habitats and biota is one of the key attributes of the region (Phillips & Muller 2006), this is unlikely to be a desirable outcome for the Coorong. Regardless, the constant flows needed to maintain a salinity target of a maximum of 1500 µS cm^{-1} EC in Lake Alexandrina was insufficient to prevent the appearance of degraded ecosystem states in the South Lagoon.

Rules-based flow addition, however, resulted in improvements in the mix of ecosystem states no matter which climate scenario was modelled. This suggested that the range of salinity targets investigated here was in an order of magnitude of what is required to maintain the ecological diversity and health of the Coorong, provided that some variability in the flow delivery is maintained (i.e. as opposed to constant flow additions). Under all climate scenarios (as modelled here), meeting those salinity targets for Lake Alexandrina resulted in an improvement in the mix of ecosystem states compared to the Standard Historical scenario, suggesting that the current degradation of the region may have been able to be avoided had such a target been imposed and met previously.

Providing sufficient environmental flows to meet the target of a maximum of 1500 µS cm^{-1} EC in Lake Alexandrina did not show the same improvements as the other two targets. This suggested that a target of no higher than a maximum of 1000 µS cm^{-1} EC should be adopted for Lake Alexandrina to ensure the ecological character of the Coorong. There was little difference evident between the predicted mix of ecosystem states when water was delivered to meet the target of 1000 µS cm^{-1} EC compared with that required to meet a mean of 700 µS cm^{-1} EC in Lake Alexandrina. Based on this analysis, it would be difficult to justify the lower target, and a moderate target of a maximum of 1000 µS cm^{-1} EC would be recommended. However, the mix of ecosystem states is one of a number of analyses that should be undertaken to understand the likely implications of environmental flow requirements on ecological condition the region, not least because of the limitations of the current model and the lack of independent testing of predictions that has been possible to date. It was for this reason that the known thresholds for individual indicator species were also considered in the setting of a target for salinities in Lake Alexandrina (Chapter 5).

It should also be re-iterated that the volumes of water required to be delivered to the Coorong increase with increasing levels of climate change. Thus, it would be more difficult to maintain those salinity targets within Lake Alexandrina under more severe climate change and a higher proportion of inflows to the Murray-Darling Basin would be required to achieve this as the effects of climate change manifest. However, this should not be taken as an excuse to avoid acting, but rather as a realistic assessment of the scale of the challenge ahead. The implications of volumes of water likely to be available from extending the Upper South East Drainage scheme to increase the volume of water through Salt Creek have been modelled in combination with the environmental flow requirements investigated below (Chapter 14).

The modelling undertaken within this chapter highlighted an unexpected result under high flow conditions. The use of the alternative model resulted in very high water levels in the Coorong resulting in the predictions of site-years in the Unhealthy Hypersaline ecosystem state in the South Lagoon. This behaviour has been explored in Appendix G. The discrepancy between the results obtained for the Natural scenario when modelled under the original ecosystem states model and the alterative model, along with the fact that the volume of water delivered under that Natural scenario was so far above the average volume in the data set used to construct the models originally, suggested that this behaviour may be an artefact of attempting to apply it outside the experience of the model. This cannot, however, be categorically determined in the absence of observational data from periods of high flow. Thus, extreme care should be used before using these results as a justification for delivering lower volumes of water because of the possible impact on the ecosystem states in the South Lagoon. Instead, in this instance, evidence based on the salinity and water level requirements of indicator species and processes (see Chapter 5) should be used to make this decision.

This potential artefact does not, however, render the remaining results in this report unreliable. The rest of the scenarios explored, with the possible exception of the Adjusted Historical 700 scenario (which had an average annual flow volume of more than 6000 GL, approximately double that of the training data set), fall within the range of experience of the model (Appendix G). This means that we can be much more confident that the predicted behaviour of ecosystem states is likely to approximate the actual response of the system to environmental flow allocations. Again, however, this would be confirmed should observational data of periods with barrage flows be available to compare to model predictions.

11.8 Summary

- **We used the same set of scenarios as investigated in Chapter 10 to identify the likely mix of ecosystem states that would be supported by the recommended flow regime**
- **The targets set to assess ecological impacts were: avoiding ecological degradation in the Coorong through the appearance of degraded ecosystem states, and maintaining the frequency of the Healthy Hypersaline state (thought to be associated with high-flow conditions).**
- **The ecosystem state model developed for the Coorong identified eight distinct ecosystem states, with four falling into each of two basins: a marine basin and a hypersaline basin.**
- **The major area of uncertainty in the ecosystem response model is in its ability to correctly predict the recovery of the system, but the model also currently lacks independent testing of predictions.**
- **Modifying the timing of flow delivery altered the mix of ecosystem states predicted for the Coorong. Each of the three projected climate scenarios investigated showed this effect, consistent with the hydrodynamic investigation above.**
- **The addition of constant flows to the Coorong, in order to maintain one of three salinity targets in Lake Alexandrina, resulted in very little variability in the mix of ecosystem states in the Coorong and the constant flows to maintain a maximum salinity of 1500 µS cm^{-1} EC in Lake Alexandrina was insufficient to prevent the appearance of degraded ecosystem states in the South Lagoon.**
- **The rules-based flow addition scenarios resulted in an improved mix of ecosystem states for each of the climate scenarios modelled, suggesting that the range of salinity targets investigated here are in an order of magnitude of what would be required to maintain the ecological diversity and health in the Coorong.**
- **The volumes of water required to be delivered to the Coorong increased with increasing levels of climate change, thus it would be more difficult to maintain those salinity targets within Lake Alexandrina under more-severe climate change and a higher proportion of inflows to the Murray-Darling Basin would be required to achieve this.**

12. Describing an environmental water requirement for the Coorong

Rebecca Lester, Peter Fairweather & Ian Webster

Describing an environmental water requirement for the Coorong, Lower Lakes and Murray Mouth region is one step in the process of planning a long-term future for the Coorong, Lower Lakes and Murray Mouth region. This environmental water requirement has been used to support the development of a Long Term Plan for the region (DEH 2010), as well as assisting in the development of environmental water requirements for key assets in the Murray-Darling Basin identified as a part of the ongoing Basin Planning process.

In order to determine an environmental water requirement, specific objectives for the region were needed. These were drawn from the larger process to develop an environmental water requirement for the Lakes and Coorong region described in this document (Chapter 3) and Lester *et al.* (2011; 2009e), and have been framed in terms of ecosystem states for the Coorong (Lester & Fairweather 2009a, 2011).

This chapter deals specifically with the water requirements for the Coorong. Thus, the relevant objectives are also Coorong-specific. However, the process was also linked to the determination of an ecological envelope of water levels for the Lakes (Muller 2010b; Appendix H) and the determination of a salinity target for Lake Alexandrina (Heneker 2010) and associated flow volume for the region.

As described above (Chapter 11), for the Coorong, the ecological targets focussed on two areas. The first was avoiding ecological degradation in the Coorong. In order to meet this target, we propose that the management of the system be based on the objective that sufficient water is delivered to the site to prevent the occurrence of degraded ecosystem states in 95% of years. An associated target regarding minimum flow requirements was that there be sufficient flow to maintain an open Murray Mouth without the need for dredging in 95% of years. The second target was around high-flow conditions, which are critical for the long-term health of an estuarine system and may not be addressed by the setting of water requirements for times of drought. Here, we have again linked the choice of objective to the ecosystem state model for the Coorong, and have set an objective that the South Lagoon of the Coorong supports the Healthy Hypersaline ecosystem state at least as frequently as was predicted for the region under an historical climate including current extraction levels. These targets reflected the conditions in the Coorong at the time of Ramsar-listing, as far as was possible to determine from the available data (Lester & Fairweather 2009a). There has been debate as to whether the condition at that time, in 1985, was already degraded and whether this is an appropriate target, however the ecological condition then was so much healthier than at the time of writing that we believed this was a good first target, and should be used while the appropriateness and realism of using a more-stringent target is discussed in managerial or public fora.

In setting these targets, it should be noted that the Coorong tends to act as two connected halves: the North Lagoon and the South Lagoon. While the ecosystem states model allowed for any of 14 individual sites in the region to exist in an ecosystem state independently of its neighbours, extensive scenario modelling indicated that, for the majority of time, the North Lagoon tended to operate a single unit and the South Lagoon as a second unit. There were instances where part of one lagoon was predicted to be in one ecosystem state and the rest in another, but this was relatively rare (e.g. see Lester *et al.* 2009b). Thus, spatial objectives were less useful than the temporal objectives specified above.

Furthermore, we also based our selection of targets for the region on the length of time that the Coorong is likely to be able to support degraded ecosystem states without jeopardising the long-term health of the region. It was thought that a period of degradation lasting less than three years would be within the ability of a resilient estuarine system to withstand, given the inherent variability within the Murray-Darling Basin (Lester *et al.* 2009e). This assumption also relied on the further condition that adequate time for recovery would be required before another period of degradation ensues. Again, three years was thought to be a good first assessment of how long an estuarine ecosystem may require for recovery (Lester *et al.* 2009e). In setting these time-frames, it should be understood that there was very little scientific evidence for this region regarding the length of time that the system could sustain degraded ecological conditions, or how long it would require to recover. These durations were partly based on modelling of the duration of previous drought periods in the region and partly on previous work regarding ecological recovery from drought (see Lester *et al.* 2009e for further detail and additional references).

Thus, this chapter explores both the minimum flow requirements for the Coorong and the flooding requirements for the region. These have been treated separately, due to the differences in the objectives and also the methods used to assess these requirements. It should be stressed that the results presented herein are preliminary, and additional analyses are required to ensure that the water volumes recommended are robust and sufficient to meet the targets listed.

12.1 Minimum barrage flow requirements for the Coorong

Two methods were used to determine the minimum barrage flow requirements for the Coorong. In using two methods, rather than selecting one over the other, we were able to assess how consistent the resultant water requirements based on each were, as well as providing some confidence that the limitations associated with one method or the other were not significantly biasing the results of the analyses. First, we assessed the proportion of degraded ecosystem states associated with different barrage flow volumes. Then, we used a model that predicted future degraded ecosystem states three years in advance and assessed how often the threshold from that model was breached when the range of barrage flow volumes required to meet salinity targets in Lake Alexandrina were delivered.

12.1.1 Minimum requirements based on the proportion of degraded ecosystem states

To determine a minimum flow volume for the Coorong, the alternative ecosystem states model (Lester & Fairweather 2009a) was used (i.e. excluding barrage flows as a driver of ecosystem states, but using primarily water levels and water quality parameters instead). This model predicted one of eight ecosystem states (or combinations of physicochemical conditions and associated biotic assemblages) based on the hydrodynamic conditions modelled for a given site in a given year (Chapter 11). The hydrodynamic conditions identified as driving the ecosystem states included:

- average annual water level (from the current year and the previous year);
- average water depth from two years previous;
- annual range in water level; and
- maximum salinity.

In order to determine the minimum flow requirements for the Coorong, a similar approach was taken to that used by Heneker (2010) to determine minimum flow requirements to maintain ecologically-significant salinities in Lake Alexandrina. One-year, two-year and three-year total flow volumes were plotted against the proportion of degraded ecosystem states per year for the Standard Historical, Standard Median and Standard Dry scenarios (these scenarios were defined as current extraction levels with actual distribution of flows throughout the year under an historical, median future or dry future climate projection, respectively and were based in the A and C scenarios developed by CSIRO [2008]; Chapter 10). These scenarios were consistent with those used in Chapters 10 and 11 and in Heneker (2010). In plotting the proportion of degraded ecosystem states in any given year, the Unhealthy

Hypersaline state was excluded due to inconsistencies in the prevalence of that state between the alternative ecosystem state model and the original ecosystem state model (see Appendix G). This meant that this analysis tended to underestimate the proportion of degraded ecosystem states, which should be borne in mind when considering the results and their interpretation. Further analysis will be required to account for this underestimation more comprehensively and to correct for it in the minimum flow volumes recommended.

In relating the proportion of degraded ecosystem states to total flows over the barrages, a one-year or two-year time lag appeared to be most relevant. This was consistent with previous work undertaken that suggested that Coorong hydrodynamics were best correlated with barrage flows at a one-year lag (Fairweather & Lester 2010). Barrage flows from more than two years prior to the year in question had less impact on the predicted mix of ecosystem states. This is likely to be due to the role of the Murray Mouth in regulating hydrodynamics within the Coorong. Mouth depth influences the transmissivity of water between the Coorong and Encounter Bay and is primarily a function of barrage flows in the current year. Thus, long-term effects of high flow events were not seen, as the majority of fresh water passes through the Mouth and seasonal siltation processes do not allow a deep Mouth to persist through time.

Compared with the analysis undertaken for Lake Alexandrina, there was a substantial amount of variability in the barrage flows required to support healthy ecosystem states in the Coorong. The minimum value for barrage flows below which there was no chance of achieving predicted healthy ecosystem states for the Coorong was very low, at 122 GL, although once the total flow for the previous two years fell below 2000 GL, there was very little chance of a wholly-healthy Coorong ecosystem (although the exclusion of the Unhealthy Hypersaline state has the potential to influence this finding).

When the total flow volume over the barrages for the previous year was considered (Figure 12.1), there was an increased likelihood that 50% or more of the Coorong would be predicted to be in a degraded ecosystem state when the flow volume was less than 6000 GL for that year. This included all simulated years for the three different climate projections modelled. The highest barrage flow for which 100% of the Coorong was predicted to be in a degraded ecosystem state was 2200 GL, with an increased likelihood of this occurring when barrage flows from the previous year were less than 1225 GL. Thus, for barrage flows less than 1225 GL $year^{-1}$, there was a high likelihood that the entire Coorong will fall into degraded ecosystem states, with more than 6000 GL $year^{-1}$required to minimise the likelihood of more than 50% of sites in degraded ecosystem states.

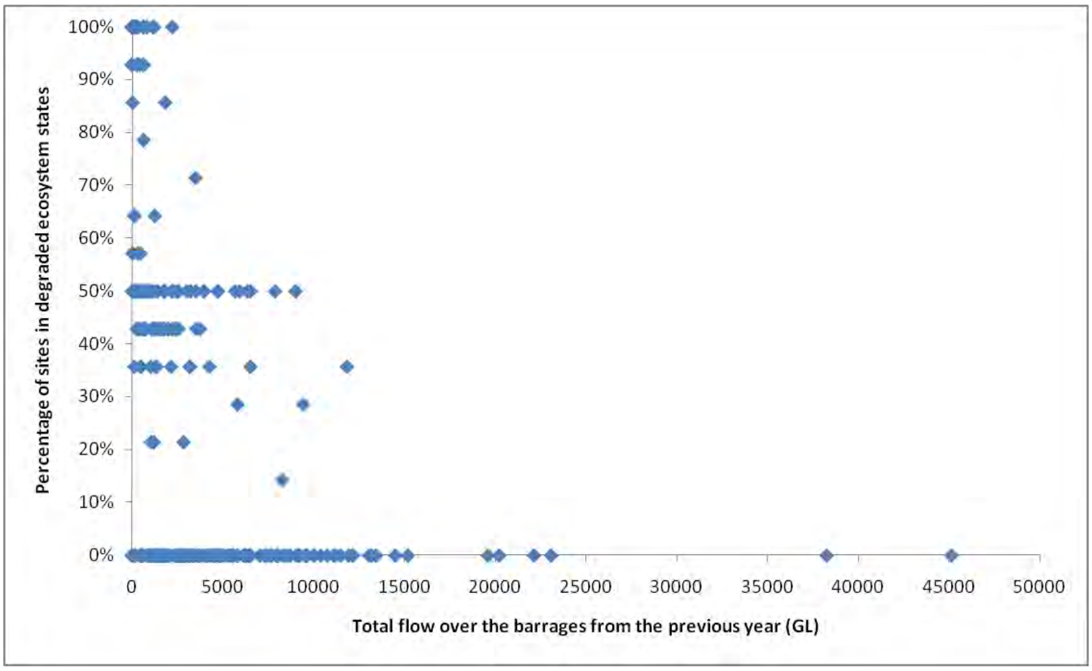

Figure 12.1: The percentage of sites in degraded ecosystem states compared with total flow over the barrages for a single year for the historical flow-delivery scenarios under three climate projections

This volume was affected by the antecedent conditions, that is the volume delivered in the prior year. When barrage flows were considered for the previous two years (Figure 12.2), there was no likelihood (i.e. 0%) that the Coorong would be predicted to support only healthy ecosystem states when total barrage flows across those two years were less than 1000 GL. Barrage outflows over two years that resulted in 100% of the Coorong having degraded ecosystem states (as simulated) varied substantially. The largest total flow over the barrages for which the entire system was still predicted to be in degraded ecosystem states was almost 6000 GL, indicating that at least this volume is required to be completely confident that the Coorong supports at least some healthy ecosystem states (although this could occur at lower flow volumes due to interactions within the system).

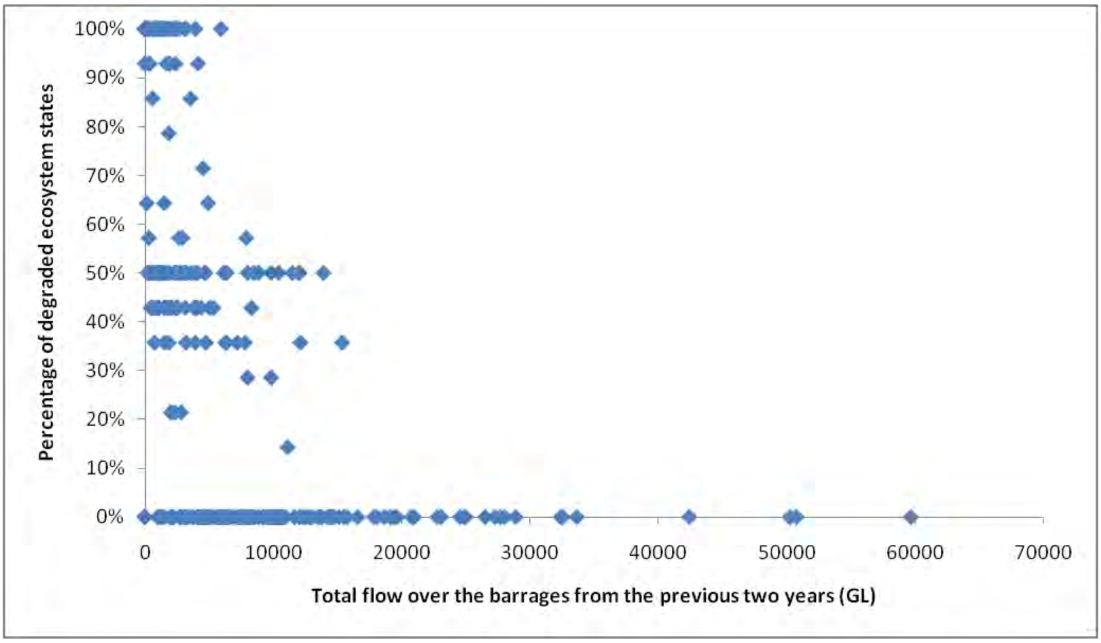

Figure 12.2: The percentage of sites in degraded ecosystem states compared with total flow over the barrages over a two-year period for the historical flow-delivery scenarios under three climate projections

Based on these analyses, for an historical flow-delivery pattern, under any climate, the flow requirements for the Coorong can be summarised thus:

- To maximise the likelihood that the Coorong supports at least some healthy ecosystem states, more than 1000 GL must be delivered across two consecutive years;
- In any single year, the total flow delivered cannot fall below 120 GL if the Coorong is not to support only degraded states;
- More than 15 000 GL delivered over two years was needed to prevent the occurrence of any degraded states in the Coorong (or 12,000 GL over one year); and
- More than 6000 GL was needed over two years before it was assured that the Coorong would support at least some healthy ecosystem states.

However, previous analysis of the mix of ecosystem states in the Coorong illustrated the large effect that the timing and distribution of flow delivery can have (see Chapters 10 and 11). The adjusted flow scenarios (i.e. where flow distributions were standardised across the year as described in Heneker; 2011) were similarly analysed to understand the minimum flow requirements under a less-variable pattern of flow delivery. The adjustment to the flow-delivery pattern resulted in regulated inter-annual flow delivery to the site which standardised the proportional distribution of flows, thus resulting in no unseasonal peaks or troughs between years.

Following the investigation using the historical pattern of flow delivery (i.e. 'standard' scenarios), a similar investigation examined total barrage flows from the preceding years, such that they were delivered in a consistent manner year to year in the same manner (Figure 12.3). Here, the minimum flow requirements were lower than when flows were less-evenly distributed through the year. The likelihood of 50% or more of the Coorong being predicted to be in the degraded ecosystem states increased substantially when flow from the previous year were less than 2000 GL (although the first instance of this occurring was at 5900 GL). A flow volume of at least 500 GL was needed to give some chance that the Coorong supported at least some healthy ecosystem states. The lowest flow volume for which there were no predicted degraded ecosystem states in the next year was 163 GL.

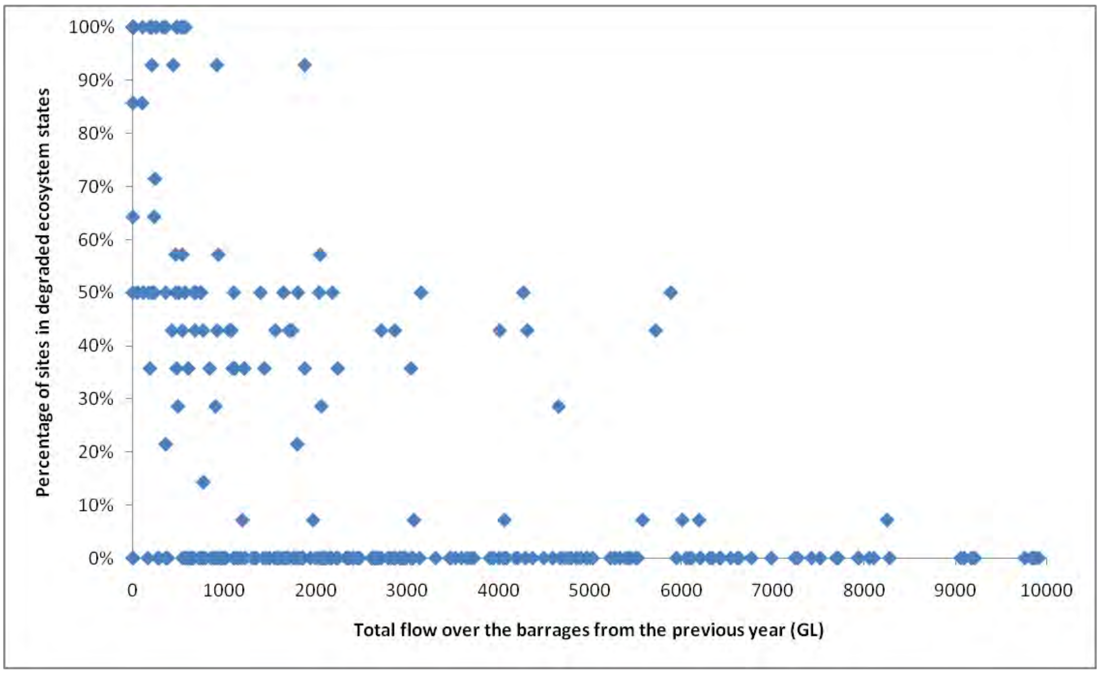

Figure 12.3: The percentage of sites in degraded ecosystem states compared with total flow over the barrages for a single year for the modified flow-delivery scenarios under three climate projections

Note the change of scale from Figure 12.1.

Again, however, volumes over the preceding two years interacted to affect the proportion of sites predicted to be in degraded ecosystem states (Figure 12.4). The highest volume for which 50% of sites were predicted to be in degraded states was just over 10 000 GL delivered over the two years, with increasing proportions of sites predicted to be in degraded states occurring when two-year flow volumes fell below 3200 GL. The highest flow volume delivered over two years for which 100% of the Coorong was predicted to be in degraded ecosystem states was 2500 GL, with a very high likelihood of there being no healthy ecosystem states when volumes were less than 950 GL over two years. The lowest flow volume for which there were no degraded ecosystem states predicted was 800 GL over two years.

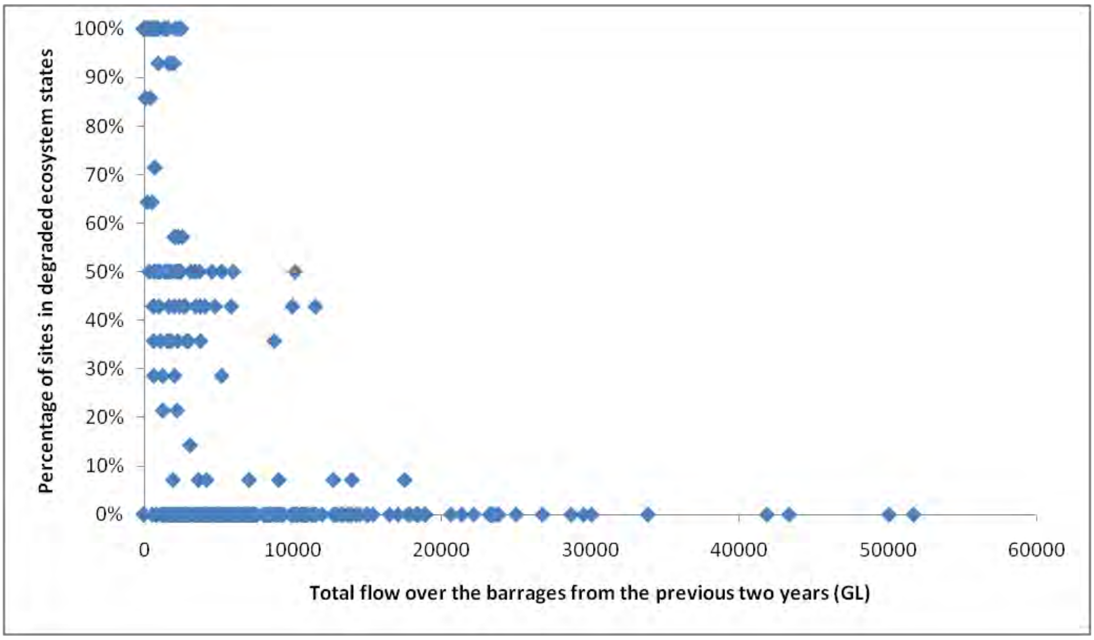

Figure 12.4: The percentage of sites in degraded ecosystem states compared with total flow over the barrages over a two-year period for the modified flow-delivery scenarios under three climate projections

Note the change of scale from Figure 12.1.

Thus, for a modified flow-delivery pattern (tending to be less variable) under any climate, the flow requirements for the Coorong can be summarised thus:

- More than 800 GL delivered across two years is needed to maximise the likelihood that the Coorong supports at least some healthy ecosystem states;
- In any single year, the total flow delivered cannot fall below 160 GL if the Coorong is to support no degraded states (although note that this value was 120 GL for the natural flow-delivery pattern);
- More than 17 000 GL delivered over two years was needed to ensure that there was no occurrence of any degraded states in the Coorong (or 8000 GL over one year); and
- More than 2500 GL was needed over two years to ensure that the Coorong supported at least some healthy ecosystem states.

Based on these findings, recommendations for minimum flow requirements for the Coorong are:

- At least 120 GL in any one year as an absolute minimum;
- At least 800 GL over any two-year sequence as an absolute minimum to ensure that some healthy ecosystem states are supported; and
- At least 2500 GL over two years as a minimum target (95% of the time) to prevent the Coorong from falling into wholly-degraded ecosystem states.

The rules-based approach for maintaining Lake Alexandrina salinities was, for the most part, sufficient to prevent the appearance of sites in degraded ecosystem states in the Coorong under an historical climate. The maximum percentage of the region that was in a degraded state at any time was 36% (in the final year of simulation, corresponding to the recent drought conditions) and degraded ecosystem states occurred in only 5 of the 114 years in the simulation. This was consistent with the impact of using rules-based addition of environmental flows under median and dry future climate change projections. Thus, providing minimum water requirements to maintain a maximum salinity of 1000 $\mu S\ cm^{-1}$ in Lake Alexandrina was likely to be sufficient to maintain the Coorong in healthy ecosystem states, at least in the vast majority of conditions.

12.1.2 Minimum requirements based on models of future degraded ecosystem states

Average South Lagoon salinity was another measure on which minimum flow requirements could be assessed. Average South Lagoon salinity of greater than 117 g L^{-1} has been shown to be the best predictor of degraded ecosystem states three years in advance (Fairweather & Lester 2010). The modelling used to develop this threshold was based on the original ecosystem states model (as opposed to the alternative ecosystem states model described above: see Lester & Fairweather 2011 for additional detail), so was independent of the analyses described above, and thus avoided the issue with consistency in the classification of site as Unhealthy Hypersaline.

The model used here uses average South Lagoon salinity to predict the likelihood that the Coorong would support degraded ecosystem states three years in the future. In developing this model, the presence or absence of any degraded state was used as the dependent variable and all available physicochemical variables were used as possible predictors of those degraded ecosystem states (Fairweather & Lester 2010). For the three-year time step (used here), a simple model with a single predictor (the average annual salinity in the South Lagoon) was a good predictor. The model did tend to slightly over-estimate the likelihood of degraded ecosystem states, with around one-fifth of healthy ecosystem states predicted to be degraded (Fairweather & Lester 2010). However, it also correctly classified every instance of degraded ecosystem states, so the overall misclassification rate was 15% (Fairweather & Lester 2010). This slight conservatism was considered to be appropriate, given the relative cost of failing to predict ecological degradation compared with the cost of occasionally intervening unnecessarily.

Again, using this method for determining a minimum flow requirement, the variability of Coorong conditions was evident. For example, when historical flow-delivery patterns were analysed, barrage flows of more than 8000 GL were required before there was no likelihood of the threshold being crossed in the following year. However, for most instances of average South Lagoon salinities in excess of 117 g L^{-1}, total flow volumes for the previous year were less than 3700 GL.

Over two years, 300 GL was the minimum barrage flow volume for which the threshold of 117 g L^{-1} was not crossed in the next year (Figure 12.5), although instances of average South Lagoon salinities greater than 117 g L^{-1} occurred for two-year flow volumes as high as 12 000 GL. There was a high likelihood that the threshold would be crossed once two-year flow volumes fell below 4000 GL.

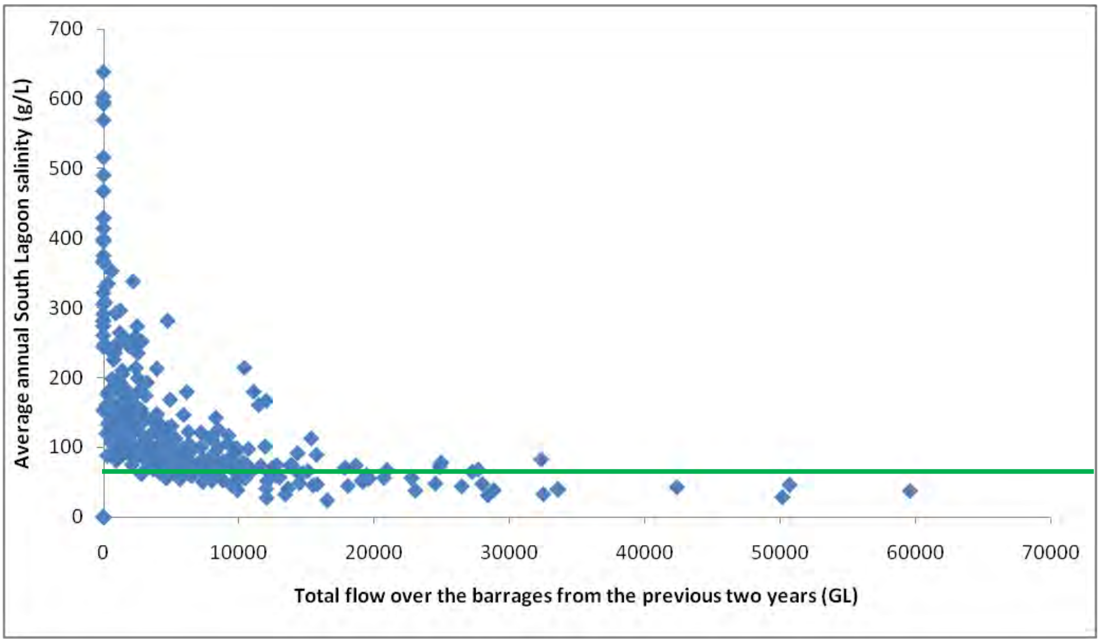

Figure 12.5: Average annual South Lagoon salinity compared with total flow over the barrages over a two-year period for the historical flow-delivery scenarios under three climate projections

The green line indicates the threshold of 117 g L^{-1} for the average annual South Lagoon salinity.

Similar variability was also evident when the scenarios using the modified flow-delivery pattern were analysed. The highest flow volume in a single year that did not prevent the threshold of 117 g L^{-1} being exceeded in the following year was 7500 GL. However, the majority of cases where that South Lagoon salinity threshold was exceeded were for flow volumes that were less than 3000 GL in the previous year. The minimum flow volume for which the threshold was not crossed was 50 GL. Again, the adjustment of the flow-delivery pattern resulted in somewhat lower flow volumes being sufficient to prevent predicted ecological degradation.

When barrage flows over a two-year period were assessed, a flow volume of more than 575 GL was required to give any chance that the average South Lagoon salinity did not exceed the 117 g L^{-1} threshold in the next year (Figure 12.6). The maximum flow over two years which was insufficient to prevent the threshold being crossed was 11 500 GL, however, in most instances, flow volumes of 3000 GL over two years were sufficient.

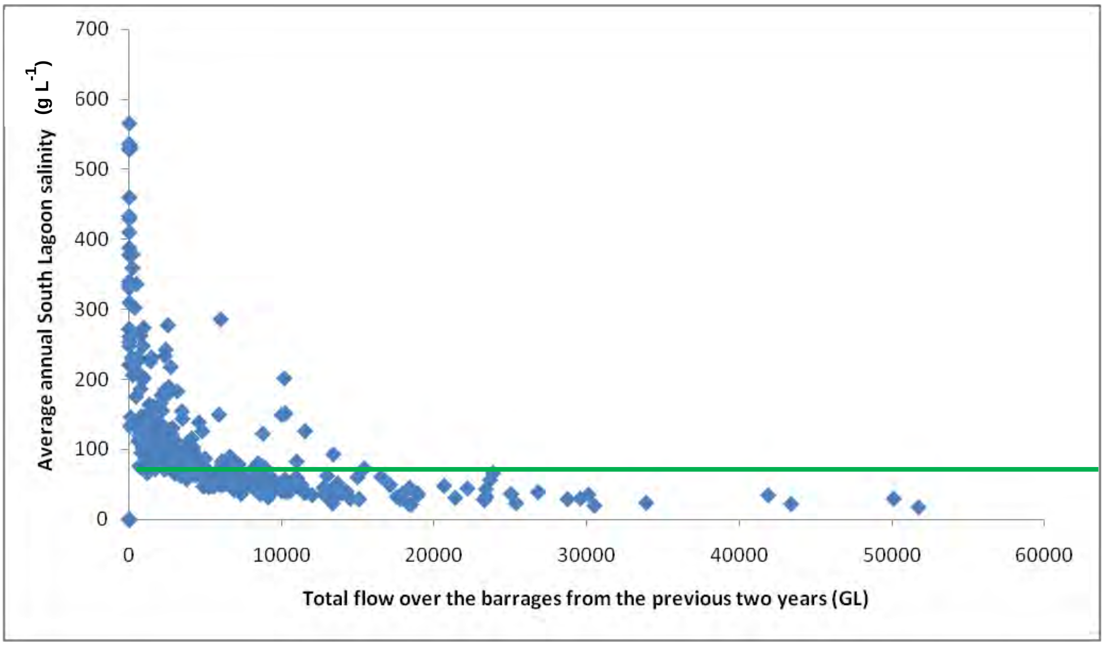

Figure 12.6: Average annual South Lagoon salinity compared with total flow over the barrages over a two-year period for the modified flow-delivery scenarios under three climate projections

The green line indicates the threshold of 117 g L^{-1} for the average annual South Lagoon salinity. Note the change in scale from Figure 12.5.

Based on these findings, recommendations for minimum flow requirements (assuming that flow delivery can be optimised) for the Coorong are:

- At least 50 GL in any one year as an absolute minimum to prevent certainty that the South Lagoon salinity threshold is exceeded;
- At least 600 GL over any two-year sequence as an absolute minimum to give some likelihood that South Lagoon salinities remain below the threshold value of 117 g L^{-1}; and
- At least 3000 GL over two years as a minimum target to prevent salinities in the South Lagoon from exceeding the threshold over which degraded ecosystem states are likely.

The rules-based approach for maintaining Lake Alexandrina salinities was sufficient to prevent the South Lagoon salinities exceeding the threshold of 117 g L^{-1} under any of the three climate projections investigated. Thus, providing minimum water requirements to maintain a maximum salinity of 1000 µS cm^{-1} in Lake Alexandrina was thought to be likely to be sufficient to prevent future degraded ecosystem states in the Coorong.

12.2 Flooding requirements for the Coorong

The above analyses focussed on minimum flow requirements for the Coorong in times of drought. However, there are significant benefits for an estuary associated with high flows that should not be overlooked in the determination of an environmental watering requirement for the Coorong. Again, in order to make some assessment of what these flow volumes might be, the ecosystem states model for the Coorong was used.

One of the limitations of the model was that we were more confident that it accurately described degraded conditions in the Coorong than more-pristine or healthier conditions. A discussion of the rationale for this can be found in Lester & Fairweather (2009a, 2011). Briefly, the data sets that were used to build the model encompassed primarily sub-optimal conditions, so high-flow conditions were outside the experience of the model as developed and thus, behaviour may not have been accurately predicted. This limitation was most relevant to the North Lagoon, where only a single ecosystem state could be described in times of moderate barrage flows or higher. This caveat should be kept in mind when reading the following results.

It was highly likely that there were additional ecosystem states in this region, particularly in times of high flow and truly-estuarine conditions but insufficient data existed to adequately describe these (Lester & Fairweather 2009a). Thus, we focussed our analysis here on the Healthy Hypersaline state, which occurs relatively rarely in the South Lagoon. There was reasonable evidence that this state was associated with relatively fresh conditions (i.e. it had the lowest average salinity of the hypersaline basin states) and high water levels (Lester & Fairweather 2009a, 2011), suggesting that it occurred either only or possibly predominantly in times of large barrage flows.

The same set of scenarios described above were analysed to inform our recommendations for flooding requirements for the Coorong. The proportion of sites predicted to be in the Healthy Hypersaline state were compared with the total flow volume for the same year, the previous year and two years previous, with one-, two- and three-year combinations of flows explored.

Again, as for the low-flow conditions, one- and two-year sequences were best related. However, for low-flow conditions, the previous year and two years previous were used to assess the mix of ecosystem states in a given year (i.e. the proportion of sites in a degraded state in $Year_x$ were assessed relative to the total flows across $Year_{x-1}$ and $Year_{x-2}$), while here the current year and the previous year were better predictors (i.e. the proportion of sites in the Healthy Hypersaline state in $Year_x$ were assessed using the total flows across $Year_x$ and $Year_{x-1}$).

Under the historical pattern of flow delivery, flows over the barrages in the current year were best-related to the proportion of sites predicted to be in the Healthy Hypersaline state (Figure 12.7). Flows of at least 6000 GL in a single year were required before the Healthy Hypersaline state was predicted for any sites. Flows over 12 000 GL in a single year resulted in a prediction of the Healthy Hypersaline state for all South Lagoon sites (i.e. a maximum of 50% of all Coorong sites). With the standard historical pattern of flow delivery, the current year was most closely related to the pattern of sites predicted to be in the Healthy Hypersaline state and investigation of the previous year as well did not add further useful information.

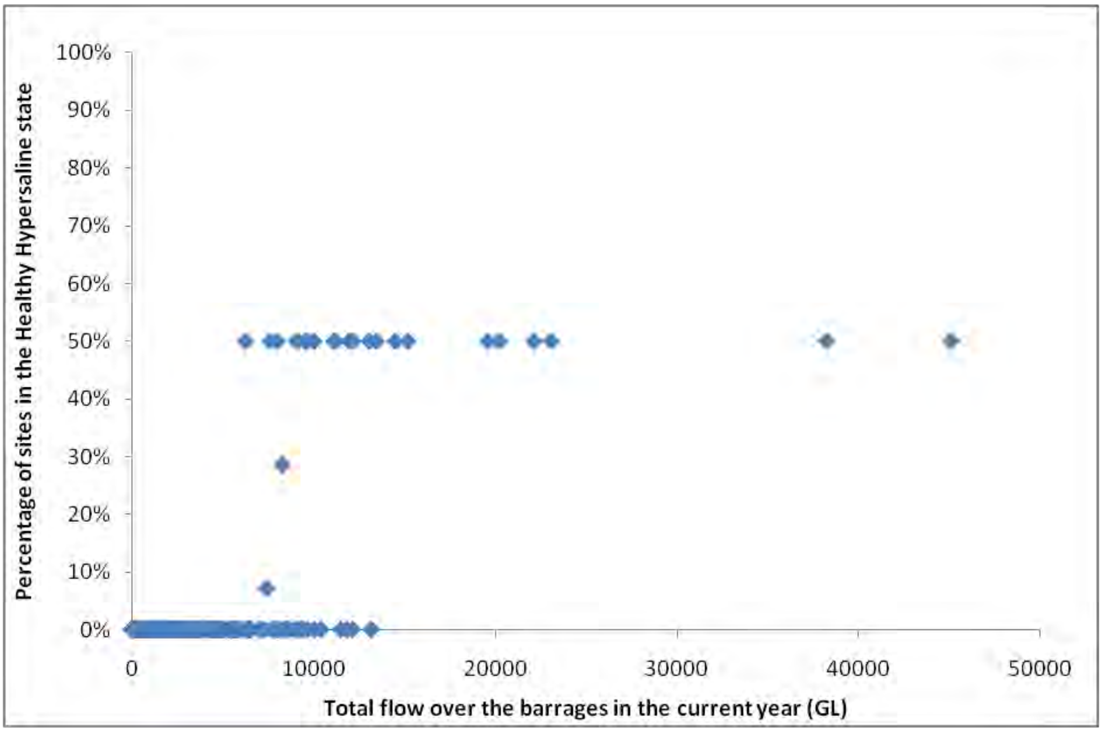

Figure 12.7: The percentage of sites in the Healthy Hypersaline state compared with total flow over the barrages for the historical flow-delivery scenarios under three climate projections

However, when the scenarios using the adjusted flow-delivery pattern were investigated, both the current year and the previous year's barrage flows were of use in interpreting the proportion of sites in the Healthy Hypersaline state. Flows of at least 6000 GL were again needed in a single year before the Healthy Hypersaline state was predicted for any sites (Figure 12.8). When total flow in one year exceeded 13 500 GL, all South Lagoon sites were in the Healthy Hypersaline state. Over two years, at least 9000 GL needed to pass through the barrages before the Healthy Hypersaline state appeared and 23 000 GL over two years was needed before all South Lagoon sites were always predicted to be in the Healthy Hypersaline state. This discrepancy between the minimum and maximum flows for which all sites were predicted to be in the Healthy Hypersaline state suggested that some factor other than barrage flows was also influencing the ecosystem states present.

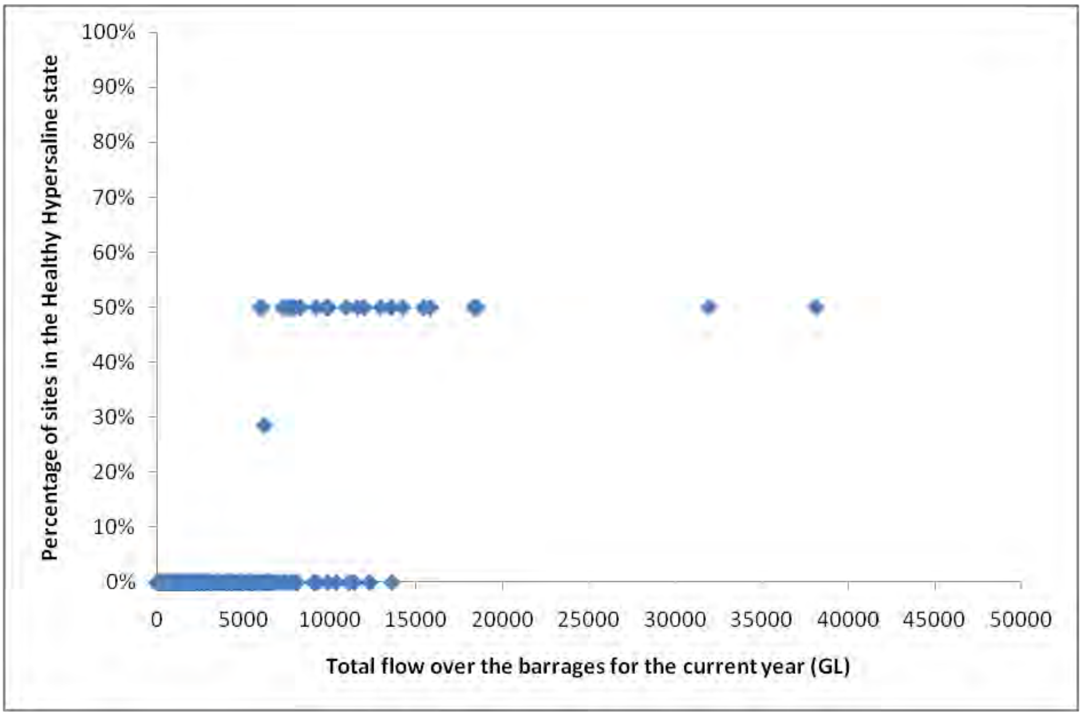

Figure 12.8: The percentage of sites in the Healthy Hypersaline state compared with total flow over the barrages for the modified flow-delivery scenarios under three climate projections

The effect of flow-delivery pattern was less apparent in the occurrence of the Healthy Hypersaline state than was the case for degraded states under low-flow conditions. There was no consistent trend for differences in flow volume between the two sets of scenarios, suggesting that flow timing and the method of delivery may be less important for high-flow events than for low flows, although additional modelling would be required to confirm this.

The scenarios in which additional environmental water was allocated using rules to maintain salinities in Lake Alexandrina of less than a maximum of 1000 $\mu S\ cm^{-1}$ EC indicated that these rules were not sufficient to necessarily produce conditions leading to the Healthy Hypersaline state in the South Lagoon of the Coorong. Flows of more than 10 000 GL over two years were required to trigger that state to be predicted (still using the current year and the previous year as described above) under either the historical or dry future climate or 9000 GL under the median future climate. Flows of greater than 20 000 GL under any climate were required to ensure that at least one site was predicted to be in that state.

The frequency with which flows of this magnitude were required was difficult to address. Taxa-specific analysis would be likely to be required to determine appropriate return intervals for high-flow events, given the lack of data relating to ecosystem states under high flow conditions. Under natural flow conditions (i.e. no extractions within the Murray-Darling Basin under historical climate conditions), flows of this magnitude were common, with flows over 6000 GL $year^{-1}$ occurring in 88% of years, flows greater than 10 000 GL $year^{-1}$ recurring one in every two years, and floods over 20 000 GL $year^{-1}$ occurring one in every 13 years, on average. However, natural flow conditions were not a practical goal. To provide a more-realistic baseline, under current extraction levels and historical climate conditions, flows of these orders would have recurred every three, seven and 30-odd years, respectively.

Under climate change, assuming current extraction levels remain constant, these flows were predicted to become less frequent. Under a median level of climate change, a 6000 GL flow was predicted for one in five years, a 10 000 GL flow had a recurrence frequency of one in 17 years and a 20 000 GL flood has an average return frequency of more than one in 30. Under a dry future climate, these return frequencies stretched to one in 17, 59 and 118 (i.e. only once in the modelled time series), respectively. It was likely that these return frequencies would have substantial implications for Coorong biota and as a preliminary estimate, return intervals no greater than those predicted under a median level of climate change should be aimed for, with historical frequencies preferable.

12.3 Discussion

Two approaches were used to determine a minimum flow requirement over the barrages: one focused on the predicted proportion of degraded ecosystem states and the other using a modelled threshold of 117 g L^{-1} for average South Lagoon salinity (although both used the described ecosystem states of the Coorong). The resulting minimum flows predicted by these two methods were highly consistent. This was encouraging, given that the Unhealthy Hypersaline state was excluded from the former analysis due to the inconsistency in the manner in which the alternative model predicted this state (which was not applicable in the latter method).

Based on these analyses, the following recommendations were made for the setting of an environmental water requirement for the Coorong:

- There should be no years in which no flow passes over the barrages. The absolute minimum barrage flow should be between 50 and 120 GL.
- Over any two-year period, at least 600 GL should be released to the Coorong to prevent certainty that South Lagoon salinity thresholds (of 117 g L^{-1}) being exceeded.
- At least 2500 GL should be released over two years as a minimum target (95% of the time) to prevent the Coorong from existing in degraded states across the entire region.

It should be noted that these were minimum flow requirements, not long-term averages or medians.

The findings of these analyses highlighted the importance of timing and manner of flow delivery for the ecosystem states of the Coorong. The historical flow-delivery pattern consistently resulted in higher minimum flow requirements compared with the sequences in which flow delivery was standardised across the year. This was in contrast to the Lakes, where flow-delivery mechanism had very little impact on hydrology. This dependency meant that any ecological benefits that were derived were contingent on the timing of flows, as much as the volume of flow and that smaller volumes could potentially have the same effect as larger volumes if delivered in an optimal manner. Additional modelling work is required to determine what the optimal flow-delivery strategy would be, but preliminary work suggested that smaller, more-consistent flows had a larger impact in drought conditions than shorter but higher-velocity releases of the same volume.

Here, we have provided our best estimate for minimum flow requirements but, until the optimal timing and delivery pattern has been identified for the region under low-flow conditions, this flow volume should be treated as preliminary. If an improved method of flow delivery were found, the minimum volumes needed may be at the lowest end of the values reported here. However, it should also be stressed that if water were not able to be delivered in line with that optimal delivery strategy due to operational constraints, additional water would be likely to be required to achieve the same ecological outcome.

Thus, based on this work, the minimum flow volumes required to maintain salinities in Lake Alexandrina were sufficient to meet the minimum flow volumes required to sustain the mix of ecosystem states in the Coorong under almost all conditions explored.

The assessment of minimum flow requirements outlined here was based on the ecosystem states model for the Coorong. This model has limitations and its predictions had yet to be tested against new observational data (see Lester & Fairweather

2009a, 2011 for additional detail) and thus we recommend that additional work be undertaken to determine whether there were any taxon-specific requirements that were not likely to be met by these recommended flow volumes, building on the work outlined in Chapter 5.

The same was true when attempting to specify high-flow requirements for the Coorong. Here, the limitations of the model with respect to describing healthy ecosystem states were brought to the fore, with only the Healthy Hypersaline state being a useful candidate for investigating the behaviour of the system under flood events. Flows of more than 6000 GL year^{-1}, and up to 20 000 GL year^{-1} were required to trigger the prediction of this state. It appeared that something other than simply flow volume over the barrages was driving the occurrence of this state (acting to hold water levels unusually high in the South Lagoon) but determining what this was would require further investigation. In the absence of the taxon-specific analysis, there was very little to guide how often flows should reach these volumes to support the ecosystem states of the Coorong, but as a first estimate, we recommend that return frequencies not stretch beyond those predicted an historical climate change, where a 6000 GL flow occurred one in five years, a 10 000 GL flow occurred one in 7 years and a 20 000 GL flood occurred a little more than one in 30 years.

These flow recommendations were made independent of the effect they were likely to have on keeping the Murray Mouth open naturally. Previous work demonstrated that under an historical or median future climate, with current levels of extraction, an intervention such as dredging at the Murray Mouth was only required once in the 114-years sequence (equating to the current drought sequence) (Lester *et al.* 2009c). Under a dry future climate, however, this would increase to approximately one in two years, on average, representing a major shift in the interventions required. Current regional management targets include having a permanently-open Murray Mouth and ideally, this would occur naturally. Unfortunately, there is no single volume that is sufficient to 'keep the Mouth open', as was commonly requested. The relationship between Mouth openness and flow is complex, but does not plateau (I. Webster, pers. comm.). That is, small flows will open the Mouth to a small degree (and not at all, below a threshold), while larger flows will open the Mouth to a larger degree. Seasonal differences in the degree of Mouth openness are natural and a desirable part of the variability in the region. Flow duration and daily discharge rate also affected the degree to which a given flow volume will scour the Mouth.

To provide some indication of the effect of flows on Mouth depth, a flow of 100 GL at 10 000 ML day^{-1} results in an effective Mouth elevation of -0.15 m AHD, while a similar flow rate for a total flow of 500 GL results in an effective elevation of -0.73 m AHD (I. Webster, pers. comm.). This can be compared to the effective elevation of -2 m AHD that was the result of the current dredging effort (note that these effective elevations were drawn from the hydrodynamics model for the Coorong and did not correspond to actual depth of the Mouth channel, see Webster 2010 for more detail). The previous target for barrage flows to maintain the Murray Mouth at a depth that ensure sufficient connectivity within the system was approximately 2000 ML day^{-1} which equates to 730 GL per annum. Thus, based on that estimate, the absolute minimum flow volumes would not be sufficient to maintain effective connectivity between the Coorong and Encounter Bay without dredging. However, the target of a minimum total flow of 2500 GL (for 95% of the time) should be sufficient to maintain a reasonable degree of connectivity (possibly depending on the method and timing of flow delivery) without the need for dredging.

12.4 Summary

- **Describing an environmental water requirement for the Coorong, Lower lakes and Murray Mouth region is an important step in the planning of a long-term future of the system.**
- **This chapter explores preliminary estimates for both the minimum flow requirements for the Coorong and the flooding requirements for the region.**
- **The following are recommended minimum environmental water requirements for the Coorong:**
    - **There should be no years in which no flow passes over the barrages. The absolute minimum barrage flow should be between 50 and 120 GL;**
    - **Over any two-year period, at least 600 GL should be released to the Coorong to prevent certainty that South Lagoon salinity thresholds (of 117 g L^{-1}) being exceeded; and**
    - **At least 2500 GL should be released over two years as a minimum target (95% of the time) to prevent the Coorong from existing in degraded states across the entire region.**
- **These findings highlighted the importance of timing and manner of flow delivery for the ecosystem states of the Coorong. The historical flow-delivery pattern consistently resulted in higher minimum flow requirements compared with the sequences in which flow delivery was standardised across the year.**
- **The minimum flow volumes required to maintain salinities in Lake Alexandrina were sufficient to meet the minimum flow volumes required to sustain the mix of ecosystem states in the Coorong under almost all conditions.**
- **High-flow requirements for the Coorong were specified as flows of more than 6000 GL $year^{-1}$ every 3 years, and 10 000 GL $year^{-1}$ every 7 years.**
- **There was no single volume of water required that was sufficient to 'keep the Mouth open', so the minimum requirements specified here should be used instead.**

13. Exploring the implications of delivering less water than specified by the EWR

Rebecca E. Lester, Rebecca A. Langley, Peter G. Fairweather & Ian T. Webster

13.1 Introduction

Robust environmental water requirements (EWRs) should be developed with explicit links between the hydrodynamic and ecological outcomes for the region, such has occurred for the CLLMM region to enhance the ability of researchers and managers to predict the ecological effects of water delivery. The development of EWRs for the CLLMM region was designed to support the Ramsar-nominated ecological character in the long term and, thus, failing to meet those EWRs is likely to have consequences in terms of the hydrodynamics and ecological character of the region.

In this report, Chapter 2 described the methodology used to develop EWRs for the CLLMM region and this chapter aims to build on the previous investigation of the impact of smaller flow volumes reaching the site than specified in the EWRs, based on the salinity targets set for Lake Alexandrina (as described in Heneker 2010). Setting these salinity targets resulted in flow-delivery rules that identified the volume of water in any given year that would need to pass the barrages to meet the low-flow EWRs for the region. A preliminary investigation of the effects of less water (using two identified low-flow sequences) explored the effects on salinity in Lakes Alexandrina and Albert (Heneker 2010) and then for the Coorong (Chapter 10). Using the existing models for the Coorong, it was possible to further explore the impact of delivering less water than specified by those EWR targets (i.e. delivering less water can be considered a failure to meet the low-flow EWRs for the overall region).

The hydrodynamics of the CLLMM region are governed by the driving forces associated with sea-level variations in Encounter Bay, winds, barrage inflows, flows through Salt Creek, precipitation and evaporation (Chapter 10; Webster 2010). Complex interactions among these variables mean that the hydrodynamics of the Coorong are not linearly related to decreasing flow (Webster 2010), so the effect of less water on the hydrodynamics of the Coorong may not be intuitive, and thus requires specific investigations.

Hydrodynamics of the Coorong have been found to drive the ecosystem states, particularly barrage flows, water levels and salinity (Lester & Fairweather 2011). The ecosystem states are one measure of ecological condition and represent the relationship between observed co-occurring biota and the environmental conditions under which these were observed (see Chapter 11). Flow thresholds linked to the future presence of degraded ecosystem states have previously been identified (Fairweather & Lester 2010) and so we have focused here on salinities and water levels to determine the impact of delivering water at a range of flow volumes below the amount identified by the EWRs. In addition, the percentage of degraded ecosystem states, as identified from using the ecosystem states model, represents a measure of ecological condition and so provides a mechanism for predicting the ecological consequences of delivering less water than specified.

This chapter investigates the potential effects of the delivery of less water on salinities, water levels and the percentage of degraded ecosystem states using a range of hydrodynamic variables, including barrage outflows, discrepancy between the total volume of barrage flow in a single year and the volume recommended by the EWRs described in this report, and the cumulative discrepancy in flow volumes relative to the EWRs over time (i.e. where EWRs are not met across multiple years, the cumulative shortfall across those years) as potential drivers of change. The barrage flows were modelled by estimating run-off in the Murray-Darling Basin for each of three possible climates (provided by the Murray-Darling Basin Authority), as total flow across all the barrages for each day between 1891 and 2008. Variations in flow (i.e. particularly barrage flow) are largely attributable to the influence of climate variability and extractions on rainfall and run-off in the Murray-Darling Basin (Chiew *et al.* 2010; Webster 2010). Thus, we explore three climatic scenarios within this chapter to provide insight into the interaction of the delivery of less water under different climate change scenarios.

This chapter aims to identify whether there were thresholds, or bands of flows, smaller than those specified by the EWRs that would be significant in their effects on salinity, water level and the percentage of degraded ecosystem states predicted in the Coorong for each of the three salinity targets identified by Heneker (2010) under each of three climate-change scenarios.

13.2 Methods

13.2.1 Flows to meet targets salinities in the CLLMM region

Salinity targets of an average of 700, and a maximum of either 1000 or 1500 µS cm^{-1} EC were selected for Lake Alexandrina based on indicator tolerances, historical salinity levels and salinities commonly recorded for fresh versus brackish wetlands (Chapter 5, Heneker 2010). Those indicator tolerances and subsequent modelling work suggested that the ideal target for the region is the long-term average of 700 µS cm^{-1} EC, with maxima of 1000 µS cm^{-1} EC in 95% of years, and never exceeding 1500 µS cm^{-1} EC in Lake Alexandrina. The rules for providing environmental flows to meet these targets are described by the following three sets of rules (Heneker 2010).

To meet the salinity target of the long-term average of 700 µS cm^{-1} EC in Lake Alexandrina, the following minimum barrage outflows have been identified for any one year as the maximum of:

1. 3150 GL
2. 8000 GL - F_{x-1}
3. 12 000 GL - F_{x-1} - F^*_{x-2}

   where F_{x-1} is the flow volume from the previous year and F^*_{x-2} is equal to the lesser of the actual outflow 2 years prior to the current year and 4000 GL.

To meet the salinity target of a maximum salinity of 1000 µS cm^{-1} EC in Lake Alexandrina, the minimum barrage outflow for any one year has been determined to be the maximum of:

1. 650 GL
2. 4000 GL - F_{x-1}
3. 6000 GL - F_{x-1} - F^*_{x-2}

   where F_{x-1} is the flow volume from the previous year and F^*_{x-2} is equal to the lesser of the actual outflow 2 years prior to the current year and 2000 GL.

To meet the salinity target of the long-term average of 1500 µS cm^{-1} EC in Lake Alexandrina, the following minimum barrage outflows have been identified for any one year as the maximum of:

1. 0 GL but with inflows delivered to replace actual losses in Lake Alexandrina (e.g. through evaporation)
2. 2000 GL - F_{x-1}
3. 3000 GL - F_{x-1} - F^*_{x-2}

where F_{x-1} is the flow volume from the previous year and F^*_{x-2} is equal to the lesser of the actual outflow 2 years prior to the current year and 1000 GL.

These flow-delivery rules identify the volume of water in any given year that will meet the low-flow environmental water requirements set for the CLLMM region. Delivering less water than is specified here can be considered a failure to meet the low-flow EWRs for the region. In investigating the effect of less water, we have considered only the low-flow EWRs (described above) rather than the high-flow EWRs of flows of more than 6000 GL year^{-1} and 10 000 GL year^{-1} with return frequencies of 1 in 3 years and 1 in 7 years, respectively (Chapter 12).

13.2.2 Identifying degraded ecosystem states

In order to assess the ecological impacts of less water actually being delivered into the system, the ecosystem states model (as described in Chapter 11) was used. For assessments made using the ecosystem states model, a distinction between degraded and healthy ecosystem states was used. Degraded states were defined as any of the Marine, Unhealthy Marine, Degraded Marine, Unhealthy Hypersaline or Degraded Hypersaline states (see Chapter 11; Appendix F). Healthy states were defined as any of the Estuarine/Marine, Average Hypersaline or Healthy Hypersaline ecosystem states (see Chapter 11; Appendix F). For each scenario the proportion of site-years that were considered degraded was calculated (see Chapter 11) as a measure of overall ecological condition within the system. The identification of degraded ecosystem states complements the measures of water level and salinity (i.e. from hydrodynamic modelling) to ensure that a range of potential effects of less water are investigated.

13.2.3 Scenarios used

Scenario modelling was used to determine the effect of lower flow volumes than those specified in the EWRs on the salinity of the Coorong. This allowed us to identify thresholds in a variety of barrage flow sequences and assess the impact of each on the salinity of the Coorong.

Climate change has the potential to dramatically affect the hydrodynamic conditions of the Coorong, including through a direct reduction in barrage flows and increases in evaporation rates. This could substantially affect the maximum number of days without flow over the barrages, salinity and thus, the ecosystem states that occur within the Coorong. Therefore, we used scenarios including historical recorded climate, as well as two climate-change projections. All scenarios used here were based on future climate scenarios that have been described by the CSIRO Sustainable Yield Project (Chiew *et al.* 2008), which is consistent with the other scenario modelling presented in this report. The three scenarios used included one which was based on the historical climate sequence, one which assumed the median climate predicted for 2030, and one which represented the tenth percentile future dry condition. The scenarios can be described as follows:

1. Benchmark conditions (hereafter called 'Standard Historical')

   This scenario included historical climate conditions, current levels of extraction from the Basin (and so current flows over the barrages) and average inflows from the USED scheme.

2. Median climate change with current extraction levels ('Standard Median')

   This scenario included a median 2030 climate, current levels of extraction from the basin and average inflows from the USED scheme.

3. Dry climate change with current extraction levels ('Standard Dry')

   This scenario included a dry 2030 climate, current levels of extraction from the Basin and average inflows from the USED scheme.

All three scenarios ran from 1891 to 2008, consistent with other scenario modelling presented in this report for the Coorong (e.g. see Chapters 10 and 11 but please note that the work based on the ecosystem response model requires several years of data to calculate some parameters, so it calculates ecosystems states only from 1895 onwards).

13.2.4 Assessing whether flow targets were met for each year

In order to assess whether each year in each scenario met the flow target for that year based on the EWRs specified above, we calculated the total annual barrage outflow (GL) for each year in each scenario. Then, the target flow volume for each year was calculated based on the flow-delivery rules outlined above as the maximum of the three rules, based on flow from the previous two years. We then compared the calculated total annual barrage flow with the target flow volume, and the years where the calculated barrage outflow was greater than the target were considered to meet the EWRs (referred to as a 'pass'). Years where this was not the case (i.e. target > calculated barrage flows) were considered to not meet the EWRs (referred to as a 'fail'). These were summed for each scenario to determine the number of years within each when the targets were met versus where they failed to be met. The average number of years that each scenario took to meet the calculated 'normal' salinity or water level (see below for methods used to calculate 'normal' values) for that lagoon again (i.e. to return after a failed year) was also calculated. The last series of years was excluded from this calculation of average return for each scenario under each salinity target because the calculated 'normal' salinity was not met by the end of the scenario year run (i.e. up to 2008). In addition, we calculated the volumetric discrepancy between the barrage outflow and the target flow to gain an understanding of the magnitude of the failure for each year. Cumulative discrepancy was calculated as the addition of total barrage outflow in a failed year (i.e. one that did not meet the salinity target) to that of the previous discrepancy, where more than one year failed to meet the targets concurrently. Each variable listed here was calculated for each salinity target for Lake Alexandrina and each climate scenario separately.

13.2.5 Estimating 'normal' conditions against which to assess recovery times

In order to assess differences in the time required for the hydrodynamics of the Coorong to recover from years in which barrage flows fell below those specified by the EWRs, we estimated normal conditions for each of the scenarios. This was done by calculating median salinities and water levels for each lagoon, using only those years where the flow targets set by the EWRs were met (i.e. years where total barrage flow was greater than the minimum volume of water specified by the rules above). This was done for each of the salinity targets for Lake Alexandrina separately.

13.2.6 Identifying thresholds in the response of the Coorong to less water

Three variables that could respond to less water were considered: salinity, water levels and the percentage of degraded ecosystem states. Salinity and water levels were considered for each of the North and South Lagoons separately, and each of the three targets set as a part of the development of the EWRs were also considered separately. That is, we investigated the effects of not meeting flows to sustain a long-term average in Lake Alexandrina of 700 μS cm^{-1} EC, then the effects of not meeting flows to maintain salinities in Lake Alexandrina of below 1000 and then 1500 μS cm^{-1} EC.

Regression tree analyses using classification and regression trees (CART) split response variable data into increasingly homogenous groups based on a variety of exploratory variables to minimise the variation within groups of a specified response variable (De'ath & Fabricius 2000; Lester & Fairweather 2009a, 2011). A regression tree was produced using each of North and South Lagoon salinity values, water levels and the percentage of degraded states as response variables under each salinity target. Potential predictor variables included total barrage outflow, a categorical variable describing whether the EWR target was met or not (i.e. pass or fail), discrepancy in flow volume, the cumulative discrepancy (when EWR were not met over multiple years, cumulative discrepancy was the incremental addition of the shortfall over that time period) in flow volume and the number of cumulative years in which the flow targets were not met. Least squares regression was used to obtain the best tree (using the one standard error rule; Brieman *et al.* 1984), where the minimum parent node was set at 10 cases and the minimum terminal node was set at one case. For each regression tree, we then determined the most influential variables (i.e. based on the reported variable importance, with a range of 0 as least important to 100 as most important), the threshold values for the key variables and steps in the degradation trajectory (i.e. the number of terminal nodes). Where variables were significantly correlated (at $\alpha = 0.05$; e.g. discrepancy and cumulative discrepancy), the variable with the higher importance in the CART analysis was retained and the other removed until we obtained a regression tree with no significantly-correlated predictor variables.

13.3 Results

13.3.1 Modelled 'normal' conditions for determining the recovery of the system

When calculating 'normal' conditions, in general salinities within the North Lagoon were, on average, lowest for each of the salinity targets for the Standard Historical scenario, compared to the Standard Median and Standard Dry scenarios, with the latter tending to have the highest 'normal' salinities (Table 13.1). The same pattern was also observed for average salinity in the South Lagoon, although there were much larger differences in median salinity between the extreme climate scenario (i.e. Standard Dry) compared to Standard Historical and Standard Median scenarios. In addition, across the salinity targets the average salinities increased for all of the scenarios (i.e. average salinities were lowest under the 700 EC rule compared to 1000 EC and 1500 EC rules).

The differences in average water levels in both the North and South Lagoons were not as prominent as those found for salinities (Table 13.1). Average North Lagoon salinities were very similar, with all scenarios recording an average of 0.4 m AHD under the 700 EC rule and 0.3 m AHD under both the 1000 EC and 1500 EC rules. South Lagoon average water levels varied only slightly across scenarios under each of the rules, mostly ranging between 0.2 m AHD and 0.4 m AHD, where the lowest water levels were found under the 1500 EC rule.

Overall, the lowest 'normal' median salinity value for the North Lagoon was 21.5 g L^{-1} under the 700 EC salinity target, while the highest was 57.5 g L^{-1} under the Standard Dry scenario using the 1500 EC target. Similarly, the lowest median salinity value for the South Lagoon was found under the Standard Median scenario using the 700 EC salinity target (59.5 g L^{-1}). The highest median salinity value for the South Lagoon was 151.7 g L^{-1} also using the 700 EC salinity target but under the Standard Dry scenario. Overall, median water levels appeared to change more with the different salinity targets rather than with the climate change scenarios (Table 13.1).

Table 13.1: Median North Lagoon (NL) and South Lagoon (SL) salinity (g L^{-1}) and water levels (m AHD) across all years in the scenarios for each of the salinity targets

Bold values are the average salinities and water levels for each Lagoon across all scenarios under each salinity target, while other values are shown for each salinity target and climate scenario combination.

Scenario	NL Salinity	SL Salinity	NL Water Level	SL Water Level
700 EC Rule	***25.4***	***64.6***	***0.4***	***0.3***
Standard Historical	24.9	63.7	0.4	0.3
Standard Median	21.5	59.5	0.4	0.4
Standard Dry	39.0	151.7	0.4	0.3
1000 EC Rule	***32.3***	***74.9***	***0.3***	***0.3***
Standard Historical	29.4	66.0	0.3	0.3
Standard Median	33.4	76.0	0.3	0.3
Standard Dry	52.1	151.4	0.3	0.3
1500 EC Rule	***39.9***	***83.7***	***0.3***	***0.2***
Standard Historical	33.3	71.7	0.3	0.3
Standard Median	38.9	83.8	0.3	0.2
Standard Dry	57.5	150.0	0.3	0.2

13.3.2 Assessing whether flow targets were met for each year

Under the 700 EC salinity target, all scenarios had fairly high failure rates, with percentage of years failing to meet the target increasing from the baseline (69% for the Standard Historical scenario) through to the median (84% for the Standard Median scenario) and drier (94% for the Standard Dry scenario) climate scenarios (Table 13.2). Most notably, under the drier climate change scenario, only 6% of years met the EWR target (i.e. in the absence of any additional environmental water). The percentage of years that failed decreased for all scenarios under the 1000 EC salinity target; where the Standard Historical scenario had the lowest percentage of years failing to meet the target, at 36%. The climate change scenarios also improved under the 1000 EC target, where the percentage of years failing to meet the target, had decreased to 45% and 86%, for the Standard Median and Standard Dry scenarios respectively.

Under the 1500 EC salinity target, all scenarios had greater percentages of years which met the EWR target, reflecting the higher salinities allowed and thus lower water requirements associated with that target (Table 13.2). The Standard Historical scenario had the greatest percentage of years which met the target, at 84%. The climate change scenarios had lower percentage of years that met the target, but under median climate conditions, the percentage of years which met the target was closer to that under baseline conditions, at 76% compared to dry climate conditions at 34%. Hence, the climate change scenarios were less likely than the baseline scenario to meet the EWR targets, under all of the salinity targets.

In addition to the number (and percentage) of years the EWR target was met or not met, the average number of years required to recover from dry periods and achieve 'normal' conditions were also calculated. The average number of years it took to return to 'normal' conditions was the most variable under the 700 EC salinity target, where the average number of years ranged from 4.4 years under baseline conditions to 18 years under dry climate conditions (Table 13.2). Under the 1000 EC salinity target, the average number of years to return was similar between all three scenarios, at 3 years under baseline conditions and 3.7 years under both median and dry climate conditions. Under the 1500 EC salinity target, both the baseline and median climate conditions had the lowest average number of years return at 1.7 years. The average number of years to return under this rule was much higher under dry climate conditions, at 6.9 years. Therefore, there was a general trend that under baseline conditions, the average number of years to return to meet the EWR targets was smaller compared to that under the climate change scenarios.

In order to gain an understanding of the magnitude of failure for each scenario under each of the three salinity targets, the volumetric discrepancy in flow was calculated. Under the 700 EC salinity target, each scenario had a positive average discrepancy, indicating that not enough water was delivered to the region (i.e. the target flow was greater than the calculated barrage flows) (Table 13.2). Such average discrepancies ranged from 1467 GL under baseline conditions to 8126 GL per year under dry climate conditions. Under the 1000 EC salinity target, both the Standard Historical and Standard Median scenarios had negative average discrepancies, which indicated that there was more than enough water being delivered under these conditions (i.e. the barrage flow was greater than the target flow). Of the two scenarios, the Standard Historical scenario had the greater average amount of extra flow (i.e. amount of flow above the target flow, a negative discrepancy), at 2777 GL per year compared to the Standard Median scenario, at 1197 GL. The Standard Dry scenario was the only scenario under this salinity target to have a positive discrepancy, with an average of 2567 GL below the target flow. Similar to the 1000 EC salinity target, under the 1500 EC salinity target both the Standard Historical and Standard Median scenarios had, on average, 4282 GL and 2956 GL more flow delivered each year than the target, respectively. Under dry climate conditions, an average discrepancy in flow was recorded of 84 GL. Hence, the magnitude of failure was generally greater under dry climate conditions and with more-stringent salinity targets.

A cumulative discrepancy was also calculated to gain an understanding of the level of failure where more than one year had failed to meet the targets consecutively. Under the 700 EC salinity target all three scenarios had reasonably high average cumulative discrepancies in flow (Table 13.2). These values ranged from 12 361 GL under baseline conditions to 110 161 GL under dry climate conditions. Under the 1000 EC salinity target, only under the Standard Historical scenario was there a greater average flow delivered to the region than the target, with an average of 2046 GL more water than was required over the model run. Both the climate change scenarios had positive cumulative discrepancies in the amount of flow, with the greatest cumulative discrepancy recorded under dry climate conditions (23 901 GL). Under the 1500 EC salinity target, both the Standard Historical and Standard Median scenarios had negative average cumulative discrepancies, which indicated that more than enough water was delivered to the region. Under baseline conditions this amount of flow was, on average, 4122 GL of additional water compared to an average of 2813 GL under median climate conditions. Again, not enough water was modelled to be delivered to the region under dry climate conditions, with an average cumulative discrepancy of 6107 GL. Hence, the average cumulative discrepancy was the greatest under dry climate conditions.

Table 13.2: Summary of the characteristics of each scenario and salinity target compared with its environmental water requirement

The average number of years after a salinity target was not met required to return to 'normal' conditions was also calculated, but it is important to note that the last series of failed years (i.e. to 2008) never returned to 'normal' conditions, and thus these years were excluded from these latter calculations. Refer to the text for a definition of 'normal' conditions.

Scenario	No. of Passes	No. of Fails	% Pass	% Fail	Ave no. years to return to 'normal'	Average discrepancy (GL)	Average cumulative discrepancy (GL)
700 EC Rule							
Standard Historical	36	80	31	69	4.4	1467	12 361
Standard Median	19	97	16	84	12.3	3418	31 233
Standard Dry	7	109	6	94	18.0	8126	110 161
1000 EC Rule							
Standard Historical	74	42	64	36	3.0	-2777	-2046
Standard Median	64	52	55	45	3.7	-1197	1315
Standard Dry	16	100	14	86	3.7	2567	23 901
1500 EC Rule							
Standard Historical	97	19	84	16	1.7	-4282	-4122
Standard Median	88	28	76	24	1.7	-2956	-2813
Standard Dry	40	76	34	66	6.9	84	6107

13.3.3 700 EC salinity target

13.3.3.1 Coorong salinity

The most influential variable on the North Lagoon salinity under the 700 EC target was discrepancy in flow (i.e. compared to flows required to meet the EWRs) in a single year (with an importance score of 100) (Figure 13.1). Other variables that were also important from the regression tree analysis (but are not represented in the tree; e.g. are treated as surrogate variables) included cumulative discrepancy (importance = 82), total barrage flows (importance = 59) and the number of years where the EWR target was not met (importance = 55). Key thresholds identified for discrepancy values included 11 058 GL and 7208 GL (Figure 13.1), with increasing salinities likely in the North Lagoon with increasing discrepancies in the amount of water required to meet the EWR in a single year. The trajectory of decline for the North Lagoon salinity under the 700 EC salinity target identified three outcomes (i.e. the number of identified terminal nodes). The majority of cases (i.e. years per scenario) fell within the first outcome identified (*n* = 142), where salinity, on average, was the lowest and had the lowest variability between cases (Figure 13.1). The second outcome in the degradation trajectory also had a reasonably high number of cases (*n* = 111) and had a higher average salinity than the first outcome, at 76.7 g L^{-1}. Finally, the last outcome in the degradation trajectory for the North Lagoon salinity under the 700 EC target had the lowest number of cases (*n* = 33), so was the least common across the three scenarios investigated but had the highest average salinity, at 150.6 g L^{-1} and the highest variability between cases (SD = 41.7).

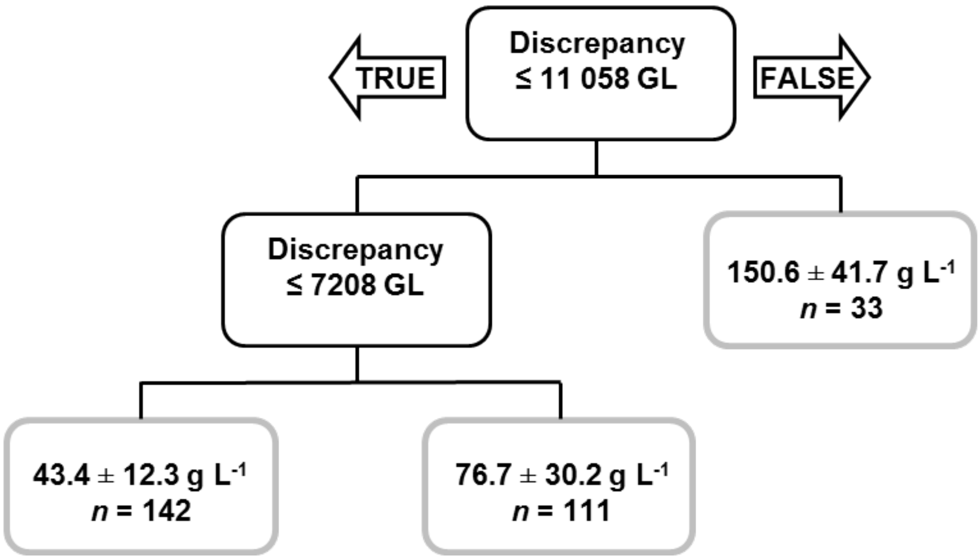

Figure 13.1: Regression tree output for the North Lagoon salinity under the 700 EC salinity target

The driving variables are represented by the black boxes and the trajectory of decline is the number of distinct breaks identified in the response variable (i.e. here two breaks in North Lagoon salinity) resulting in conditions shown by each terminal node (as light grey boxes = outcomes). Thresholds for each driving variable are displayed, in addition to the average North Lagoon salinity ± standard deviation and number of cases (i.e. the number of fail years across each of the three scenarios modelled) for each terminal node.

Regression tree analysis for the South Lagoon salinity under the 700 EC target identified cumulative discrepancy (i.e. discrepancy in the water column over time, as opposed to in a single year as for North Lagoon salinity) as the most influential variable (importance = 100) (Figure 13.2). Other important variables included the number of years failed (importance = 67) and total barrage flow (importance = 11). For this analysis, discrepancy in a single year was removed because it was correlated with (but less important than) cumulative discrepancy (*r* = 0.57). Key thresholds for cumulative discrepancy were 203 144 GL, 45 038 GL and 264 136 GL (Figure 13.2). For salinity in the South Lagoon, we identified four outcomes in the trajectory decline. Outcome 1 had the greatest number of years (*n* = 150) and the lowest average salinity, of 90.3 g L^{-1}. Outcome 2 had an average salinity approximately double to that found in outcome 1, with a reasonably high number of the cases (Figure 13.2), indicating that conditions fell within that outcome relatively often. Average South Lagoon salinity in the third outcome in the trajectory decline was 348.6 g L^{-1} and contained many fewer cases than the previous outcomes, with only 14. Finally, the last outcome in the trajectory decline identified for South Lagoon salinity had the fewest cases (*n* = 7) and the highest average salinity, at 558.1 g L^{-1}. In addition, the final two outcomes of the decline trajectory in South Lagoon salinity had the highest variability between cases, with standard deviation = 102.3 and 117. Both of these outcomes include salinities that are physically unrealistic due to changes in the solubility of salts at high concentration (Webster 2010) but still indicate that conditions would be extremely harsh.

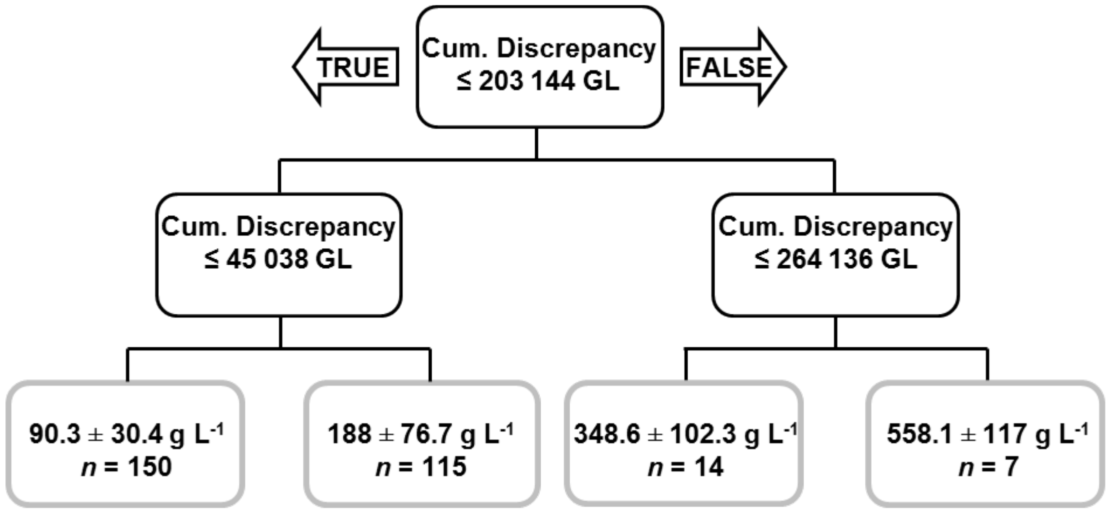

Figure 13.2: Regression tree output for the South Lagoon salinity under the 700 EC salinity target

See Figure 13.1 for further explanation.

13.3.3.2 Coorong water levels

Discrepancy in the flow volume for a single year was identified as the most influential variable on North Lagoon water levels (Figure 13.3). Regression tree analysis also indicated that other key variables included cumulative discrepancy (importance = 27) and the number of years where the EWR target was not been met (importance = 26). Total barrage flow was removed from this analysis because it was correlated with (but less important than) discrepancy (*r* = -0.62). Two thresholds were identified for discrepancy in a single year, which were 11 150 GL and 7004 GL. The North Lagoon water-level tree found three outcomes in the trajectory of decline for that variable (Figure 13.3). Outcome 1 had the greatest number of cases (*n* = 139) and the highest average water level, at 0.3 m AHD. Outcome 2 also had a reasonably large number of cases (*n* = 118) and a similar average water level to outcome 1, at 0.2 m AHD. The last outcome in the trajectory of decline for North Lagoon water levels had the fewest cases, at 29, and the lowest average water level, at -0.01 m AHD. Overall the variability between cases within each of the outcomes in the degradation trajectory was very similar, at standard deviation = 0.07 (outcomes 1 and 3) or 0.08 (outcome 2).

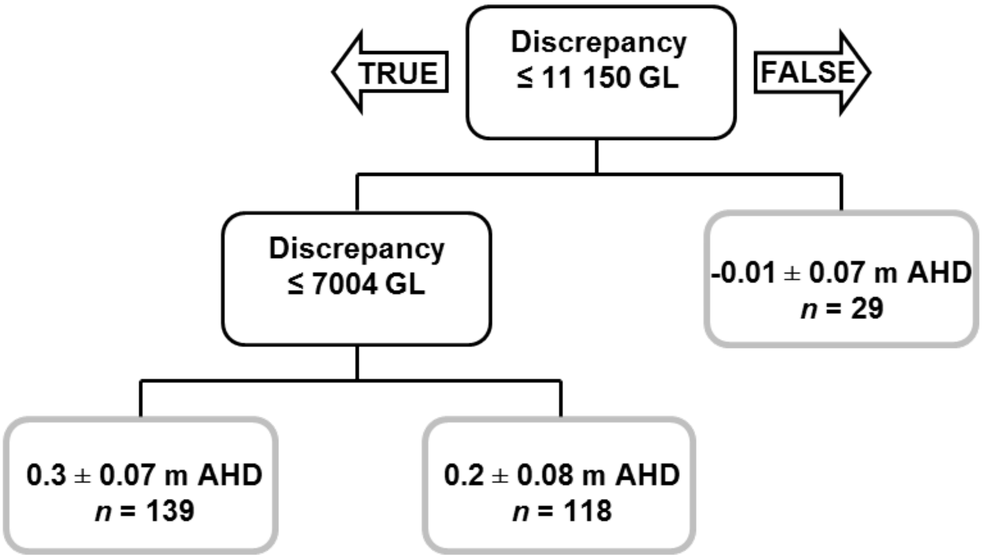

Figure 13.3: Regression tree output for the North Lagoon water level under the 700 EC salinity target

See Figure 13.1 for further explanation.

Regression tree analysis for South Lagoon water levels identified discrepancy in barrage flows for a single year as the most influential variable (Figure 13.4). Total barrage flow (importance = 71.5), cumulative discrepancy (importance = 28.8) and the number of years where the EWR target was not met (importance = 26.2) were identified as other key variables. Two key thresholds for discrepancy were found, at 11 150 GL and 7004 GL (notably the same values as the thresholds identified for the North Lagoon water levels). Three outcomes in the degradation trajectory were found in the South Lagoon water-level regression tree and each outcome had the same number of cases as those allocated to the corresponding outcome in the North Lagoon water level tree. The average water levels found in the South Lagoon water-level tree were lower than those observed in the North Lagoon for the corresponding terminal node, consistent with our understanding of the actual relationship between water levels in the North and South Lagoons (Figures 13.3 and 13.4). Outcome 1 for South Lagoon water levels had a higher average water level than the other two outcomes, at 0.2 m AHD. Outcome 2 had a moderate average water level at 0.07 m AHD, with outcome 3 having the lowest average water level at -0.3 m AHD. The variability among the cases was the same for each of the degradation trajectory outcomes, all with a standard deviation of 0.1.

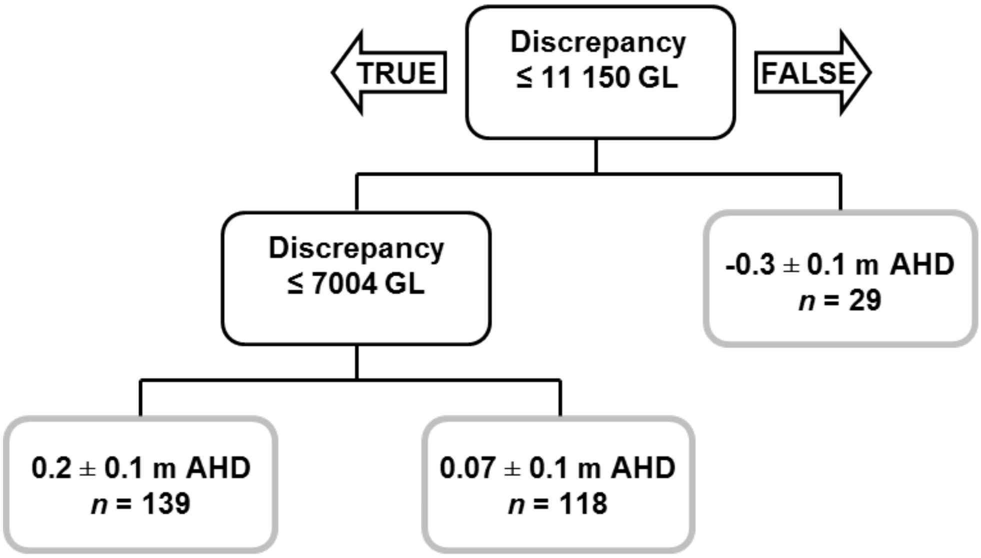

Figure 13.4: Regression tree output for the South Lagoon water level under the 700 EC salinity target

See Figure 13.1 for further explanation.

13.3.3.3 Degraded ecosystem states

Discrepancy in flow volume for a single year was identified as the most influential variable on the percentage of degraded ecosystem states in the Coorong under the 700 EC target (Figure 13.5). The number of years for which the EWR target was not met and total barrage flows were also considered important, with importance scores of 45 and 34, respectively. Cumulative discrepancy was removed when creating the percentage of degraded ecosystem states tree because it was correlated with (but less important than) discrepancy (*r* = 0.57). One key threshold (or break) for discrepancy of 7711 GL, and two outcomes in the degradation trajectory were found. Outcome 1 had the greatest number of cases, indicating it was the more common condition, and had a lower average percentage of degraded ecosystem states compared to outcome 2 (Figure 13.5). Both outcomes had similar variability between cases, with standard deviations of 27% and 30%, respectively.

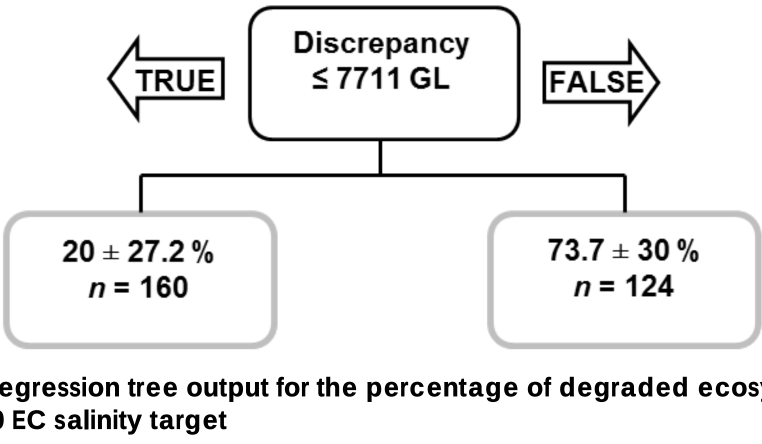

Figure 13.5: Regression tree output for the percentage of degraded ecosystem states under the 700 EC salinity target

See Figure 13.1 for further explanation.

13.3.4 1000 EC salinity target

13.3.4.1 Coorong salinity

Under the 1000 EC salinity target, regression tree analysis identified that discrepancy over time (i.e. cumulative discrepancy) was the most influential variable on North

Lagoon salinity (Figure 13.6). Other key variables included the number of years the EWR target was not met (importance = 79) and total barrage flows (importance = 47). Discrepancy in the water column in a single year was removed from this analysis because it was correlated with (but less important than) cumulative discrepancy (*r* = 0.54). Three thresholds were identified for discrepancy in the water column, including 29 288 GL, 11 202 GL and 57 306 GL. Four outcomes in the degradation trajectory of North Lagoon salinity under the 1000 EC target were identified. Outcome 1 had the greatest number of cases (*n* = 95), indicating that it was the most common condition, and the lowest average salinity, at 56.4 g L^{-1}. Outcome 2 had a moderate average salinity at 77.7 g L^{-1} across 53 of the cases. Outcomes 3 and 4 had lower number of cases and increasing average salinities, at 121.9 g L^{-1} and 174.9 g L-`, respectively. The variability between the cases across the trajectory outcomes ranged from standard deviation = 13.4 in outcome 1 to 49.6 in outcome 4.

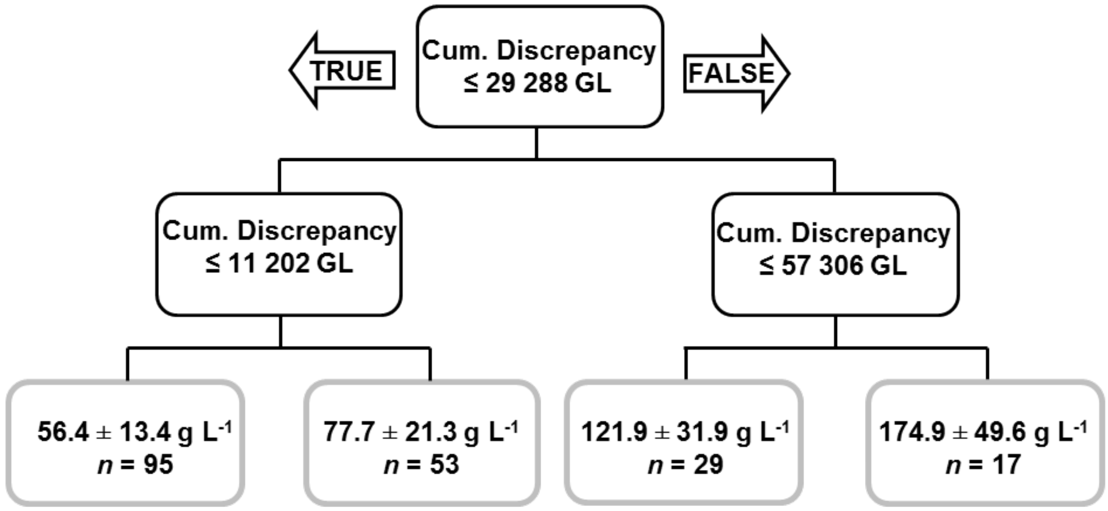

Figure 13.6: Regression tree output for the North Lagoon salinity under the 1000 EC salinity target

See Figure 13.1 for further explanation.

Figure 13.7 shows the regression tree produced for the South Lagoon salinity under the 1000 EC target. The most influential variable on the South Lagoon salinity was cumulative discrepancy. Other key variables included the number of years the EWR target was not met (importance = 76) and total barrage flow (importance = 14). Discrepancy in the water column in a single year was removed from this analysis as it was found to be correlated with (but less important than) cumulative discrepancy (*r* = 0.54). Three thresholds were identified for cumulative discrepancy, at 20 302 GL, 36 580 GL and 57 306 GL. Like North Lagoon salinity, the South Lagoon salinity regression tree also identified four outcomes in the degradation trajectory. Outcome 1 had the largest number of cases (by far in comparison with the other 3 outcomes) (*n* = 124) and the lowest average salinity, at 120.4 g L^{-1}. Outcome 2 had an average salinity of 208.6 g L^{-1}, across 35 of the cases. Outcomes 3 and 4 had very similar number of cases (*n* = 18 and 17, respectively) but outcome 4 had a much higher average salinity (highest of all outcomes), at 453.2 g L^{-1}. Outcome 4 also had the greatest variability across the outcomes with a standard deviation of 136.6 (Figure 13.7). As for South Lagoon salinities under the 700 EC target, these last two outcomes in particular, have unrealistically high salinity values but would represent extremely, and increasingly, harsh ecological conditions.

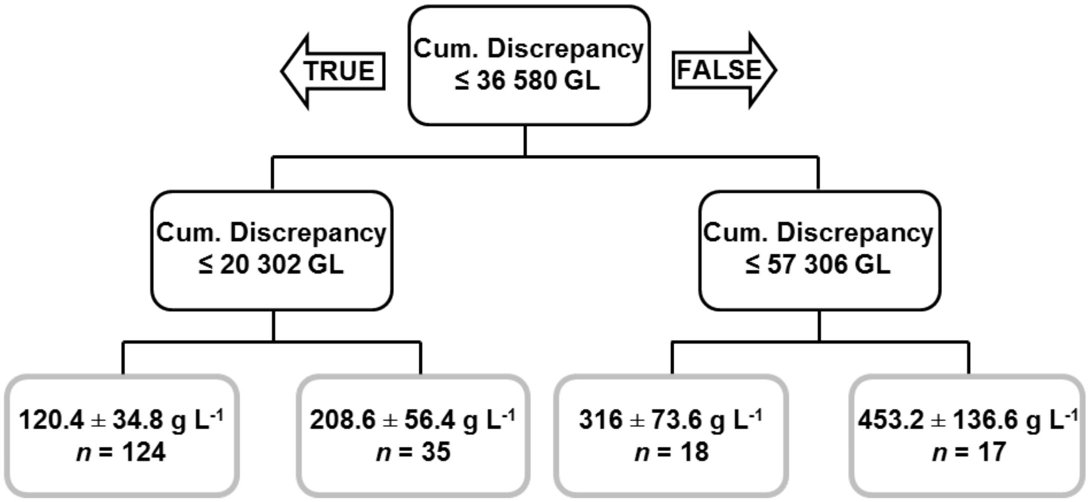

Figure 13.7: Regression tree output for the South Lagoon salinity under the 1000 EC salinity target

See Figure 13.1 for further explanation.

13.3.4.2 Coorong water levels

Discrepancy in the flow volume for a single year was identified as the most influential variable on North Lagoon water levels under the 1000 EC salinity target (Figure 13.8). Total barrage flows (importance = 73.5), cumulative discrepancy (importance = 14) and the number of years the EWR target was not met (importance = 14) were other key variables of influence. A single threshold was found for discrepancy by the regression tree analysis, of 5150 GL. Therefore, two outcomes in the degradation trajectory were identified (Figure 13.8). Outcome 1 had the majority of the cases (*n* = 165) and a higher average water level of 0.2 m AHD. Outcome 2 had a low average water level, at -0.003 m AHD across 29 of the cases analysed and was thus less common than the first outcome. The variability across cases within each of the degradation outcomes was the same, with a standard deviation of 0.1.

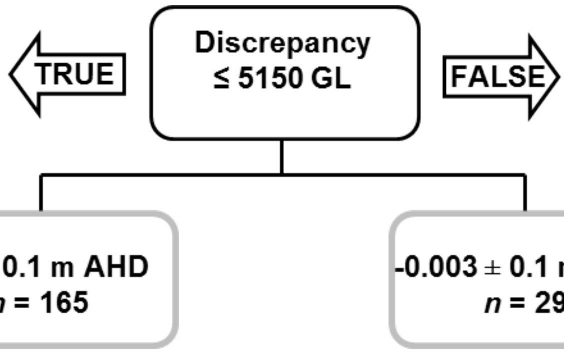

Figure 13.8: Regression tree output for the North Lagoon water level under the 1000 EC salinity target

See Figure 13.1 for further explanation.

As for North Lagoon water levels, under the 1000 EC salinity target, the most influential variable on South Lagoon water levels was discrepancy in flow volume for a single year (Figure 13.9). Other key variables identified included total barrage flow (importance = 65), cumulative discrepancy (importance = 17) and the number of years the EWR target was not met (importance = 17). A single threshold for discrepancy was found (5150 GL) and thus two outcomes in the degradation trajectory, as was the case (and the threshold) for North Lagoon water levels. The two trajectory outcomes had the same number of cases as those found in the North Lagoon water level tree, but the average water levels were lower for both outcomes, at 0.1 and -0.3 m AHD, respectively. The variability across cases within each of the degradation outcomes was the same, with a standard deviation of 0.1.

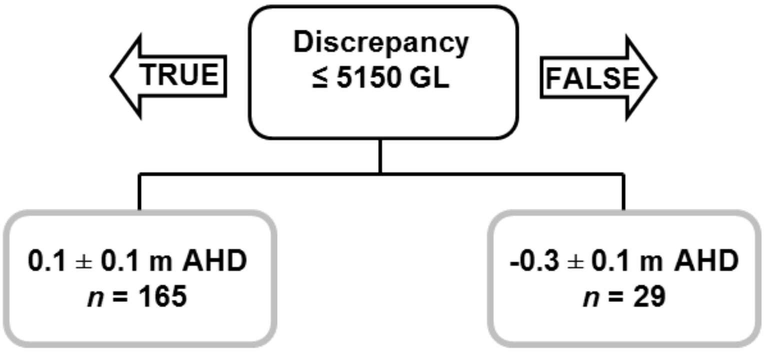

Figure 13.9: Regression tree output for the South Lagoon water level under the 1000 EC salinity target

See Figure 13.1 for further explanation.

13.3.4.3 Degraded ecosystem states

Cumulative discrepancy was found to be the most influential variable on the percentage of degraded ecosystem states under the 1000 EC salinity target (Figure 13.10). The number of years the EWR target was not met and total barrage flows were other key variables identified from the analysis, with variable importance scores of 84 and 82, respectively. Discrepancy in flow volume for a single year was removed from this analysis because it was found to be correlated with (but less important than) cumulative discrepancy ($r = 0.54$). Two thresholds were identified in the regression tree for cumulative discrepancy and barrage flow (Figure 13.10). Unlike previous trees, Figure 13.10 demonstrated the influence of two variables in driving the degradation trajectory of degraded ecosystem states under the 1000 EC salinity target. This degradation trajectory contained three outcomes, with outcome 1 having the greatest number of cases ($n = 94$) and the lowest average percentage of degraded ecosystem states (27.8%). In contrast, outcome 3 had the highest average percentage of degraded ecosystem states (94.6%) and the lowest number of cases across the three outcomes ($n = 41$). The average percentage of degraded ecosystem states in outcome 2 was 64.5% across 58 cases (note that the order in which the outcomes appear in Figure 13.10 is not important to their interpretation, but is a function of true statements always appearing to the left of the tree). Both outcomes 1 and 3 had higher variability across their cases, with outcome 2 having much smaller variation (i.e. approximately half) (Figure 13.10).

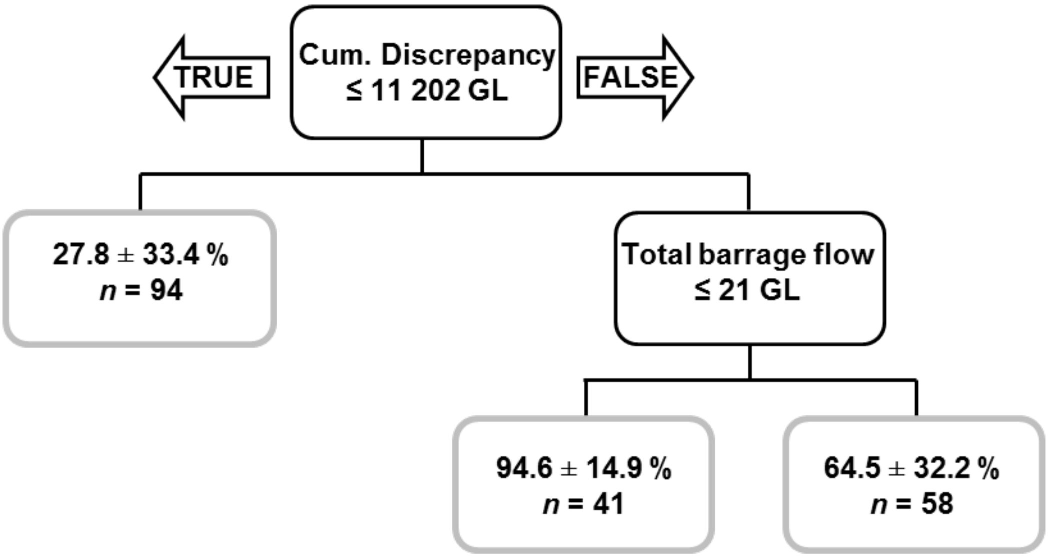

Figure 13.10: Regression tree output for the percentage of degraded ecosystem states under the 1000 EC salinity target

See Figure 13.1 for further explanation.

13.3.5 1500 EC salinity target

13.3.5.1 Coorong salinity

The most influential variable on North Lagoon salinity under the 1500 EC salinity target was cumulative discrepancy (Figure 13.11). The number of years that the EWR target was not met and total barrage flows were also identified as key variables, with influence scores of 96 and 31, respectively. A single threshold for cumulative discrepancy and thus two outcomes in the degradation trajectory were found (Figure 13.11). Outcome 1 of the degradation trajectory had the highest number of cases and the lowest average salinity, at 72.6 g L^{-1}. The average salinity of cases within outcome 2 was 147.3 g L^{-1}, found across 40 cases. The variability between cases in outcome 1 was approximately half of that between cases in outcome 2 (Figure 13.11), indicating that variability in North Lagoon salinity increased as the average salinity increased.

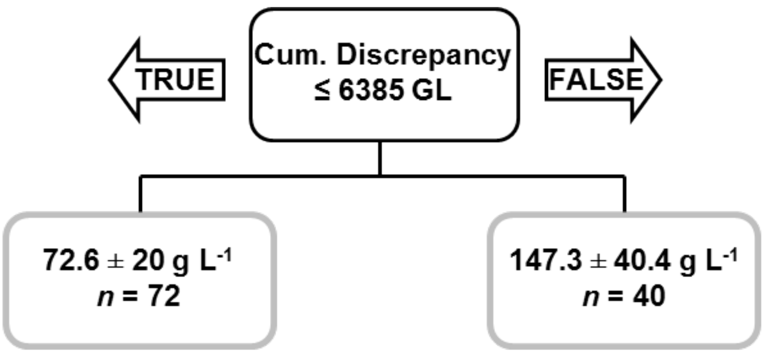

Figure 13.11: Regression tree output for the North Lagoon salinity under the 1500 EC salinity target

See Figure 13.1 for further explanation.

Discrepancy in flow volume for a single year was the most influential variable on South Lagoon salinity under the 1500 EC salinity target (Figure 13.12). Two thresholds for cumulative discrepancy of 8248 GL and 17 530 GL and three outcomes in the degradation trajectory were identified. Outcome 1 contained the majority of the cases (*n* = 75) and the lowest average salinity of 152 g L^{-1}, although this salinity level was already quite high. Outcome 2 had a moderate average salinity (in comparison with the other two steps in the trajectory) of 294.2 g L^{-1} across 17 of the cases analysed. Outcome 3 had the highest average salinity of 434.9 g L^{-1} across 20 of the cases analysed. As for previous analyses involving South Lagoon salinity, this is unrealistically high. Both outcomes 1 and 2 had similar variability between cases within their outcomes and these outcomes were much less variable than outcome 3 for South Lagoon salinity (Figure 13.12).

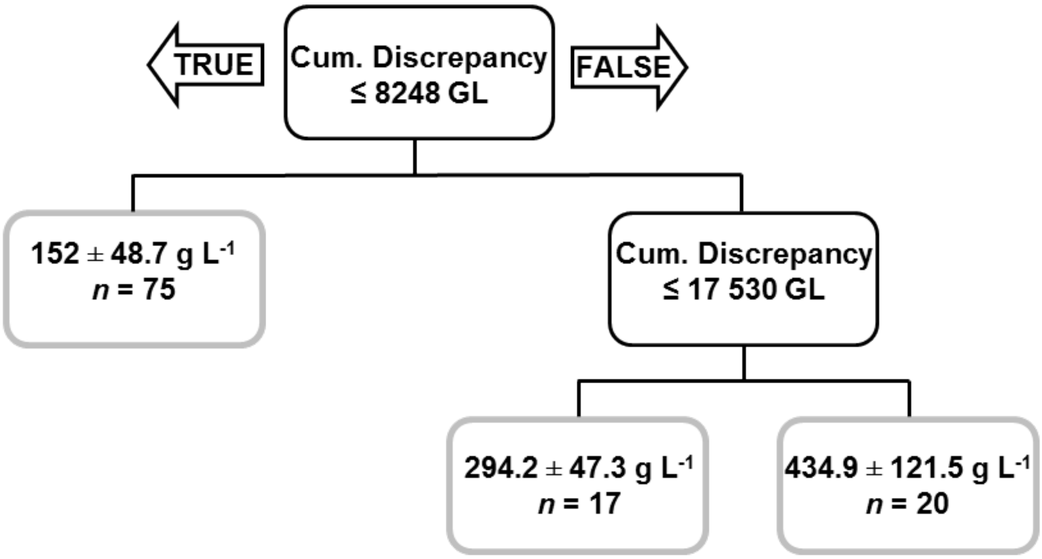

Figure 13.12: Regression tree output for the South Lagoon salinity under the 1500 EC salinity target

See Figure 13.1 for further explanation.

13.3.5.2 Coorong water levels

North Lagoon water level was influenced the most by discrepancy in flow volume for a single year (Figure 13.13). Other key variables included cumulative discrepancy (importance score = 62), the number of years the EWR target had was not met (importance = 48) and total barrage flow (importance = 47). A single threshold for discrepancy and two outcomes in the degradation trajectory were identified (Figure 13.13). Outcome 1 of the degradation trajectory had the greatest number of cases and the highest average water level, at 0.2 m AHD. Outcome 2 had an average water level of -0.01 m AHD across 28 cases. Both outcomes had the same variability among their cases, with a standard deviation of 0.1.

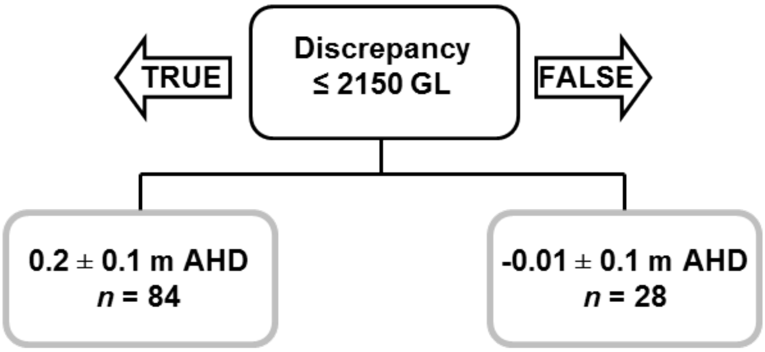

Figure 13.13: Regression tree output for the North Lagoon water level under the 1500 EC salinity target

See Figure 13.1 for further explanation.

The most influential variable on South Lagoon water level was discrepancy in flow volume for a single year (Figure 13.14). Cumulative discrepancy (importance = 64), the number of years that the EWR target was not met (importance = 48) and total barrage flow (importance = 38) were also identified as key variables. From the South Lagoon water-level regression tree analysis, a single threshold for discrepancy was found, at 2150 GL. Therefore, two outcomes in the degradation trajectory were identified. Outcome 1 was the more common condition, representing the majority of the cases from the analysis (*n* = 84) and a higher average water level, at 0.1 m AHD. Outcome 2 had a much lower average water level of -0.3 m AHD across the 28 cases identified within this step. Variability between cases within each of the outcomes in the degradation trajectory was the same, both with standard deviations of 0.1.

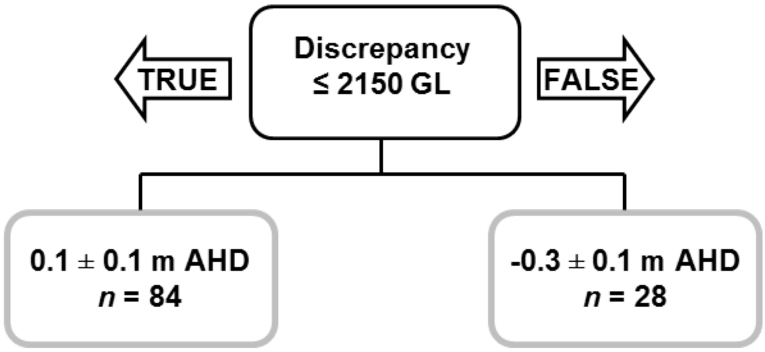

Figure 13.14: Regression tree output for the South Lagoon water level under the 1500 EC salinity target

See Figure 13.1 for further explanation.

13.3.5.3 Degraded ecosystem states

The percentage of degraded ecosystem states under the 1500 EC salinity target was mostly influenced by cumulative discrepancy in flow volume (Figure 13.15). Discrepancy in flow volume for a single year and the number of years that the EWR target was not met were also identified as key variables, with importance scores of 71 and 66, respectively. A single threshold for cumulative discrepancy and two outcomes in the degradation trajectory for the percentage degraded ecosystem states were found (Figure 13.15). Outcome 1 had the smallest number of cases (*n* = 36) with an average percentage of degraded ecosystem states of 36%. Outcome 2 contained the majority of the cases within this analysis (*n* = 76) and had an average percentage of 86% of degraded states. Greater variability was also found between cases in outcome 1 compared to outcome 2 of the degradation trajectory (Figure 13.15).

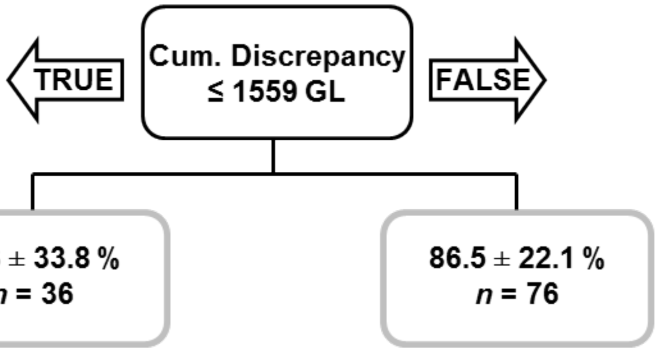

Figure 13.15: Regression tree output for the percentage of degraded ecosystem states under the 1500 EC salinity target

See Figure 13.1 for further explanation.

13.4 Discussion

The analysis described within this chapter was designed to provide some indication of the implications of delivering less water to the Coorong than prescribed by the low-flow EWRs for the region. This was in recognition of the fact that there is not a linear relationship between flow and the hydrodynamics of the Coorong, nor between flow and the ecosystem states of the Coorong. Thus, it was likely that there would be thresholds of response in the system, whereby additional small change may result in disproportionately large changes in condition.

The identification of thresholds, or bands of flows smaller than those specified by the EWRs, linked with marked changes in response was possible for all of the variables investigated. Each subsequent threshold represented an increased likelihood of ecological degradation, either by increasing salinity, decreasing water level or increased percentages of degraded ecosystem states (all of which are linked). This indicated that there are increasing levels of risk associated with lower flows in dry periods, particularly significant in their effects on salinity, water levels (for the North and South Lagoons separately) and the percentage of degraded ecosystem states within the CLLMM region. These risks are summarised for South Lagoon water level (Figure 13.16) and both North and South Lagoon water levels (Figure 13.17), showing the influence of increasing discrepancies in the volumes of water delivered across the three salinity targets investigated. Using these diagrams, it is possible to predict the relative risk associated with increasingly large discrepancies in the amount of water delivered compared to the amount specified by the EWR. As the discrepancy becomes larger (i.e. moves to the right of the figure), thresholds for each salinity target are crossed, moving through the steps in the decline trajectory and resulting in more-severe hydrodynamic conditions. A similar summary figure could not be constructed for either North Lagoon salinity or the percentage of degraded ecosystem states, as the most important variable driving shifts in those differed among salinity targets, so could not easily be displayed as a single figure.

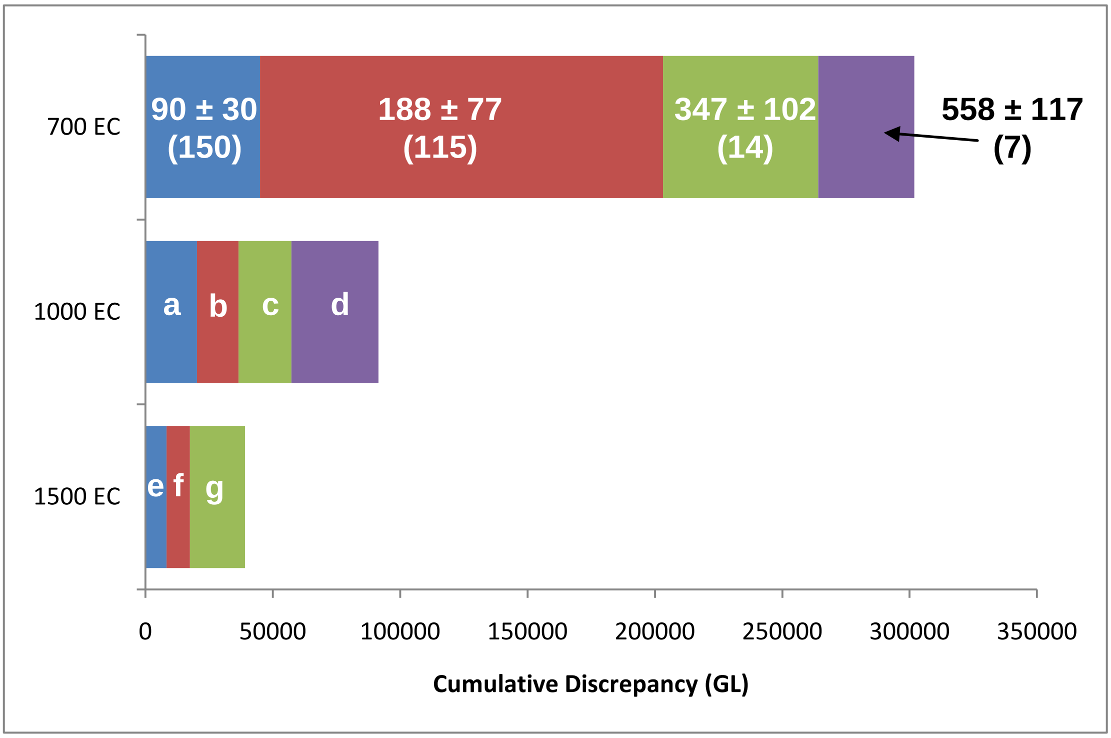

Figure 13.16: Summary of the steps of decline for South Lagoon salinity

Each coloured bar represents one outcome in the decline trajectory for each salinity target (listed on the y-axis). The numbers shown over each outcome bar illustrate the average salinity (g L^{-1}) ± the standard deviation and the number of cases for that step in parentheses. Note: a = 120 ± 35 (124); b = 209 ± 56 (35); c = 316 ± 74 (18); d = 453 ± 137 (17); e = 152 ± 49 (75); f = 294 ± 47 (17) and ; g = 435 ± 121 (20). The maximum value shown (i.e. maximum within each bar) is the maximum cumulative discrepancy in barrage flows (compared to the volume prescribed by the EWR) reached within the data set for each salinity target modelled (i.e. represents the model experience).

Steps on the South Lagoon salinity trajectory of decline were always associated with the cumulative discrepancy in the volume of water. This meant that the combined effect of low flows over time was likely to be driving changes in the salinity in the South Lagoon. This is consistent with our observations during recent drought years when insufficient barrage flows, resulting in a loss of estuarine condition, led to the accumulation of salt across years. In addition, to the changing environmental conditions, changes in the biological condition of the area would also be expected (i.e. to more degraded conditions; Lester & Fairweather 2011). Hence, the highest salinity bands identified, particularly under climate change, were so extreme that would be highly unlikely that even specialist salt-lagoon biota would be able to survive under those conditions.

Conditions driving the decline of condition for North Lagoon salinity were slightly more variable than for the South Lagoon. Cumulative discrepancy was generally identified as the key variable influencing North Lagoon salinity. This was the case under two of the salinity targets (i.e. 1000 EC and 1500 EC) but, for the 700 EC salinity target, North Lagoon salinity was associated with discrepancy in the volume of water in a single year. Simulated North Lagoon salinities also increased with increasing levels of climate change, with average salinities increasing from median to dry climate conditions. Hence, under climate change, the increased salinities would pose a serious threat to the ecology of the Coorong as a whole, including in the North Lagoon.

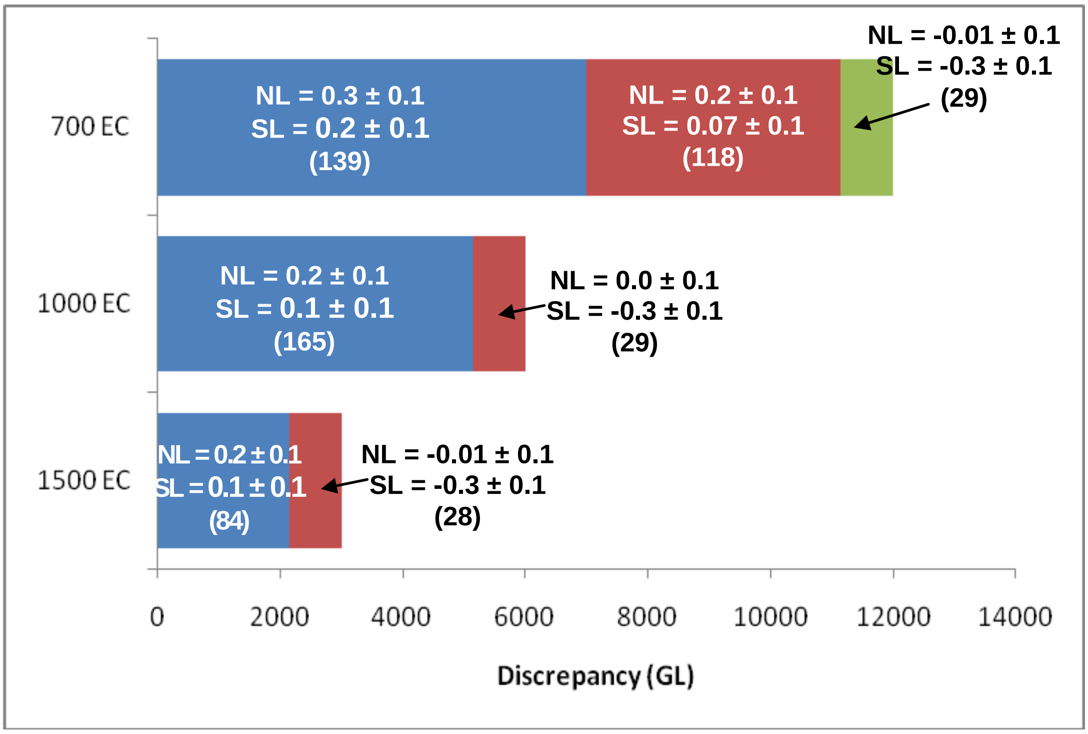

Figure 13.17: Summary of the steps of decline for North and South Lagoon water levels

Note that the steps in the trajectory of decline and the thresholds were consistent for water levels in the two lagoons across the three salinity targets. Each coloured bar represents one outcome in the decline trajectory for each salinity target (listed on the y-axis). The numbers shown over each outcome bar illustrate the average water level (m AHD) ± the standard deviation and the number of cases for that step in parentheses, with NL representing North Lagoon values and SL representing South Lagoon values. The maximum value shown (i.e. maximum within each bar) is the maximum discrepancy in barrage flows in any one year (compared to the volume prescribed by the EWR) reached within the data set for each salinity target modelled (i.e. represents the model experience).

Water levels in both lagoons were most closely associated with the discrepancy in flows compared to EWRs in a single year. This is likely to reflect the more immediate relationship between barrage flows and water levels in the Coorong (i.e. compared to salinity). Barrage flows have been shown to play a very large role in the dynamics of water level in the Coorong, including allowing seasonal sea-level variations to penetrate into the Coorong by the maintaining the opening of the Murray Mouth Channel (Webster 2010). It is this seasonal rise and fall in water level that also drives the major exchange of water between the two lagoons (Webster 2010). Hence, the influence of discrepancy in flows in a single year will significantly affect the water levels within the Coorong, influencing not only the hydrodynamics of the system but also potentially the ecological condition.

Water-level thresholds and the number of steps in the decline trajectory were consistent for the North and South Lagoons for each of the three salinity targets investigated (Figure 13.17), while the actual simulated water level for each step was lower in the South Lagoon than its North Lagoon counterpart. For all three of the salinity targets, smaller discrepancies were associated with water levels that remained above sea level (~0 m AHD), while larger discrepancies resulted in water levels in both lagoons that fell below sea level. Such low water levels are likely to substantially affect the productivity of mudflat habitat and thus the quality of habitat and food resources in the region, particularly for migratory waders or fish. For example, changes in the water level regime can influence the suitability of shoreline mudflats for invertebrates, with exposure for as little as a week being sufficient to eliminate them (Rolston & Dittmann 2009). In addition, low water levels (associated with low barrage flows) could also substantially affect the likelihood of *Ruppia tuberosa* persistence in the region (Paton 2010).

The percentage of degraded ecosystem states was best associated with a range of different variables across the three sets of flow rules. These included discrepancy in flows in a single year, cumulative discrepancy and total barrage flows. Association with these variables was likely to be a result of the non-linear relationship between barrage flows and ecosystem states, partly as a result of interactions with weather, tides and local sea level. However, despite the more-complex relationship between the percentage of degraded ecosystem states and barrage flows, increasingly low barrage flows were associated with increasing percentages of degraded ecosystem states. That is, for each salinity target, there was a trajectory of decline in the percentage of degraded ecosystem states. This trajectory illustrated that small discrepancies (or cumulative discrepancies) in flows compared to the EWRs resulted in small to moderate percentages of degraded ecosystem states. Increased discrepancies (or cumulative discrepancies or total barrage flows) were then associated with a threshold beyond which the percentage of degraded states increased dramatically. This demonstrates the increasing risk of failing to meet the EWRs through time and highlights the likely damage to the ecological condition of the Coorong.

As for all analyses using the ecosystem states model, the recovery potential and trajectory for the Coorong are currently unknown and have not yet been adequately defined. As such there is the need to carefully consider what constitutes recovery in these systems. In this chapter we have used a surrogate (median conditions under each scenario) but the 'natural' conditions vary under each climate. This variation, in itself, would have an impact on the ecological character of the system and therefore additional work needs to be done to improve our understanding of the effect of climate change on the ecology of the Coorong. Furthermore, negative discrepancies in flow (i.e. where simulated flows exceed the flows identified by the EWRs) should not be taken as an indication of excess water in the region. This analysis only considered the low-flow EWRs for the Coorong, and no effort was made to assess whether high-flow requirements were met. These high-flow requirements are also critical to the long-term ecological condition of the Coorong and should not be ignored when determining a regime of barrage flows (e.g. under plans such as the Murray-Darling Basin Plan).

Some data were available at the time of writing relating to the recent barrage flows as a result of flooding upstream in the Murray-Darling Basin. Between November 25th 2010 and May 1st 2011, 9300 GL was estimated to have entered the Coorong (1688 GL in 2010 and 7612 GL in 2011 to that date). Previous model runs end in 2008, so a complete time series of barrage flows was not available; however, no barrage flows were known to occur since 2007, so the missing time points were assumed to include no barrage flows. Thus, we can assume that 2010 again failed to meet the rules associated with all three salinity targets, but that, to that date, 2011 would already exceed the water requirements associated with 1000 EC and 1500 EC targets, with further flows through the remainder of this year required to meet the 700 EC target. Under an historical climate, it took an average of 1.7 and 3.0 years to return to 'normal' conditions for the 1000 EC and 1500 EC rules, respectively. Thus, should flows continue into 2012, there would be a good chance that the hydrodynamic condition of the Coorong would recover, and that ecological recovery would also begin.

13.5 Summary

- **We identified thresholds in the trajectories of decline in order to assess the level of risk associated with delivering less water to the Coorong than specified by the EWR.**

- **Thresholds were identified for each of North and South Lagoon salinities and water levels and the percentage of degraded ecosystem states.**
- **The discrepancy between total barrage flows and the EWR, either for a single year or through time, were most consistently the best predictor of increasing deterioration in Coorong hydrodynamics or ecosystem states.**
- **The thresholds and outcomes identified here enable managers to estimate the effects of particular volumes of water, where they are lower than the recommended EWRs.**
- **This allows some assessment of the level of risk associated with increasingly small volumes of water for the Coorong.**

14. Investigating synergies and interactions between water delivered via the barrages versus the Upper South East Drainage scheme

Rebecca E. Lester, Rebecca A. Langley, Peter G. Fairweather & Ian T. Webster

14.1 Introduction

Reduced freshwater inflows through the Coorong barrages in the last decade, with a period of no barrage flows between 2007 and late 2010, resulted in salinity in the South Lagoon reaching levels that have precluded the presence of a healthy ecosystem in the lagoon (Brookes *et al.* 2009). In particular, salinity has exceeded tolerance levels for survival and reproduction of many aquatic taxa (e.g. fish and invertebrates) and the plants that comprise the food resource for many species of waterbirds for which the Coorong is renowned (Brookes *et al.* 2009). It is generally agreed that in order to lower salinity levels in the South Lagoon, additional fresh water must enter the Coorong (Brookes *et al.* 2009).

In setting an EWR for the region (Chapters 10-12), flows from the River Murray were considered to be the major driver of hydrodynamics, and thus ecological condition, in the Coorong. However, the Coorong also has a second source of fresh water, via Salt Creek, towards to south-eastern end of the South Lagoon. Thus, here we consider whether providing additional freshwater to the system, via augmenting the Upper South East Drainage (USED) scheme, could be an alternative to providing some fraction of flows from the River Murray.

In the past, Salt Creek is thought to have been a more-significant source of water than it has been in recent years, as a result of significant drainage of swampland and some localised diversions to the ocean in the South East of South Australia. Part of this drainage network, the USED scheme, uses Salt Creek as an outlet and thus has acted as a source of some relatively-small volumes of fresh water to the Coorong in recent years. There are current proposals to expand the current USED scheme to provide additional freshwater to wetlands in the South East and to the South Lagoon of the Coorong. A number of possible flow paths are being considered, with different inherent losses and different potential maximum capacities (Montazeri *et al.* 2010; Lester *et al.* 2009c). Larger volumes have been proposed than have flowed through Salt Creek in recent years (i.e. 1980s to the present). Given the location of the input (i.e. in the often hypersaline South Lagoon), it is possible that these inputs may have a large effect on water levels and salinities in the South Lagoon compared with River Murray water. The effects of climate change and other management actions also have the potential to affect the volume and timing of flows from the South East and therefore also the ecological condition of the Coorong. Given the range of interacting factors that may affect the hydrodynamics of the South Lagoon, it was important to consider the EWR in combination with these factors to see whether less water may be required from the River Murray than has been documented previously.

Previous investigations on additional USED freshwater flows into the Coorong were undertaken on an earlier version of the expansion proposal. Then the effects of the various flow paths, climate change and the effect of flow volumes (with potential delivery timing) from the South East on the hydrodynamics and ecological condition in the Coorong were modelled (Lester *et al.* 2009c). This investigation was centred on the likely maximum effect of USED flows, so assumed continued drought, or zero-barrage flow, conditions. Thus this work cannot be used directly as an indication of the interactions between flows from the USED scheme and the River Murray, although, the findings are a useful starting point for this investigation.

The main findings of that previous research included:

- An average volume of 60 GL year^{-1} was recommended as a target for the USED scheme, as this was a volume where positive effects of the additional water were optimised, during periods of no barrage flows.
- Larger volumes of water would also be required with increasingly levels of climate change (than the recommended target of 60 GL year^{-1} from the USED);
- Proposed flow path 2D (which involved diversion of additional flow from Drain M via a flow path including Reedy Creek, Blackford Drain and Morella Basin; Peters *et al.* 2009) with a maximum diversion of 250 ML day^{-1} had the greatest positive impact of the proposed configurations on the hydrodynamics and ecosystem states of the Coorong, particularly under extreme climate change projections;
- One possibility for improving the impact of additional water may be to store a portion for release during late spring or early summer to minimise disconnection of the lagoons over the summer periods and limit evapoconcentration; and
- If climate change progresses at a rapid rate, the inclusion of additional freshwater from the South East may be necessary, in conjunction with other management interventions, to support a range of ecosystem states in the Coorong at times of no barrage flows (Lester *et al.* 2009c).

In this chapter, we aim to explore the interactions between flows from the River Murray and the proposed expansion to the USED scheme to determine the likely effect on Coorong hydrodynamics and ecosystem states in periods when barrage flows are occurring (i.e. in contrast to the previous study). We also provide recommendations regarding any reductions in the volume of fresh water likely to be required from the River Murray should such a scheme be operating. We based our assessment on the proposal for USED expansion presented in DEH (2010), including the volumes, flow regimes & assumptions available at that time, so our findings and the conclusions drawn are reliant on those and may require refinement should the proposal change subsequently.

14.2 Methods

14.2.1 Likelihood of large USED flows when barrage flows are small

The efficacy of expanding the USED scheme to provide additional water to the Coorong would be maximised if high-flow events via USED scheme were not linked to high-flow events from the River Murray. That is, the biggest benefit to the Coorong is likely to occur when flows from the USED scheme are high in years when barrage flows are low. This combination is most likely to occur if there is only a weak (or no) relationship between flows in the South East and barrage flows.

We used average rainfall in the South East (SE) as a surrogate for potential USED flows. Average rainfall was calculated using 5 locations (including Kingston, Lucindale, Padthaway, Salt Creek and Willalooka) within the South East selected because they were on the proposed flow path. Daily rainfalls for each were used to calculate an annual average across locations. For each year, average SE rainfall was plotted against total barrage flows. A linear regression was undertaken to determine the relationship between the two using Systat v.12.

14.2.2 Hydrodynamic model

A one-dimensional hydrodynamic model simulates water levels and salinities within the Coorong from the Murray Mouth south, including the North and South Lagoons (Chapter 10, Webster 2007, 2010). The model was forced by sea level changes, wind, flow through the barrages, evaporation, precipitation, exchange through the Mouth, and flows from the USED scheme (Webster 2007, 2010). See Chapter 10 for further detail on configuration and calibration of the hydrodynamic model. Overall, the hydrodynamic model was able to adequately represent the time series of water levels and salinities throughout the Coorong system. This enabled it to be the initial step of the scenario analyses for this chapter to determine the effect of using water from the USED scheme to off-set the use of water from the River Murray on the hydrodynamics of the system. These analyses include an assessment of the impact USED flows on the hydrodynamics of the system under a range of conditions, including various additional proposed volumes, models of flow delivery and three climate scenarios.

14.2.3 Ecosystem state model

In order to assess the ecological condition in the Coorong, an ecosystem response model was used to identify the proportion of site-years which would be considered as being in a healthy or degraded ecosystem state across each of the scenarios investigated. For a more detailed description of the construction of the ecosystem states model see Chapter 11 and descriptions of the characteristic taxa and conditions associated with each state are given in Appendix F. For this chapter, the ecosystem states model was used to predict the ecological condition of the system (i.e. the representative mix of ecosystem states present across site-years) and the impact increased volumes of water from the USED scheme under a range of conditions.

14.2.4 Scenario analyses

In order to assess the likely ecological outcomes of potential USED flow types (i.e. historical flows, consistent USED flows from year to year, and a more-realistic assessment of inter-annually variable USED flows) in conjunction with climate change conditions and dredging intervention (i.e. presence or absence of dredging at times of low flows resulting in siltation of the Murray Mouth), the predictive model was applied to a set of 19 possible future scenarios for the Coorong (Table 14.1). All scenarios were based on one of three future climate scenarios (i.e. historical, median future and dry future), as described in Chapter 10. All scenarios used a 22-year model run (1986 to 2007), which was the length of the available flow data for the USED scheme. As stated above, the details of the proposed USED scheme expansion were those outlined in DEH (2010). These scenarios can be grouped into sets and are defined as follows:

Scenarios investigating benchmark conditions:

1. Benchmark conditions including dredging (Baseline & dredging)

   This scenario included historical climate conditions, with historical barrage flows, average recorded USED flows and dredging of the Murray Mouth when required.

Scenarios investigating the effect of consistent inter-annual average USED volumes:

2. Historic climate and a flow volume of 18 GL including dredging (Historical Consistent 18 GL & dredging)

   This scenario included historical climate conditions, with historical barrage flows, a consistent annual average USED flow volume of 18 GL year^{-1} and dredging of the Murray Mouth when required. The intra-annual pattern of USED flow matched the average modelled flow sequence from investigations into possible future diversions (Peters *et al.* 2009).

3. Historic climate and a flow volume of 36 GL including dredging (Historical Consistent 36 GL & dredging)

   This scenario was as per the Historical Consistent 18 GL & dredging, but with a consistent average USED flow volume of 36 GL year^{-1}.

4. Historic climate and a flow volume of 63 GL including dredging (Historical Consistent 63 GL & dredging)

This scenario was as per the Historical Consistent 18 GL & dredging, but with a consistent average USED flow volume of 63 GL $year^{-1}$.

5. Median climate and a flow volume of 9 GL including dredging (Median Consistent 9 GL & dredging)

   This scenario included projected median future climate conditions, with barrage flows modelled using that climate projection, with a consistent annual average USED flow volume of 9 GL $year^{-1}$ (adjusted to reflect drier conditions under the climate scenario) and dredging of the Murray Mouth when required. As for the Historical Consistent 18 GL & dredging scenario, the intra-annual pattern of USED flow matched the average modelled flow sequence from investigations into possible future diversions (Peters *et al.* 2009).

6. Median climate and a flow volume of 24 GL including dredging (Median Consistent 24 GL & dredging)

   This scenario was as per the Median Consistent 9 GL & dredging, but with a consistent average USED flow volume of 24 GL $year^{-1}$.

7. Median climate and a flow volume of 63 GL including dredging (Median Consistent 63 GL & dredging)

   This scenario was as per the Median Consistent 9 GL & dredging, but with a consistent average USED flow volume of 63 GL $year^{-1}$.

8. Dry climate and a flow volume of 4 GL including dredging (Dry Consistent 4 GL & dredging)

   This scenario included projected dry future climate conditions, with barrage flows modelled using that climate projection, with a consistent annual average USED flow volume of 4 GL $year^{-1}$ (adjusted compared to the equivalent scenarios using other climates to reflect drier conditions for this climate scenario) and dredging of the Murray Mouth when required. As for the Historical Consistent 18 GL & dredging scenario, the intra-annual pattern of USED flow matched the average modelled flow sequence from investigations into possible future diversions (Peters *et al.* 2009).

9. Dry climate and a flow volume of 14 GL including dredging (Dry Consistent 14 & dredging)

   This scenario was as per the Dry Consistent 4 GL & dredging, but with a consistent average USED flow volume of 14 GL $year^{-1}$.

10. Dry climate and a flow volume of 63 GL including dredging (Dry Consistent 63 & D)

    This scenario was as per the Dry Consistent 4 GL & dredging, but with a consistent average USED flow volume of 63 GL $year^{-1}$.

Scenarios investigating the effect of variable inter-annual average USED volumes:

11. Historic climate and a flow volume of 18 GL including dredging (Historical Variable 18 GL & dredging)

    This scenario included historical climate conditions, with historical barrage flows, an annual average USED flow volume of 18 GL $year^{-1}$ delivered so that modelled flows varied among years within the model sequence proportional to historical USED flow records. Dredging of the Murray Mouth was included when required. The intra-annual pattern of flows matched previous scenarios.

12. Historic climate and a flow volume of 36 GL including dredging (Historical Variable 36 GL & dredging)

This scenario was as per the Historical Variable 18 GL & dredging, but with a variable average USED flow volume of 36 GL $year^{-1}$.

13. Historic climate and a flow volume of 63 GL including dredging (Historical Variable 63 & dredging)

    This scenario was as per the Historical Variable 18 GL & dredging, but with a variable average USED flow volume of 63 GL $year^{-1}$.

14. Median climate and a flow volume of 9 GL including dredging (Median Variable 9 GL & dredging)

    This scenario included projected median future climate conditions, with barrage flows modelled using that climate projection and an annual average USED flow volume of 8 GL $year^{-1}$ delivered so that modelled flows varied among years within the model sequence (with the average volume adjusted to reflect drier conditions under this climate scenario but delivered consistently to that in the Historical Variable 18 GL & dredging scenario). Dredging of the Murray Mouth was included when required. The intra-annual pattern of flows matched previous scenarios.

15. Median climate and a flow volume of 24 GL including dredging (Median Variable 24 GL & dredging)

    This scenario was as per the Median Variable 9 GL & dredging, but with a variable average USED flow volume of 24 GL $year^{-1}$.

16. Median climate and a flow volume of 63 GL including dredging (Median Variable 63 GL & dredging)

    This scenario was as per the Median Variable 9 GL & dredging, but with a variable average USED flow volume of 63 GL $year^{-1}$.

17. Dry climate conditions and a flow volume of 4 GL including dredging (Dry Variable 4 GL & dredging)

    This scenario included projected dry future climate conditions, with barrage flows modelled using that climate projection, with a variable annual average USED flow volume of 4 GL $year^{-1}$ (adjusted to reflect drier conditions under the climate scenario but maintaining a delivery pattern consistent with that of the Historical Variable 18 GL & dredging scenario) and dredging of the Murray Mouth when required. The intra-annual pattern of flows matched previous scenarios 11-16.

18. Dry climate conditions and a flow volume of 14 GL including dredging (Dry Variable 14 GL & dredging)

    This scenario was as per the Dry Variable 4 GL & dredging, but with a variable average USED flow volume of 14 GL $year^{-1}$.

19. Dry climate conditions and a flow volume of 63 GL including dredging (Dry Variable 63 GL & dredging)

    This scenario was as per the Dry Variable 4 GL & dredging, but with a variable average USED flow volume of 63 GL $year^{-1}$.

This range of scenarios was investigated to provide an analysis across the range of possible future climates for which the simulations were available (Pearce *et al.* 2007), and to explore a number of possible USED flow volumes to determine the hydrological and ecological outcomes of any additional USED flows delivered to the system and the relative impact of those flows depending on the level of flow over the barrages. All scenarios included here include dredging of the Murray Mouth, as this has been the previous management response to low barrage flows, so was considered to be the most realistic option because of the likelihood of this management intervention continuing in the future (although other similar scenarios could also exclude dredging).

14.2.5 Interactions between USED and barrage flows

Finally, the results of the Baseline & dredging scenario was compared to the Historical 18, 36 or 63 GL (& dredging) scenarios to explore the interactions between barrage and USED flows. Specific years were identified that represented high, medium and low barrage-flow years. These were: high = 1989, 1990, 1993 & 1996; medium = 1987, 1988, 1998 & 2001; and low = 2002, 2004, 2006 & 2007.

For each scenario, the average maximum salinity, average minimum water level and the average percentage of degraded ecosystem states were calculated for each set of years (i.e. high, medium and low). The percent change for each variable compared to the Baseline & dredging scenario was calculated, giving a matrix of the effect of adding either 18, 36 or 63 GL of water via the USED scheme during high, medium and low barrage flow years. This enabled an assessment of the influence of different volumes from the USED scheme relative to River Murray flows, and was done both for the consistent addition of USED water, and a variable inter-annual delivery pattern.

Table 14.1: Summary of scenarios investigated in this chapter

Note: '+'denotes present in the scenario.

No.	Scenario	Climate	USED flow type	Annual flow volume (GL)	MM Dredging
1	Baseline & dredging	Historic	Historic	7	+
2	Historical Consistent 18 GL & dredging	Historic	Consistent	18	+
3	Historical Consistent 36 GL & dredging	Historic	Consistent	36	+
4	Historical Consistent 63 GL & dredging	Historic	Consistent	63	+
5	Median Consistent 9 GL & dredging	Median	Consistent	9	+
6	Median Consistent 24 GL & dredging	Median	Consistent	24	+
7	Median Consistent 63 GL & dredging	Median	Consistent	63	+
8	Dry Consistent 4 GL & dredging	Dry	Consistent	4	+
9	Dry Consistent 14 GL & dredging	Dry	Consistent	14	+
10	Dry Consistent 63 GL & dredging	Dry	Consistent	63	+
11	Historical Variable 18 GL & dredging	Historic	Variable	18	+
12	Historical Variable 36 GL & dredging	Historic	Variable	36	+
13	Historical Variable 63 GL & dredging	Historic	Variable	63	+
14	Median Variable 9 GL & dredging	Median	Variable	9	+
15	Median Variable 24 GL & dredging	Median	Variable	24	+
16	Median Variable 63 GL & dredging	Median	Variable	63	+
17	Dry Variable 4 GL & dredging	Dry	Variable	4	+
18	Dry Variable 14 GL & dredging	Dry	Variable	14	+
19	Dry Variable 63 GL & dredging	Dry	Variable	63	+

14.3 Results

14.3.1 Likelihood of large USED flows when barrage flows are small

A moderate relationship was detected between average South East daily rainfall (based on the five SE locations) and flows over the barrages from the River Murray (*r* = 0.499). However, this relationship was statistically significant (*P* = 0.018). This suggests that potential flows in from the USED scheme are likely to be similar in relative magnitude to barrage flow volumes (i.e. higher USED flows are more likely to occur in years of high barrage flows), however, this is also a possibility that high-flow years for the USED could coincide with low barrage flows, when large volumes from the USED would have the maximum impact on the Coorong. In fact, further investigation of the points above the line (which represents the expected relationship) suggests that additional water than expected may be delivered 36% of the time, and when barrage flows are low, additional rainfall than represented by the relationship was available in 44% of years. This is a very preliminary analysis, however, and does not include an assessment of how much additional water (above that expected by the defined relationship) would be available, nor how well observed rainfall along the proposed flow path may approximate likely USED flows.

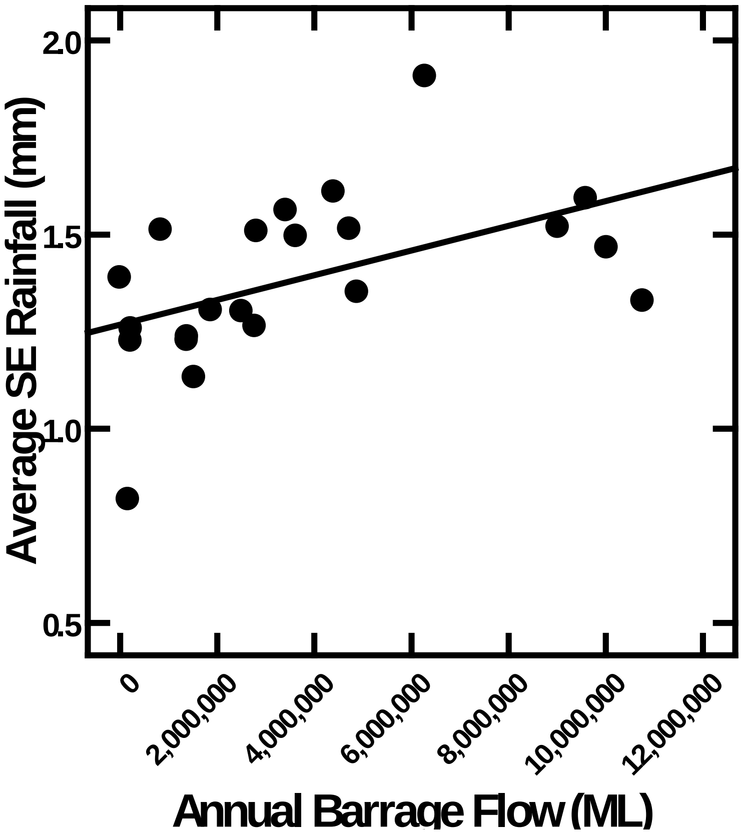

Figure 14.1: Comparison of average rainfall in the South East (as an average daily rainfall for the five SE locations; see Section 14.2.1) with total annual barrage flows for 1986 to 2007

14.3.2 Hydrodynamic drivers of ecosystem states

As highlighted in Chapter 11, four hydrodynamic variables have been shown to drive the mix of ecosystem states present in the Coorong. Therefore, these variables, which include average water level, maximum salinity, the average depth from two years previous and the annual range in water level, were investigated further to identify the influence of additional USED flow volumes.

Current Coorong condition

Investigating the Baseline & dredging scenario, gives us an understanding of the current conditions within the Coorong, including recent USED flows, and thus provides a benchmark against which to compare the other scenarios (i.e. those with historic climate including dredging conditions).

Figure 14.2 shows the distributions of each of the variables driving the ecosystem states of the Coorong under the Baseline conditions including dredging. The distributions are presented as boxplots (refer to Appendix E for an overview of how to read each type of figure presented). For the most part, the hydrodynamic drivers for the Baseline & dredging scenario remained within expected ranges. The average water level across the Coorong as a whole was always above the lowest water threshold (i.e. the lowest green line in Figure 14.2a), with a median of 1.46 m AHD (although individual sites may have crossed the threshold).

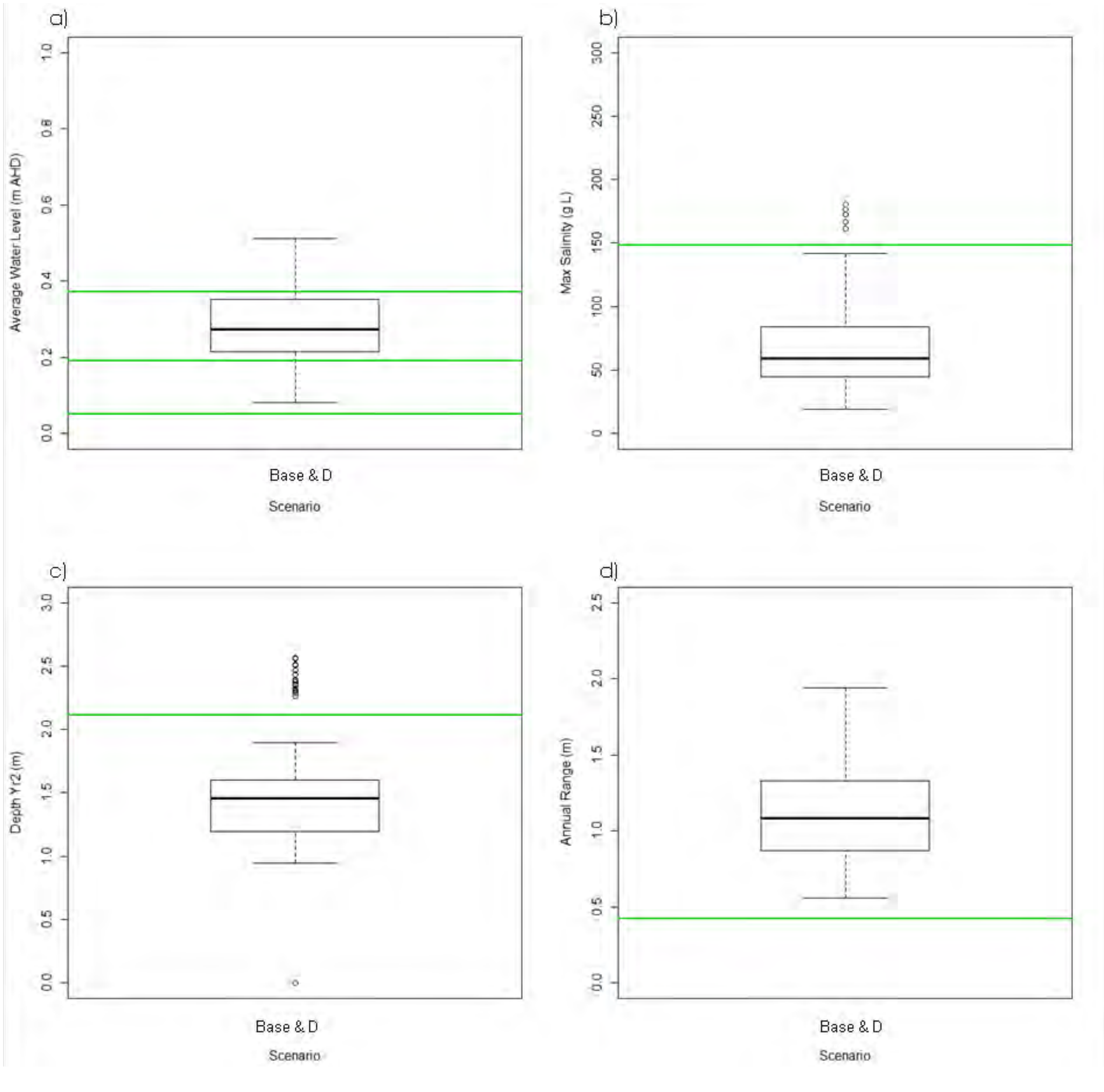

Figure 14.2: Boxplots showing the distribution of values for each of the variables driving the ecosystem states of the Coorong for the Baseline including dredging scenario. a) Average water level (m AHD), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Annual range in water level (m)

Base & D is the Baseline & dredging scenario. Information on how to read the figure is presented in Appendix E.

Water levels were occasionally above the higher threshold, thought to be associated with healthy South Lagoon ecosystem states. The maximum salinity was usually below the threshold for that variable, although occasional outliers fell above the line. Median maximum salinity was 59.1 g L^{-1}. Similarly, depths from two years previous were usually below the threshold for that variable, although occasional outliers had higher depths, and the median depth across the scenario was 0.27 m. Median annual range in water level for the Baseline & dredging scenario was 1.09 m.

Effect of consistent average USED volume including dredging under a historical climate

When the effects of consistent inter-annual delivery of additional flows via the USED scheme were investigated under an historical climate, there was little influence on three of the four hydrodynamic drivers (Figure 14.3).

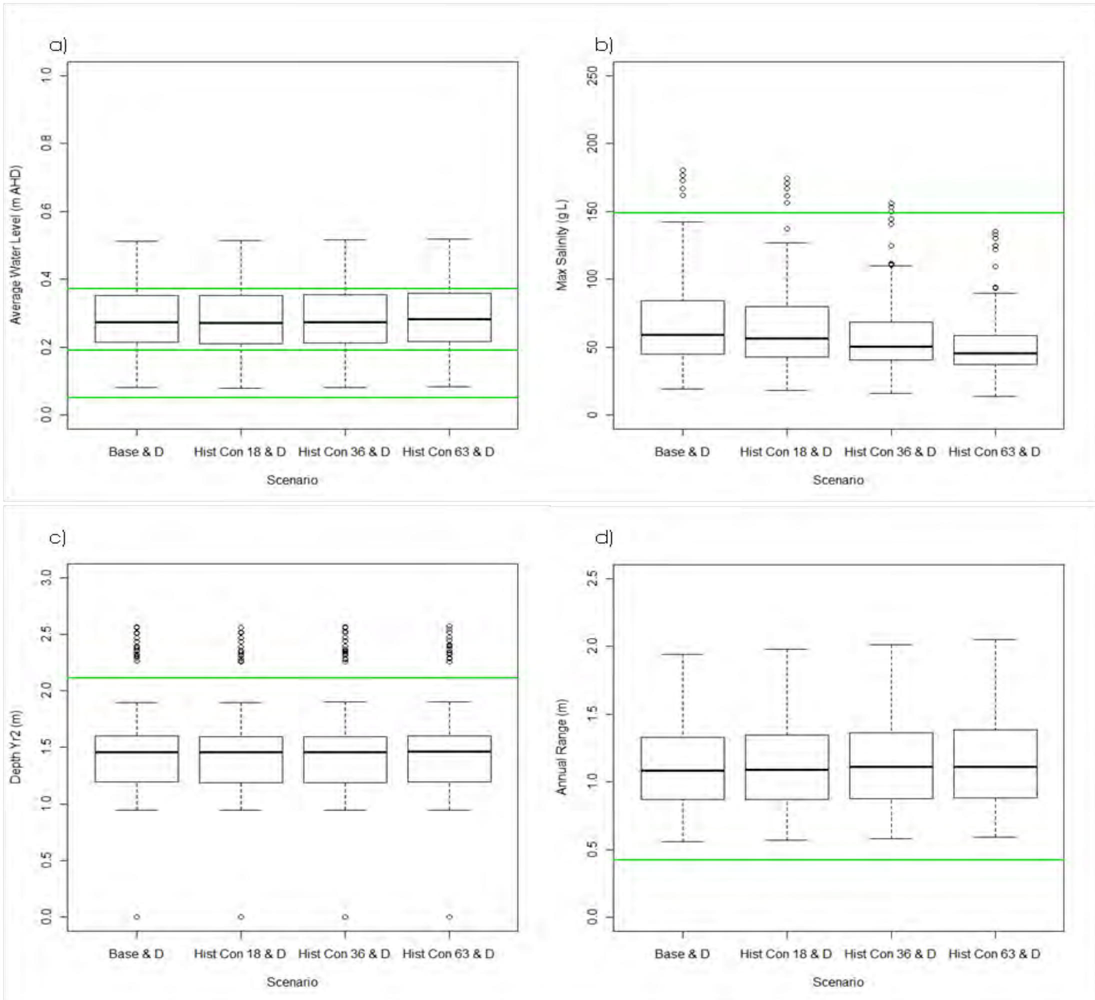

Figure 14.3: Boxplots showing the comparison between variables driving the ecosystem states of the Coorong for the consistent average USED volume with dredging scenarios under an historical climate. a) Average water level (m AHD), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Annual range in water level (m)

Base & D is the Baseline & dredging scenario, Hist Con 18 & D is the Historical Consistent 18 GL & dredging scenario, Hist Con 36 & D is the Historical Consistent 36 GL & dredging scenario and Hist Con 63 & D is the Historical Consistent 63 GL & dredging scenario. Information on how to read the figure is presented in Appendix E.

The only driver for which a large change was evident was maximum salinity. For maximum salinity, the extreme outliers became less saline as increasing volumes of water were added via the USED scheme. The median maximum salinity declined from 59.1 g L^{-1} under the Baseline & dredging scenario to 56.4, 50.2, and 45.3 g L^{-1} as 18, 36 or 63 GL per annum were added, respectively. The largest values for the annual range in water level also increased only very slightly as increasing volumes of water were added via the USED scheme. There, the maximum value increased from 1.09 m under the Baseline & dredging scenario to 1.11 m under the Historical Consistent 63 & dredging scenario.

There was a small positive cumulative difference in North Lagoon hydrodynamic drivers, increasing in magnitude with increasing volumes via the USED scheme (Figure 14.4). This represented an improvement in both the average water level and the depth from two years previous, compared to the Baseline & dredging scenario.

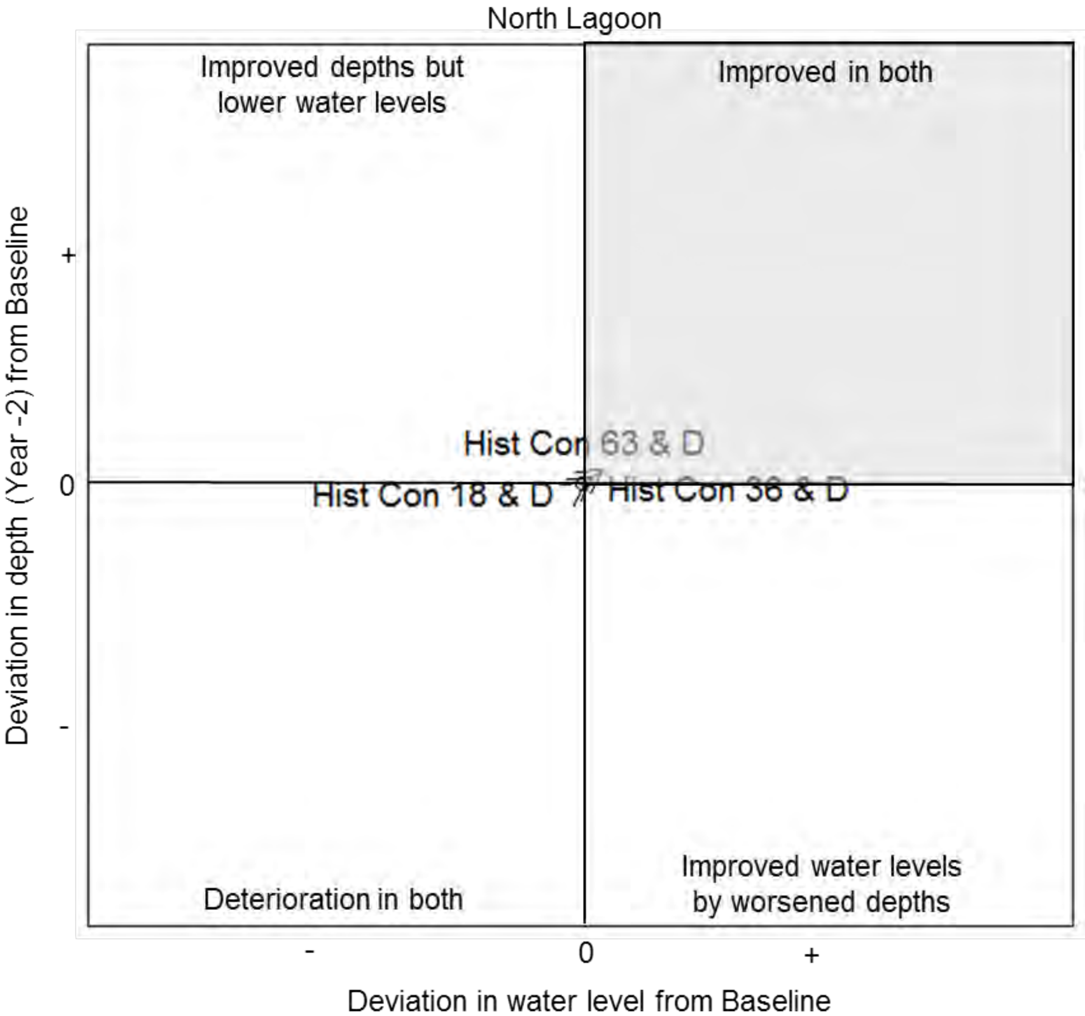

Figure 14.4: Comparison of the consistent average USED volume with dredging scenarios for the North Lagoon under an historical climate

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline & dredging scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Baseline & dredging condition (as shown by the 0,0 origin). Vectors in the upper-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and greater depths). Information on how to read the figure is presented in Appendix E. Hist Con 18 & D is the Historical Consistent 18 GL & dredging scenario, Hist Con 36 & D is the Historical Consistent 36 GL & dredging scenario and Hist Con 63 & D is the Historical Consistent 63 GL & dredging scenario.

The cumulative impact on South Lagoon hydrodynamics was more complex (Figure 14.5). There, there was an improvement in both maximum salinity and water level when a consistent volume of 63 GL was added each year. However, the Historical Consistent 36 GL & dredging scenario resulted in an improvement in the maximum salinity only, while the Historical Consistent 18 GL & dredging scenario had a small improvement in maximum salinity and a small deterioration in average water level.

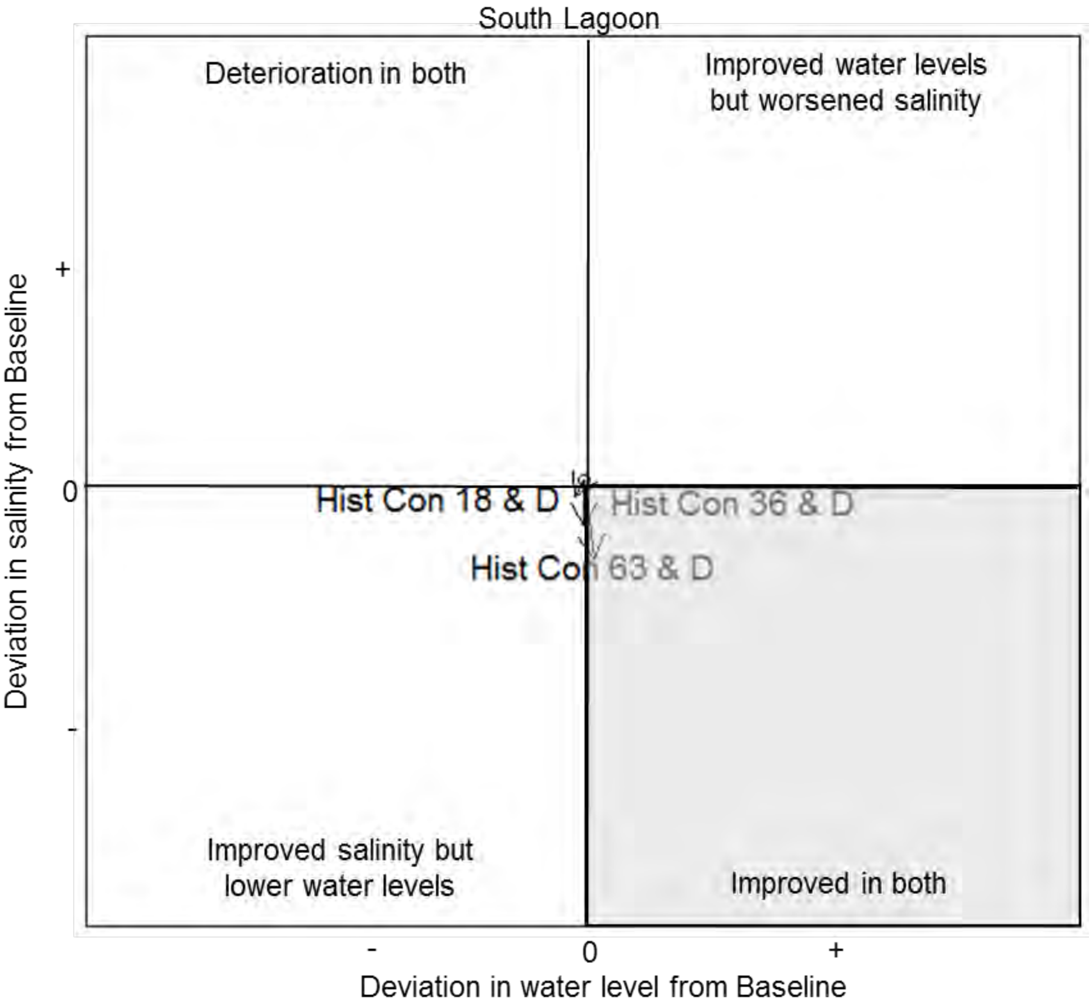

Figure 14.5: Comparison of the consistent average USED volume with dredging scenarios for the South Lagoon under an historical climate

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline & dredging scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline & dredging condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and lower salinities). Information on how to read the figure is presented in Appendix E. Hist Con 18 & D is the Historical Consistent 18 GL & dredging scenario, Hist Con 36 & D is the Historical Consistent 36 GL & dredging scenario and Hist Con 63 & D is the Historical Consistent 63 GL & dredging scenario.

Effect of consistent average USED volume including dredging under a median future climate

Consistent with scenarios including an historical climate, scenarios investigating the effect of adding increasing volumes of water via the USED scheme in a consistent inter-annual pattern showed the greatest impact was on the maximum salinity variable (Figure 14.6). Even with an additional 63 GL per annum, there was insufficient water to keep maximum salinities below the threshold in all years in the simulation. The proportion of years, and the overall maximum salinity reached, however, did decline with increasing volumes of additional water. There was also a reduction in the median maximum salinity from 70.2 g L^{-1} under the Median Consistent 9 GL & dredging to 64.6 g L^{-1} and then 51.1 g L^{-1} under the Median Consistent 24 GL and 63 GL & dredging scenarios, respectively. Very little change was observed in the other hydrodynamic drivers investigated.

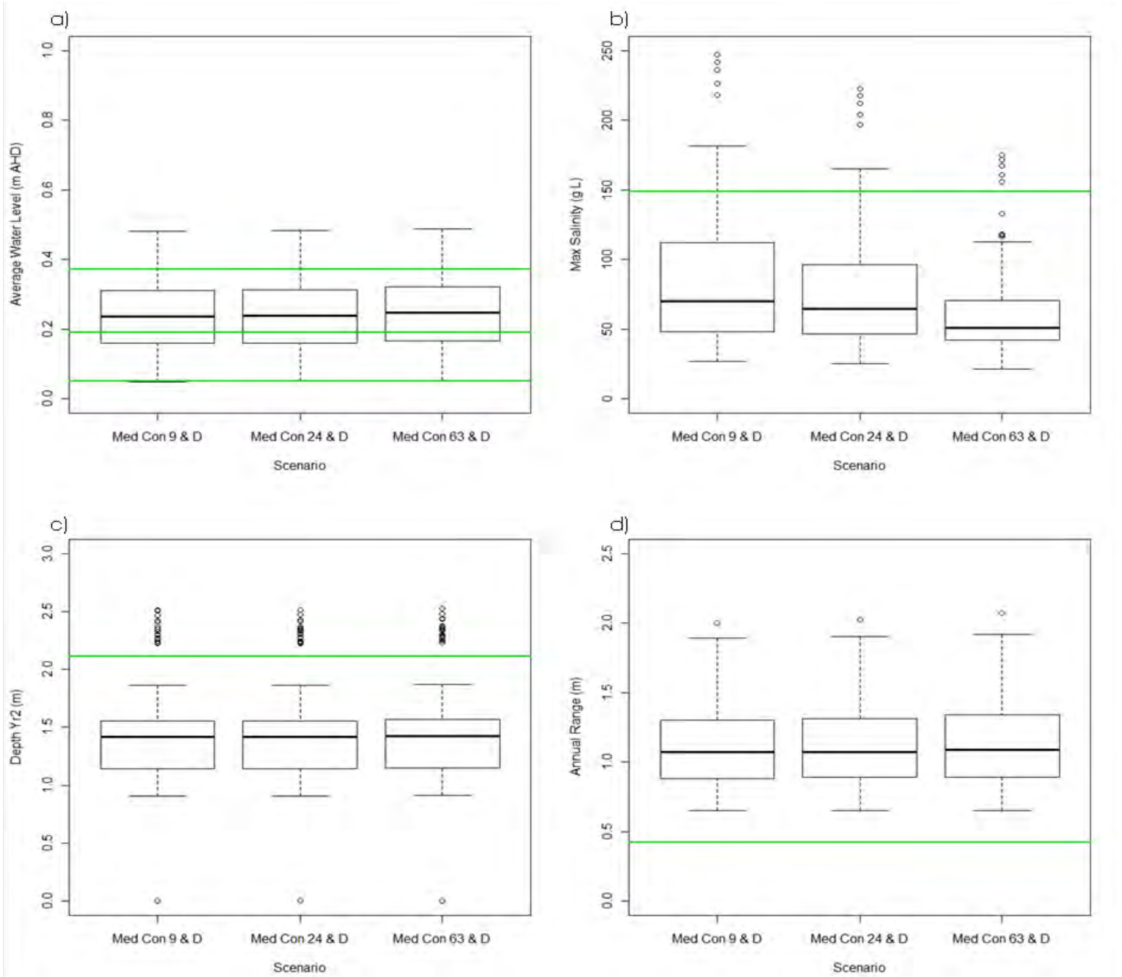

Figure 14.6: Boxplots showing the comparison between variables driving the ecosystem states of the Coorong for the consistent average USED volume with dredging scenarios under a median future climate. a) Average water level (m AHD), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Annual range in water level (m)

Med Con 9 & D is the Median Consistent 9 GL & dredging scenario, Med Con 24 & D is the Median Consistent 24 GL & dredging scenario and Med Con 63 & D is the Median Consistent 63 GL & dredging scenario. Information on how to read the figure is presented in Appendix E.

All scenarios involving a median future climate, irrespective of the amount of additional water via the USED scheme represented deterioration in both water levels and depths in the North Lagoon compared to the Baseline & dredging scenario (Figure 14.7). There was little difference among the scenarios with consistently-added additional water via the USED scheme, but increasing volumes resulted in slightly lower deteriorations in both variables.

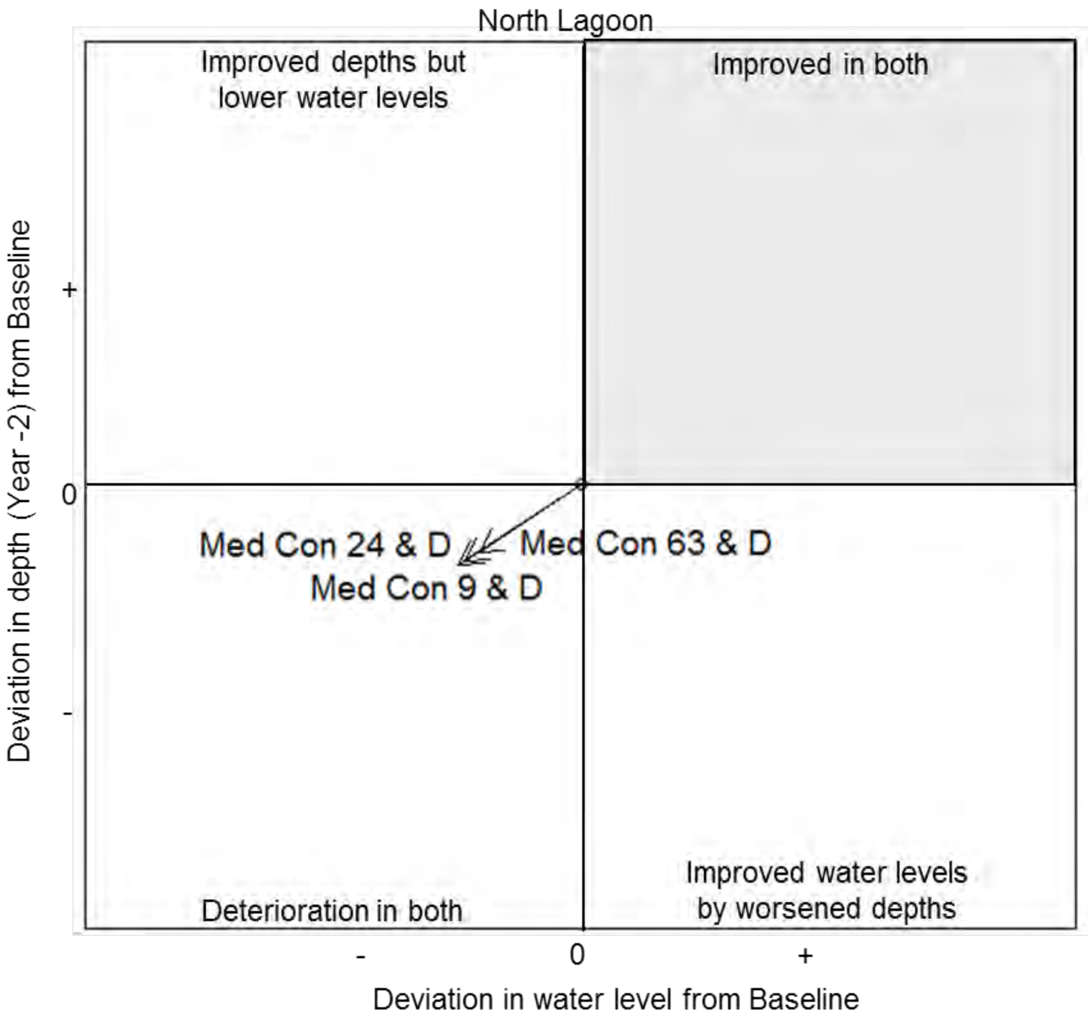

Figure 14.7: Comparison of the consistent average USED volume with dredging scenarios for the North Lagoon under a median future climate

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline & dredging scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Baseline & dredging condition (as shown by the 0,0 origin). Vectors in the upper-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and greater depths). Information on how to read the figure is presented in Appendix E. Med Con 9 & D is the Median Consistent 9 GL & dredging scenario, Med Con 24 & D is the Median Consistent 24 GL & dredging scenario and Med Con 63 & D is the Median Consistent 63 GL & dredging scenario.

Again, the effect in the South Lagoon was more complex (Figure 14.8). Here, all three scenarios involved deterioration in water levels compared to the Baseline & dredging scenario (which is unsurprising given that they involve a median future climate). There was little change associated with increasing volumes of additional water for that variable. However, for maximum salinity, there was a large improvement associated with increasing volumes delivered consistently via the USED scheme. When 63 GL were delivered per annum, maximum salinities were improved relative to the Baseline & dredging scenario, despite the median future climate, indicating that that volume of additional water was sufficient to counteract the effect of climate for that variable.

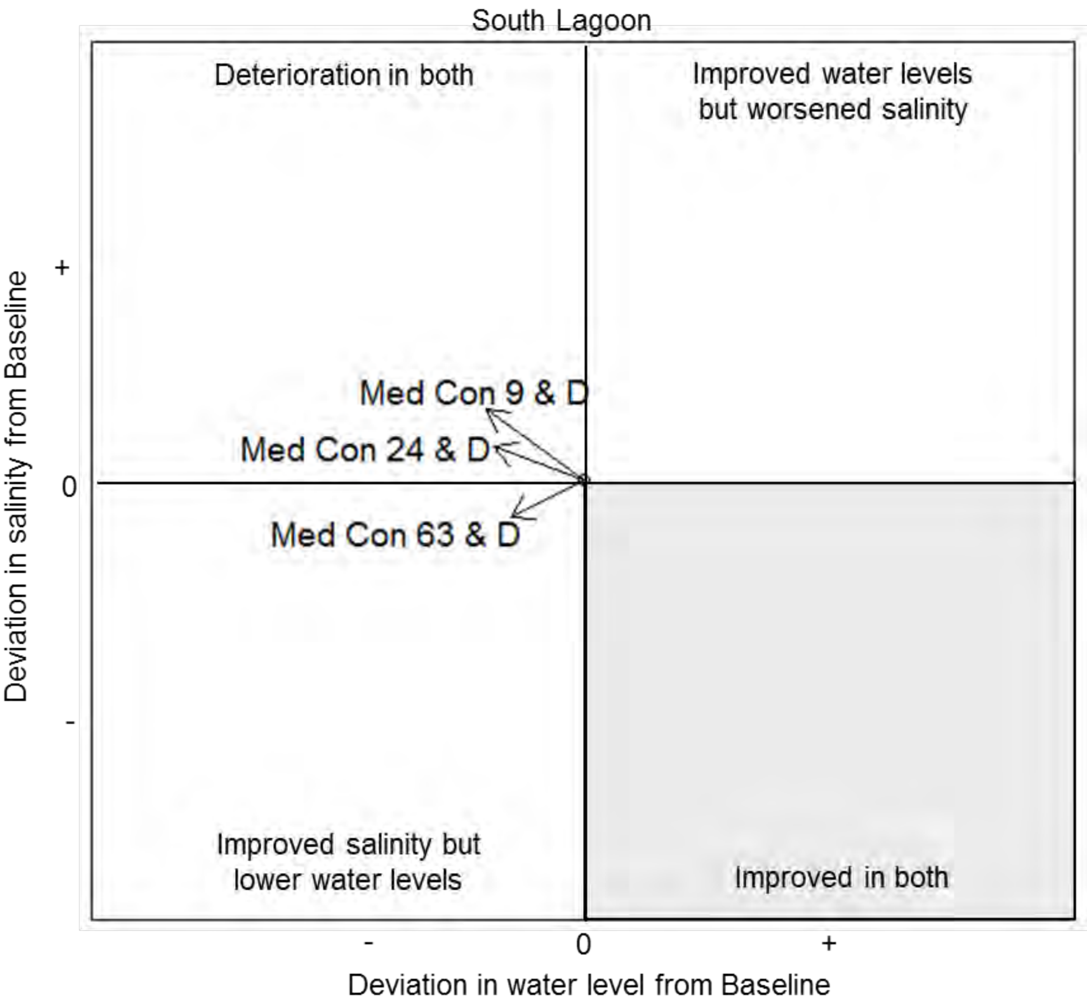

Figure 14.8: Comparison of the consistent average USED volume with dredging scenarios for the South Lagoon under a median future climate

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline & dredging scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline & dredging condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and lower salinities). Information on how to read the figure is presented in Appendix E. Med Con 9 & D is the Median Consistent 9 GL & dredging scenario, Med Con 24 & D is the Median Consistent 24 GL & dredging scenario and Med Con 63 & D is the Median Consistent 63 GL & dredging scenario.

Effect of consistent average USED volume including dredging under a dry future climate

Again, under a dry future climate, there was little shift in most hydrodynamic drivers when increasing volumes of water were added via the USED in a consistent inter-annual pattern (Figure 14.9). The same pattern as was evident under a median future climate appeared in the maximum salinities across the three scenarios. The absolute maximum reached for each scenario was 337.7 g L^{-1}, 308.2 g L^{-1} and 209.9 g L^{-1} for the Dry Consistent 4 GL, 14 GL and 63 GL & dredging scenarios, respectively. These values were substantially higher than the corresponding maxima under a median or historical climate, consistent with the drier conditions. There was also a substantial change in the median maximum salinity, from 110.1 g L^{-1} for the Dry Consistent 4 GL & dredging scenario to 65.3 g L^{-1} for the Dry Consistent 63 GL & dredging scenario. As for previous scenarios involving a dry future climate (Chapters 10 & 11), the maximum values reported here are unrealistic due to complex interactions between very high salinities and evaporation, but would represent very harsh conditions, outside the tolerances of the vast majority of Coorong taxa.

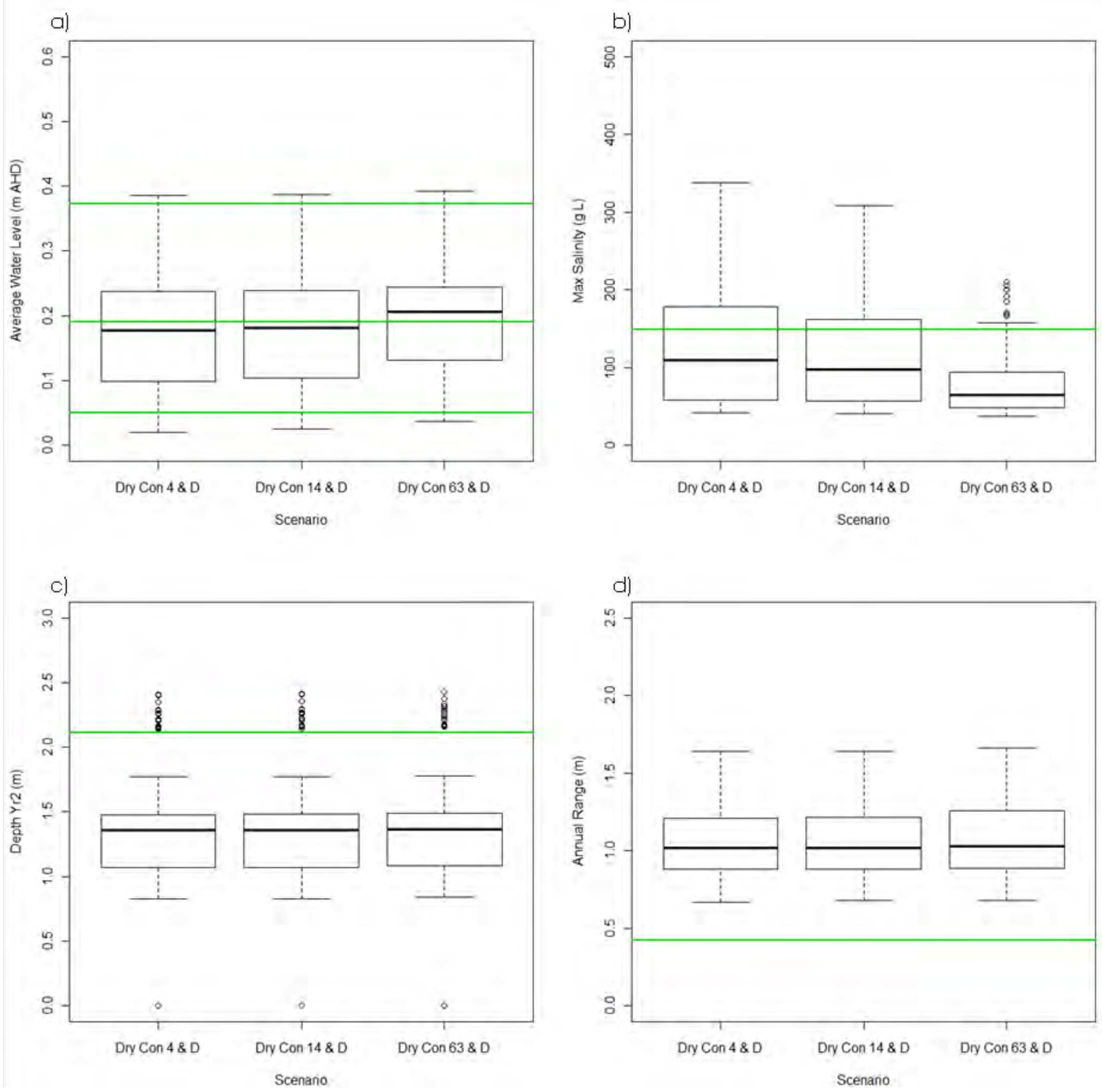

Figure 14.9: Boxplots showing the comparison between variables driving the ecosystem states of the Coorong for the consistent average USED volume with dredging scenarios under a dry future climate. a) Average water level (m AHD), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Annual range in water level (m)

Dry Con 4 & D is the Dry Consistent 4 GL & dredging scenario, Dry Con 14 & D is the Dry Consistent 14 GL & dredging scenario and Dry Con 63 & D is the Dry Consistent 63 GL & dredging scenario. Information on how to read the figure is presented in Appendix E.

For the North Lagoon drivers of water level and depth, no modelled volume of additional water via the USED scheme was sufficient to counteract the effect of a dry future climate (Figure 14.10). There was no difference distinguishable between the addition of 4 and 14 GL per annum, although an additional 63 GL per year had a small impact.

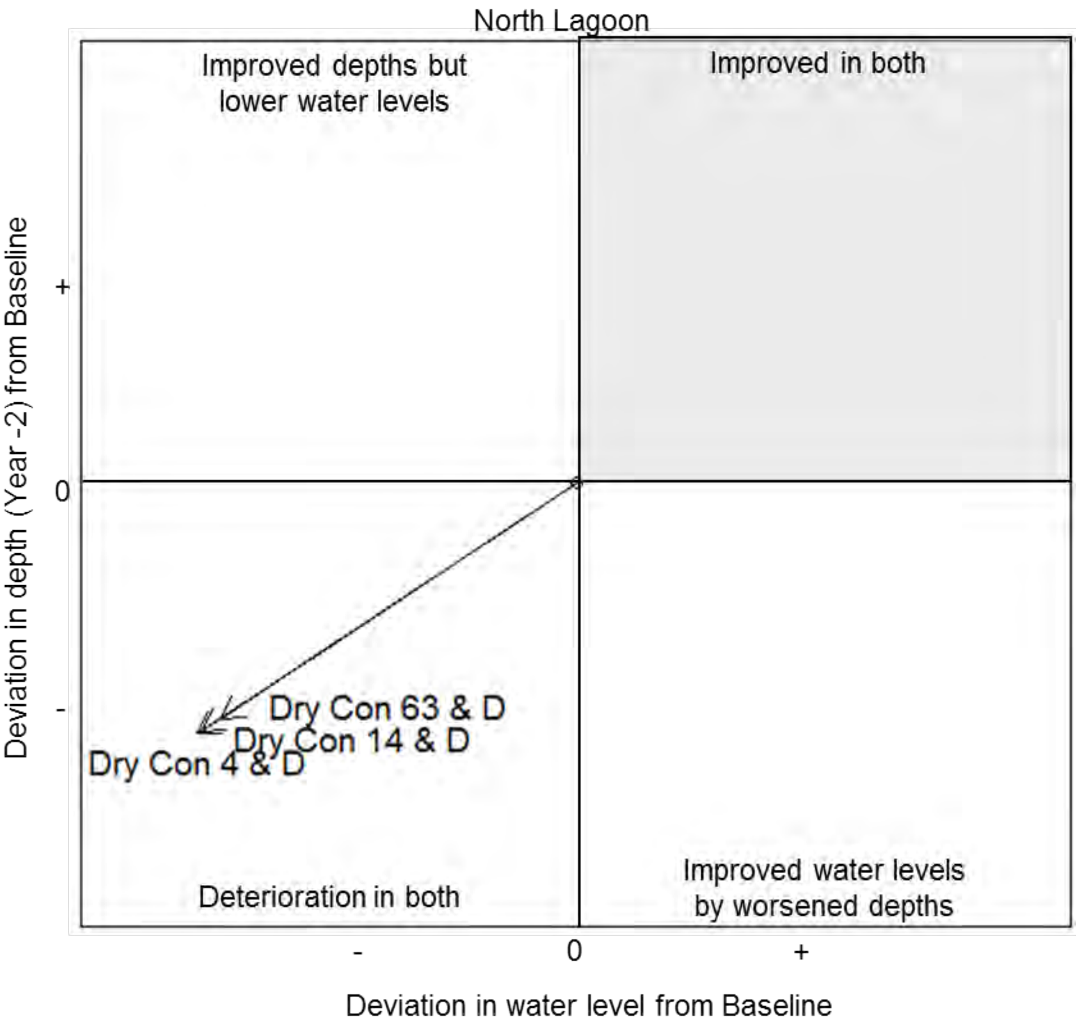

Figure 14.10: Comparison of the consistent average USED volume with dredging scenarios for the North Lagoon under a dry future climate

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline & dredging scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Baseline & dredging condition (as shown by the 0,0 origin). Vectors in the upper-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and greater depths). Information on how to read the figure is presented in Appendix E. Dry Con 4 & D is the Dry Consistent 4 GL & dredging scenario, Dry Con 14 & D is the Dry Consistent 14 GL & dredging scenario and Dry Con 63 & D is the Dry Consistent 63 GL & dredging scenario

In the South Lagoon, there was again a clear deterioration in water levels compared to the Baseline with dredging for all scenarios, indicating that the additional volumes investigated did not counteract the effects of a dry future climate (Figure 14.11). Increasing amounts of additional water did have some influence on maximum salinities, with an additional 63 GL per year representing only a small deterioration compared to the Baseline & dredging scenario for that variable.

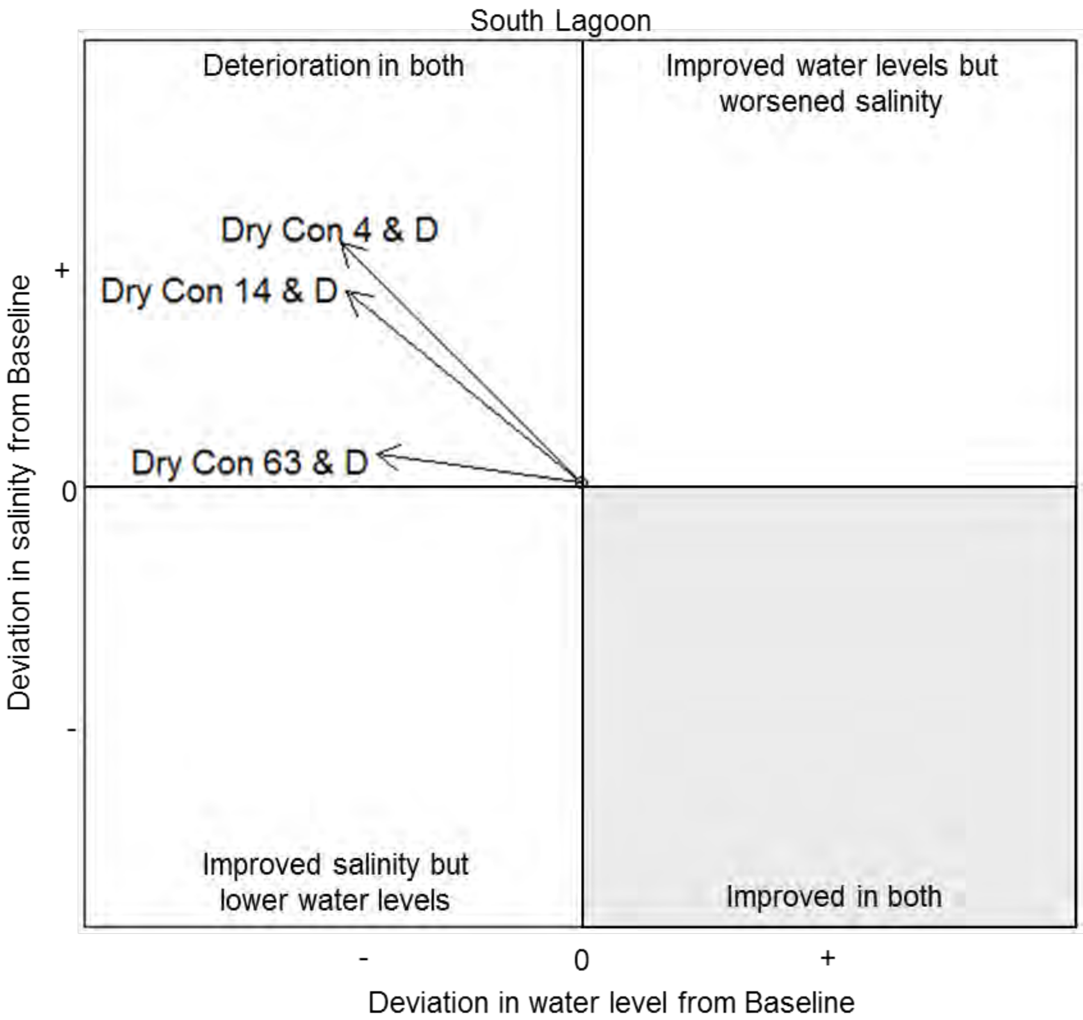

Figure 14.11: Comparison of the consistent average USED volume with dredging scenarios for the South Lagoon under a dry future climate

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline & dredging scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline & dredging condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and lower salinities). Information on how to read the figure is presented in Appendix E. Dry Con 4 & D is the Dry Consistent 4 GL & dredging scenario, Dry Con 14 & D is the Dry Consistent 14 GL & dredging scenario and Dry Con 63 & D is the Dry Consistent 63 GL & dredging scenario

Effect of variable average USED volume including dredging under an historical climate

Where additional water delivered via the USED scheme in a consistent pattern among years only had a substantial influenced on the maximum salinity of the Coorong, varying the pattern of delivery among years in a more-realistic pattern had an effect on all four hydrodynamic drivers of ecosystem states (Figure 14.12). The largest impact was again on maximum salinities, but the effect for each amount of additional water was much larger. For example, the median maximum salinity under the Historical Variable 36 GL & dredging scenarios was 52.5 g L^{-1}, compared to 56.4 g L^{-1} for the Historical Consistent 36 GL & dredging scenario shown above. When the additional water was delivered in a variable inter-annual pattern, average water levels increased, with the greatest change evident in the minimum values for each scenario. A similar but smaller impact was also seen for depths and annual ranges.

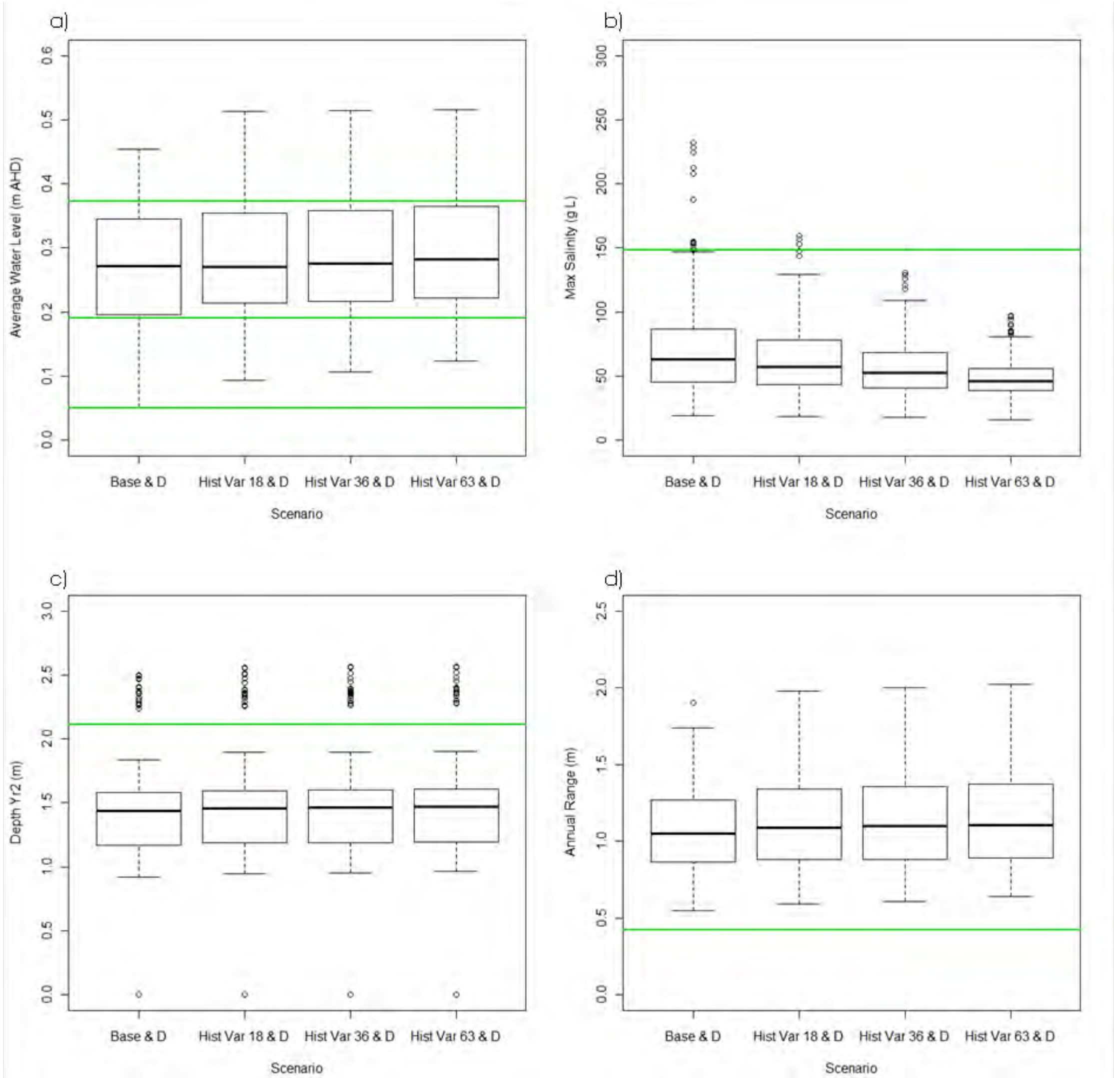

Figure 14.12: Boxplots showing the comparison between variables driving the ecosystem states of the Coorong for the variable average USED volume with dredging scenarios under an historical climate. a) Average water level (m AHD), b) Maximum salinity (g L-1), c) Average water depth from two years previous (m), and d) Annual range in water level (m)

Base & D is the Baseline & dredging scenario, Hist Var 18 & D is the Historical Variable 18 GL & dredging scenario, Hist Var 36 & D is the Historical Variable 36 GL & dredging scenario and Hist Var 63 & D is the Historical Variable 63 GL & dredging scenario. Information on how to read the figure is presented in Appendix E.

Little difference was evident for North Lagoon hydrodynamic drivers as a result of adding the water in an inter-annually variable fashion (Figure 14.13) compared with the same volumes added consistently (Figure 14.4). Again, only small differences were detected, but there was a slight increase in the degree of improvement with increasing volumes of additional water.

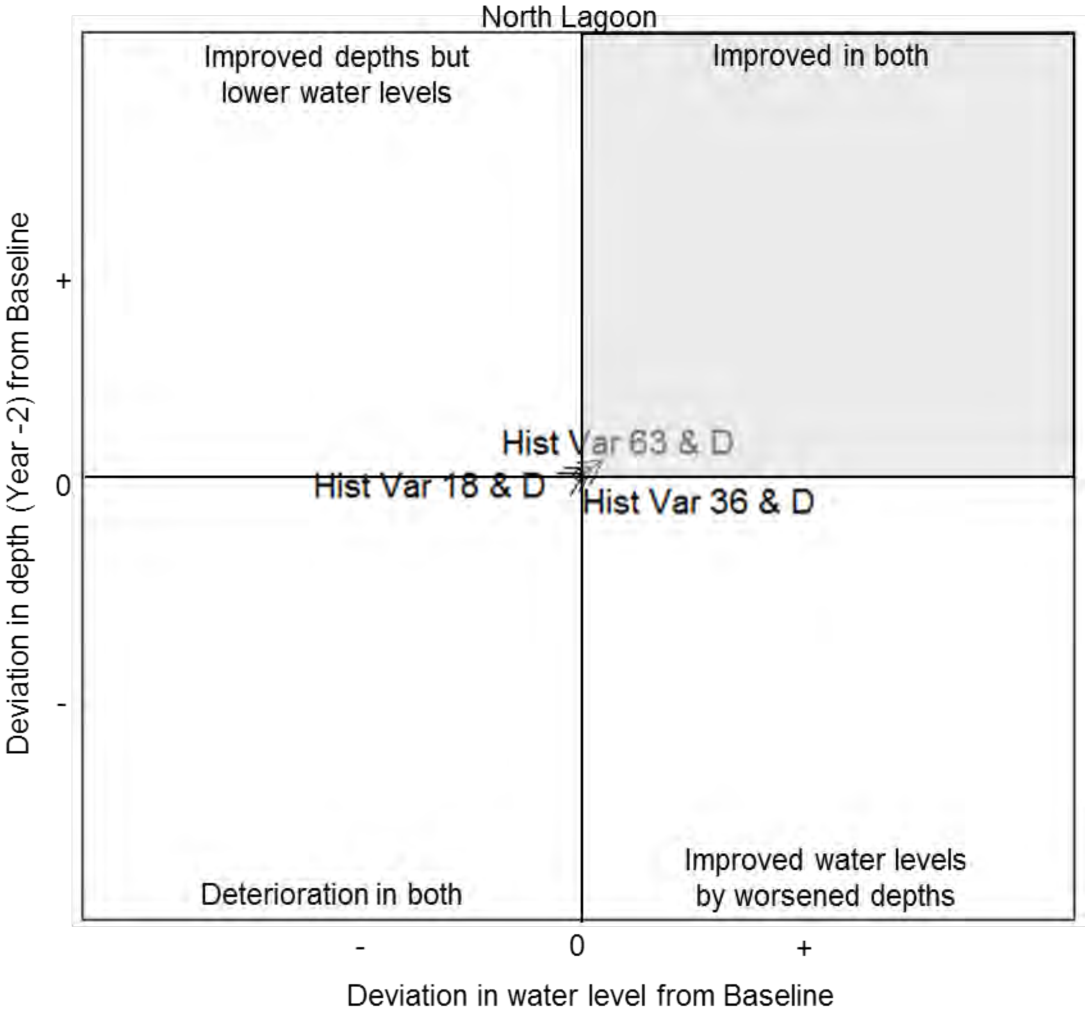

Figure 14.13: Comparison of the variable average USED volume with dredging scenarios for the North Lagoon under an historical climate

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline & dredging scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Baseline & dredging condition (as shown by the 0,0 origin). Vectors in the upper-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and greater depths). Information on how to read the figure is presented in Appendix E. Hist Var 18 & D is the Historical Variable 18 GL & dredging scenario, Hist Var 36 & D is the Historical Variable 36 GL & dredging scenario and Hist Var 63 & D is the Historical Variable 63 GL & dredging scenario.

In the South Lagoon, there was additional improvement in maximum salinity and average water level associated with the inter-annually variable delivery of additional water (Figure 14.14), compared with the same volumes delivered consistently (Figure 14.5). In particular, average water levels improved, although the Historical Variable 18 GL & dredging scenario still showed a very slight overall deterioration in water levels compared to the Baseline & dredging scenario.

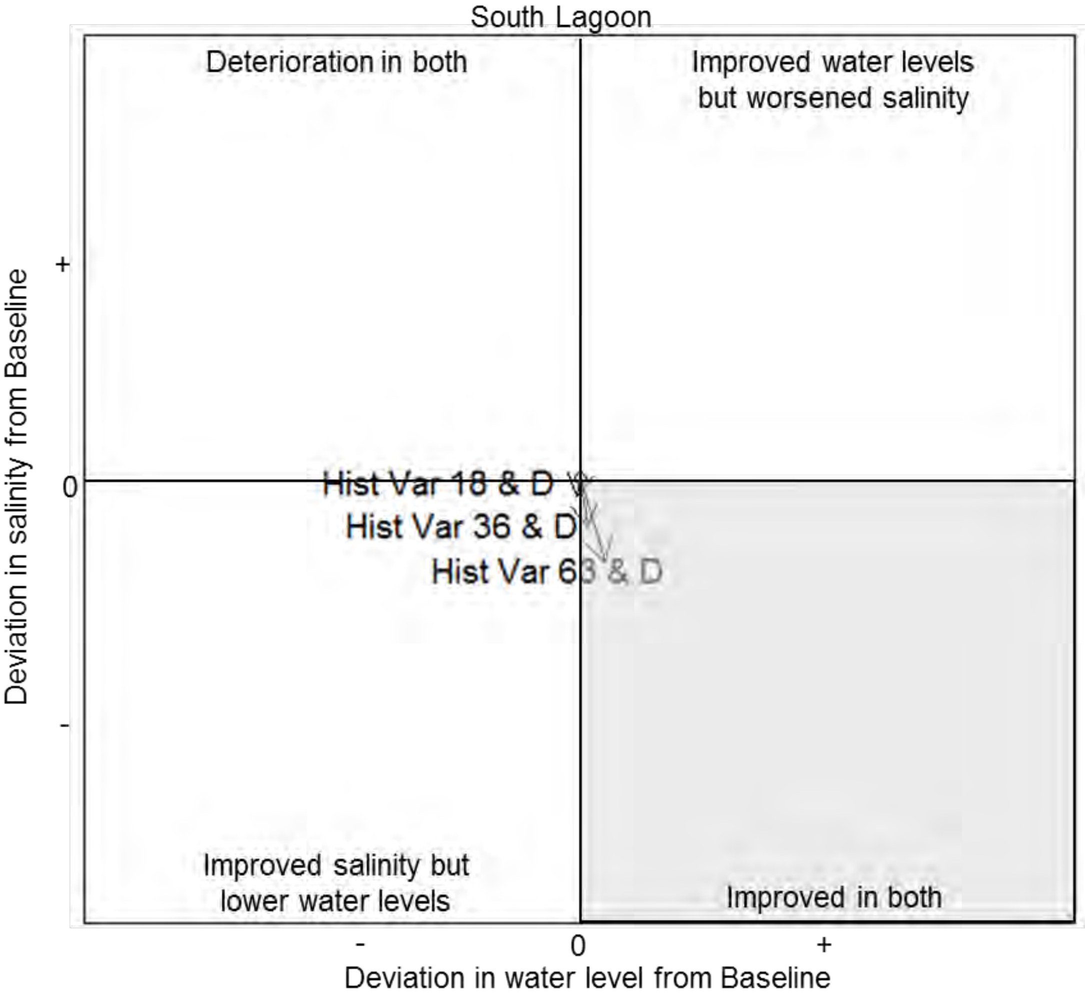

Figure 14.14: Comparison of the variable average USED volume with dredging scenarios for the South Lagoon under an historical climate

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline & dredging scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline & dredging condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and lower salinities. Information on how to read the figure is presented in Appendix E. Hist Var 18 & D is the Historical Variable 18 GL & dredging scenario, Hist Var 36 & D is the Historical Variable 36 GL & dredging scenario and Hist Var 63 & D is the Historical Variable 63 GL & dredging scenario.

Effect of variable average USED volume including dredging under a median future climate

As for the scenarios investigating an historical climate, changes as a result of augmenting USED flows in a variable pattern among years were evident (Figure 14.15). However, the changes with increasing volumes of water were smaller, except for maximum salinities. The biggest change was in the absolute maximum salinity values, from 330.4 g L^{-1} under the Median Variable 9 GL & dredging scenario to 275.0 g L^{-1} and 168.3 g L^{-1} for the Median Variable 24 GL and 63 GL & dredging scenarios, respectively.

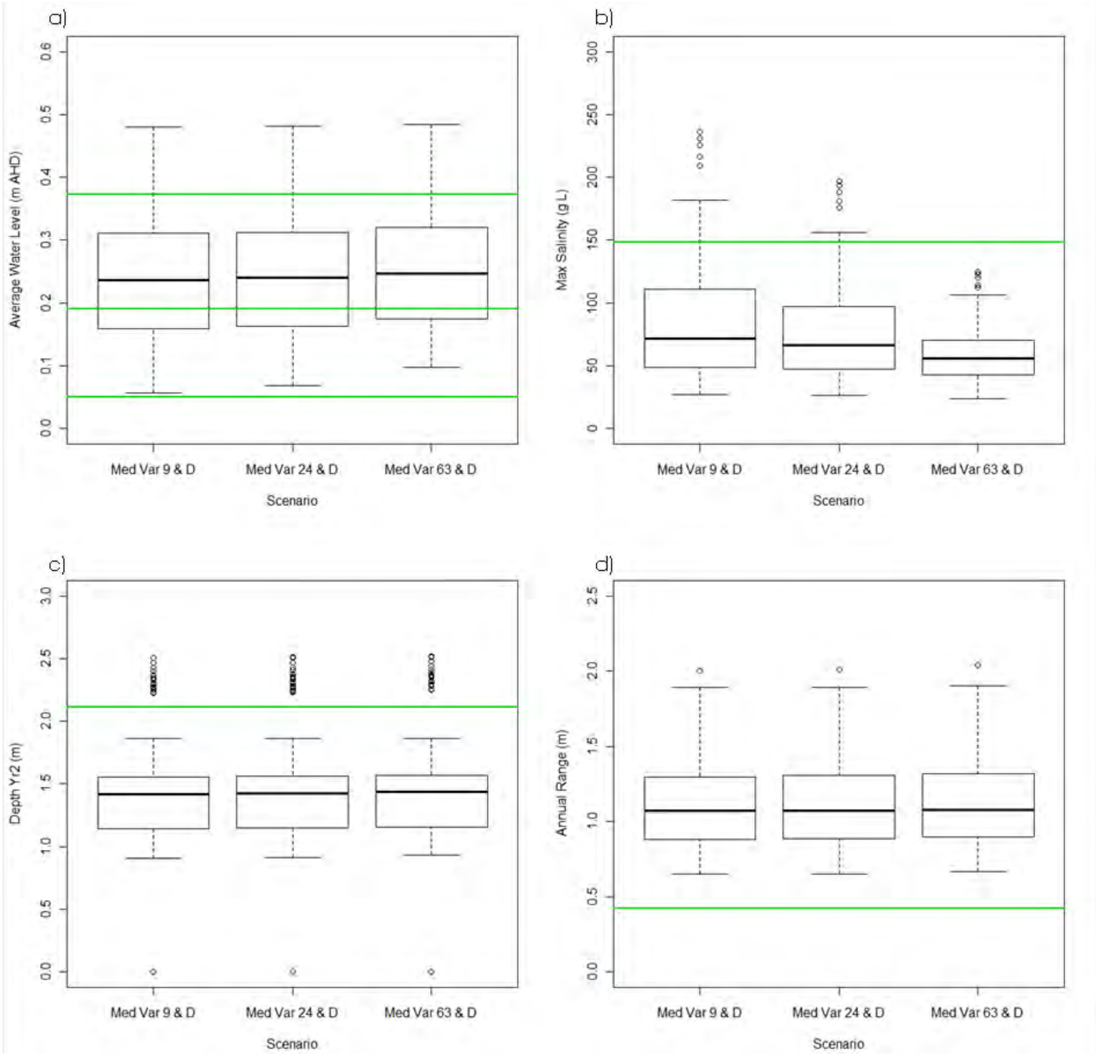

Figure 14.15: Boxplots showing the comparison between variables driving the ecosystem states of the Coorong for the variable average USED volume with dredging scenarios under a median future climate. a) Average water level (m AHD), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Annual range in water level (m)

Med Var 9 & D is the Median Variable 9 GL & dredging scenario, Med Var 24 & D is the Median Variable 24 GL & dredging scenario and Med Var 63 & D is the Median Variable 63 GL & dredging. Information on how to read the figure is presented in Appendix E.

The cumulative impact of additional flow volumes via the USED scheme under a median climate using a variable flow pattern was extremely similar in the North Lagoon as that using a consistent flow pattern (Figures 14.16 and 14.7). This was also true for the hydrodynamic drivers in the South Lagoon, although the variable flow pattern resulted in slightly smaller deteriorations, on the whole (Figures 14.17 and 14.8).

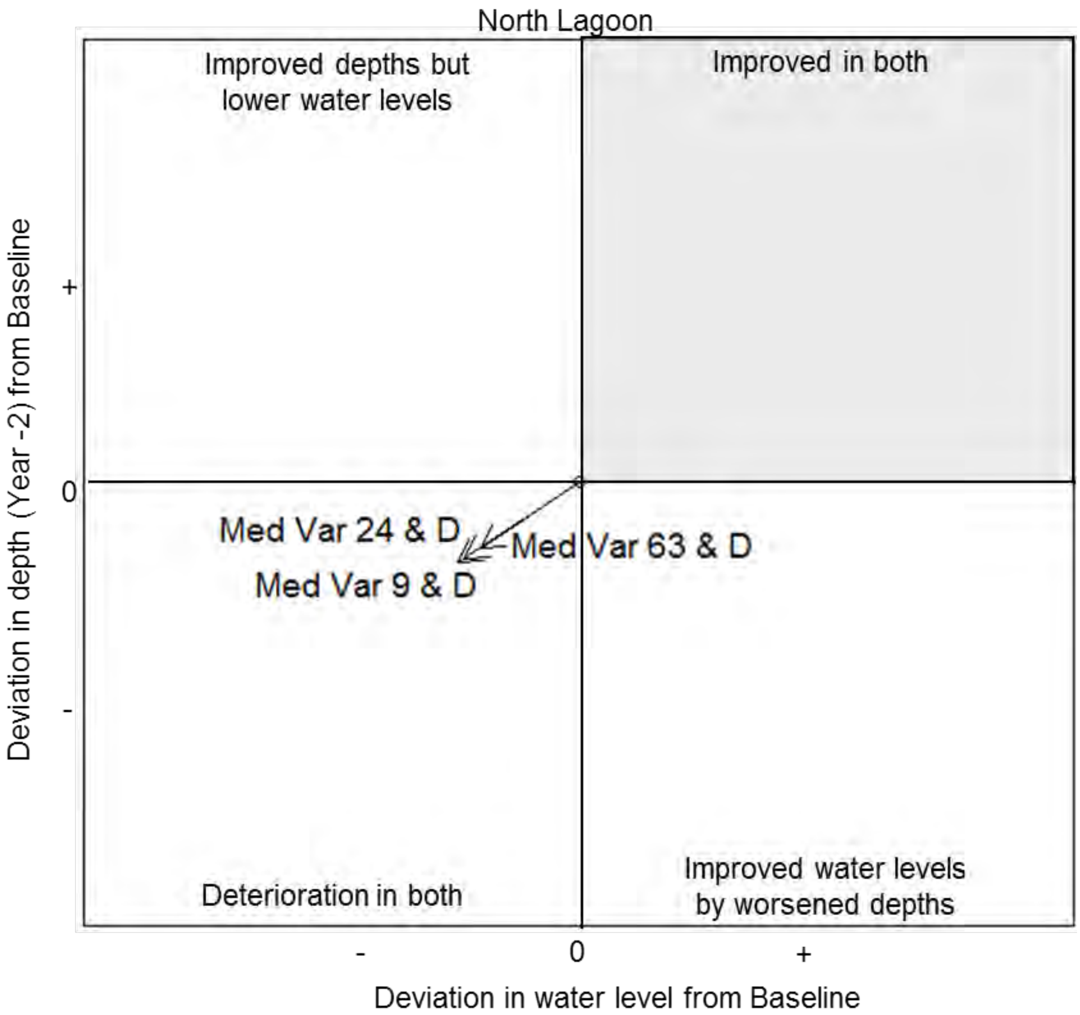

Figure 14.16: Comparison of the variable average USED volume with dredging scenarios for the North Lagoon under a median future climate

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline & dredging scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Baseline & dredging condition (as shown by the 0,0 origin). Vectors in the upper-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and greater depths). Information on how to read the figure is presented in Appendix E. Med Var 9 & D is the Median Variable 9 GL & dredging scenario, Med Var 24 & D is the Median Variable 24 GL & dredging scenario and Med Var 63 & D is the Median Variable 63 GL & dredging.

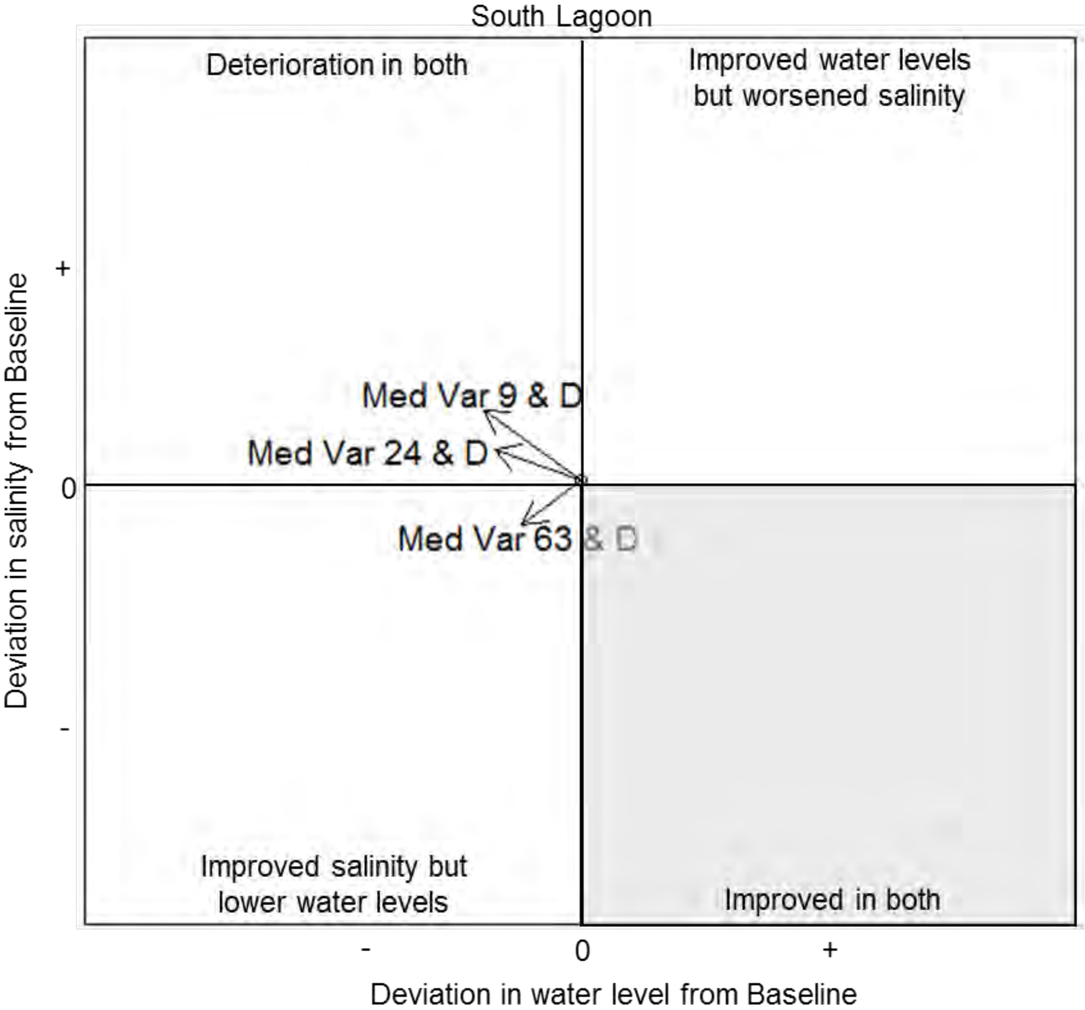

Figure 14.17: Comparison of the variable average USED volume with dredging scenarios for the South Lagoon under a median future climate

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline & dredging scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline & dredging condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and lower salinities). Information on how to read the figure is presented in Appendix E. Med Var 9 & D is the Median Variable 9 GL & dredging scenario, Med Var 24 & D is the Median Variable 24 GL & dredging scenario and Med Var 63 & D is the Median Variable 63 GL & dredging.

Effect of variable average USED volume including dredging under a dry future climate

The same pattern seen for the median future climate with a variable inter-annual pattern of additional USED flow was observed under a dry future climate (Figure 14.18). Again, there were small improvements in all variables associated with increasing volumes of additional water, but maximum salinities were most affected. Here, the median maximum salinity was 110.5 g L^{-1} under the Dry Variable 4 GL & dredging scenario, 102.3 g L^{-1} under the Dry Variable 14 GL & dredging scenario and 68.8 g L^{-1} under the Dry Variable 63 GL & dredging scenario.

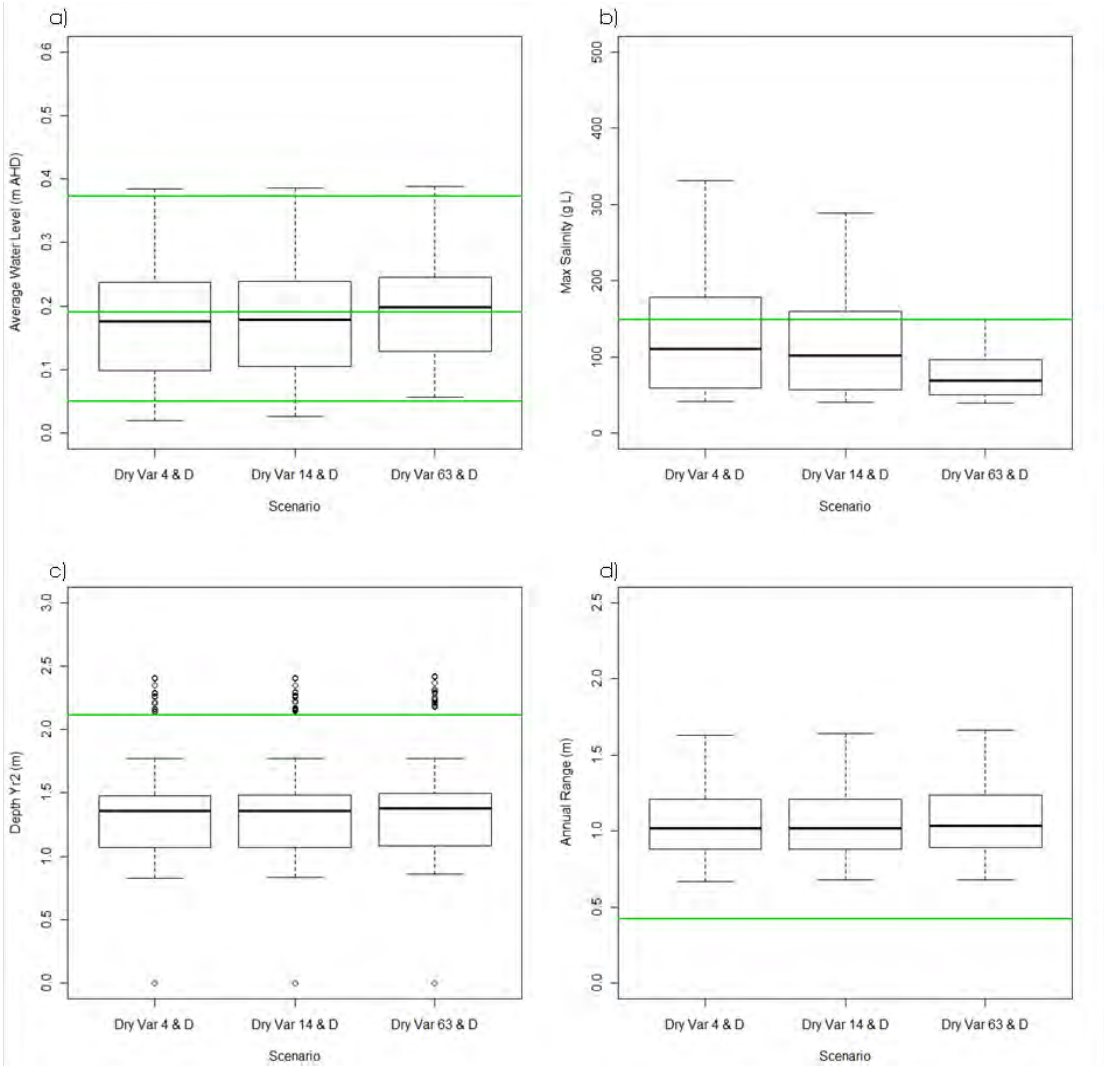

Figure 14.18: Boxplots showing the comparison between variables driving the ecosystem states of the Coorong for the variable average USED volume with dredging scenarios under a dry future climate. a) Average water level (m AHD), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Annual range in water level (m)

Dry Var 4 & D is the Dry Variable 4 GL & dredging scenario, Dry Var 14 & D is the Dry Variable 14 GL & dredging scenario and Dry Var 63 & D is the Dry Variable 63 GL & dredging scenario. Information on how to read the figure is presented in Appendix E.

As for the boxplots, the patterns observed for the scenarios including variable inter-annual delivery of additional USED flows under a dry future climate were consistent with those observed under a median future climate (Figures 14.19 and 14.20).

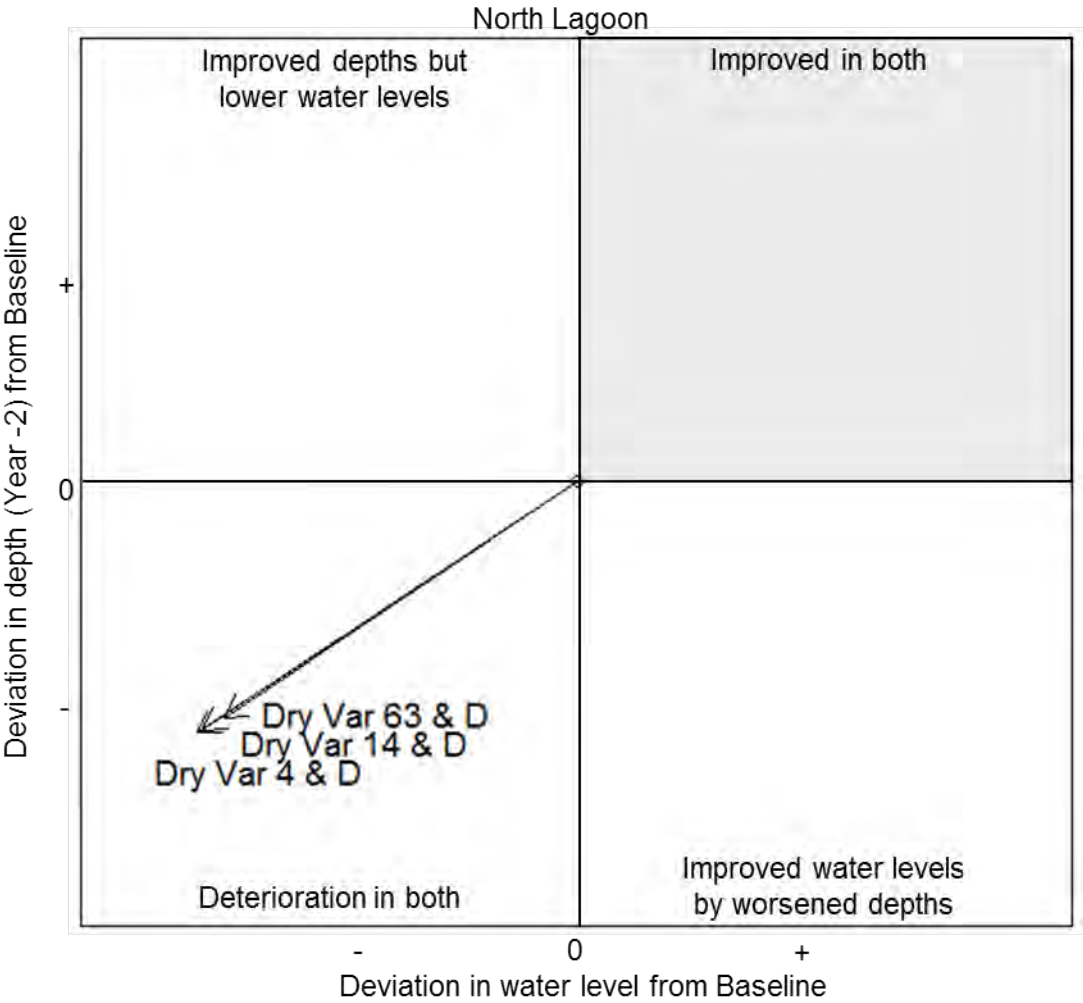

Figure 14.19: Comparison of the variable average USED volume with dredging scenarios for the North Lagoon under a dry future climate

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline & dredging scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Baseline & dredging condition (as shown by the 0,0 origin). Vectors in the upper-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and greater depths). Information on how to read the figure is presented in Appendix E. Dry Var 4 & D is the Dry Variable 4 GL & dredging scenario, Dry Var 14 & D is the Dry Variable 14 GL & dredging scenario and Dry Var 63 & D is the Dry Variable 63 GL & dredging scenario.

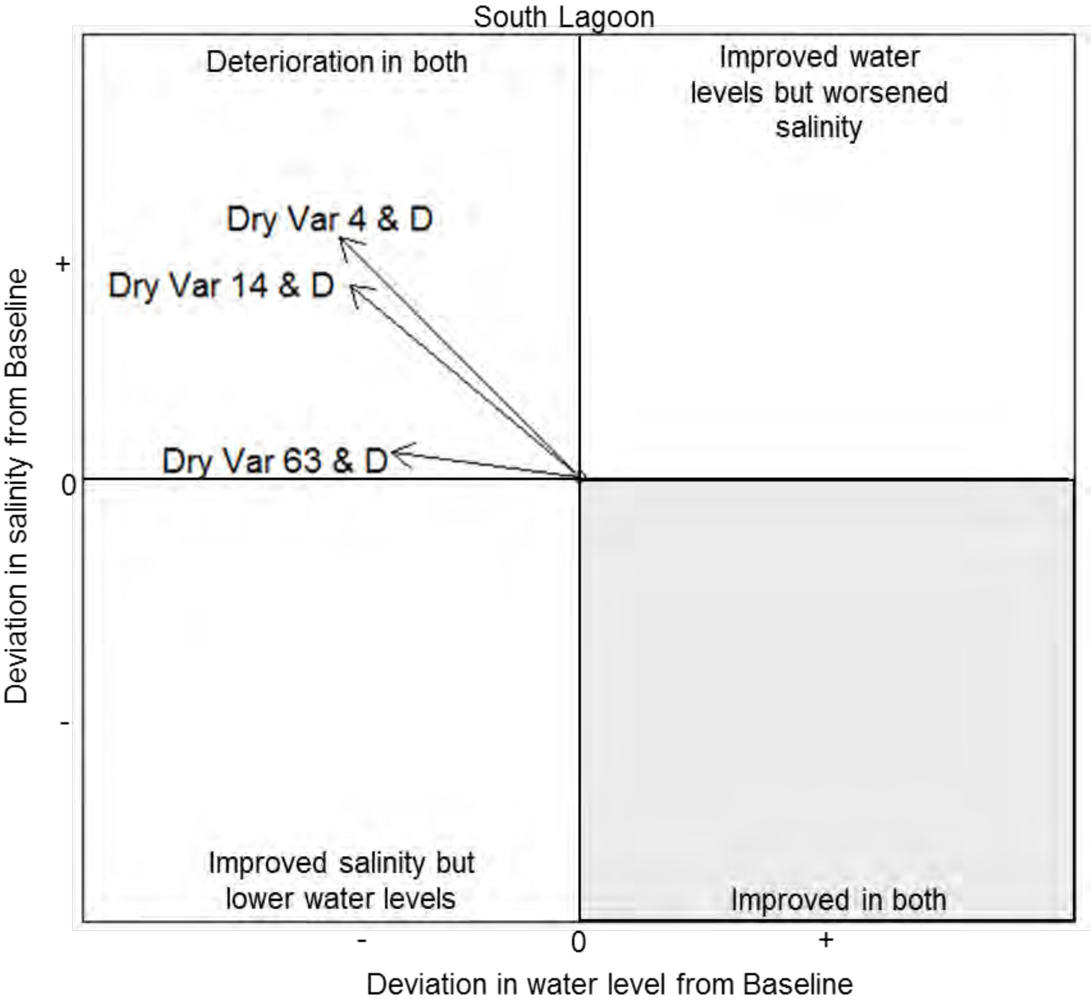

Figure 14.20: Comparison of the variable average USED volume with dredging scenarios for the South Lagoon under a dry future climate

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline & dredging scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline & dredging condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and lower salinities). Information on how to read the figure is presented in Appendix E. Dry Var 4 & D is the Dry Variable 4 GL & dredging scenario, Dry Var 14 & D is the Dry Variable 14 GL & dredging scenario and Dry Var 63 & D is the Dry Variable 63 GL & dredging scenario.

14.3.3 Ecological impact of additional USED volumes

Effect of consistent average USED volume including dredging under an historical climate

The effects of consistently-delivered additional water coming via the USED scheme on the ecosystem states of the Coorong were subtle (Figure 14.21). There was no change in the North Lagoon for any scenario and the only change in the South Lagoon was in the proportion of Average Hypersaline compared to Degraded Hypersaline states. When 18 GL year^{-1} was delivered in this fashion, the six ecosystem states of the Coorong predicted were identical to the Baseline & dredging scenario (Figures 14.21 and 14.22). The addition of either 36 GL or 63 GL did alter the relative proportions of the ecosystem states but again, the difference was slight with less than 2% of site-years in the 22-year model run changing from Degraded Hypersaline to Average Hypersaline when 63 GL were added each year (Figure 14.22).

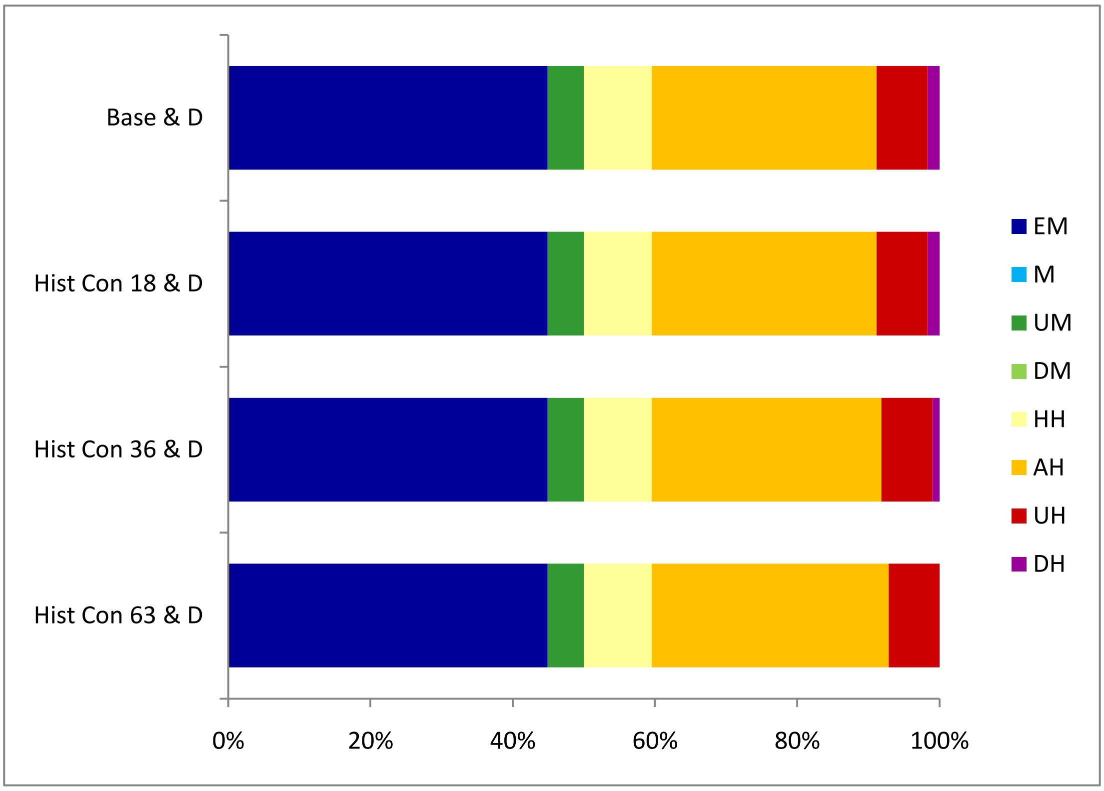

Figure 14.21: Comparing the proportion of site-years in each ecosystem for consistent average USED volume with dredging scenarios under an historical climate

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Information on how to read the figure is presented in Appendix E. Base & D is the Baseline & dredging scenario, Hist Con 18 & D is the Historical Consistent 18 GL & dredging scenario, Hist Con 36 & D is the Historical Consistent 36 GL & dredging scenario and Hist Con 63 & D is the Historical Consistent 63 GL & dredging scenario.

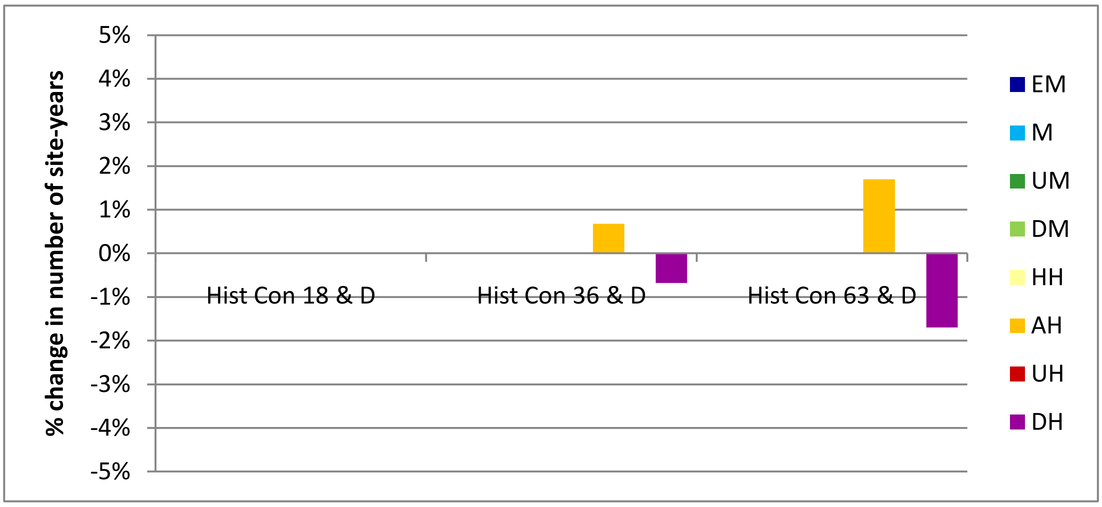

Figure 14.22: Deviations in the proportion of site-years in each ecosystem state compared to the Baseline & dredging scenario for the consistent average USED volume with dredging scenarios under an historical climate

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Information on how to read the figure is presented in Appendix E. Hist Con 18 & D is the Historical Consistent 18 GL & dredging scenario, Hist Con 36 & D is the Historical Consistent 36 GL & dredging scenario and Hist Con 63 & D is the Historical Consistent 63 GL & dredging scenario.

Effect of consistent average USED volume including dredging under a median future climate

Under a median future climate, the effects of additional water via the USED scheme on the ecosystem states of the Coorong were more apparent (Figure 14.23), although six states were always predicted to occur. Again, there was no change in the ecosystem states of the North Lagoon under any scenario. In the South Lagoon, however, there was a decreasing proportion of site-years in the Degraded Hypersaline state, with corresponding increases in the proportion of Average Hypersaline site-years (Figure 14.23). The proportion of site-years in the Degraded Hypersaline state declined from 10% when 9 GL per annum was added via the USED scheme, to 5% and 2% when 24 GL or 63 GL were added in the same consistent manner, respectively (Figure 14.23).

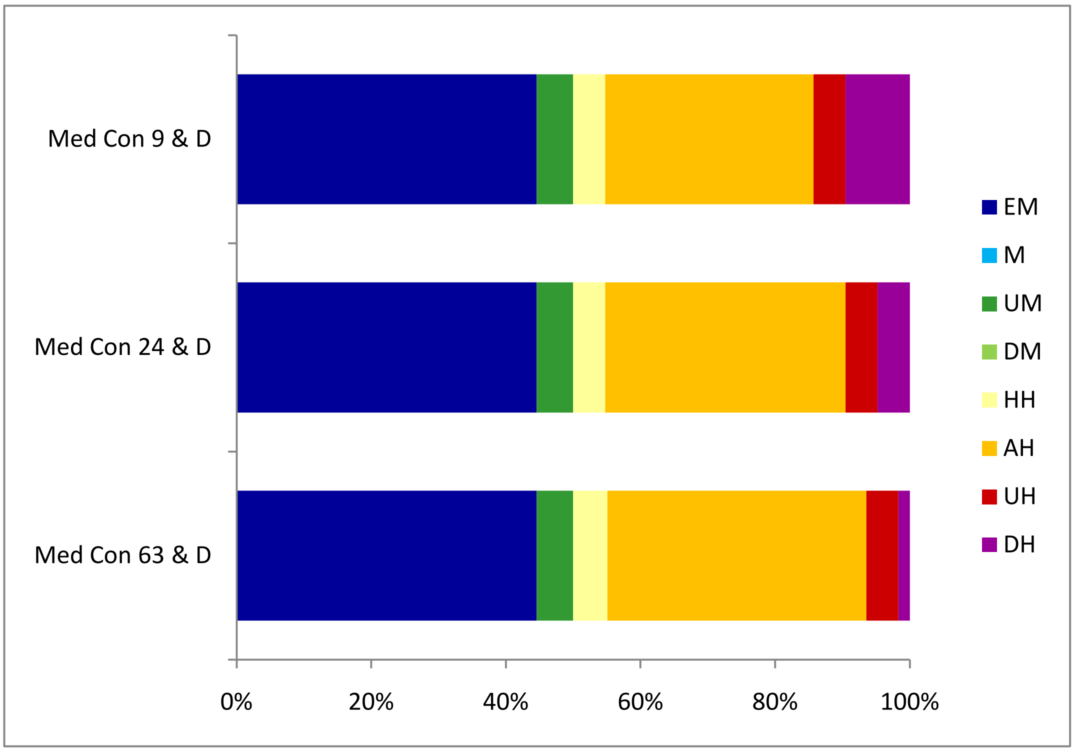

Figure 14.23: Comparing the proportion of site-years in each ecosystem for consistent average USED volume with dredging scenarios under a median future climate

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Information on how to read the figure is presented in Appendix E. Med Con 9 & D is the Median Consistent 9 GL & dredging scenario, Med Con 24 & D is the Median Consistent 24 GL & dredging scenario and Med Con 63 & D is the Median Consistent 63 GL & dredging scenario.

Effect of consistent average USED volume including dredging under a dry future climate

The change was more marked under a dry future climate (Figure 14.24), although four states were always predicted to occur. Again, the difference was seen in the proportion of site-years in the Average Hypersaline state compared with the Degraded Hypersaline state. With the consistent annual addition of 4 GL, the proportion of Degraded Hypersaline site-years was 38%. This declined to 30% with the addition of 14 GL and 4% with the addition of 63 GL. No volume explored was sufficient to prevent degraded ecosystem states occurring in the Coorong for the whole model run and no volume had an influence on the ecosystem states of the North Lagoon.

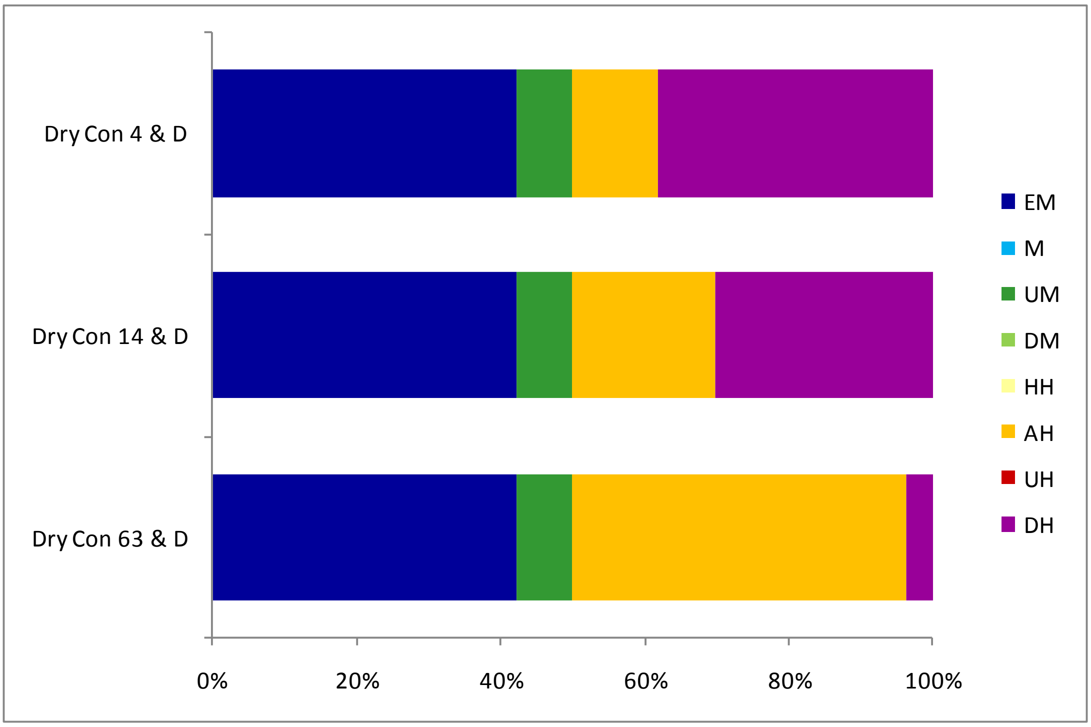

Figure 14.24: Comparing the proportion of site-years in each ecosystem for consistent average USED volume with dredging scenarios under a dry future climate

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Information on how to read the figure is presented in Appendix E. Dry Con 4 & D is the Dry Consistent 4 GL & dredging scenario, Dry Con 14 & D is the Dry Consistent 14 GL & dredging scenario and Dry Con 63 & D is the Dry Consistent 63 GL & dredging scenario.

Effect of variable average USED volume including dredging under an historical climate

Adding the additional water from the USED scheme in a variable inter-annual pattern was a more realistic approach and resulted in a slightly better mix of ecosystem states for the same volume of water added in a consistent inter-annual pattern (Figures 14.25 and 14.21). The addition of 36 GL per annum in a variable pattern resulted in no site-years in the Degraded Hypersaline ecosystem state, with more site-years in an Average Hypersaline state than the Baseline with dredging scenario (Figure 14.25). Again, there was no change in North Lagoon ecosystem states, or in the proportion of Healthy Hypersaline or Unhealthy Hypersaline ecosystem states (Figure 14.26).

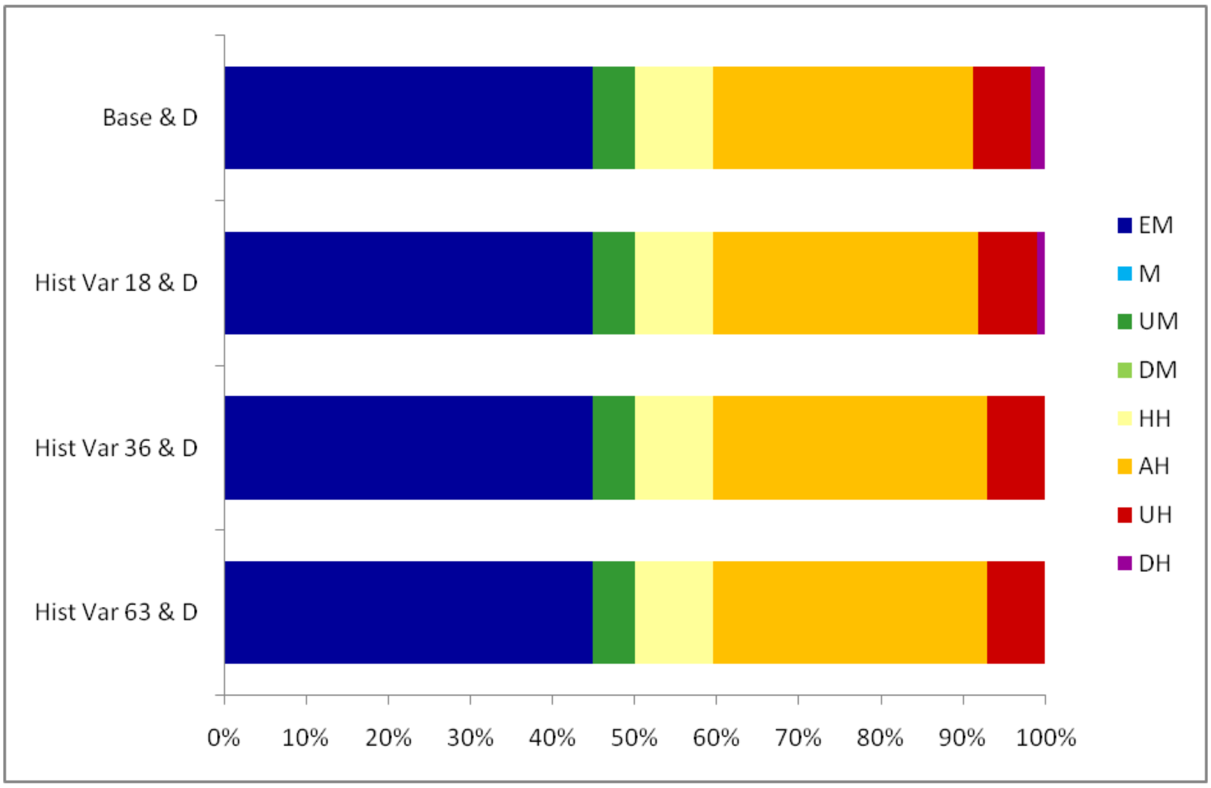

Figure 14.25: Comparing the proportion of site-years in each ecosystem for variable average USED volume with dredging scenarios under an historical climate

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Information on how to read the figure is presented in Appendix E. Base & D is the Baseline & dredging scenario, Hist Var 18 & D is the Historical Variable 18 GL & dredging scenario, Hist Var 36 & D is the Historical Variable 36 GL & dredging scenario and Hist Var 63 & D is the Historical Variable 63 GL & dredging scenario.

Figure 14.26: Deviations in the proportion of site-years in each ecosystem state compared to the Baseline & dredging scenario for the variable average USED volume with dredging scenarios under an historical climate

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Information on how to read the figure is presented in Appendix E. Hist Var 18 & D is the Historical Variable 18 GL & dredging scenario, Hist Var 36 & D is the Historical Variable 36 GL & dredging scenario and Hist Var 63 & D is the Historical Variable 63 GL & dredging scenario.

Effect of variable average USED volume including dredging under a median future climate

As for the historical climate, when additional water from the USED scheme was added in a variable inter-annual pattern under a median future climate simulation, there was a slightly better mix of ecosystem states (again changing for six to five; Figure 14.27) than for the same volume of water added consistently (see Figure 14.23). The differences were again apparent in the proportions of site-years in the Degraded Hypersaline and Average Hypersaline state, with 63 GL per annum required to prevent any appearance of the Degraded Hypersaline state. No change was evident for the other ecosystem states or in the North Lagoon.

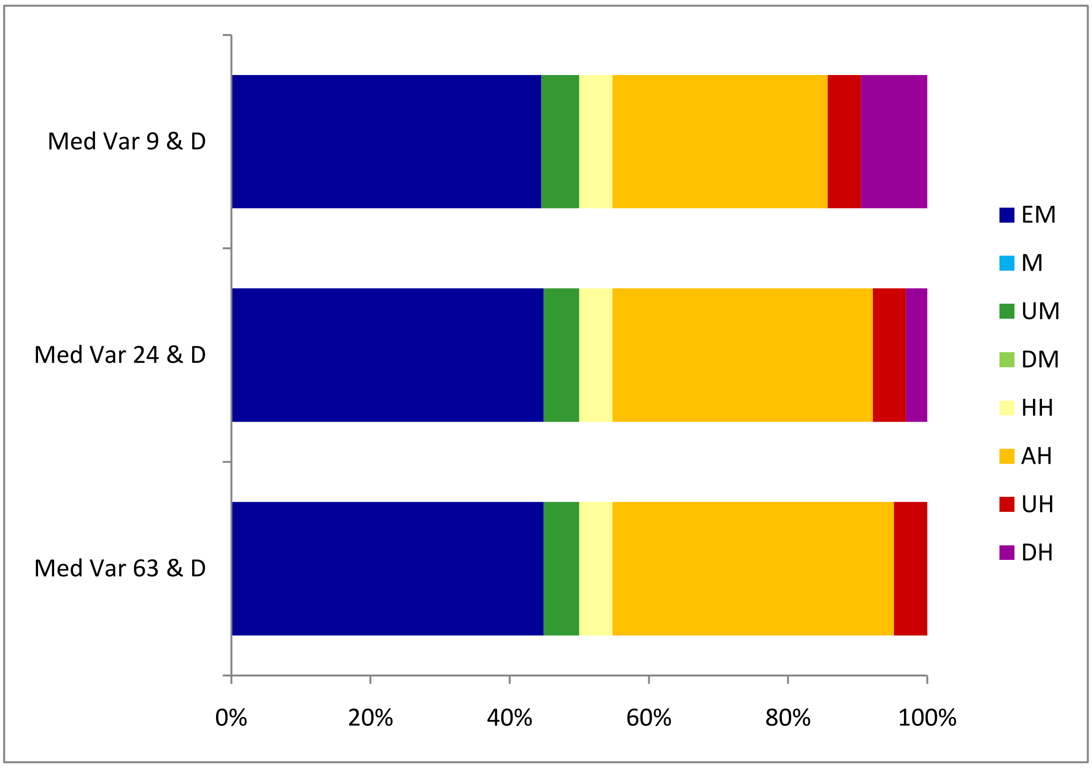

Figure 14.27: Comparing the proportion of site-years in each ecosystem for variable average USED volume with dredging scenarios under a median future climate

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Information on how to read the figure is presented in Appendix E. Med Var 9 & D is the Median Variable 9 GL & dredging scenario, Med Var 24 & D is the Median Variable 24 GL & dredging scenario and Med Var 63 & D is the Median Variable 63 GL & dredging scenario.

Effect of variable average USED volume including dredging under a dry future climate

The addition of 4 GL from the USED scheme under a dry future climate did not prevent the majority of the South Lagoon from being in the Degraded Hypersaline state under a dry future climate simulation (Figure 14.28). The proportion of Degraded Hypersaline site-years declined from 39% under the Dry Variable 4 GL & dredging scenario to 33% and 0.3% under the Dry Variable 14 GL and 63 GL & dredging scenarios, respectively, but no volume of water explored prevented the appearance of that state (although it was much reduced with 63 GL), nor had an influence on North Lagoon ecosystem states.

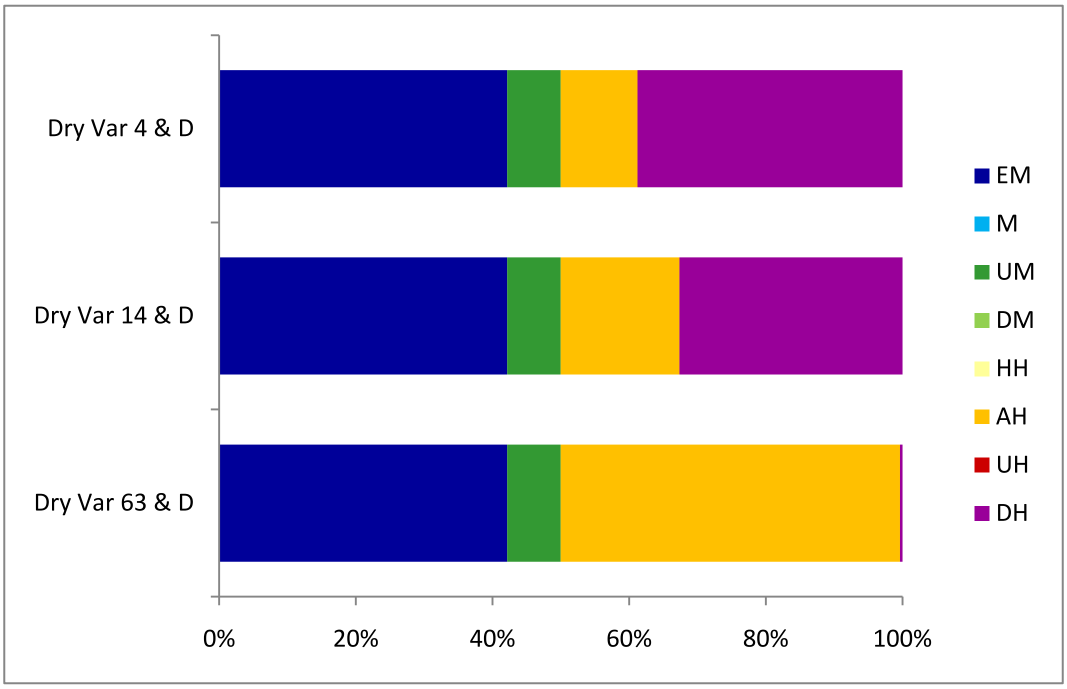

Figure 14.28: Comparing the proportion of site-years in each ecosystem for variable average USED volume with dredging scenarios under a dry future climate

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Information on how to read the figure is presented in Appendix E. Dry Var 4 & D is the Dry Variable 4 GL & dredging scenario, Dry Var 14 & D is the Dry Variable 14 GL & dredging scenario and Dry Var 63 & D is the Dry Variable 63 GL & dredging scenario.

Summary of ecological impacts

In summary, changes arising associated with an expanded USED scheme, from applying the ecosystem states model, involved increasing percentages of Average Hypersaline site-years and decreasing percentages of Degraded Hypersaline site-years. No other ecosystem state was affected under any of the scenarios explored. The relative percentages of Average Hypersaline site-years for each scenario are summarised in Figure 14.29. Increasing volumes of USED water resulted in increasing percentages of Average Hypersaline site-years under each scenario set. This effect of additional USED water was magnified with increasingly severe climate change scenarios. Variable inter-annual delivery of water from the USED resulted in slightly higher percentages of Average Hypersaline site-years than the same volume added consistently, year-to-year, under the same climate projection (except under the dry future climate where proportions were very similar but consistent delivery resulted in slightly higher proportions of Average Hypersaline site-years).

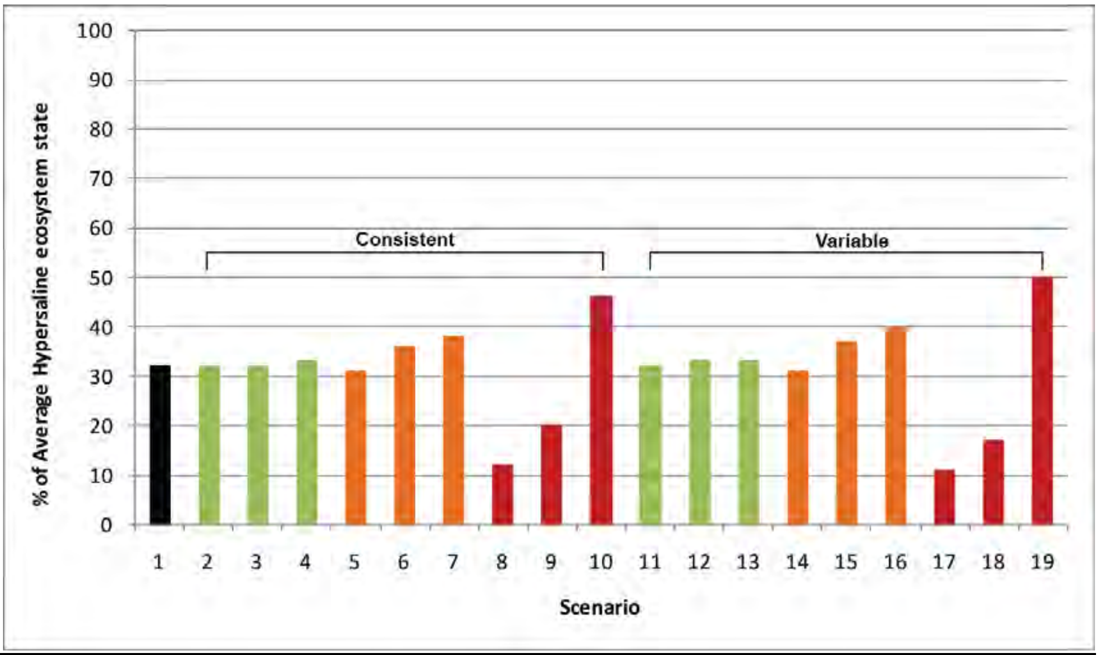

Figure 14.29: Percentage of Average Hypersaline site-years for each scenario explored

Note: Scenario numbers represent 1 = Baseline & dredging, 2 = Historical Consistent 18 GL & dredging, 3 = Historical Consistent 36 GL & dredging, 4 = Historical Consistent 63 GL & dredging, 5 = Median Consistent 9 GL & dredging, 6 = Median Consistent 24 GL & dredging, 7 = Med Con 63 & D is the Median Consistent 63 GL & dredging, 8 = Dry Consistent 4 GL & dredging, 9 = Dry Consistent 14 GL & dredging, 10 = Dry Consistent 63 GL & dredging, 11= Historical Variable 18 GL & dredging, 12 = Historical Variable 36 GL & dredging, 13 = Historical Variable 63 GL & dredging, 14 = Median Variable 9 GL & dredging, 15 = Median Variable 24 GL & dredging, 16 = Median Variable 63 GL & dredging, 17 = Dry Variable 4 GL & dredging, 18 = Dry Variable 14 GL & dredging, and 19 = Dry Variable 63 GL & dredging. Bar colours represent black = Baseline, green = Historic climate, orange = Median Climate, and red = dry future climate.

14.3.4 Interactions between USED and barrage flows

The effects of the additional USED water on maximum salinities, minimum water levels and the proportion of degraded ecosystem states were explored in more detail for high, moderate and low barrage-flow years under an historical climate scenario, with water from the USED scheme delivered consistently versus in a variable inter-annual manner. As for previous results, the variable inter-annual delivery pattern had the slightly larger impact and was more realistic, so only those results have been presented here.

Additional water did result in lower maximum salinities in the Coorong, with the largest changes occurring in the South Lagoon (Sites 8-14; Figure 14.30). Even under the highest barrage flows, there was also an impact on North Lagoon salinities, but this was always small (<10% decline). When barrage flows were high, the effect on maximum salinities was lower for the whole Coorong, and was always less than 10% in the North Lagoon, no matter what additional volume was delivered via the USED scheme. In the South Lagoon, reduction in salinity of approximately 30% were observed even with high barrage flows when 36 or 63 GL of USED water was added. Under moderate barrage flows, when large volumes (i.e. 63 GL per annum) were delivered via the USED scheme, there was a moderate impact on South Lagoon salinities (reductions of around 20%), while high USED flows combined with low barrage flows had a substantial impact on maximum South Lagoon salinities, with decreases of more than 40% at some sites.

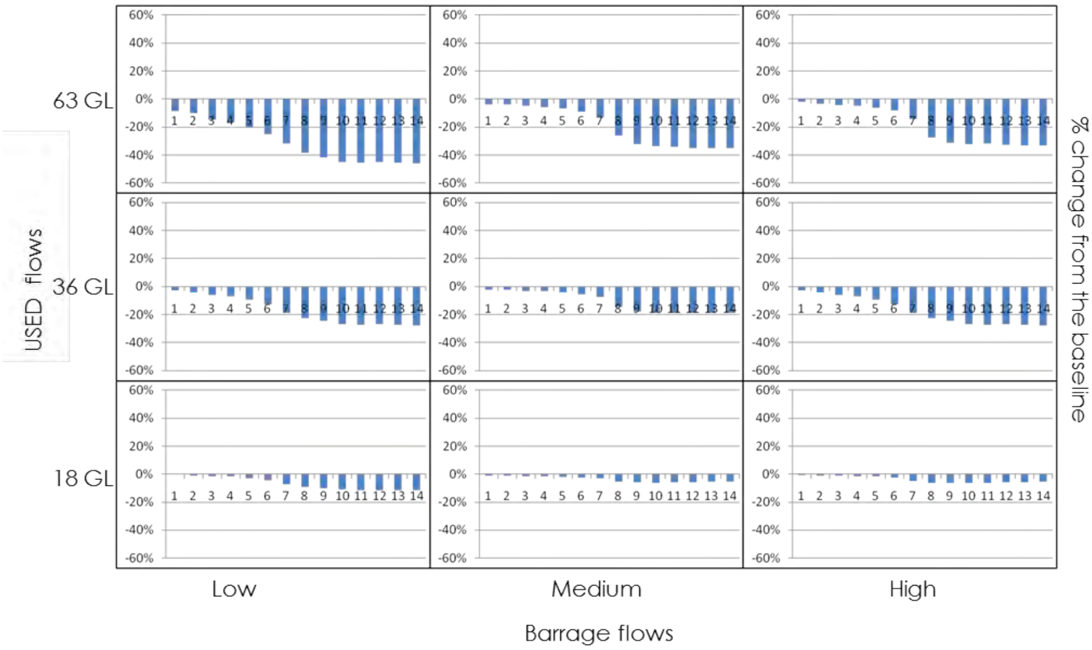

Figure 14.30: Matrix of interactions of high, medium and low barrage flows with 18, 36 and 63 GL via the USED scheme for percent change in maximum salinity

Note: Each panel includes the average percent change in maximum salinity across four years (refer to Section 14.2.5 for a list of years) based on a variable inter-annual delivery of USED flows. The percent change is calculated relative to the Baseline & dredging scenario. The x-axis shows sites along the length of the Coorong, with site 1 nearest the Murray Mouth, site 7 the southern-most North Lagoon site, site 8 the northern-most South Lagoon site and site 14 at Salt Creek in the South Lagoon.

There was a much smaller impact on water levels, even for high USED flows combined with low barrage flows (Figure 14.31). The maximum change predicted in minimum water level was only a 12% increase, and this was not uniformly observed across the whole of the South Lagoon. In some instances, the addition of water via the USED scheme was predicted to have a slightly negative effect on minimum water levels, but these changes were in the order of a few centimetres. These shifts are unlikely to be ecologically significant.

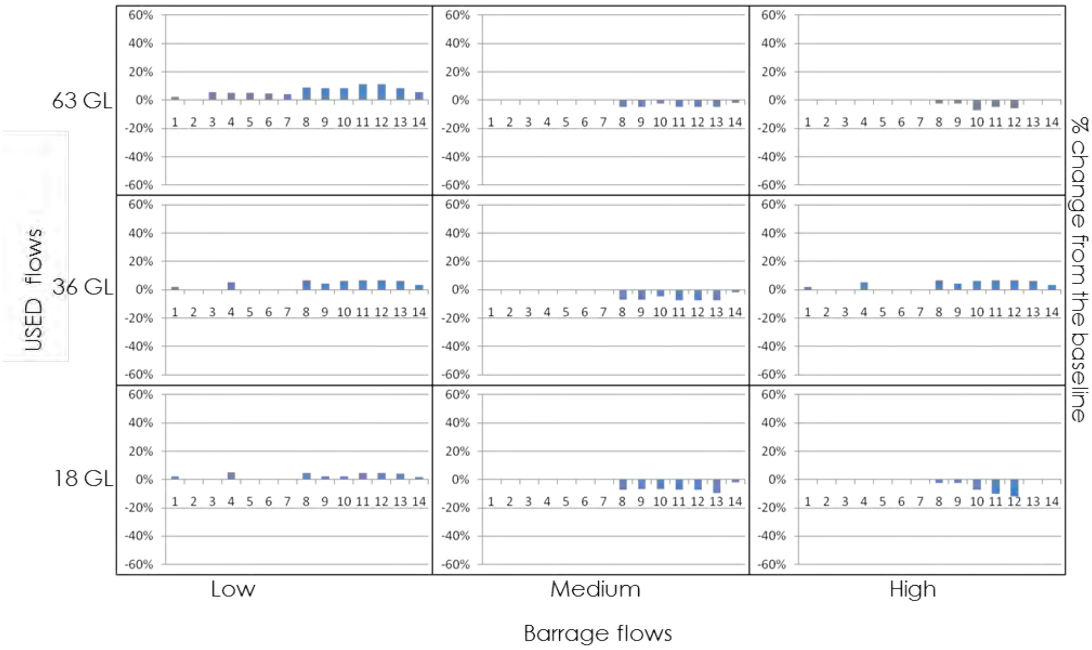

Figure 14.31: Matrix of interactions of high, medium and low barrage flows with 18, 36 and 63 GL via the USED scheme for percent change in minimum water level

Note: Each panel includes the average percent change in minimum water level across four years (refer to Section 14.2.5 for a list of years) based on a variable inter-annual delivery of USED flows. The percent change is calculated relative to the Baseline & dredging scenario. The x-axis shows sites along the length of the Coorong, with site 1 nearest the Murray Mouth, site 7 the southern-most North Lagoon site, site 8 the northern-most South Lagoon site and site 14 at Salt Creek in the South Lagoon.

There was relatively little change in the proportion of degraded ecosystem states under any combination of USED and barrage flows. Sites 10 to 14 (from the middle to the south end of the South Lagoon) were the only ones to show any alteration, changing ecosystem states in one year each under each of the low and high barrage-flow years when 36 GL water was added and when 63 GL was added in low barrage-flow years. Sites 10 and 11 also showed one fewer degraded ecosystem state when 18 GL was added during low barrage flow years. Thus, there was some improvement in South Lagoon ecosystem states under low barrage flow years with any of the volumes added via the USED scheme, but not a pattern of increasing levels of improvement with increasing USED volumes and decreasing barrage flows. This complex response is likely to be due to non-linearities in the model results, and it is unclear whether it would constitute an ecologically-significant change.

14.4 Discussion

Investigating the interaction of barrage flows and USED flows was designed to determine whether USED flows could be seen as an alternative source of water to the River Murray, particularly in times of low flows in the Murray-Darling Basin. Previous work (Lester *et al.* 2009c) indicated that volumes of at least 60 GL year^{-1} were required from the South East to have a substantial impact on South Lagoon hydrodynamics, but this investigation had assumed that recent drought conditions were ongoing, and thus may have been less relevant to a situation in which there were ongoing barrage flows. Here, we assumed that barrage flows would resume in line with simulated patterns under an historical, median future or dry future climate projection. Throughout the investigation, we assumed that the proposal for the USED scheme as outlined in DEH (2010) would apply and that intra-annual flows would follow a standardised pattern consistent with the average proposed flow delivery across flow paths from Peters *et al.* (2009), and that the pattern of inter-annual flows would be consistent with historical USED flow records. Differences in the hydrodynamics and ecosystem states of the Coorong have been observed previously with changes in flow delivery regime (Chapters 10 & 11), so should the proposed USED scheme expansion change, it would be necessary to investigate the effect of those changes on the findings presented here.

The results of this investigation suggested that there was a small, but not-unrealistic possibility that high flows would be available from the South East during low barrage flow years, given the moderate relationship between rainfall in the South East and barrage flows over the 22 years of the simulations used in this chapter. Thus, an expanded USED scheme would have some potential to provide water when River Murray water was relatively scarce (about 44% or just under half of times when needed). This was the first step in demonstrating that an expanded USED scheme may have the potential to influence Coorong hydrodynamics and ecological condition in times of low flows in the Murray-Darling Basin. However, in most instances, it is likely that high USED flows would correspond to high barrage flow years, when the additional water was not likely to be needed.

The next step in determining the potential influence of an expanded USED scheme was to model the effect of a range of flow volumes on the hydrodynamics and ecosystem states of the Coorong. In the majority of cases, the influence of the USED flows modelled here tended to be small for the majority of the time and at the majority of sites. Large average annual flows (e.g. modelled as 63 GL) were needed to have any substantial impact, both on the hydrodynamic conditions and the ecosystem states, in line with the recommendations of the previous study (Lester *et al.* 2009c). The exception was under climate change, where the larger volumes explored did result in substantial reductions in the proportion of the Degraded Hypersaline state, particularly under a dry future climate. It should be noted, however, that while decreasing percentages of Degraded Hypersaline site-years is always a positive outcome, simply increasing the percentage of Average Hypersaline site-years, as was the case here, may not be a uniformly positive outcome, depending on the corresponding proportion of Healthy Hypersaline site-years. For example, while the percentage of Average Hypersaline site-years under a dry future climate was higher than under an historical climate (see Figure 14.29), that was due to a lack of any Healthy Hypersaline site-years, which is likely to be a less than ideal outcome (although still an improvement on the large proportion of Degraded Hypersaline site-years predicted in the absence of additional USED flows). So the interventions explored here may not be sufficient to restore the ecological condition of the Coorong. Furthermore, in all cases explored, the effect on the North Lagoon was minimal or undetectable, while recent drought conditions have certainly had a negative impact on that lagoon also (Brookes *et al.* 2009).

Finally, the interaction between USED and barrage flows was explored. The influence of small, medium and large volumes of water from the expanded USED scheme (i.e. 18, 36 and 63 GL, respectively) was explored under low, medium and high barrage-flow years. High USED flows when barrage flows were low had a substantial impact on maximum salinities (up to 40% change) in the South Lagoon, although the impact in the North Lagoon was small. Moderate USED flows also reduced South Lagoon maximum salinities by approximately 20% under moderate or low barrage flows. When barrage flows were high, however, there was less impact, even for high USED flows. However, no combination of USED and barrage flows resulted in large changes in minimum water levels or in the percentage of degraded ecosystem states and, in some instances, slightly lower minima were predicted. Small and inconsistent changes in the percentage of degraded ecosystem states were observed, although when barrage flows were low, additional water from the USED scheme resulted in at least two fewer degraded site-years. This suggests that, although there was some influence on maximum salinities and South Lagoon ecosystem states as a result of USED flows, the change was not likely to be sufficient to have a regular impact on either the general hydrodynamics nor the ecological condition of the region as a whole. As a result, we conclude that the River Murray must remain the primary source of fresh water to the Coorong if the current ecological condition is to be maintained, whether the USED scheme is extended or not.

This investigation focused on the changes that additional water via the USED scheme could have on the hydrodynamics & ecosystem states of the Coorong, but did not actively explore whether an expanded USED scheme could replace some part of the EWR recommended here. Further research would be required to determine whether any change in the EWR could occur if the proposed USED scheme were to be expanded. Additional research could also investigate the impact of a range of potential flow regimes beyond the one considered here. At the time of writing, such detail was not available, so could not be included. Given the predicted effect of flow regime change on the ecological condition of the Coorong, the latter has the potential to be significant, but large reductions in the EWR from the River Murray proposed here for the CLLMM region would be unlikely.

14.5 Summary

- **We made a preliminary investigation into interactions between USED and barrage flows and their effects on Coorong hydrodynamics and ecosystem states.**
- **Additional flows from the USED scheme appear possible in 44% of years when barrage flows are low.**
- **Additional flows via the USED scheme had the largest influence on maximum salinity, with mixed results on water levels and little influence on ranges in water level or depth. Only very small changes were simulated for the North Lagoon, and patterns were consistent across climate projections.**
- **The additional flow volumes investigated were predicted to result in fewer degraded ecosystem states, particularly under climate change, but states thought to be associated with high flows were not induced, and no change was observed in the North Lagoon for any volume under any scenario.**
- **Additional investigation of the impact of increasing flow volumes under low, medium and high barrage flows show that the largest impacts were on maximum salinities in the South Lagoon, when barrage flows were low. Changes in minimum water level were small but there was some reduction in the percentage of degraded ecosystem states.**
- **The River Murray must remain the primary source of fresh water for the Coorong to maintain Ramsar-listed ecological condition, but expanding the USED scheme could provide a useful insurance policy for the South Lagoon if EWRs are not met.**

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16. Appendix A: Salinity and electrical conductivity

Rebecca E. Lester, Ian T. Webster & Peter G. Fairweather

The salinity of a water body is the mass of iconic compounds per unit volume of water (Williams 1986). Salinity is commonly measured as g L^{-1} or mg L^{-1} (equivalent to parts per thousand and parts per million respectively).

Electrical conductivity (EC) is a measure of the water's ability to conduct an electrical current. Electrical conductivity (measured at 25°C in units of mS cm^{-1} or µS cm^{-1}) can be used to estimate salinity because a relationship exists between the levels of dissolved salts in a water body and its conductivity.

Williams (1986) established a linear relationship between the salinity and EC for Australian salt lakes. It should be noted that this relationship does not hold for freshwater lakes (salinity below 3 g L^{-1}), when an increased diversity of ions is present, or in highly saline water (>70 g L^{-1}). Organic acids can also contribute to the conductance of water, particularly in freshwater, thus altering the relationship between salinity and EC (Boulton & Brock 1999). Thus a separate equation was used for low salinities (<3 g L^{-1}) (Hart *et al.* 1991).

It should be noted that electrical conductivity and salinity are not interchangeable, and that temperature and overall salinity levels can affect the conversion between the two. Thus, conversions should be interpreted with care (as the measured temperature is often not reported to assist with the conversion), and wherever possible, the units in which measurements were made should be retained. However, to allow for easier comparisons across different units, the following formulae can be applied to convert between salinity and EC (assuming that measurements were taken at 25 °C):

- For salinity <3 g L^{-1} (EC <5500 µS cm^{-1}) : Salinity = 0.68 µS cm^{-1} EC (Hart *et al.* 1991)
- For salinity >3 g L^{-1} (EC >5500 µS cm^{-1}) : Salinity = 0.466 µS cm^{-1} EC (Williams 1986)

17. Appendix B: Abbreviated outcomes table

Table 17.1 lists the ecological outcomes and the abbreviation of each which has been used throughout this report. In previous documentation relating to this work, Roman numerals have also been used to refer to each outcome so those are included here for completeness.

Table 17.1: List of abbreviated outcomes for each of the objectives

No.	Abbreviated outcome	Outcome
Self-sustaining populations		
i.	Successful recruitment	Successful recruitment of local breeding species occurs through time (i.e. individuals recruit often enough to sustain the population)
ii.	Suitable habitat	Suitable habitat exists for breeding, feeding, shelter and development of individuals to accommodate all life history stages (Closs *et al.* 2004)
iii.	Suitable food resources	Suitable food resources exist for a variety of species (Closs *et al.* 2004)
iv.	Suitable water quality	Water quality within tolerances for all life history stages for a variety of species for the majority of time (Boulton & Brock 1999; Closs *et al.* 2004)
Population connectivity		
v.	Species connectivity	Exchange of species occurs between Lakes, Coorong, from upstream habitats, regional wetlands and tributaries (including the South East of South Australia), the ocean (and possibly other nearby estuaries) and terrestrial environments to enable spatial connectivity (Closs *et al.* 2004)
vi.	Viable propagule bank	Viable propagule banks exist to enable temporal connectivity (Boulton & Brock 1999)
vii.	No barriers to recruitment	No barriers to connectivity (either physical, temporal or seasonal) exist that prevent eventual intraspecific connectivity amongst life history stages/sexes for the purpose of breeding or recruitment (Closs *et al.* 2004)
Hydraulic connectivity		
viii.	Lateral hydraulic connectivity	Floodplains (& mudflats, island habitats etc.) are hydraulically connected laterally to permanent water bodies (e.g. via a variable flow regime) (Boulton & Brock 1999; Edgar 2001)
ix.	Water residence times finite	Residence times for water in each of the management units are not infinite
x.	Regional hydraulically connected	The River, Lakes, tributaries, Coorong, ocean and South East are hydraulically connected. Ideally this would mimic natural levels of connectivity but at a minimum it needs to occur often enough during periods that are critical for ecological functionality (e.g. seasonally and inter-annually) (Boulton & Brock 1999)
xi.	Longitudinal biological connectivity	Exchange of energy, nutrients and carbon between management units, and from upstream or to downstream of the site, indicating longitudinal connectivity of these parameters (Boulton & Brock 1999; Edgar 2001)
xii.	No accumulation of pollutants	Pollutants delivered to the site are passed through and do not accumulate at abnormally high rates (e.g. sediment, salinity, acid, metals, agrochemicals)
iv.	Suitable water quality	Water quality within tolerances for all life history stages for a variety of species for the majority of time (Boulton & Brock 1999; Closs et al. 2004). NB: This outcome also appears under Section 4.1.
Habitat complexity and diversity		
xiii.	Lateral habitat diversity	A diverse range of habitat units exist across the site both above and below the water line (e.g. submerged plants to reed

No.	Abbreviated outcome	Outcome
		beds to paperbark or samphire to ephemeral mudflats to clean shorelines)
xiv.	Habitat variability	There is temporal and spatial variability in available habitats
Persistent salinity gradient across site		
xv.	Range of salinities with appropriate maxima	Spatial and temporal variability of salinity stays within maximum salinity tolerances of a variety of species within discrete habitat areas maintaining fresh, estuarine, marine and hypersaline communities. A range of salinities are represented across the site (with no areas outside maximum salinity tolerances for all life histories of a variety of species for extended periods or across extended areas) (Edgar 2001)
xvi.	Temporal variability in salinity	Salinities vary through time (with no areas outside maximum salinity tolerances all life histories of a variety of species for extended periods or across extended areas) (Edgar 2001)
xvii.	Communities requiring varied salinities supported	Communities requiring a variety of salinity regimes are supported across the site (e.g. ranging through fresh, estuarine, marine and hypersaline) (Edgar 2001)
Flow and water level variability		
xviii.	Temporal variability in flow	A range of flow volumes are delivered to the site through time (Boulton & Brock 1999)
xix.	Seasonal variability in flows	Seasonality of flows exists (mimicking the pattern of the natural hydrograph) (Boulton & Brock 1999)
xx.	Seasonal variability in water levels	Seasonality of water levels exists (mimicking natural patterns) (Boulton & Brock 1999)
xxi.	Communities requiring varied hydrology supported	Communities requiring a variety of hydrological conditions are supported across the site (e.g. patches of dry, ephemeral and permanently-inundated habitats)
xxii.	Communities requiring flooding supported	Communities and processes requiring occasional flooding (e.g. to cue spawning or stimulate germination) are supported by the site
xxiii.	Tidal signal apparent	A tidal signal is apparent in the Murray Mouth region
Redundancy and appropriateness of ecological function		
xxiv.	Complex food webs present	Complex, diverse food webs across the site
xxv.	Functions performed by multiple species	Multiple species are present that are capable of performing similar functions (e.g. shredding of organic matter, microbial processing, food sources) within the site
xxvi.	Efficient nutrient cycling	Working, efficient and appropriate cycling of nutrients and carbon occurs throughout the site with appropriate biogeochemical pathways present at each location (also with connections to upstream/downstream etc.)
xxvii.	Control of invasive species	Invasive species do not dominate and are not spreading uncontrollably through the region (Walker & Salt 2006)
xxviii.	Acid- & saline-tolerant & terrestrial species present	Proportions of acid-tolerant, saline-tolerant and terrestrial species remain approximately constant in the medium to long term (although these should vary spatially and on short temporal scales)
Aquatic-terrestrial connectivity		
xxix.	Wide riparian & littoral	Variable water levels allow wide riparian and littoral zones to develop and persist through time (both as plants and as

No.	Abbreviated outcome	Outcome
	zones supported	propagules) (Boulton & Brock 1999)
xxx.	Lateral connectivity of vegetation	Interconnected mosaic of diverse vegetation from terrestrial, through riparian and submerged down to the extent of the euphotic zone (Boulton & Brock 1999)
xxxi.	Balance of aquatic & terrestrial species	Ecosystem supports a balanced mix of terrestrial and aquatic taxa through space and time
xxxii.	Exchange between aquatic & terrestrial systems	Exchange of energy, nutrients and carbon occurs between aquatic and terrestrial ecosystems (Boulton & Brock 1999)
xxxiii.	Regular oxidation of sulfidic material	Variable water levels regularly oxidise sulfidic material and limit the formation of new acid sulfate soils around the shallow water margin

18. Appendix C: Literature on indicators

Table 18.1: Summary of available literature for each vegetation indicator regarding known tolerances to flow-related variables

Note: Citations are numbered for ease of presentation. A key to the numbers is located at the end of this table. Location symbols are defined as follows: Lx = Lake Alexandrina; Lb = Lake Albert; T = tributaries; RM = River Murray; MM = Murray Mouth; NL = North Lagoon of the Coorong; SL = South Lagoon of the Coorong; & O = Ocean.

Common name	Scientific name	Functional Group	Location	Life span	Flow-related requirements					Species Metric	Rationale
					Salinity* ($g\ L^{-1}$)	ARF	Connectivity	Water level (m AHD)	Timing		
Samphire & saltmarsh communities	Including: Tecticornia *pergranulata* ssp. *pergranulata*, *Suaeda australis*, *Sarcocornia quinqueflora*, *Juncus kraussi*, *Sporobolus virginicus* & *Parapholis incurva*	Terrestrial damp Terrestrial dry	Lx, Lb, MM, NL, SL	Long-lived	*J. kraussi* requires salinities <20 ppt for growth & <7 ppt TDS for recruitment; *T. pergranulata ssp. pergranulata* shoot biomass greatest when <200 mol m^{-3} & >300 mol m^{-3} [2]; germination reduced at high salinities[3]; Can survive up to 80 ppt but with reduced growth & germination above 20 ppt[1]	Inundation require for seed germination[3]	Abundance is greater at reduced connectivity; Requires intermittent upstream connectivity to provide freshwater flows for estuarine habitat	Requires varied water levels for germination but prolonged inundation can lead to decomp'n[3]		Abundance; Distribution; Recruitment events; Population demography	• provide a food source for black-tailed godwit, curlew sandpiper, red-necked stint, sharp-tailed sandpiper & orange-bellied parrot[4] • provide habitat in riparian areas, including for wading migratory waterfowl[1] • may mediate a balance of nutrients & organic matter between the saltmarsh & other interacting systems[4] • are among the most productive known ecosystems & usually export energy into adjacent ecosystems[1] • tolerant of sedimentation & salinity fluxes[4] • under natural conditions are less prone to invasive species due to extreme conditions of salinity & waterlogging[4]
Paperbark	*Melaleuca halmaturorum*	Amphibious fluctuation tolerator - woody	Lx, MM, NL, SL	Long-lived (>100 years)[5]	Salinities of 43 ppt do not affect survivorship but growth is dramatically reduced[6]	Inundation required for seed germination[5]	Requires lower salinities to germinate & recruit[7]	Varied water levels allow for seed germination[5]	Flowers late spring[5]	Abundance; Distribution; Recruitment events; Population demography	• dominant riparian habitat present in LL, MM & C • survivorship of seedlings dependant on age & size[5] • productive habitat for fauna as important rookery sites, nesting & sheltered feeding grounds[8] • provide food source for insect & bird species[5] rabbits[9] & detrital inputs are an important food source for aquatic food webs[10] • Seeds require exposed sediment to germinate, remain viable between 30 & 80 days[5]
Lignum	*Muehlenbeckia florulenta*	Amphibious fluctuation tolerator - woody	Lx, Lb MM	Long-lived[11]	Tolerant of >100 ppt[12]	Frequent floods promote vigorous growth	Occurs on floodplains inundated 3 – 10 years[13]	>0.6 for >1 year increases mortality[14]		Abundance; Distribution; Recruitment events; Population demography	• common perennial shrub found in ephemeral swamps & floodplains[11] • provides habitat for native & feral animals[11] • can survive without rainfall or flooding & is saline tolerant[13] • widely distributed in MDB[13] • important breeding habitat for water birds[13] & refuge for rabbits & feral pigs[11] • requires connectivity for seed dispersal[13]

Common name	Scientific name	Functional Group	Location	Life span	Flow-related requirements					Species Metric	Rationale
					Salinity* (g L^{-1})	ARF	Connectivity	Water level (m AHD)	Timing		
Diverse reed beds	Including: *Phragmites australis*, *Typha domingensis*, *Schoenplectus validus*	Amphibious fluctuation tolerator-emergent reeds	Lx, Lb	Perennial	*P. australis*: <10 ppt[13]; *T. domingensis*: <50 mM for growth & 100 mM for survival[13]; *P. australis* & *T. domingensis* observed in >17 ppt in LL[7]	Flooding at least every 2 years for survival of *P. australis*		<2	Budding & growth of young shoots in spring, flowers late summer-late march[14]	Abundance; Distribution; Recruitment events; Population demography	• common in stationary & slow moving water bodies[11] • important food & habitat for biota[11] • stabilise banks & prevent erosion[11] • tolerate brackish waters[11] • produce numerous seeds • vegetative growth more common in *Phragmites australis*[11]
Cutting grass sedgelands	Including: *Gahnia filium* & *G. trifida*	Amphibious fluctuation responder-floating	Lx, Lb, SL								
Water milfoils	*Myriophyllum salsugineum* & *M. caput-medusae*	Amphibious fluctuation responder-floating	Lx, Lb	Perennial	<9 ppt[15]					Abundance; Distribution; Recruitment events; Population demography	• submerged plants, widely dispersed throughout inland Australia[16] • seasonally emergent fruits & flowers • tolerant of slightly saline waters & often grows in brackish waters[11] • grows in shallow to deep waters[11] • important habitat for native fish[17], birds & frogs[18] • important food source for shrimp & waterbirds[19] • requires permanently-inundated habitats but can tolerate short periods of drought[16]
Ribbonweed	*Vallisneria australis*	Submergent *K*-selected	Lx, Lb	Perennial		Ideal flood timing: annually[13]		1.5 - 2[7]	Flowers in summer[13]	Abundance; Distribution; Recruitment events; Population demography	• submergent macrophyte which grows in shallow to deep water[16] • in eastern Australia, grows in flowing & stationary habitats • can grow in up to 7m depth in clear waters[13] • primary food source for aquatic taxa
Water ribbons	*Triglochin procerum*	Semi-emergent	Lx, Lb, T	Short-lived	Tolerant of 8 ppt for at least 6 weeks[20]			<2[11]	Seeds germinate in autumn, flowers in spring & summer; fruits in late summer & autumn[11]	Abundance; Distribution; Recruitment events; Population demography	• seeds germinate in autumn, generally in shallow water, & growth & flowering takes place in spring and summer[11] • fruiting occurs in late summer or autumn[11] • valuable habitat for waterbirds & fish[11] • water regime is the primary factor determining productivity of water ribbons[21]

Common name	Scientific name	Functional Group	Location	Life span	Flow-related requirements					Species Metric	Rationale
					Salinity* ($g L^{-1}$)	ARF	Connectivity	Water level (m AHD)	Timing		
Spiny rush	*Juncus acutus*	Pest, amphibious fluctuation responder-floating	Lx, Lb, MM		For germination <17.5 ppt[22]					Abundance; Distribution; Recruitment events; Population demography	• introduced estuarine rush • grows to 1.5m high in saltmarshes & dunes • requires wet soils for establishment but is intolerant of high water levels[23]
Large-fruited sea tassel	*Ruppia megacarpa*	Submergent *K*-selected	Lx, Lb, (NL)	Perennial	Tolerant of 12-50 ppt[24]	Requires freshwater flows for seed germin'n[25]		<3[25]	Flowers in summer & autumn[11]	Abundance; Distribution; Recruitment events; Population demography	• native, submerged perennial plants • extensive rhizome system • in particular conditions can complete a life cycle in 60-80 days[11] • important habitat for macroinvertebrates & meiofauna[26, 27] • provides food for invertebrates, fish & waterbirds[27, 28]
Tuberous sea tassel	*Ruppia tuberosa*	Submergent *r*-selected	Lx, Lb, NL, (SL)	Annual	Modelled salinity threshold 54.3 ppt[28]; recorded in salinities up to 230 ppt[29]	Fluctuating water levels required for germination		0.1 – 0.4[25]	Flowers & fruits Sept/Nov; seeds set before habitats dry in Nov/ Dec[29]	Abundance; Distribution; Recruitment events; Population demography	• grows in ephemeral habitats • seeds & turions are produced & lie dormant during dry habitat phases • important habitat for fish, macroinvertebrates & meiofauna[27, 28] • food source for invertebrates, fish & waterbirds[28]
Black Swamp vegetation	Mixed assemblages	Mixed groups									

* where salinity is given in units other than $g L^{-1}$, this has been specified.

Key to vegetation references:

[1] Nicol 2007
[2] Short & Colmer 1999
[3] Purvis *et al.* 2009
[4] Saintilan 2009
[5] Denton & Ganf 1994
[6] van der Moezel *et al.* 1991
[7] J. Nicol pers. comm.
[8] Phillips & Muller 2006
[9] Cooke 1988
[10] Gregory *et al.* 1991
[11] Sainty & Jacobs 1994
[12] van der Sommen 1980
[13] Chong & Walker 2005
[14] Rogers 2010a
[15] Orr *et al.* 1988
[16] Romanowski 1992
[17] Bice *et al.* 2008
[18] DWLBC 2010
[19] Roberts & Marston 2000
[20] Goodman *et al.* 2010
[21] Deegan *et al.* 2010
[22] Greenwood & MacFarlane 2006
[23] Florabase 2011
[24] Brock 1979
[25] Brock 1982a
[26] Geddes 2003
[27] Fogarty 2009
[28] Rogers & Paton 2009
[29] Brock 1981

Table 18.2: Summary of available literature for each macroinvertebrate indicator regarding known tolerances to flow-related variables

Note: Citations are numbered for ease of presentation. A key to the numbers is located at the end of this table. For location symbol explanations refer to Table 18.1. For metrics and rationale, refer to the tables in Chapter 7.

Common name	Scientific name	Functional Group	Life span	Flow-related requirements			
				Salinity* (g L^{-1})	Connectivity	Water level	Timing
				Generally macroinvertebrates without impermeable exoskeletons (e.g. pulmonate gastropods) not tolerant of elevated salinity & majority of freshwater macroinvertebrates tolerant up to 2[1]			
Freshwater crayfish (yabby)	*Cherax destructor*	Freshwater mobile	Approx. 4 years[5]	Adults more tolerant than juveniles; normal behavioural responses (loss of activity) affected at range of 12-18[3]; number of freshwater crustaceans display salinity tolerances in the lab that are well outside the range of salinities they occupy in nature; hence field salinity tolerance expected to be lower with range where behaviour not affected	Able to burrow & survive in ephemeral aquatic habitats; can survive several years between floods	Prefer to be under water, are able to survive drought[2]	Spawning period noted to be between July & January in WA[4]
Mayfly larvae	Ephemeroptera	Freshwater mobile (terrestrial flying adults)	Most adults are short lived, lasting only a matter of days or even hours[1]; larval life 40-110 days[6]	Baetidae LC50 range 3.7-5.4; non-baetid <8.6-10.2[7]			
Stonefly larvae	Plecoptera	Freshwater mobile (terrestrial flying adults)	Adults can live up to a month[1]	10.2-13.6[7]			Most adults emerge around spring or autumn
Caddisfly larvae	Trichoptera	Freshwater mobile (terrestrial flying adults)	Examples of very short-lived & adults that live for many months (e.g. *Odontocerum albicorne* & *Glyphotaelius pellucidus*, respectively)[8]	6.1-26.2[7]			
Amphipoda	Including *Melita zeylanica*, *Paracorophium* spp. & *Megamphopus* spp.	Freshwater mobile		10-60 for *Melita* & *Paracorophium*, & 10-50 for *Megamphopus*[9]; lower LD50 for *Melita* & *Paracorophium* is 1 ppt & upper LD50 is 62 for *Melita* & 60.5 for *Paracorophium* [10]	*Melita zeylanica* often associated with submerged wood	Elevated temperatures accelerate growth & condense life cycle[11]	
Hydra	*Hydra* spp.	Freshwater sessile	4 years sufficient time to exhibit signs of senescence (e.g. increased mortality)[12]	One of the most salt-sensitive invertebrate genera[13]; *H. Viridissima* laboratory salinity ranges 24 hr LC50 = 4.0; 48 hr LC50 = 3.3, 72 hr LC50 = 2.9 & 96 hr LC50 = 2.6[14]	Attach themselves to stones & submerged wood[2]	Most freshwater cnidarians are sessile, freely floating in the water column	Reproduces by asexual budding; when sexual reproduction occurs, there is no free-swimming stage
Freshwater mussel	*Velesunio ambiguus*	Fresh sessile (mobile larvae)	10-15 years (shells)[15]	observed to have sub-lethal effects at 2 (transition between osmoregulation & osmoregularity)[16]; sustainable populations unlikely at salinities >3.5[17]	Does not inhabit fast flowing water because cannot anchor against current[2]; young mussels	Able to tolerate prolonged dry spells, burying themselves in the mud & sealing shell tight	In winter, females brood young for spring/summer release[15]

Common name	Scientific name	Functional Group	Life span	Flow-related requirements			
				Salinity* (g L^{-1})	Connectivity	Water level	Timing
					attach themselves to gill tissues of fish & remain there until developed[2]	until water returns; may live out of water year or more[15]; endure low oxygen & high water temps[15]	
Segmented worms	Oligochaeta	Estuarine sessile	e.g. *Tubificoides amplivasatus* (subtidal species) long maturity time of 200 days inferring life span of several years[18]	Highly variable tolerance[18]	May resuspend or swim in water column to migrate to more favourable areas[19]	Non-pelagic larvae	Seasonal cycle, boom in summer & decline in winter; asexual reproduction[19]
Freshwater Limpets	Ancylidae	Estuarine sessile		Egg tolerance 6.3 (5.6-6.8), hatchling survival at 8.2 & older stage tolerance at 7.5[13]			
Brackish water crab	Hymenosomatidae		Studied field populations have 1-year life cycle, some survived in laboratory conditions >2 years after hatching[20]	Salinity range between 47-58.5 (*Amarinus lacustris*)[7]	After release juveniles drift with stream flow until they settle out onto substratum in downstream regions of no or low flow (*A. lacustris*)[20]	Reproductive cycle appears to show both ontogenetic & sex-related changes in habitat use during life cycle[20]	Non-ovigorous females Jan-April, ovigorous females first appear Aug - Sept & present in greatest numbers in Nov – Jan[20]
Blackfly larvae	Simuliidae			Low salinity tolerance between 3.5-6.8[21]			
Marsh Beetle	Scirtidae			LC50 salinity tolerance >20.4 (at both 72 hr & 96 hrs)[22]			
Tubeworms	*Ficopomatus enigmaticus*	Estuarine sessile	Longevity estimates include 20-24 months, 4-5 years & in lab conditions 10-12 years[23]	10-65; highest salinity at which large populations of active worms seen was 67, but some newly settled solitary individuals found in higher salinities; changes affect reproduction & may trigger spawning[24], optimal 10-30	Passive spawning with the water currents[23]	Grow larger & faster in shallow water with low salinity & current speeds[25]; common in low intertidal & shallow subtidal areas; pelagic larvae	Multi-annual spawners[23]
Bivalve	*Arthritica helmsi*	Estuarine sessile	Short life-cycle[26]	Ability to tolerate a wide range of salinities[26]; 15-35 ppt in winter & 25-55 ppt in summer; suffer mortality during high temperature & salinity; 10-45 ppt (*A. semen*)[27]	More abundant in permanently open estuaries[28]		Continuous reproduction
Polychaete worm	*Nephtys australiensis*	Estuarine motile	2+ years[29]	10-60; been collected from 5 -39[30]		Planktonic development of larvae in the water column[31]	
Polychaete worm	*Simplisetia aequisetis*	Marine mobile	Complete their life cycle in 1-1.5 years[32]	Reported in salinities 10-35; decline in abundance when salinity <5[30]; occurrence in subtidal sediment of Coorong salinities up to 70[33]			
Brine shrimp	*Parartemia zietziana*	Hypersaline mobile		>200[34]			
Goolwa Cockle	*Donax deltoides*	Marine sessile		Tolerant of salinities 20-45 ppt[35]	Essential to provide food supply through nutrient loading		

* where salinity is given in units other than g L^{-1}, this has been specified.

Key to invertebrate references

[1]James *et al.* 2003
[2] Gooderham & Tsyrlin 2002
[3] Mills & Geddes 1980
[4] Beatty *et al.* 2005
[5] Beatty 2005
[6] Marchant & Yule 1996
[7] Kefford *et al.* 2003
[8] Stevens *et al.* 2000
[9] Geddes 2005
[10] Kangas & Geddes 1984
[11] Neuparth *et al.* 2002
[12] Martinez 1998
[13] Kefford *et al.* 2007a
[14] Zalizniak *et al.* 2006
[15] Jennings *et al.* 2009
[16] Muschal 2006
[17] Walker 1981
[18] Giere 2006
[19] Nilsson *et al.* 2000
[20] Johnston & Robson 2005.
[21] Velasco *et al.* 2006
[22] Kefford *et al.* 2006
[23] Kupriyanova & Dittmann unpub. data
[24] Geddes & Butler 1984
[25] Schwindt *et al.* 2004
[26] Kanandjembo *et al.* 2001
[27] Wells & Threlfall 1982
[28] Hastie & Smith 2006
[29] Robertson 1979
[30] Dittmann *et al.* 2006
[31] King *et al.* 2004
[32] Beesley *et al.* 2000
[33] Geddes 2003
[34] Geddes 1976
[35] Nell & Gibbs 1986

Table 18.3: Summary of available literature for each fish indicator regarding known tolerances to flow-related variables

Note: Citations are numbered for ease of presentation. A key to the numbers is located at the end of this table. For location symbol explanations refer to Table 18.1. For metrics, refer to the tables in Chapter 8.

Common name	Scientific name	Functional group	Location	Flow-related requirements						Species Metric	Rationale
				Temp. (°C)	Salinity (g L^{-1})	ARF	Connectivity	Water level	Timing		
Murray cod	*Macquaria peelii peelii*	Large-bodied native freshwater predator	RM, Lx, Lb	10-30, spawn >15	Adults 14.5, LC50 direct transfer[1], larvae & juveniles 12, LC50 direct transfer[2]	Strong correlation suggested between recruitment and river flow[3]	RM, Lx, Lb		Spawning annually[4,5]	Abundance; Fisheries take; Movements; Distribution; Food web structure; Fish kills; Tissue composition	• large, iconic, long lived (>40 years) species[6] • now declining & EPBC-listed as vulnerable • commercial & recreational species in Lx & Lb • little recent data • feeds on fish, crustaceans & frogs[6] • prefers habitat with in-stream cover such as rocks, snags & deeper holes[6] • no significant recruitment below Lock 1 since 1994[7]
Golden perch	*Macquaria ambigua ambigua*	Large-bodied native freshwater predator	RM, Lx, Lb, MM(f)	Spawn > 20[6]	Tolerate rapid changes in salinity, 8.3 LC50 (larv)[1] 14.4 LC50 (ad)[8]	Flow-dependent spawning[9], prolonged increases of within-channel flows >15 000 ML day^{-1} [10,11]	RM, Lx, Lb, MM(f)		Spawn when flow-related conditions right[9,10,11]	Abundance; Fisheries take; Population demographics; Movements; Food web structure; Disease; Fish kills; Distribution	• widespread in RM & Lx • predominately found in lowland, warmer, turbid, slow-flowing rivers of the MDB[6] • adults are opportunistic carnivores, feeding on fishes, crustaceans & insects[6] • juveniles feed on insect larvae & microcrustaceans[6] • commercial fishery still operating in Lx but likely to be uncommon in Lb[12] • adults often associated with structure, deeper holes, & rocky areas[6] • completes life cycle in freshwater[13]
Bony herring	*Nematolosa erebi*	Large-bodied native freshwater	RM, Lx, Lb, MM(f)	9-38[15], spawn > 20[15]	< 35[16]		RM, Lx, Lb, MM(f)	>0.5 shallow bays Lx[15]	Spawn Lx shallows late spring/ summer[15]	Abundance; Fisheries take; Population demographics; Fish kills; Tissue composition	• common & widespread[6] • all life stages use variety of habitats[15,17] • adults open water[15,17] • spawning in shallow bays in Lx in late spring/summer[15]
Australian smelt	*Retropinna semoni*	Common small native freshwater	RM, Lx, Lb, MM(f)	11-15[18]	28 (juv)[19], 59 LC50 (ad)[20]	Spawning not flow-dependent	RM, Lx, Lb, MM(f)		Spawn spring/ summer[18,6]	Abundance; Population demographics; Disease; Fish kills; Food web structure	• common & widespread • prefer slow-moving or still-water habitats[21,22,6] • adults pelagic • open water taxon • opportunistic carnivore, feeding on zooplankton & insects[18]
Murray hardyhead	*Craterocephalus fluviatilis*	Rare small native freshwater	RM, Lx, Lb		≥ 30 >35[23]	Spawn not flow-dependent	RM, Lx, Lb		Spawn spring & summer[19]	Abundance; Population demographics; Recruitment events; Disease; Food web structure; Tissue composition; Distribution	• omnivorous small-bodied native freshwater species • formerly abundant but not declining & considered critically-endangered nationally[6] • associated with off-channel habitats & submerged vegetation[24] • observed >35 g L^{-1} salinity, highly tolerant[23] • omnivorous, primarily eating microcrustaceans, & some insects & algae[25,26]
Yarra pygmy perch	*Nannoperca obscura*	Rare small native freshwater	Lx, T	Spawn 16 -24[6]	6.3 LC50 (juv) 3.01[27]	Spawning & recruitment dependent on water level more than flow	Lx, T			Abundance; Population demographics; Recruitment events; Disease; Fish kills; Food web structure; Tissue composition	• restricted distribution to parts of Lx[28, 22] • highly associated with in-stream aquatic vegetation[29] • higher water means access to good quality nursery habitats • likely to be locally extinct[30]

Common name	Scientific name	Functional group	Location	Flow-related requirements: Temp. (°C)	Salinity (g L^{-1})	ARF	Connectivity	Water level	Timing	Species Metric	Rationale
Carp	*Cyprinus carpio*	Exotic fresh	RM, Lx, Lb, MM(f)	>15[31]	12.5, LC50 was 15 with acclimat'n [32]	Spawn in wetlands following inundation[33]	RM, Lx, Lb, MM(f)	Can survive in shallow water	Spawn spring & summer	Abundance; Fisheries take; Recruitment events; Food web structure; Population demographics	• common & widespread pest[6] • long lived (15-17 years[34]), oldest carp 32 years[35] • larvae & juveniles prefer wetlands & floodplains[19] • adults inhabit various habitats both open water & associated vegetation in Lakes[19] • tolerant of DO <1 mg L^{-1} for short periods[36] so may indicate degraded conditions • pH tolerance range from below 5.0 to above 10.5[37] • considered to be ecologically destructive because they re-suspend benthos & compete with native species for food & habitat[38,39]
Congolli	*Pseudaphritis urvillii*	Diadromous catadromous	RM, Lx, Lb, MM, NL		Tolerates a range of salinities. Relies on freshwater, estuarine & marine waters to complete lifecycle[6]	Every year (ideal), every 2 years (min); segregated sexes, diadromous[40]	RM, Lx, Lb, MM, NL barrages open required to complete life cycle		All times (ideal) Autumn - summer (min) downstream: autumn/ winter; estuarine/ marine spawning: winter/spring, upstream migrations: spring/ summer[40,41]	Abundance; Population demographics; Recruitment events; Distribution; Disease; Food web structure	• iconic diadromous fish (fresh-estuarine/marine connectivity)[6] • short-lived (<5 years)[41] • need to spawn & recruit at least every 2 years to be self-replicating • actual spawning locations unknown, probably pelagic eggs/larvae in estuary or sea, unlikely dependent upon vegetation[40] • larvae inhabit estuarine/marine habitats, juveniles inhabit estuary before migrating to freshwater habitats as adults[40,41] • adults require free movement between fresh & estuarine habitats[40,41]
Common galaxias	*Galaxias maculatus*	Diadromous catadromous	RM, Lb, Lx, MM		1-30[43], LC50 values of 62 after gradual acclimat'n & 45 after direct transfer. Observed in field at >49[42]		RM, Lx, Lb, MM		Migrate downstream to spawn in winter, juveniles migrate upstream in spring/ summer[40]	Abundance; Movements; Distribution; Recruitment events; Food web structure; Tissue composition	• native species common in LL[43,21,22] • opportunistic carnivore, consuming insects, microcrustaceans & amphipods[44] • reside in slow-flowing waters, streams, irrigation drain & lake margins[21,43,22] • migrate to estuaries to spawn[45,46] in winter[40] although can complete lifecycle in landlocked lakes[47] • eggs deposited on riparian vegetation & develop out of the water[18,19] • larvae develop in marine/estuarine habitat & migrate upstream in spring/summer[40] • many fish perish after spawning although some fish survive another year[18]
Short-headed lamprey	*Mordacia mordax*	Diadromous anadromous	RM, Lx, Lb, MM, O		Freshwater to marine[45]	Ammocetes move downstream in response to flows[48]	RM, Lx, Lb, MM, O		Upstream migration for spawning Aug-Nov[45]	Abundance; Recruitment events; Distribution; Movements	• primitive, native species[6] • marine/estuarine adult residence[18] • young adults are parasitic on fishes for 1-2 years then migrate upstream into rivers to spawn during August – November[45,18] • spawns in small, shallow, gravel-bottomed tributaries[18] • ammocetes prefer soft substrates in slow flowing waters near the stream edge[45,6] • ammocetes are filter feeders & live burrowed in sediments for several years before metamorphosing into adults & migrating downstream[18,6] • have been substantially affected by in stream barriers to movements[6] & have not been collected in the Coorong since 2006/2007[40]

Common name	Scientific name	Functional group	Location	Flow-related requirements						Species Metric	Rationale
				Temp. (°C)	Salinity ($g\ L^{-1}$)	ARF	Connectivity	Water level	Timing		
Yellow-eyed mullet	*Aldrichetta forsteri*	Estuarine	Lx, Lb, MM, NL		86 LC50 (juv)[19], <35 (adult)[49]	Fresh flows not important for spawning	Lx, Lb, MM, NL		Spawn January-March[50]	Abundance; Fisheries take; Population demographics; Food web structure; Disease; Distribution; Fish kills	• common in estuary & NL, rare in Lakes[51,19] • feed on detritus, seagrass, algae, polychaetes, molluscs & crustaceans[52,53] • larvae- estuarine/marine, juveniles - estuarine, structures or shallow beaches; adults - estuarine pelagic, deeper channels[51, 54] • spawn in Coorong specific sites unknown
Black bream	*Acanthopagrus butcheri*	Estuarine	Lx, Lb, MM		Peak concentration for larvae & eggs salinity 13-28 ppt[55]; adults observed 0.3->40[56, 57]	Fresh flows may be important for spawning, establishing estuarine conditions & a halocline to trigger spawning[58, 59]	Lx, Lb, MM free movement across barrages		Spawn between spring & summer in lower salinity water located around the halocline[58, 59]	Abundance; Fisheries take ; Distribution; Population demographics	• common in estuary, rare in Lakes[40] • commercial species with annual catches significantly declining in recent years[60] • observed moving into fishways[40] • adults found in estuaries, lower reaches of rivers & lakes, prefer deeper water with hard substrates & complex structure[60] • juveniles similar but probably prefer shallow habitats with complex structure (e.g. reefs)[19] • spawn in lower salinity water, located around halocline[58, 59] • freshwater flows may be important to successful recruitment & trigger spawning[55, 58, 59]
Small-mouthed hardyhead	*Atherinosoma microstoma*	Estuarine	RM, Lx, Lb, MM, NL, SL		Tolerant both low (LC50 3.3) & elevated salinities (LC50 108)[61]; been observed in salinities high as 100-130 [62, 63]; Only fish in SL when salinity >80 ppt[43]		RM, Lx, Lb, MM, NL, SL free movement across barrages		Spawns in multiple batches in spring (Aug-Dec) annually[64]	Abundance; Population demographics; Distribution; Recruitment events	• distributed across lakes & Coorong, only fish in South Lagoon in recent times[44] • generalist, euryhaline species (extremely wide salinity range) that moves between fresh & estuarine[64, 21, 22, 40, 61] • adults & juveniles typically estuarine & associated with submerged vegetation, but also occur in LL edge habitats or those with submerged aquatic vegetation[6] • environmental cues can trigger spawning (e.g. reduced salinity)[64] • critical part of trophic structure of Coorong as a consumer of zooplankton & insects & as a prey item for selected piscivorous birds[62, 6, 59]
Mulloway	*Argyrosomus japonicus*	Marine predator	Lx, Lb, MM, O			Aggregation of large fish around MM following discharge[66]; recruitment likely to be linked to barrage outflow[67]	Lx, Lb, MM, O barrages open, no dredges but MM open		Spawn likely spring & early summer[67, 68, 66]	Abundance; Population demographics; Distribution; Food web structure; Fish kills; Tissue composition;	• large, long-lived (>20 years) predator[53] • feeds primarily on fish but also crabs, prawns & worms[53] • moderately common in estuary, rare in Lakes • commercial species[12] • spawning unknown, likely possibly ocean beaches or near MM (adults aggregate spring/summer)[66] • likely larvae – ocean, juveniles use estuarine & hyposaline waters, typically deep holes & gutters, Coorong is nursery ground[66, 69] • adults near shore surf zone & occasionally enter estuaries; open water taxon[69]
Sandy sprat	*Hyperlophus vittatus*	Marine	MM, NL, O			Attempt to enter LL during freshwater discharges[70]			Attempt to enter LL during freshwater discharges[70]	Abundance; Food web structure; Population demographics; Fish kills;	• small-bodied marine clupeoid (max length ~10 cm[71]) • found in shallow bays, estuaries & coastal beaches[71] • highly abundant in Coorong[40] • pelagic spawning occurs in spring/summer in the gulfs & Coorong may be used as nursery area[71]

Common name	Scientific name	Functional group	Location	Flow-related requirements						Species Metric	Rationale
				Temp. (°C)	Salinity (g L-1)	ARF	Connectivity	Water level	Timing		
										Distribution	• live to 4 years old[71] • commercial species
Australian salmon	*Arripis truttacea*	Marine	MM, NL, O	Tolerant of extremes [53]	Tolerant of extremes but prefer estuarine to marine salinities[53]	Not dependent on freshwater flows	MM, O		Migrate to WA to spawn in autumn[72], enter Coorong as juveniles July -Sept[73]	Abundance; Distribution; Population demographics; Food web structure; Fish kills	• medium-sized piscivorous species[53] • adults inhabit surf beaches & surge zones around rocky reefs, juveniles utilise shallow bays & estuaries as nursery grounds[53] • juveniles common in the Coorong[75, 64] • tolerant of temperature & salinity extremes [53] • migrate to spawn from SA to WA in autumn[72], juveniles enter the Coorong July-September[73] • consume fish[72] including gobies & juvenile flounder[74] • mature 3-6 years, at ~700 mm in length & 5 kg[72] • maximum age ~9 years & weigh ~10.5 kg[72]
Bronze-whaler shark	*Carcharhinus brachyurus*	Large marine predator	MM, O		<38[54]	Not dependent on freshwater flows	MM, O			Abundance; Distribution	• large shark (>3m) [53] • nearshore species, common in surf zone & to depths of 100 m[53] • occasionally enters coastal bays, estuaries & inshore areas, including freshwater[53] • viviparous, giving birth to litters of 7-20 pups [53] • can live for up to 30 years[78] • consumes benthic & pelagic bony fishes & cephalopods[75, 76] • rarely found in Coorong but occasionally recorded by Lakes & Coorong fisheries[77]

Key to fish references

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[75] Campagno *et al.* 1989
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Table 18.4: Summary of available literature for each bird indicator regarding known tolerances to flow-related variables

Note: Citations are numbered for ease of presentation. A key to the numbers is located at the end of this table. For location symbol explanations refer to Table 18.1.

Indicator species Common name	Scientific name	Functional Group	Location where found	Flow-related requirements		Species Metric	Rationale
				ARI	Connectivity		
Black swan	*Cygnus atratus*	Resident euryhaline	RM, Lx, Lb, MM, NL, SL	Needs reeds or deep water to float nests[1]	RM, Lx, Lb, MM, NL, SL	Eggs, nests	• Breeding June-Sept • Need reeds for nest building & water deep enough to secure nests from predation until fledging • Ngarrindjeri well-being case study

Key to bird reference

[1] Phillips & Muller 2006

Table 18.5: Summary of available literature for each amphibian indicator regarding known tolerances to flow-related variables

Note: Citations are numbered for ease of presentation. A key to the numbers is located at the end of this table. For location symbol explanations refer to Table 18.1.

Common name	Scientific name	Functional Group	Location where found	Flow-related requirements				Species Metric	Rationale
				ARI	Connectivity	Water level (m AHD)	Timing		
Southern bell frog	*Litoria raniformis*	Resident, salt intolerant	RM, Lx, Lb	Needs wet reeds connected to permanent water over summer & autumn (submerged vegetation)	RM, Lx, Lb	Vegetation 0.3-0.6	Calls: Aug-April (reeds) tadpoles: summer/aut metamorph: late summer/autumn or overwinters[1]	Calls, tadpoles	• EPBC-listed • usually associated with vegetated wetlands often amongst sedges, submerged vegetation (e.g. *Vallisneria spiralis*) or logs • adults are opportunistic predators, known to be cannibalistic • adults are not adapted to saline environments • males call from August - April from reeds • tadpoles are free swimming, develop during summer & autumn with metamorphosis late summer & autumn • tadpoles may overwinter & metamorphose the following winter

Key to amhibian reference

[1] Phillips & Muller 2006

Table 18.6: Summary of available literature for each process indicator regarding known tolerances to flow-related variables

Note: Citations are numbered for ease of presentation. A key to the numbers is located at the end of this table. For location symbol explanations refer to Table 18.1 For metrics and rationale, refer to the tables in Chapter 9.

Process	Process Descriptor	Relevant taxa/examples	Location	Flow-related requirements					Process Metric	Rationale
				Turbidity	ARI	Connectivity	Water level (m AHD)	Timing		
Photosynthesis	Primary Producers	Plants & algae	RM, Lx, Lb ,T, MM, NL, SL	Reduces light penetration			0.3- >0.85	Spring freshes	Chl *a*, plant cover (%) & area (ha)	• need a balance between algal & plant primary production to give a range of detritus (energy captured by photosynthesis as organic material)[1] & provide food, oxygen & other services in a range of habitats
Decomposition	Detritivores	Macroinvertebrates bacteria, fungi, carbon, nutrient cycling	RM, Lx, Lb ,T, MM, NL, SL		Every year	RM, Lx, Lb, T, MM, NL, SL barrages open	>0.5 barrages open	Preferably at all times	Macroinvertebrate (presence & abundance), oxic:anoxic interface position, sediment redox, DOC, POM, biogeochemical cycles	• need a supply of a range of detritus (large, small, labile, refractile) to support a range of decomposers (which in turn are a range of food sources for fish & birds) & ensure energy (carbon) is flowing through appropriate biogeochemical processes (e.g. methane production dominating sulfate reduction in freshwater)[1] • carbon supplies biogeochemical cycles: inundation & exposure vs. decomposition rates
Nutrient cycling	Elements processed by organisms to give energy & build tissue	Macronutrients including carbon, hydrogen, oxygen, nitrogen & phosphorus, & micronutrients such as iron & chloride	RM, Lx, Lb ,T, MM, NL, SL				Water level may alter the rates of nutrient cycling	At all times	Rates of nitrification, denitrification, sulphate reduction rates, TKN & TP retention rates	• nutrient cycling is strongly linked to the hydrological cycle & thus may indicate hydraulic connectivity[2] • nutrient input & output are directly related to the volume of water moving in & out of the ecosystem[2] • cycling of nutrients indicates multiple species are present
Functional connectivity	Impedances to flow & species movement	Structures (e.g. barrages, regulators, weir); water levels; dredges; changes to flow timing	RM, Lx, Lb, T, MM, NL, SL		Every year	RM, Lx, Lb, T, MM, NL, SL barrages open MM open	>0.5, barrages open, MM open	Preferably at all times	Location of obstruction, degree of transparency, barrage opening (specific gates), bathymetry, MM depths	• barrages can be used to release water from the lakes from a height of +0.5 m AHD • barrages overtopped at +0.85 m AHD[3] • reverse head conditions limit barrage operations • temporary structures (either existing or proposed) need to be removed (or made ecologically transparent)
Response to salinity dynamics	Changes to water salinity	Macroinvertebrates vegetation & fish	RM, Lx, Lb, MM, NL, SL		Flush every year to keep Lx <1000 µS cm^{-1} EC	RM, Lx, Lb, T, MM, NL, SL, barrages open			Salinity concentration	• salinity influences biotic population dynamics, habitat complexity & ecological processes[4,5] • salinity can both directly or indirectly affect biota[4] • increasing salinity reduces the

Process	Process Descriptor	Relevant taxa/examples	Location	Flow-related requirements: Turbidity	ARI	Connectivity	Water level (m AHD)	Timing	Process Metric	Rationale
										exchange of oxygen & nutrients[4] • biodiversity generally decreases with increasing hypersalinity (>40 ppt)[6]
Response to acid/base dynamics	Exposure of sulfuric material & alkalinisation	Oxidation of ASS & mobilisation of products, pH	RM wetlands, Lx, Lb, MM		Flush every year to reduce S burden	RM, Lx, Lb, T, MM, NL, SL barrages open	0.3- >0.85 >trigger levels (min)	At all times	ASS (location, ha, % exposed), metals [ppt], pH (water & sediments), MBO (location, ha)	• target pH of 6.5 based on fish recruitment needs (for adults never <5, never >10) • exposure of sulfuric material (acid sulfate soils) leads to oxidation of sulfidic materials to sulfuric acid which liberates other sediment constituents (e.g. metals & metalloids)[6] • need to keep sulfuric material inundated to prevent oxidation[7] • alkalinisation can reduce productivity, quality & limit diversity of some vegetation[8] • alkalinisation can positively influence germination of marsh vegetation[9]
Response to sediment dynamics	Geo-morphological changes	Bathymetry, flow paths	RM, Lx, Lb, MM, NL, SL	May increases sediment deposition	Flush every year to transport suspended solids & algae	RM, Lx, Lb, T, MM, NL, SL, barrages open	>0.5 barrages open			• prevent sedimentation behind structures with flushing flows
Water clarity	Depth of light penetration reduced by turbid water	Suspended solids, algae	RM, Lx, Lb, MM, NL, SL	Reduces light penetration	Flush every year to transport suspended solids & algae	RM, Lx, Lb, T, MM, NL, SL barrages open	0.3-0.8 to promote vegetation		NTU, chl *a*, erosion of lake shore	• turbidity reduces light penetration, encourages biofilms & diseases[10] • algae & suspended solids carry carbon & nutrients to MM & out to sea
Terrestrialisation	Drying of water regime	Macroinvertebrates vegetation	RM, Lx, Lb ,T, MM, NL, SL		Floodplains inundated every 3-5 years	RM, Lx, Lb, T, MM, NL, SL barrages, open	>0.5 to >0.85		Proportion of terrestrial species	• terrestrialisation rates can indicate habitat diversity • seasonal trends often occur due to seasonal changes in hydrological cycles
Colonisation	Colonisation of plants & animals including pests	Invasive species include carp, *Juncus acutus*, Kikuyu, redfin, *Ficopomatus enigmaticus*	RM, Lx, Lb, MM, NL, SL		Floodplains inundated every 3-5 years	RM, Lx, Lb, MM, NL, SL (although not if water borne pests)			Carp, *Ficopomatus*, kikuyu, *Juncus acutus*, redfin	• colonisation of taxa only occur if suitable resources are available[11] • also can be used to determine colonisation of desirable taxa
Bioaccumulation	Toxicity & accumulation of carbon	Fish, vegetation, macroinvertebrates	Lx, Lb, MM (NL, SL)		Flush every year to prevent build-up	Lx, Lb, MM, O			Biotic distribution & biomass, rates of growths, recruitment, photosynthesis, productivity, & concentrations of As, Fe, Al.	• higher levels of metal or organic pollutants may cause a decline in community density, composition, & behaviour[12]

Process	Process Descriptor	Relevant taxa/examples	Location	Flow-related requirements					Process Metric	Rationale
				Turbidity	ARI	Connectivity	Water level (m AHD)	Timing		
Food web functionality	Linkages present between organisms	Vegetation, macroinvertebrates fish	RM, Lx, Lb ,T, MM, NL, SL			Increased connectivity will promote more diverse food webs		At all times	Biotic distribution, abundance & biomass; richness of functional feeding guilds, particularly predators, relative food chain lengths, diversity of nutrient & carbon	• richness of functional feeding guilds indicates suitable habitats & food sources exist for a variety of organisms[13,14] • presence of apex predators indicate suitable tropic pyramid[13,14] • biotic diversity indicates complex & diverse food webs exist

Key to ecological process references

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19. Appendix D: Metric tables

Table 19.1: Definitions for the metrics used in Chapters 6 – 9 with descriptions of the criteria for meeting the outcomes, presented in alphabetic order

Metric	Definition	Criteria for meeting outcome	Example applications
Abundance	Measure abundance of an organism at specified locations on a specified time interval & compare changes in abundance over space & time	Abundance of organism should change within expected bounds through time for the outcome to be met for each species (although location may shift with changing conditions). Any large shifts (whether increases or decreases), particularly across multiple species, should be considered potential indicators of changes in ecological condition & should be further investigated.	See also Changes in assemblage abundance through space &/or time
Change in assemblage diversity through space &/or time	Measure the number of taxa present as a part of a specific assemblage at specified locations on a specified time interval & compare changes in richness over space & time	Assemblage richness should remain relatively stable with time. Increases should indicate improving conditions (unless exotic species make for the increase). Decreasing richness may indicate unfavourable conditions & should be further investigated.	Depending on how specified, this metric could be used to identify changes in the distribution of one or more of the following examples: functional feeding groups; or benthic infaunal communities
Changes in assemblage abundance through space &/or time	Measure the relative abundance of a particular assemblage (or community) at given locations at specified time intervals	As for assemblage composition, abundances are also expected to change in response to changed environmental conditions, whether these are in space &/or time. Again, expected boundaries should be determined for the assemblages of interest & any abundances outside those bounds should be investigated as potential indicators of declining ecological condition. For example, vegetation cover should remain at a relatively constant level, at a level that is enough to provide sufficient habitat & ecosystem services but not so high that the vegetation smothers the area.	Depending on how specified, this metric could be used to identify changes in the abundance of one or more of the following examples: decomposers; or apex predators. Could also be used simply as presence/absence in some instances, or as cover or condition for vegetation assemblages
Changes in assemblage composition through space &/or time	Measure the composition of a particular assemblage (or community) at given locations at specified time intervals. Depending on how specified, this metric can be used to identify changes in space, through time, or both	Generally, assemblage composition is expected to shift naturally in space & time. Changes should be, however, within expected boundaries, with very large shifts, or trends of declining complexity (or increasing numbers of invasive species) thus likely to be indicative of a decline in ecological condition. Specific comparisons are likely to have additional requirements. For example, vegetation	The metric could also be used to identify changes in the composition of one or more of the following examples: mobile taxa; migratory taxa; functional feeding groups; particular life-history stages;

Metric	Definition	Criteria for meeting outcome	Example applications
		assemblage composition should consist of a range of species (esp. perennials) which remain relatively constant over temporal scales. Native species should be dominant, with no invasive species becoming more prevalent in any area. Migratory assemblages should not decline consistently through time.	vegetation; or phytoplankton
Changes in assemblage distribution through space &/or time	Map the presence of each category of interest (see example applications) through space &/or time	The distribution of assemblages should broadly remain within historical distribution ranges & should only alter within expected bounds. Small changes in distribution are likely to occur, particularly for fast-responding assemblages (e.g. planktonic assemblages), in response to drought, during particularly wet conditions or for seasonal changes. Large changes, or changes to areas outside previous known boundaries should be considered potential indicators for change.	Depending on how specified, this metric could be used to identify changes in the distribution of one or more of the following examples: decomposers; functional feeding groups; mobile taxa; phytoplankton; or biomass.
Changes in nutrient dynamics within the region	Obtain a measure of the nutrient dynamics for an assemblage (or location) of interest & compare that measure across specified locations at a specified time interval. Specific measures used could include employing BIOLOG plates to measure microbial carbon sources, for example, or switches between clear- & turbid-water states for lake ecosystems	Whether changes in nutrient dynamics are considered to be positive or negative again depends on the exact variable that is changing. In many instances, there is little information available on the effect of changing nutrient dynamics, but this represents a significant knowledge gap & should be addressed. As a first step, expected ranges should be set for each variable & changes outside that range should be investigated. Particularly at first, it is possible that changes outside the range may not be ecologically meaningful (depending on the range set, esp. for limited experience) or that the ranges may be set to broadly & that changes within the range may have adverse effects. In either instance, the range should be refined so that it is (eventually) ecologically relevant.	Depending on how specified, the metric could be used to detect changes in, for example: the diversity of sources of nutrients (e.g. via stable isotope analysis); uptake, exchange &/or output rates of nutrients (e.g. by terrestrial plants); changes in the nutrient budget for a specified region
Changes in photosynthetic activity in space &/or time	Obtain a measure of the photosynthetic activity occurring within an ecosystem of interest & compare that measure across specified locations at a specified time interval	As for nutrient dynamics, the ecological consequences of measures of photosynthetic activity are largely not well-understood. Again, preliminary ranges of acceptable change should be set empirically & then refined as the ecological consequences of a range of values become apparent.	Specific measures of photosynthesis could include, for example: PAM fluorometry; the relative proportions of different photosynthetic pigments; or NDVI scores across the site as a whole
Changes in population demographics	Obtain a measure of the demographics of a population of interest & compare	Whether changes in population demographics are considered to be positive or negative will depend on the	The measure of demography could include, for example:

Metric	Definition	Criteria for meeting outcome	Example applications
	that measure across specified locations at a specified time interval. This metric may also be specified to be a measure of the variability of population dynamics or for specific assemblages (e.g. vegetation or phytoplankton)	precise measure being considered. In general, increases in the proportion of (or a consistent number of) young individuals is likely to be indicative of good ecological condition (although this does not hold for invasive species). Variability is natural, particularly for taxa that have environmental recruitment cues (e.g. to flooding) & expected ranges should be defined empirically for each metric. Changes outside that range should be investigated as they may be indicative of a negative shift in ecological condition.	the number of young of yea (YoY); the presence of seedlings or tadpoles; or a size class distribution, depending on the population being considered
Changes in ratio of two groups (e.g. aquatic & terrestrial) of taxa through space &/or time	Obtain a measure of the relative quantity of each specified group & calculate a ratio of the two, comparing these ratios for different specified locations at specified time intervals. The quantity could be a measure of abundance, percent coverage or biomass, for example. Depending on how specified, this metric can be used to identify changes in space, through time or both. In some instances it is the variability, rather than the absolute value of the ratio which is of interest	Dimensionless ratios are excellent measures of the relative quantity of one group compared to another. For example, in a wetland system, you would expect to have a mixture of aquatic & terrestrial taxa. Changes in the ratio (outside of expected bounds) indicate that the balance of one group compared to the other has shifted, which may be indicative of declines in ecological condition. Using the previous example, large increases in either the proportion of aquatic or terrestrial taxa is likely to be indicative of negative change, with the former potentially indicating prolonged flooding & the latter prolonged drought. Large changes in the variability of the ratio (e.g. how quickly the value changes) are likely to be indicative of a decline in ecological condition.	Depending on how specified, this metric could be used to detect changes in the ratios of one or more of the following examples: acid-tolerant to sensitive; salt-tolerant to sensitive; taxa with a range of flooding requirements; or aquatic to terrestrial taxa
Changes in recruitment patterns through space & time	A measure of successful recruitment events should be identified for a specified assemblage. This measure should be compared for specified locations on a specified time interval	Whether changes (outside expected bounds empirically determined from prior studies) are considered to be positive or negative will depend on the parameter under consideration. Generally, shifts in recruitment patterns from those observed under optimal conditions can be considered to be indicative of a decline in ecological condition. However, for invasive species, any increase may be considered negative & *vice versa* for threatened species, even within historical bounds.	This measure could include the number of one or more of the following examples: taxa recruiting; eggs; "new" individuals; the range of FFGs recruiting. It could also include measuring the viability, distribution, abundance or diversity of propagules
Changes in the level of toxins in tissues in space &/or through time	Measure the concentration of a toxin (or pollutant) of interest in biotic tissue at specified locations at a specified time interval. An alternative could be to measure the rate of uptake of pollutants	For many toxins, precise concentrations at which negative effects are apparent are not available for the majority of taxa of interest. This is particularly the case for sub-lethal impacts (as opposed to LC50 values). However, changes in concentrations or a pattern of	

Metric	Definition	Criteria for meeting outcome	Example applications
	from sediments (e.g. by plants or detritivores)	increasing concentrations through time (or in space) are likely to be indicative of at least a finite risk of a decline in ecological condition. Acceptable concentrations of toxins in threatened species may be lower than for other similar taxa. As more information is gathered, acceptable ranges of values can be refined to be ecologically relevant.	
Changes in the rate of an identified process	Obtain a measure of the rate of an ecological process of interest & compare these rates across specified locations at specified time intervals. In some instances, it is the variability of the rate in question, rather than the absolute value, which is of interest, or in the overall budget for a process (e.g. nutrient budgets). The method which is used to measure process rates will vary with the process under consideration (e.g. placement of artificial litter bags to measure decomposition or invertebrate colonisation, marking of growing stems for vegetation growth rates)	Whether changes are considered to be positive or negative will depend on the process under consideration. Generally, increases in the rate of a process could be considered to be an increase in the activity or efficiency of an ecosystem. However, an increased rate of colonisation by an invasive taxon or in increased rates of sediment transport is more likely to indicate a stressed environment & should be seen as indicative of a negative ecological change. Some variability in the rate of processes is natural within an ecosystem, so expected ranges of change would need to be defined for each process in relation to previous experience & changes outside that range would be considered as potential indicators of a decline in ecological condition.	Depending on how specified, this metric could be used to detect changes in the rate of one or more of the following processes: decomposition; colonisation (e.g. of litter bags or by invasive taxa); growth rates; photosynthesis; nutrient input, uptake & loss; sediment oxidation; sediment transport
Changes in the structure or complexity of food webs through space &/or time	Measure the trophic links of the members of an assemblage using dietary studies or stable isotope analyses at specified locations on a specified time interval & compare changes in structure & complexity over space & time	Food web structure can provide an excellent understanding of the functionality of an assemblage. More complex food webs, with greater numbers of trophic levels (e.g. complex links amongst primary producers, first-order & higher-order consumers) can indicate good ecological condition (but recognising that some assemblages are naturally more complex than others). Decreases in the complexity of a food web or in the number of trophic levels may indicate declining ecological condition & should be further investigated.	Depending on how specified, this metric could be used to identify changes associated with one or more of the following examples: number of trophic levels; presence of terrestrial &/or aquatic fauna in gut contents; structure of food webs; or number of taxa identified per trophic level
Changes in water quality	Directly measure water-quality variables at specified locations over specified timeframes. Wherever possible, continuously-logged values & measurements taken through the water column are preferable to spot measurements. Where spot	In addition to understanding the ecological effects of changes in water quality, it remains important to know what the absolute values for water quality metrics are. Water quality should be within the specified healthy ranges for each variable, & for nutrients, within the relevant ANZECC water guidelines, or within known tolerances for the range of relevant life history stages of	Variables could include, for example: salinity; dissolved oxygen concentration; water pH; turbidity; & nutrient (e.g. various oxides of nitrogen, phosphate, carbon, ammonia) or suspended

Metric	Definition	Criteria for meeting outcome	Example applications
	measurements are necessary, replicate measurements should be taken	organisms of interest.	sediment concentrations
Detritus composition & condition	Obtain a measure of the range of sources of detritus (e.g. through stable isotope analyses), the amount present (e.g. via gravimetric or loss-on-ignition methods) or the condition of detritus (e.g. size fractions present) & compare this measure across specified sites at a given time interval	The range & condition of detritus available in an ecosystem is important as many taxa rely on detritus as a food source (either directly or indirectly via a detrital food chain). Having a diverse range of detrital sources, in a variety of conditions, is likely to provide the greatest resource for consumers & support the most diverse food web. As for other metrics, it is likely that the composition & condition of detritus will change naturally, so an expected range of acceptable variation should be set empirically. Measurements outside that range may indicate declining ecological condition & should be further investigated.	Depending on how specified, the metric could be used to detect changes in, for example: dissolved organic matter (DOM) or particulate organic matter (POM) concentrations; DOM to POM ratios; leaf litter coverage; variability &/or diversity of organic matter sources
Disease	Obtain a measure of the incidence of disease, or a surrogate measure, such as the overall condition of the organism	Increases in the incidence of disease will always be negative. For indirect indicators of disease, care may be needed that changes are in fact indicative of an increase in disease.	
Distribution	Map the presence of the organism through space	The distribution of an organism should change within expected bounds through time & should remain within any known historical distribution ranges for the organism. Small changes in distribution are likely to occur, particularly for mobile or short-lived species, in response to drought, particularly wet conditions or seasonal change. Large changes, or changes to areas outside previous known boundaries should be considered potential indicators for change.	See also Changes in assemblage distribution through space &/or time
Feeding rates	The feeding rates of filtrating taxa should be determined using the volume of water cleared per unit time over specified spatial & temporal scales. For deposit or other feeders, the ingestion rate of should be measured over specified spatial & temporal scales. For herbivores, predators or scavengers, feeding behaviours may also provide information on feeding rates	Steady increases in feeding rates are likely to indicate improvement in food availability & thus, potentially, ecological condition. Sudden changes may be indicative of a sudden shift in food availability so should be further investigated (e.g. feeding rates may increase suddenly if food availability declines as organisms expend additional energy to collect the same volume of food). Successful feeding, as opposed to feeding attempts, should be measured where possible.	
Fish kills	Determine the extent of any increases in frequency of fish mortality events over	No peaks in fish mortality events should be observed. Instances where fish mortality is greater than is expected	

Metric	Definition	Criteria for meeting outcome	Example applications
	specified spatial scales	naturally may be due to adverse environmental conditions & limited connectivity.	
Fisheries take	Level of take of fished individuals assessed as appropriate based on abundances from the previous year &/or the assessment of conditions for the current year (where stock are being assessed in real time)	Fisheries take can provide a measure of stock levels for upcoming years. Thus, persistent declines in fisheries take (e.g. fishing quotas or catch data) are likely to indicate declining ecological condition. Increases in quotas & catch numbers (provided the basis for setting quotas remains the same) may indicate an improvement in ecological condition.	Fishing quotas for *Donax deltoides* & catch data for various fish species
Food web structure	The isotopic signatures of taxa should be determined so that trophic levels can be compared over space & time	The isotopic signature of a taxon can indicate the prey items upon which it has been feeding. These prey items are likely to change depending on the ecological condition, & may be more diverse in good conditions. Large shifts in the food web structure (i.e. range of prey being consumed), particularly simplification of the structure, are likely to indicate negative changes in ecological condition & should be further investigated.	
Host presence (for *Velesunio ambiguus)*	Presence of the native fish species, such as Australian smelt, bony bream, golden perch, silver perch, catfish, Murray cod, flat-headed gudgeon, western carp-gudgeon, Mitchellian hardyhead & congolli (Hiscock 1951; Walker 1981), which can be hosts for the glochidia life stage of *Velesunio ambiguus* at relevant spatial & time scales	An absence of the range (or majority) of potential host species over periods longer than twice the usual interval of recruitment events (or ¾ of the known lifespan of the organism) should be considered indicative of a decline in ecological condition.	
Morphology	The morphology of some taxa is altered under adverse environmental conditions	Consistent morphology (such a bilateral symmetry), indicative of good environmental conditions, would indicate the outcome is being met. Changes in the incidence of sub-optimal morphology (such as fluctuating asymmetry) is likely to be an indicator of deteriorating ecological condition & should be further investigated.	
Movements	Determine the movements of fish taxa at specified locations over a specified time interval & compare changes over space & time	Fish movements should remain within their usual bounds through time. Large changes in the direction or distance of fish movements are likely to indicate adverse environmental conditions for fish species. Diadromous fish species (i.e. those requiring access to both fresh & estuarine/marine habitats) should move upstream or	Fish movement studies using acoustic tagging

Metric	Definition	Criteria for meeting outcome	Example applications
		downstream for spawning at relevant temporal scales.	
New settlement on mounds (*Ficopomatus enigmaticus)*	New settlement of *Ficopomatus enigmaticus* should be determined by marking current mounds appropriately & determining the new growth of the mound of relevant time scales	Rapid increases in the settlement rate of *Ficopomatus enigmaticus*, particularly relative to historical rates, are likely to indicate declines in ecological condition & should be further investigated. In the historically-estuarine regions, declines in settlement rates may also be a negative change.	
Population demographics	Determine the population structure at specified locations over a specified time interval & compare changes over space & time	The birth rates of populations should be at least equivalent to the death rates in any population, to indicate populations are not declining. Population demographics should remain within historic bounds, with a mix of larval, juvenile, young adult & senescent individuals & a shift to either end of that spectrum may indicate adverse changes in ecological condition.	The size & age structure of fish may indicate presence of recent recruitment events. Comparisons between freshwater & estuarine taxa or between two species or the sex ratio above versus below the barrages may also be relevant. See also Changes in population demographics
Presence of all life history stages	The presence of all relevant life history stages of taxa should be determined at relevant spatial & temporal scales	The presence of all life history stages for an organism over relevant temporal scales (e.g. seasonally) signifies that an organism is successfully recruiting through time. The absence of some life history stages, particularly juvenile stages, may be caused by inadequate ecological conditions & may result in a lack of recruits during that season. Not all organisms will use the region at all life history stages.	
Prevalence of *Ficopomatus* infestation	Determine the change in density of *Ficopomatus* mounds where already present & monitor relevant sites for arrival of *Ficopomatus enigmaticus*	Large increases in the density (or % cover or size) of *Ficopomatus* mounds in areas where *Ficopomatus* is already present & many new recruits inhabiting new areas should be considered indicative of infestations, which are likely to be a result of declines in ecological condition (i.e. increased salinities), particularly in traditionally freshwater areas.	
Ratio of oligochaete to polychaete abundance	Determine the abundances of Oligochaeta & Polychaeta (annelid worms) & the ratio between these, over relevant spatial & temporal scales	Oligochaeta are more indicative of freshwater environments, while Polychaeta are indicative of estuarine & marine environments. Shifts in the ratio at any one site through time are likely to indicate shifts in the ecological character (esp. salinity) of that region. Small fluctuations are likely to occur naturally, but large changes should indicate that further investigation is	

Metric	Definition	Criteria for meeting outcome	Example applications
		needed.	
Recruitment events	Successful recruitment events should be identified through the measurement of larval or juvenile recruits	The presence of larval or juvenile recruits is indicative that recruitment events are occurring. These should occur more than once within the known lifespan of the organism. No detected recruitment events over a period of ¾ of the known lifespan of an organism (or more than twice the usual interval between events, whichever is shorter) should be considered indicative of a decline in ecological condition & would warrant investigation.	See also Population demographics
Sediment organic content	The dry weight & loss on ignition (% organic content) of the sediment should be determined at specified locations on a specified interval & compare changes in sediment organic content in space & time	A range of concentrations of organic content in sediment should exist spatially throughout the site, but this should remain within expected bounds through time. Large shifts in sediment organic content are likely to indicate adverse changes in ecological condition.	See also Detritus composition & condition
Spawning events	Successful spawning events should be identified through the measurement of gametes in the environment.	The presence of gametes is indicative that spawning events are occurring. Spawning events should occur more than once within the known lifespan of the organism. No detected spawning over a period of ¾ of the known lifespan of an organism (or more than twice the usual interval between events, whichever is shorter) should be considered indicative of a decline in ecological condition & would warrant investigation. Note that timing of sampling is critical to successfully detecting spawning events, even when they are occurring.	See also Recruitment events
Taxon diversity	Measure the number of taxa present at specified locations on a specified time interval & compare changes in taxon richness over space & time	Taxon richness should change within expected bounds through time. Increases should indicate improving conditions (unless exotic species make for the increase). Decreasing taxon richness may indicate unfavourable conditions & should be further investigated.	See also Change in assemblage diversity through space &/or time
Tissue composition	Measure the concentration of appropriate tissues for known pollutants	Individual high concentrations (relative to appropriate guidelines or LC50 values) or steady increases in concentrations through time should be considered indicative of a decline in ecological condition.	See also Changes in the level of toxins in tissues in space &/or through time
Toxins in environmental media	Obtain a measure of the levels of toxins present within the sediment & compare this across specified sites at a given time interval	The level of toxins present should not increase above background levels. Any such increase is likely to indicate an adverse change in ecological character.	Depending on how specified, the metric could be used to detect changes in heavy metal concentrations

Table 19.2: Vegetation indicator metrics for each of the objectives and outcomes provided in Chapter 3, including the relevant temporal and spatial scales

Lx = Lake Alexandrina, Lb = Lake Albert, T = Tributaries, MM = Murray Mouth, NL = North Lagoon, SL = South Lagoon & O = Ocean. Refer to Table 19.1 for definitions for each metric used and a description of the likely significance of changes in each.

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
Self-sustaining populations					
Successful recruitment	Samphire & saltmarsh communities, paperbark woodlands, lignum, diverse reed beds, water milfoils, ribbonweed, water ribbons, spiny rush, *Ruppia megacarpa*, *Ruppia tuberosa*	Abundance	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing may vary for some taxa & could follow likely adverse conditions for aquatic plants
	Samphire & saltmarsh communities, paperbark woodlands, lignum, diverse reed beds, water milfoils, ribbonweed, water ribbons, spiny rush, *Ruppia megacarpa*	Distribution	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	
	Samphire & saltmarsh communities	Recruitment events	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods) &/or episodic following freshes	Timing of recruitment events for local samphire & saltmarsh species is unknown
	Paperbark woodlands	Population demographics	At specified* sites in Lx, MM, NL & SL	Annually (following high flow period)	
Suitable habitat	Samphire & saltmarsh communities, paperbark woodlands, diverse reed beds, ribbonweed, water ribbons, spiny rush, *Ruppia megacarpa*, *Ruppia tuberosa*	Abundance	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing may vary for some taxa & could follow likely adverse conditions for aquatic plants
	Samphire & saltmarsh communities, paperbark woodlands, diverse reed beds, ribbonweed, water ribbons, spiny rush, *Ruppia megacarpa*, *Ruppia tuberosa*	Distribution	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	
	Paperbark woodlands	Population demographics	At specified* sites in Lx, MM, NL & SL	Annually (following high flow period)	
Suitable food resources	Samphire & saltmarsh communities, paperbark woodlands, diverse reed beds,	Abundance	At specified* sites in Lx, Lb, T,	Twice yearly (following high & low flow periods)	Timing may vary for some taxa & could follow likely adverse

Desired outcomes	**Taxon/Assemblage**	**Metric**	**Spatial scale**	**Temporal scale**	**Notes**
	ribbonweed, water ribbons, *Ruppia megacarpa*, *Ruppia tuberosa*		MM, NL & SL		conditions for aquatic plants
	Samphire & saltmarsh communities, paperbark woodlands, diverse reed beds, ribbonweed, water ribbons, *Ruppia megacarpa*, *Ruppia tuberosa*	Distribution	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	
	Samphire & saltmarsh communities	Recruitment events	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing of recruitment events for local samphire & saltmarsh species is unknown
	Paperbark woodlands	Population demographics	At specified* sites in Lx, MM, NL & SL	Annually (following high flow period)	
Suitable water quality	Samphire & saltmarsh communities, spiny rush	Abundance	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing may vary for some taxa & could follow likely adverse conditions
	Samphire & saltmarsh communities, lignum, diverse reed beds, water milfoils, ribbonweed, spiny rush, *Ruppia megacarpa*, *Ruppia tuberosa*	Distribution	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	
	Samphire & saltmarsh communities	Population demographics	At specified* sites in Lx, Lb, MM, NL & SL	Annually (following high flow period)	
Population connectivity					
Species connectivity	Lignum	Distribution	At specified* sites in Lx, Lb & MM	Twice yearly (following high & low flow periods)	
	Water ribbons, *Ruppia tuberosa*	Abundance	At specified* sites in Lx, Lb, T, NL & SL	Twice yearly (following high & low flow periods)	Timing may vary for some taxa & could follow likely adverse conditions
Viable propagule bank	Samphire & saltmarsh communities, paperbark woodlands, lignum, diverse reed beds, water milfoils, water ribbons, *Ruppia megacarpa*, *Ruppia tuberosa*	Abundance	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing may vary for some taxa & could follow likely adverse conditions for aquatic plants
	Samphire & saltmarsh communities, paperbark woodlands, lignum, water milfoils, spiny rush	Distribution	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
No barriers to recruitment	Samphire & saltmarsh communities, water milfoils	Abundance	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing may vary for some taxa & could follow likely adverse conditions for aquatic plants
	Samphire & saltmarsh communities, lignum, water milfoils	Distribution	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	
	Samphire & saltmarsh communities, lignum	Population demographics	At specified* sites in Lx, Lb, MM, NL & SL	Annually (following high flow period)	
Hydraulic connectivity					
Lateral hydraulic connectivity	Samphire & saltmarsh communities, paperbark woodlands, lignum, diverse reed beds, *Ruppia tuberosa*	Abundance	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing may vary for some taxa & could follow likely adverse conditions for aquatic plants
	Samphire & saltmarsh communities, paperbark woodlands, diverse reed beds	Distribution	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	
Water residence times finite	Water milfoils, spiny rush	Distribution	At specified* sites in Lx, Lb & MM	Twice yearly (following high & low flow periods)	
	Spiny rush, *Ruppia megacarpa*	Abundance	At specified* sites in Lx, Lb, MM & NL	Twice yearly (following high & low flow periods)	Timing may vary for some taxa & could follow likely adverse conditions for aquatic plants
Region hydraulically connected	Samphire & saltmarsh communities, diverse reed beds, *Ruppia megacarpa*	Distribution	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	
	Ruppia tuberosa	Abundance	At specified* sites in Lx, Lb, NL & SL	Twice yearly (following high & low flow periods)	
Longitudinal biological connectivity	Samphire & saltmarsh communities	Detritus composition & condition	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions or flood events
No accumulation of pollutants	Samphire & saltmarsh communities	Abundance	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions
	Samphire & saltmarsh communities, paperbark woodlands, water milfoils, spiny	Distribution	At specified* sites in Lx, Lb,	Twice yearly (following	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
	rush, *Ruppia megacarpa*, *Ruppia tuberosa*		MM, NL & SL	high & low flow periods)	
Habitat complexity					
Lateral habitat diversity	Samphire & saltmarsh communities, water ribbons	Abundance	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions or flood events
	Samphire & saltmarsh communities, lignum, diverse reed beds, water milfoils, ribbonweed, water ribbons, spiny rush, *Ruppia megacarpa*, *Ruppia tuberosa*	Distribution	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	
Habitat variability	Ribbonweed	Distribution	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions or flood events
	Ribbonweed, *Ruppia tuberosa*	Abundance	At specified* sites in Lx, Lb, NL & SL	Twice yearly (following high & low flow periods)	
Persistent salinity gradient across site					
Range of salinities with appropriate maxima	Samphire & saltmarsh communities, paperbark woodlands, diverse reed beds, spiny rush	Abundance	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing may vary for some taxa & could follow likely adverse conditions
	Samphire & saltmarsh communities, paperbark woodlands, lignum, diverse reed beds, water milfoils, water ribbons, spiny rush, *Ruppia megacarpa*, *Ruppia tuberosa*	Distribution	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	
	Samphire & saltmarsh communities	Population demographics	At specified* sites in Lx, Lb, MM, NL & SL	Annually (following high flow period)	
	Diverse reed beds	Changes in assemblage composition through space & time	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions or flood events
Temporal variability in	Samphire & saltmarsh communities, paperbark woodlands, spiny rush, *Ruppia*	Abundance	At specified* sites in Lx, Lb,	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions or flood

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
salinity	*megacarpa*, *Ruppia tuberosa*		MM, NL & SL		events
	Samphire & saltmarsh communities, paperbark woodlands, spiny rush, *Ruppia megacarpa*, *Ruppia tuberosa*	Distribution	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	
Communities requiring varied salinities supported	Samphire & saltmarsh communities, paperbark woodlands, diverse reed beds	Abundance	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing may vary for some taxa & could follow likely adverse conditions or flood events
	Samphire & saltmarsh communities, paperbark woodlands, lignum, diverse reed beds, water milfoils, water ribbons, spiny rush, *Ruppia tuberosa*	Distribution	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	
	Samphire & saltmarsh communities	Population demographics	At specified* sites in Lx, Lb, MM, NL & SL	Annually (following high flow period)	
	Diverse reed beds	Changes in community composition in space & time	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions or flood events
Flow & water level variability					
Temporal variability in flow	Samphire & saltmarsh communities, paperbark woodlands, lignum, diverse reed beds	Abundance	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions or flood events
	Samphire & saltmarsh communities, paperbark woodlands, lignum, diverse reed beds, spiny rush	Distribution	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	
	Samphire & saltmarsh communities	Population demographics	At specified* sites in Lx, Lb, MM, NL & SL	Annually (following high flow period)	
	Diverse reed beds	Changes in community composition in space & time	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	
Seasonal variability in flows	Samphire & saltmarsh communities	Changes in assemblage composition	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
		through space & time			
	Paperbark woodlands, water ribbons, *Ruppia tuberosa*	Abundance	At specified* sites in Lx, MM, NL & SL	Twice yearly (following high & low flow periods)	
	Paperbark woodlands	Distribution	At specified* sites in Lx, MM, NL & SL	Twice yearly (following high & low flow periods)	
Seasonal variability in water levels	Samphire & saltmarsh communities, diverse reed beds	Changes in assemblage composition through space & time	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	
	Paperbark woodlands, diverse reed beds, water ribbons, spiny rush, *Ruppia tuberosa*	Abundance	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	
	Paperbark woodlands, diverse reed beds, spiny rush	Distribution	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	
Communities requiring varied hydrology supported	Samphire & saltmarsh communities, Paperbark woodlands, diverse reed beds, lignum, water milfoils, ribbonweed, water ribbons, spiny rush, *Ruppia megacarpa*, *Ruppia tuberosa*	Distribution	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions or flood events
	Paperbark woodlands, diverse reed beds, spiny rush, *Ruppia tuberosa*	Abundance	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions or flood events
Communities requiring flooding supported	Samphire & saltmarsh communities, water ribbons	Recruitment events	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing of recruitment events for local samphire & saltmarsh species is unknown. Seeds of water ribbons recruit in autumn & flower in spring/summer.
	Paperbark woodlands, water ribbons, *Ruppia tuberosa*	Abundance	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions or flood events
	Paperbark woodlands, lignum, spiny rush,	Distribution	At specified*	Twice yearly (following	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
	Ruppia tuberosa		sites in Lx, Lb, MM, NL & SL	high & low flow periods)	
Tidal signal apparent	Samphire & saltmarsh communities	Changes in assemblage composition through space & time	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions or flood events
Redundancy & appropriateness of ecological function					
Complex food webs present	Samphire & saltmarsh communities, paperbark woodlands, lignum, diverse reed beds, ribbonweed, water ribbons, *Ruppia megacarpa*, *Ruppia tuberosa*	Abundance	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing may vary for some taxa & could follow likely adverse conditions or flooding for aquatic plants
	Samphire & saltmarsh communities, paperbark woodlands, lignum, diverse reed beds, ribbonweed, water ribbons, *Ruppia megacarpa*, *Ruppia tuberosa*	Distribution	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	
Functions performed by multiple species	Paperbark woodlands, ribbonweed, water ribbons, *Ruppia megacarpa*	Abundance	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions
	Paperbark woodlands, ribbonweed, water ribbons, *Ruppia megacarpa*, *Ruppia tuberosa*	Distribution	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	
Efficient nutrient cycling	Samphire & saltmarsh communities, paperbark woodlands, lignum, diverse reed beds, ribbonweed, water ribbons, *Ruppia megacarpa*	Abundance	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing may vary for some taxa & could follow likely adverse conditions or flooding
	Samphire & saltmarsh communities, paperbark woodlands, lignum, diverse reed beds, ribbonweed, water ribbons, *Ruppia megacarpa*, *Ruppia tuberosa*	Distribution	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	
Control of invasive species	Samphire & saltmarsh communities, diverse reed beds	Abundance	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions
	Diverse reed beds, spiny rush	Distribution	At specified* sites in Lx, Lb &	Twice yearly (following high & low flow periods)	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
			MM		
Acid- & saline-tolerant & terrestrial species present	Samphire & saltmarsh communities, paperbark woodlands	Abundance	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions
	Paperbark woodlands, lignum, diverse reed beds, *Ruppia megacarpa*, *Ruppia tuberosa*	Distribution	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	
Aquatic-terrestrial connectivity					
Wide riparian & littoral zones supported	Samphire & saltmarsh communities, paperbark woodlands, spiny rush, *Ruppia tuberosa*	Abundance	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions or flooding
	Samphire & saltmarsh communities, paperbark woodlands, lignum, diverse reed beds, spiny rush, *Ruppia tuberosa*	Distribution	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	
	Diverse reed beds	Changes in assemblage composition through space & time	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions or flooding
Lateral connectivity of vegetation	Samphire & saltmarsh communities, paperbark woodlands, water ribbons, spiny rush, *Ruppia tuberosa*	Abundance	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions or flooding
	Samphire & saltmarsh communities, paperbark woodlands, lignum, diverse reed beds, water milfoils, ribbonweed, water ribbons, spiny rush, *Ruppia megacarpa*, *Ruppia tuberosa*	Distribution	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	
Balance of aquatic & terrestrial species	Samphire & saltmarsh communities, paperbark woodlands, lignum, diverse reed beds, water milfoils, ribbonweed, water ribbons, spiny rush, *Ruppia megacarpa*, *Ruppia tuberosa*	Distribution	At specified* sites in Lx, Lb, T, MM, NL & SL	Twice yearly (following high & low flow periods)	Timing could follow likely adverse conditions or flooding
	Water ribbons, *Ruppia tuberosa*	Abundance	At specified* sites in Lx, Lb, T, NL & SL	Twice yearly (following high & low flow periods)	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
Exchange between aquatic & terrestrial systems	Samphire & saltmarsh communities, paperbark woodlands, lignum, diverse reed beds, *Ruppia tuberosa*	Distribution	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	
	Samphire & saltmarsh communities, paperbark woodlands, lignum, diverse reed beds, *Ruppia tuberosa*	Abundance	At specified* sites in Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	
	Lignum	Detritus composition & condition	At specified* sites in Lx, Lb & MM	Twice yearly (following high & low flow periods)	
Regular oxidation of sulfidic material	No taxa identified as relevant	NA	NA	NA	

* Use existing monitoring sites where possible

Table 19.3: Macroinvertebrate indicator metrics for each of the objectives and outcomes provided in Chapter 3, including the relevant temporal and spatial scales

Lx = Lake Alexandrina, Lb = Lake Albert, MM = Murray Mouth, C = Coorong & SL = South Lagoon. Refer to Table 19.1 for definitions for each metric used and a description of the likely significance of changes in each.

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
Self-sustaining populations					
Successful recruitment	*Velesunio ambiguus*, Ephemeroptera, Amphipoda, Ancylidae, Hymenosomatidae, *Parartemia zietziana*	Abundance	At specified* sites in SL (for *P. zietziana*) & Lx & Lb (for remaining taxa)	Twice yearly (following high & low flow periods)	Timing for *P. zietziana* may vary
	Ephemeroptera, Plecoptera, Trichoptera, Amphipoda, *Hydra* spp., Ancylidae, Hymenosomatidae, *Parartemia zietziana*	Distribution	At specified* sites in SL (for *P. zietziana*) & Lx & Lb (for remaining taxa)	Twice yearly (following high & low flow periods)	Timing for *P. zietziana* may vary
	Cherax destructor, *Ficopomatus enigmaticus*, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp.	Recruitment events	At specified* sites in Lx, Lb & C	Twice yearly (following high & low flow periods), up to monthly for estuarine taxa	Recruitment events may be undesirable in freshwater locations for *F. enigmaticus*. Timing & frequency may vary among taxa
Suitable habitat	Ancylidae, Hymenosomatidae, Scirtidae, community composition	Abundance	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	
	Cherax destructor, Ephemeroptera, Plecoptera, Trichoptera, Amphipoda, Oligochaeta, *Hydra* spp., Ancylidae, Hymenosomatidae, Scirtidae, Simuliidae, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp., *Donax deltoides*	Distribution	At specified* sites in the C, Lx & Lb & around/outside MM	Twice yearly (following high & low flow periods)	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
	Ephemeroptera, Amphipoda	Taxon diversity	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	
	Velesunio ambiguus	Presence of all life history stages	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	
	Ficopomatus enigmaticus, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp.	Recruitment events	At specified* sites in Lx, Lb & C	Twice yearly (following high & low flow periods), up to monthly for estuarine taxa	Timing & frequency may vary among taxa
Suitable food resources	*Velesunio ambiguus*, *Cherax destructor*, Ephemeroptera, Plecoptera, Trichoptera, Amphipoda, Oligochaeta, *Hydra* spp., Ancylidae, Hymenosomatidae, Scirtidae, Simuliidae, community composition	Abundance	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	
	Ephemeroptera, Plecoptera, Trichoptera, *Parartemia zietziana*, *Hydra* spp., Ancylidae, Hymenosomatidae, Scirtidae, Simuliidae	Distribution	At specified* sites in SL (for *P. zietziana*) & Lx & Lb (for remaining taxa)	Twice yearly (following high & low flow periods)	Timing for *P. zietziana* may vary
	Amphipoda, Oligochaeta	Taxon diversity	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	
	Ficopomatus enigmaticus, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp., *Parartemia zietziana*, *Donax deltoides*	Feeding rates	At specified* sites in C & around/outside MM	Twice yearly (following high & low flow periods)	Timing for *P. zietziana* may vary
	Arthritica helmsi, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp.	Food web structure	At specified* sites in C	Twice yearly (following high & low flow periods)	
	Donax deltoides	Fishing quotas		Annually (spring - before season opening)	
Suitable water quality	Plecoptera, Trichoptera,	Abundance	At specified* sites in Lx	Twice yearly (following high	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
	Oligochaeta, Ancylidae, Hymenosomatidae, Simuliidae, community composition		& Lb	& low flow periods)	
	Velesunio ambiguus, *Cherax destructor*, Ephemeroptera, Plecoptera, Trichoptera, *Hydra* spp., Ancylidae, Hymenosomatidae, Simuliidae, *Ficopomatus enigmaticus*, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp., *Parartemia zietziana*, *Donax deltoides*	Distribution	At specified* sites in C, Lx & Lb & around/outside MM	Twice yearly (following high & low flow periods)	Timing for *P. zietziana* may vary
Population connectivity					
Species connectivity	Plecoptera, Trichoptera, Scirtidae, *Parartemia zietziana* (after adverse conditions), *Donax deltoides*	Abundance	At specified* sites in SL (for *P. zietziana*) & Lx & Lb & around/ outside MM (for remaining taxa)	Twice yearly (following high & low flow periods)	Timing for *P. zietziana* may vary
	Ephemeroptera, Plecoptera, Trichoptera, *Hydra* spp., Scirtidae, *Ficopomatus enigmaticus*, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp.	Distribution	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	
	Velesunio ambiguus	Recruitment events	At specified* sites in Lx & Lb	Annually (following high flow period)	Timing & frequency may need to be refined
	Ficopomatus enigmaticus	New settlement on mounds *(F. enigmaticus)*	At specified* sites in C, Lx & Lb	Annually (following high flow period)	
Viable propagule bank	Simuliidae (after adverse conditions), *Cherax destructor* (numbers underground)	Abundance	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	Timing may be refined depending on capture rates for *C. destructor* & may be episodic for

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
					Simuliidae
	Arthritica helmsi, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp., *Donax deltoides*	Recruitment events	At specified* sites in C, Lx & Lb & around MM	Monthly	Timing & frequency may vary among taxa. Peaks in recruitment events are likely for estuarine taxa & timing should be refined to reflect these
	Velesunio ambiguus	Host presence	At specified* sites in Lx & Lb	Annually (following high flow period)	
	Velesunio ambiguus	Spawning events	At specified* sites in Lx & Lb	Annually (following high flow period)	
No barriers to recruitment	Ephemeroptera, Hymenosomatidae, *Donax deltoides* (within size-classes)	Abundance	At specified* sites around/outside MM & Lx & Lb	Twice yearly (following high & low flow periods)	
	Ephemeroptera, Plecoptera, Trichoptera, *Hydra* spp., Ancylidae, Hymenosomatidae, *Ficopomatus enigmaticus*, *Simplisetia aequisetis*, *Capitella* spp.	Distribution	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	
	Cherax destructor, Plecoptera, Trichoptera, *Ficopomatus enigmaticus*, *Simplisetia aequisetis*, *Capitella* spp.	Recruitment events	At specified* sites in C, Lx & Lb	Annually (following high flow period), up to monthly for estuarine taxa	Timing & frequency may vary among taxa. Peaks in recruitment events are likely for estuarine taxa & timing should be refined to reflect these
	Velesunio ambiguus	Host presence *(for Velesunio ambiguus)*	At specified* sites in Lx & Lb	Annually (following high flow period)	
	Velesunio ambiguus	Spawning events	At specified* sites in Lx & Lb	Annually (following high flow period)	
Hydraulic connectivity					
Lateral hydraulic connectivity	Ephemeroptera, Trichoptera,	Abundance	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	Timing could follow likely adverse events or flooding
	Ephemeroptera, Trichoptera, *Arthritica helmsi*, *Nephtys*	Distribution	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	Timing could follow likely adverse events or flooding

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
	australiensis, *Simplisetia aequisetis*, *Capitella* spp.				
	Velesunio ambiguus	Recruitment events	At specified* sites in Lx & Lb	Annually (following high flow period)	Timing & frequency may vary among taxa. Timing could follow likely adverse events or flooding
Water residence times finite	Ephemeroptera, Ancylidae, Hymenosomatidae, Simuliidae	Abundance	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	Timing could follow likely adverse events or flooding
	Ephemeroptera, Plecoptera, Trichoptera, Oligochaeta, *Hydra* spp., Ancylidae, Hymenosomatidae, Simuliidae, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp.	Distribution	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	Timing could follow likely adverse events or flooding
Region hydraulically connected	Ephemeroptera, Hymenosomatidae, Simuliidae	Abundance	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	Timing could follow likely adverse events or flooding
	Ephemeroptera, Trichoptera, Hymenosomatidae, Simuliidae, *Ficopomatus enigmaticus*, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp.	Distribution	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	Timing could follow likely adverse events or flooding
Longitudinal biological connectivity	Trichoptera, *Hydra* spp., Simuliidae, *Capitella* spp.	Distribution	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	Timing could follow likely adverse events or flooding
	Simuliidae	Distribution	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	Timing could follow likely adverse events or flooding
	Capitella spp.	Sediment organic content	At specified* sites in C	Twice yearly (following high & low flow periods)	
No accumulation of pollutants	Ancylidae, Scirtidae, Simuliidae	Abundance	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	Timing could follow likely adverse events or flooding
	Ephemeroptera, Plecoptera,	Distribution	At specified* sites in Lx	Twice yearly (following high	Timing could follow likely

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
	Trichoptera, Amphipoda (tolerant taxa only), Oligochaeta, *Hydra* spp., Ancylidae, Scirtidae, Simuliidae		& Lb	& low flow periods)	adverse events or flooding
	Velesunio ambiguus, *Cherax destructor*, *Ficopomatus enigmaticus*, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp., *Donax deltoides* (for metals)	Tissue composition	At specified* sites in C, Lx & Lb & around/ outside MM	Twice yearly (following high & low flow periods)	Timing may need to be adjusted depending on initial results. Timing could follow likely adverse events or flooding
	Oligochaeta	Ratio of oligochaete to polychaete abundance	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	
Habitat complexity					
Lateral habitat diversity	Plecoptera, Trichoptera, Ancylidae, Scirtidae, Simuliidae, community composition	Abundance	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	
	Ephemeroptera, Ancylidae, Scirtidae, Simuliidae, *Donax deltoides*	Distribution	At specified* sites outside MM & in Lx & Lb	Twice yearly (following high & low flow periods)	
	Amphipoda	Taxon diversity	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	
Habitat variability	*Donax deltoides*	Distribution	At specified* sites outside MM	Twice yearly (following high & low flow periods)	
Persistent salinity gradient across site					
Range of salinities with appropriate maxima	*Parartemia zietziana*, community composition	Abundance	At specified* sites in SL	Twice yearly (following high & low flow periods)	Timing for *P. zietziana* may vary
	Velesunio ambiguus, *Cherax destructor*, Ephemeroptera, Plecoptera, Trichoptera, *Hydra* spp., Ancylidae, Hymenosomatidae, Scirtidae, *Ficopomatus*	Distribution	At specified* sites in C, Lx & Lb & around/outside MM	Twice yearly (following high & low flow periods)	Timing for *P. zietziana* may vary

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
	enigmaticus, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp., *Parartemia zietziana*, *Donax deltoides*				
	Amphipoda, Oligochaeta	Taxon diversity	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	
	Donax deltoides	Recruitment events	At specified* sites around/outside MM	Annually (spring - before season opening)	Timing & frequency may vary among taxa
Temporal variability in salinity	*Parartemia zietziana*, community composition	Abundance	At specified* sites in SL	Twice yearly (following high & low flow periods)	Timing for *P. zietziana* may vary
	Velesunio ambiguus, *Cherax destructor*, Ephemeroptera, Plecoptera, Trichoptera, *Hydra* spp., Ancylidae, Hymenosomatidae, Scirtidae, *Ficopomatus enigmaticus*, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp., *Parartemia zietziana*, *Donax deltoides*	Distribution	At specified* sites in C, Lx & Lb & around/ outside MM	Twice yearly (following high & low flow periods)	Timing for *P. zietziana* may vary
	Amphipoda, Oligochaeta	Taxon diversity	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	
	Capitella spp.	Sediment organic content	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	
Communities requiring varied salinities supported	Oligochaeta (saline tolerant taxa), *Parartemia zietziana*, community composition	Abundance	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	Timing for *P. zietziana* may vary
	Velesunio ambiguus, *Cherax destructor*, Ephemeroptera, Plecoptera, Trichoptera, Oligochaeta, *Hydra* spp., Ancylidae, Hymenosomatidae, Scirtidae, *Ficopomatus enigmaticus*, *Arthritica*	Distribution	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	Timing for *P. zietziana* may vary

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
	helmsi, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp., *Parartemia zietziana*				
	Amphipoda, Oligochaeta	Taxon diversity	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	
	Velesunio ambiguus, *Cherax destructor*, *Ficopomatus enigmaticus*, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp.	Recruitment events	At specified* sites in C, Lx & Lb	Annually (following high flow period)	Timing & frequency may vary among taxa
Flow & water level variability					
Temporal variability in flow	Ephemeroptera, Plecoptera, Trichoptera, *Hydra* spp., Amphipoda, Hymenosomatidae, Simuliidae, *Donax deltoides*, community composition	Abundance	At specified* sites in Lx & Lb & around/outside MM	Twice yearly (following high & low flow periods)	
	Velesunio ambiguus, *Cherax destructor*, Ephemeroptera, Amphipoda, *Hydra* spp., Hymenosomatidae, Simuliidae, *Ficopomatus enigmaticus*, *Arthritica helmsi*	Distribution	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	
Seasonal variability in flows	Oligochaeta, Hymenosomatidae, *Donax deltoides*, community composition	Abundance	At specified* sites in C, Lx & Lb & around/outside MM	Twice yearly (following high & low flow periods)	
	Velesunio ambiguus, *Cherax destructor*, Ephemeroptera, Trichoptera, Oligochaeta, Hymenosomatidae, *Arthritica helmsi*	Distribution	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	
	Plecoptera	Recruitment events	At specified* sites in Lx & Lb	Annually (following high flow period)	Timing & frequency may vary among taxa
Seasonal variability in	Oligochaeta,	Abundance	At specified* sites in C,	Twice yearly (following high	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
water levels	Hymenosomatidae		Lx & Lb	& low flow periods)	
	Velesunio ambiguus, *Cherax destructor*, Ephemeroptera, Trichoptera, Oligochaeta, Hymenosomatidae, *Ficopomatus enigmaticus*, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp.	Distribution	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	
	Ephemeroptera, Plecoptera	Recruitment events	At specified* sites in Lx & Lb	Annually (following high flow period)	Timing & frequency may vary among taxa
Communities requiring varied hydrology supported	Plecoptera, Trichoptera, Scirtidae, Simuliidae	Abundance	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	
	Velesunio ambiguus, *Cherax destructor*, Ephemeroptera, Plecoptera, Trichoptera, *Hydra* spp., Amphipoda, Ancylidae, Hymenosomatidae, Scirtidae, Simuliidae, *Ficopomatus enigmaticus*, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp., *Donax deltoides*	Distribution	At specified* sites in the Lx & Lb & around/outside MM	Twice yearly (following high & low flow periods)	
	Amphipoda	Taxon diversity	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	
Communities requiring flooding supported	Plecoptera, Trichoptera	Abundance	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	
	Velesunio ambiguus, *Cherax destructor*, Plecoptera, Trichoptera, Hymenosomatidae, *Ficopomatus enigmaticus*, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp.	Distribution	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	

Desired outcomes	**Taxon/Assemblage**	**Metric**	**Spatial scale**	**Temporal scale**	**Notes**
	Hymenosomatidae	Recruitment events	At specified* sites in Lx & Lb	Annually (following high flow period)	Timing & frequency may vary among taxa
Tidal signal apparent	*Ficopomatus enigmaticus*, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp., *Donax deltoides*	Distribution	At specified* sites in C, Lx & Lb & around/outside MM	Twice yearly (following high & low flow periods)	
	Donax deltoides	Recruitment events	At specified* sites outside MM	Annually (following high flow period)	
Redundancy & appropriateness of ecological function					
Complex food webs present	*Velesunio ambiguus*, Ephemeroptera, Plecoptera, Trichoptera, Ancylidae, Hymenosomatidae, Simuliidae, *Parartemia zietziana*, *Donax deltoides*, community composition	Abundance	At specified* sites in C, Lx & Lb & around/outside MM	Twice yearly (following high & low flow periods)	Timing for *P. zietziana* may vary
	Cherax destructor, *Ficopomatus enigmaticus*, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp., *Parartemia zietziana*, *Donax deltoides*	Distribution	At specified* sites in C, Lx & Lb & around/outside MM	Twice yearly (following high & low flow periods)	Timing for *P. zietziana* may vary
	Amphipoda, *Hydra* spp.	Taxon diversity	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	
Functions performed by multiple species	Plecoptera, Trichoptera, Ancylidae, Hymenosomatidae, Simuliidae, *Parartemia zietziana*, community composition	Abundance	At specified* sites in SL (for *P. zietziana*) & Lx & Lb (for remaining taxa)	Twice yearly (following high & low flow periods)	Timing for *P. zietziana* may vary
	Velesunio ambiguus, *Cherax destructor*, Simuliidae, *Ficopomatus enigmaticus*, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia*	Distribution	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
	aequisetis, *Capitella* spp.				
	Ephemeroptera, Plecoptera, Trichoptera, Amphipoda	Taxon diversity	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	
Efficient nutrient cycling	*Ficopomatus enigmaticus*, *Donax deltoides*	Feeding rate	At specified* sites in C, Lx & Lb & around/outside MM	Twice yearly (following high & low flow periods)	
	Arthritica helmsi	Food web structure	At specified* sites in C, Lx & Lb & around MM	Twice yearly (following high & low flow periods)	
Control of invasive species	*Parartemia zietziana*, community composition	Abundance	At specified* sites in SL	Twice yearly (following high & low flow periods)	Timing for *P. zietziana* may vary
	Ficopomatus enigmaticus	Distribution	At specified* sites in C, Lx & Lb & around MM	Twice yearly (following high & low flow periods)	
	Velesunio ambiguus	Prevalence of *Ficopomatus* infestation	At specified* sites in Lx & Lb	Annually (following high flow period)	Timing could follow adverse conditions
Acid- & saline-tolerant & terrestrial species present	Plecoptera, Trichoptera, Amphipoda, Oligochaeta, Ancylidae, Scirtidae, *Parartemia zietziana*, community composition	Abundance	At specified* sites in SL (for *P. zietziana*) & Lx & Lb (for remaining taxa)	Twice yearly (following high & low flow periods)	Timing for *P. zietziana* may vary
	Velesunio ambiguus, *Cherax destructor*, Plecoptera, Trichoptera, Ephemeroptera, Amphipoda, Oligochaeta, Ancylidae, Scirtidae, *Ficopomatus enigmaticus*, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp.	Distribution	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	
	Amphipoda	Taxon diversity	At specified* sites in C, Lx & Lb & around MM	Twice yearly (following high & low flow periods)	
	Ephemeroptera	Morphology	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	
Aquatic-terrestrial connectivity					
Wide riparian & littoral zones supported	Plecoptera, *Ficopomatus enigmaticus*, *Arthritica helmsi*, *Nephtys australiensis*,	Distribution	At specified* sites in C, Lx & Lb &	Twice yearly (following high & low flow periods)	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
	Simplisetia aequisetis, *Capitella* spp., *Donax deltoides*		around/outside MM		
Lateral connectivity of vegetation	No taxa identified as relevant	NA	NA	NA	
Balance of aquatic & terrestrial species	Ephemeroptera, Scirtidae, community composition	Abundance	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	
	Velesunio ambiguus, *Cherax destructor*, Ephemeroptera, Plecoptera, Scirtidae, *Donax deltoides*	Distribution	At specified* sites around/outside MM & in Lx & Lb	Twice yearly (following high & low flow periods)	
	Donax deltoides	Fishing quotas		Annually (following high flow period)	
Exchange between aquatic & terrestrial systems	*Cherax destructor*, Ephemeroptera, community composition	Abundance	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	
	Ephemeroptera, Plecoptera, Trichoptera, *Capitella* spp.	Distribution	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	
	Cherax destructor	Feeding rates	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	
	Ficopomatus enigmaticus, *Donax deltoides*	Feeding rates	At specified* sites in C, Lx & Lb & around/outside MM	Twice yearly (following high & low flow periods)	
	Capitella spp.	Sediment organic content	At specified* sites in C, Lx & Lb & around MM	Twice yearly (following high & low flow periods)	
	Donax deltoides	Fishing quotas		Annually (following high flow period)	
Regular oxidation of sulfidic material	*Velesunio ambiguus*, *Cherax destructor*, Ephemeroptera, Plecoptera, Trichoptera, *Ficopomatus enigmaticus*, *Arthritica helmsi*, *Nephtys australiensis*, *Simplisetia aequisetis*, *Capitella* spp.	Distribution	At specified* sites in C, Lx & Lb	Twice yearly (following high & low flow periods)	

* Use existing monitoring sites where possible

Table 19.4: Fish indicator metrics for each of the objectives and outcomes provided in Chapter 3, including the relevant temporal and spatial scales

Lx = Lake Alexandrina, Lb = Lake Albert, T = Tributaries, MM = Murray Mouth, NL = North Lagoon, SL = South Lagoon & O = Ocean. Refer to Table 19.1 for definitions for each metric used and a description of the likely significance of changes in each.

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
Self-sustaining populations					
Successful recruitment	Golden perch, bony herring, Australian smelt, Murray hardyhead, Yarra pygmy perch, carp, congolli, common galaxias, short headed lamprey, yellow-eyed mullet, black bream, small-mouthed hardyhead	Abundance	At specified* sites in RM, Lx, Lb, T, MM, NL, SL & O	Twice yearly (following high & low flow periods)	Successful recruitment strongly correlated with river flow (Murray cod & golden perch), barrage flow (congolli), connectivity between habitats (short headed lamprey & yellow-eyed mullet) & food availability following barrage flow & timing of river flow (black bream) so could use campaign-based sampling after flow & likely adverse events
	Golden perch, bony herring, carp, yellow-eyed mullet, black bream	Fisheries take	At specified* sites in RM, Lx, Lb, MM & NL	Annually	
	Golden perch, bony herring, Australian smelt, Murray hardyhead, Yarra pygmy perch, carp, congolli, common galaxias, yellow-eyed mullet, black bream, small-mouthed hardyhead	Population demographics	At specified* sites in RM, Lx, Lb, MM, T, NL & SL	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Murray hardyhead, Yarra pygmy perch, Australian smelt, carp, congolli, common galaxias, short headed lamprey, golden perch, bony herring, small-mouthed hardyhead	Recruitment events	At specified* sites in RM, Lx, Lb, MM, T, NL, SL & O	Twice yearly (autumn/winter & spring/summer)	Successful recruitment strongly correlated with barrage flow (congolli) & connectivity between habitats (short headed lamprey, golden perch & bony herring) so could use campaign-based sampling after flow events. Recruitment is likely to vary naturally intra-annually. Critical common galaxias recruit annually or every second year
	Common galaxias, small-mouthed hardyhead	Distribution	At specified* sites in RM, Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	Congolli distribution dependent on barrage flow so could use campaign-based sampling after flow & likely adverse events
Suitable habitat	Golden perch, bony herring, Murray hardyhead, Yarra pygmy perch, carp, congolli, common galaxias, Australian salmon, short	Abundance	At specified* sites in RM, Lx, Lb, T, MM, NL, SL & O	Twice yearly (following high & low flow periods)	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
	headed lamprey, yellow-eyed mullet, mulloway, sandy sprat, black bream, small-mouthed hardyhead				
	Golden perch, bony herring, carp, yellow-eyed mullet, mulloway, black bream	Fisheries take	At specified* sites in RM, Lx, Lb, MM & O	Annually	
	Golden perch, bony herring, Australian smelt, Murray hardyhead, Yarra pygmy perch, carp, congolli, common galaxias, Australian salmon, mulloway, black bream, small-mouthed hardyhead	Population demographics	At specified* sites in RM, Lx, Lb, MM, T, NL, SL & O	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Golden perch	Movements	At specified* sites in RM, Lx, Lb & MM	Twice yearly (following high & low flow periods)	
	Yarra pygmy perch, carp, congolli, common galaxias, short headed lamprey, Australian smelt	Recruitment events	At specified* sites in RM, Lx, Lb, MM, T, NL & O	Twice yearly (autumn/winter & spring/summer)	Recruitment is likely to vary naturally intra-annually. Critical Common galaxias recruit annually or every second year
	Congolli, common galaxias, short headed lamprey, yellow-eyed mullet, small-mouthed hardyhead	Distribution	At specified* sites in RM, Lx, Lb, MM, NL, SL & O	Twice yearly (autumn/winter & spring/summer)	Distribution of congolli dependent on barrage flow & short headed lamprey on connectivity of habitats so could use campaign-based sampling after flow & likely adverse events
Suitable food resources	Bony herring, congolli, common galaxias, Australian salmon, mulloway, sandy sprat, small-mouthed hardyhead	Abundance	At specified* sites in RM, Lx, Lb, T, MM, NL, SL & O	Twice yearly (following high & low flow periods)	
	Bony herring, mulloway	Fisheries take	At specified* sites in RM, Lx, Lb, MM & O	Annually	
	Bony herring, Australian salmon, mulloway, sandy sprat	Population demographics	At specified* sites in RM, Lx, Lb, MM, T, NL & O	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Murray cod, golden perch, bony herring, Australian smelt, Murray hardyhead, carp, congolli, common galaxias, Australian	Food web structure	At specified* sites in RM, Lx, Lb, MM, NL, SL & O	Twice yearly (following high & low flow periods)	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
	salmon, yellow-eyed mullet, mulloway, sandy sprat, black bream, small-mouthed hardyhead				
	Congolli	Recruitment events	At specified* sites in RM, Lx, Lb, MM & NL	Twice yearly (autumn/winter & spring/summer)	Successful recruitment strongly correlated with barrage flow (Congolli) & food availability following barrage flow & timing of river flow (black bream) so could use campaign-based sampling after flow events. Recruitment is likely to vary naturally intra-annually
Suitable water quality	Murray cod, Australian smelt, Murray hardyhead, Yarra pygmy perch, congolli, common galaxias, Australian salmon, mulloway, small-mouthed hardyhead	Abundance	At specified* sites in RM, Lx, Lb, MM, T, NL, SL & O	Twice yearly (following high & low flow periods)	
	Australian smelt, Yarra pygmy perch, congolli, common galaxias, Australian salmon, small-mouthed hardyhead	Population demographics	At specified* sites in RM, Lx, Lb, MM, T, NL, SL & O	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Murray cod, mulloway	Fisheries take	At specified* sites in RM, Lx, Lb, MM & O	Annually	
	Murray cod, golden perch, Australian smelt, Murray hardyhead, Yarra pygmy perch, congolli, common galaxias, Australian salmon, mulloway, small-mouthed hardyhead	Disease	At specified* sites in RM, Lx, Lb, MM, T, NL, SL & O	Twice yearly (following high & low flow periods)	Could use campaign-based sampling after likely adverse conditions (e.g. low flow conditions)
	Murray cod, golden perch, Australian smelt, Murray hardyhead, Yarra pygmy perch, Australian salmon, mulloway, small-mouthed hardyhead	Fish kills	At specified* sites in RM, Lx, Lb, MM, T, NL, SL & O	Following likely adverse conditions	
	Congolli, common galaxias, small-mouthed hardyhead	Recruitment events	At specified* sites in RM, Lx, Lb, MM, NL & SL	Twice yearly (autumn/winter & spring/summer)	Recruitment is likely to vary naturally intra-annually. Successful recruitment strongly correlated with barrage flow (Congolli) & possibly dependent on low to elevated salinities (small-mouthed hardyhead) so could use campaign-based sampling after flow events.

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
					Critical common galaxias recruit annually or every second year
	Congolli, common galaxias, mulloway, small-mouthed hardyhead	Distribution	At specified* sites in RM, Lx, Lb, MM, NL, SL & O	Twice yearly (following high & low flow periods)	Distribution of congolli dependent on barrage flow & yellow-eyed mullet on the provision of suitable estuarine habitat & ocean connectivity so could use campaign-based sampling after flow & likely adverse events
Population connectivity					
Species connectivity	Murray cod, golden perch	Movements	At specified* sites in RM, Lx, Lb & MM	Twice yearly (following high & low flow periods)	
	Australian salmon, short headed lamprey, mulloway, sandy sprat, small-mouthed hardyhead	Abundance	At specified* sites in RM, Lx, Lb, MM, NL, SL & O	Twice yearly (following high & low flow periods)	
	Australian salmon, mulloway, sandy sprat, Murray cod, golden perch, small-mouthed hardyhead	Population demographics	At specified* sites in RM, Lx, Lb, MM, NL, SL & O	Annually (winter)	
	Mulloway	Fisheries take	At specified* sites in Lx, Lb, MM & O	Annually	
	Mulloway, sandy sprat, small-mouthed hardyhead	Distribution	At specified* sites in RM, Lx, Lb, MM, NL, SL & O	Twice yearly (following high & low flow periods)	Mulloway & sandy sprat distribution dependent on habitat connectivity so could use campaign-based sampling after flow & likely adverse events
Viable propagule bank	No taxa identified as relevant	NA	NA	NA	
No barriers to recruitment	Murray cod, golden perch	Movements	At specified* sites in RM, Lx, Lb & MM	Twice yearly (following high & low flow periods)	.
	Australian smelt, congolli, common galaxias, Australian salmon, short headed lamprey, mulloway, sandy sprat	Abundance	At specified* sites in RM, Lx, Lb, MM, T, NL & O	Twice yearly (following high & low flow periods)	
	Mulloway	Fisheries take	At specified* sites in Lx, Lb, MM & O	Annually	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
	Golden perch, Australian smelt, Murray hardyhead, Yarra pygmy perch, carp, congolli, common galaxias, Australian salmon, mulloway, sandy sprat	Population demographics	At specified* sites in RM, Lx, Lb, MM, T, NL & O	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Murray hardyhead, Yarra pygmy perch, carp, congolli, common galaxias, Murray cod	Recruitment events	At specified* sites in RM, Lx, Lb, MM, T & NL	Twice yearly (autumn/winter & spring/summer)	Recruitment is likely to vary naturally intra-annually. Successful recruitment strongly correlated with barrage flow (congolli) & suitable estuarine habitat provision & ocean connectivity (yellow-eyed mullet) so could use campaign-based sampling after flow events
	Congolli, common galaxias, short headed lamprey, Yarra pygmy perch	Distribution	At specified* sites in RM, Lx, Lb, MM, T, NL & O	Twice yearly (following high & low flow periods)	Distribution of congolli dependent on barrage flow & short-headed lamprey on connectivity of habitats so could use campaign-based sampling after flow & likely adverse events
Hydraulic connectivity					
Lateral hydraulic connectivity	Golden perch, Yarra pygmy perch, carp, common galaxias, congolli	Population demographics	At specified* sites in RM, Lx, Lb, MM, T & NL	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Golden perch, Murray hardyhead, congolli, sandy sprat, bony herring	Food web structure	At specified* sites in RM, Lx, Lb, MM, NL & O	Twice yearly (following high & low flow periods)	
	Yarra pygmy perch, carp, congolli, common galaxias, yellow-eyed mullet, small-mouthed hardyhead	Abundance	At specified* sites in RM, Lx, Lb, MM, T, NL & SL	Twice yearly (following high & low flow periods)	
	Yarra pygmy perch, carp, common galaxias, golden perch, congolli	Recruitment events	At specified* sites in RM, Lx, Lb, MM, T & NL	Twice yearly (autumn/winter & spring/summer)	Recruitment is likely to vary naturally intra-annually. Critical common galaxias recruit annually or every second year
	Carp, yellow-eyed mullet	Fisheries take	At specified* sites in RM, Lx, Lb, MM & NL	Annually	
	Common galaxias, yellow-eyed mullet, small-mouthed hardyhead	Distribution	At specified* sites in RM, Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	
Water residence	Murray cod, golden perch, bony herring, Australian smelt, Yarra	Disease	At specified* sites in RM, Lx,	Twice yearly (following high &	Could use campaign-based sampling following likely adverse conditions (e.g. low flow

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
times finite	pygmy perch		Lb, MM, T & O	low flow periods)	conditions)
	Murray cod, golden perch, bony herring, Australian salmon, Australian smelt, mulloway, sandy sprat, Yarra pygmy perch	Fish kills	At specified* sites in RM, Lx, Lb, MM, T, NL & O	Following likely adverse conditions	
	Sandy sprat, small-mouthed hardyhead	Population demographics	At specified* sites in RM, Lx, Lb, MM, NL, SL & O	Twice yearly (following high & low flow periods)	Demographics are likely to vary naturally intra-annually
	Australian salmon, mulloway, sandy sprat, small-mouthed hardyhead	Abundance	At specified* sites in RM, Lx, Lb, MM, NL, SL & O	Twice yearly (following high & low flow periods)	
	Australian salmon, Murray cod, golden perch, bony herring, small-mouthed hardyhead	Distribution	At specified* sites in RM, Lx, Lb, MM, NL, SL & O	Twice yearly	
	Mulloway	Fisheries take	At specified* sites in Lx, Lb, MM & O	Annually	
	Small-mouthed hardyhead	Recruitment events	At specified* sites in RM, Lx, Lb, MM, NL & SL	Twice yearly (autumn/winter & spring/summer)	Recruitment is likely to vary naturally intra-annually
Region hydraulically connected	Murray cod, golden perch	Movements	At specified* sites in RM, Lx, Lb & MM	Twice yearly (following high & low flow periods)	Strong correlation with river flow for both species so could use campaign-based sampling following flow events
	Congolli, common galaxias, Australian salmon, short headed lamprey, mulloway, sandy sprat, black bream	Abundance	At specified* sites in RM, Lx, Lb, MM, NL & O	Twice yearly (following high & low flow periods)	
	Australian smelt, Murray hardyhead	Food web structure	At specified* sites in RM, Lx, Lb & MM	Twice yearly (following high & low flow periods)	
	Congolli, common galaxias, Australian salmon, mulloway, sandy sprat, black bream	Population demographics	At specified* sites in RM, Lx, Lb, MM, NL & O	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Congolli, common galaxias	Recruitment	At specified* sites in RM, Lx,	Twice yearly (autumn/winter	Recruitment is likely to vary naturally intra-annually. Critical common galaxias recruit

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
		events	Lb, MM & NL	& spring/summer)	annually or every second year. Successful recruitment of congolli strongly correlated with barrage flow so could use campaign-based sampling following flow events
	Congolli, common galaxias, Australian salmon, bronze whaler shark, short headed lamprey, mulloway, sandy sprat, black bream	Distribution	At specified* sites in RM, Lx, Lb, MM, NL & O	Twice yearly (following high & low flow periods)	Distribution of congolli dependent on barrage flow, & short headed lamprey, mulloway & sandy sprat on habitat connectivity so could use campaign-based sampling following flow & likely adverse event
	Mulloway, black bream	Fisheries take	At specified* sites in Lx, Lb, MM & O	Annually	
Longitudinal biological connectivity	Bony herring, Australian smelt, Murray hardyhead, Yarra pygmy perch, carp, congolli, common galaxias, Australian salmon, bronze whaler shark, golden perch, yellow-eyed mullet, mulloway, sandy sprat, black bream, small-mouthed hardyhead	Food web structure	At specified* sites in RM, Lx, Lb, MM, T, NL, SL & O	Twice yearly (following high & low flow periods)	
	Australian smelt, common galaxias, Australian salmon, bronze whaler shark, yellow-eyed mullet, mulloway, sandy sprat, small-mouthed hardyhead	Abundance	At specified* sites in RM, Lx, Lb, MM, NL, SL & O	Twice yearly (following high & low flow periods)	
	Yellow-eyed mullet, mulloway	Fisheries take	At specified* sites in Lx, Lb, MM, NL & O	Annually	
	Golden perch, Australian smelt, congolli, common galaxias, mulloway, sandy sprat, small-mouthed hardyhead	Population demographics	At specified* sites in RM, Lx, Lb, MM, NL, SL & O	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Congolli, common galaxias, golden perch	Recruitment events	At specified* sites in RM, Lx, Lb, MM & NL	Twice yearly (autumn/winter & spring/summer)	Recruitment is likely to vary naturally intra-annually. Critical common galaxias recruit annually or every second year. Successful recruitment of congolli strongly correlated with barrage flow so could use campaign-based sampling following flow events
	Common galaxias	Distribution	At specified*	Twice yearly	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
			sites in Lx, Lb, MM	(following high & low flow periods)	
No accumulation of pollutants	Murray cod, golden perch, bony herring, Australian smelt, Murray hardyhead, Yarra pygmy perch, carp, congolli, common galaxias, Australian salmon, yellow-eyed mullet, mulloway, black bream, small-mouthed hardyhead	Tissue composition	At specified* sites in RM, Lx, Lb, MM, T, NL, SL & O	Twice yearly (following high & low flow periods)	
Habitat complexity					
Lateral habitat diversity	Bony herring, carp	Population demographics	At specified* sites in RM, Lx, Lb & MM	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Yarra pygmy perch, congolli, yellow-eyed mullet, small-mouthed hardyhead	Abundance	At specified* sites in RM, Lx, Lb, MM, T, NL & SL	Twice yearly (following high & low flow periods)	
	Carp	Recruitment events	At specified* sites in RM, Lx, Lb & MM	Twice yearly (autumn/winter & spring/summer)	Recruitment is likely to vary naturally intra-annually
	Yarra pygmy perch, common galaxias, Murray hardyhead, yellow-eyed mullet, small-mouthed hardyhead	Distribution	At specified* sites in RM, Lx, Lb, MM, T, NL & SL	Twice yearly (following high & low flow periods)	Distribution of congolli dependent on barrage flow & yellow-eyed mullet on the provision of suitable estuarine habitat & ocean connectivity so could use campaign-based sampling following flow & likely adverse events
	Yellow-eyed mullet	Fisheries take	At specified* sites in Lx, Lb, MM & NL	Annually	
Habitat variability	Congolli, common galaxias, yellow-eyed mullet, black bream	Abundance	At specified* sites in RM, Lx, Lb, MM & NL	Twice yearly (following high & low flow periods)	
	Congolli, common galaxias	Population demographics	At specified* sites in RM, Lx, Lb, MM & NL	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Congolli, common galaxias	Recruitment events	At specified* sites in RM, Lx,	Twice yearly (autumn/winter &	Recruitment is likely to vary naturally intra-annually. Critical common galaxias recruit annually or every second year. Successful

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
			Lb, MM & NL	spring/summer)	recruitment of congolli strongly correlated with barrage flow so could use campaign-based sampling following flow events
	Yarra pygmy perch, carp, common galaxias, yellow-eyed mullet, bony herring, Murray hardyhead, black bream	Distribution	At specified* sites in RM, Lx, Lb, MM, T & NL	Twice yearly (following high & low flow periods)	Distribution of congolli dependent on barrage flow & yellow-eyed mullet on the provision of suitable estuarine habitat & ocean connectivity so could use campaign-based sampling following flow & likely adverse events
	Yellow-eyed mullet	Fisheries take	At specified* sites in Lx, Lb, MM & NL	Annually	
Persistent salinity gradient across site					
Range of salinities with appropriate maxima	Murray cod, golden perch, Yarra pygmy perch	Disease	At specified* sites in RM, Lx, Lb, MM & T	Twice yearly (following high & low flow periods)	Could also use campaign-based sampling following likely adverse (e.g. low flow) conditions
	Murray cod, golden perch, Yarra pygmy perch	Fish kills	At specified* sites in RM, Lx, Lb, MM & T	Following adverse conditions	
	Murray cod, golden perch, congolli, Australian salmon, mulloway, sandy sprat, black bream, small-mouthed hardyhead	Population demographics	At specified* sites in RM, Lx, Lb, MM, NL, SL & O	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Common galaxias, Australian salmon, bronze whaler shark, yellow-eyed mullet, mulloway, sandy sprat, black bream, small-mouthed hardyhead	Abundance	At specified* sites in RM, Lx, Lb, MM, NL, SL & O	Twice yearly (following high & low flow periods)	
	Yarra pygmy perch, congolli, small-mouthed hardyhead	Recruitment events	At specified* sites in RM, Lx, Lb, MM, T, NL & SL	Twice yearly (autumn/winter & spring/summer)	Recruitment is likely to vary naturally intra-annually. Successful recruitment of congolli strongly correlated with barrage flow & small-mouthed hardyhead possibly dependent on low to elevated salinities so could use campaign-based sampling following flow events
	Congolli, common galaxias, bronze whaler shark, Murray cod, golden perch, Yarra pygmy perch, yellow-eyed mullet, black	Distribution	At specified* sites in RM, Lx, Lb, MM, T, NL, SL & O	Twice yearly (following high & low flow periods)	Congolli distribution dependent on barrage flow so could use campaign-based sampling following flow & likely adverse events

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
	bream, small-mouthed hardyhead				
	Yellow-eyed mullet, mulloway	Fisheries take	At specified* sites in Lx, Lb, MM & O	Annually	
Temporal variability in salinity	Murray cod, golden perch, congolli, Australian salmon, bronze whaler shark, yellow-eyed mullet, mulloway, sandy sprat, black bream	Abundance	At specified* sites in RM, Lx, Lb, MM, NL & O	Twice yearly (following high & low flow periods)	
	Murray cod, congolli, Australian salmon, bronze whaler shark, yellow-eyed mullet, mulloway, sandy sprat, golden perch, Yarra pygmy perch, black bream	Distribution	At specified* sites in RM, Lx, Lb, MM, T, NL & O	Twice yearly (following high & low flow periods)	Distribution of congolli dependent on barrage flow & yellow-eyed mullet & sandy sprat on the provision of suitable estuarine habitat & ocean connectivity so could use campaign-based sampling following flow & likely adverse events
	Murray cod, golden perch, yellow-eyed mullet, mulloway, black bream	Fisheries take	At specified* sites in RM, Lx, Lb, MM, NL & O	Annually	
	Golden perch, congolli, mulloway, sandy sprat, black bream, small-mouthed hardyhead	Population demographics	At specified* sites in RM, Lx, Lb, MM, NL, SL & O	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Murray cod, Yarra pygmy perch	Fish kills	At specified* sites in RM, Lx, Lb & T	Following adverse conditions	
	Murray cod, Yarra pygmy perch	Disease	At specified* sites in RM, Lx, Lb & T	Twice yearly (following high & low flow periods)	Could use campaign-based sampling following likely adverse conditions (e.g. low flow_ conditions
	Murray hardyhead, black bream, small-mouthed hardyhead	Recruitment events	RM, Lx, Lb, MM, NL & SL	Twice yearly (autumn/winter & spring/summer)	Recruitment is likely to vary naturally intra-annually. Recruitment of black bream is dependent on the provision of access to estuarine habitats & small-mouthed hardyhead is possibly dependent on low to elevated salinities
Communities requiring varied salinities supported	Congolli, common galaxias, Australian salmon, bronze whaler shark, black bream	Abundance	At specified* sites in RM, Lx, Lb, MM, NL & O	Twice yearly (following high & low flow periods)	
	Congolli, common galaxias,	Distribution	At specified*	Twice yearly	Congolli distribution dependent on barrage

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
	bronze whaler shark, black bream		sites in TM, Lx, Lb, T, MM, NL & O	(following high & low flow periods)	flow so could use campaign-based sampling following flow & likely adverse events
	Congolli, common galaxias, Australian salmon, black bream, small-mouthed hardyhead	Population demographics	At specified* sites in RM, Lx, Lb, MM, NL, SL & O	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Congolli, common galaxias, black bream, small-mouthed hardyhead	Recruitment events	At specified* sites in RM, Lx, Lb, MM, NL & SL	Twice yearly (autumn/winter & spring/summer)	Recruitment is likely to vary naturally intra-annually. Critical common galaxias recruit annually or every second year. Successful recruitment of congolli strongly correlated with barrage flow & small-mouthed hardyhead is possible dependent on low to elevated salinities so could use campaign-based sampling following flow events
	Black bream	Fisheries take	At specified* sites in Lx, Lb & MM	Annually	
Flow & water level variability					
Temporal variability in flow	Murray cod, short headed lamprey, black bream	Abundance	At specified* sites in RM, Lx, Lb, MM & O	Twice yearly (following high & low flow periods)	
	Murray cod, black bream	Fisheries take	RM, Lx, Lb & MM	Annually	
	Murray cod, golden perch	Population demographics	At specified* sites in RM, Lx, Lb & MM	Twice yearly (autumn/winter & spring/summer)	
	Golden perch	Spawning events	At specified* sites in RM, Lx, Lb & MM	Annually spring/summer	
	Golden perch	Movements	At specified* sites in RM, Lx, Lb & MM	Twice yearly (following high & low flow periods)	Strong correlation with river flow so could use campaign-based sampling following flow events
	Black bream	Distribution	At specified* sites in Lx, Lb & MM	Twice yearly (following high & low flow periods)	
Seasonal variability in	Congolli, common galaxias, mulloway, golden perch, black	Population demographics	At specified* sites in RM, Lx,	Twice yearly (autumn/winter &	Demographics are likely to vary naturally intra-annually

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
flows	bream		Lb, MM, NL & O	spring/summer)	
	Congolli, common galaxias, black bream	Recruitment events	At specified* sites in RM, Lx, Lb, MM & NL	Twice yearly (autumn/winter & spring/summer)	Recruitment is likely to vary naturally intra-annually. Critical common galaxias recruit annually or every second year. Successful recruitment of congolli strongly correlated with barrage flow & black bream linked to food availability following barrage flows & the timing of river flow so could use campaign-based sampling following flow events
	Congolli, common galaxias, black bream	Distribution	At specified* sites in RM, Lx, Lb, MM & NL	Twice yearly (following high & low flow periods)	Congolli distribution dependent on barrage flow so could use campaign-based sampling following flow & likely adverse events
	Common galaxias, short headed lamprey, mulloway, black bream	Abundance	At specified* sites in RM, Lx, Lb, MM, NL & O	Twice yearly (following high & low flow periods)	
	Mulloway, black bream	Fisheries take	At specified* sites in Lx, Lb, MM & O	Annually	
	Golden perch	Movements	At specified* sites in RM, Lx, Lb & MM	Twice yearly (following high & low flow periods)	Strong correlation with river flow so could use campaign-based sampling following flow events
	Golden perch	Spawning events	At specified* sites in RM, Lx, Lb & MM	Annually spring/summer	
Seasonal variability in water levels	Bony herring, Yarra pygmy perch, carp	Population demographics	At specified* sites in RM, Lx, Lb, MM & T	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Yarra pygmy perch	Abundance	At specified* sites in Lx & T	Twice yearly (following high & low flow periods)	
	Yarra pygmy perch, carp	Recruitment events	At specified* sites in RM, Lx, Lb, MM & T	Twice yearly (autumn/winter & spring/summer)	Recruitment is likely to vary naturally intra-annually
Communities requiring varied hydrology supported	Murray cod, bony herring, Australian smelt, Murray hardyhead, Yarra pygmy perch, congolli, common galaxias, Australian salmon, bronze whaler	Abundance	At specified* sites in RM, Lx, Lb, MM, T, NL, SL & O	Twice yearly (following high & low flow periods)	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
	shark, short headed lamprey, yellow-eyed mullet, mulloway, sandy sprat, black bream				
	Murray cod, bony herring, mulloway, black bream, small-mouthed hardyhead	Fisheries take	At specified* sites in RM, Lx, Lb, MM & O	Annually	
	Golden perch, Australian smelt, Murray hardyhead, Yarra pygmy perch, carp, congolli, common galaxias, Australian salmon, mulloway, sandy sprat, small-mouthed hardyhead	Population demographics	At specified* sites in RM, Lx, Lb, MM, T, NL, SL & O	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Murray hardyhead, Yarra pygmy perch, carp, congolli, black bream	Recruitment events	At specified* sites in RM, Lx, Lb, MM, T, & NL	Twice yearly (autumn/winter & spring/summer)	Recruitment is likely to vary naturally intra-annually. Successful recruitment of congolli strongly correlated with barrage flow & black bream recruitment is linked to food availability following barrage flow & the timing of river flow so could use campaign-based sampling following flow events
	Common galaxias, Australian salmon, Murray cod, golden perch, yellow-eyed mullet	Distribution	At specified* sites in RM, Lx, Lb, MM, NL & O	Twice yearly (following high & low flow periods)	
Communities requiring flooding supported	Murray cod, Murray hardyhead, carp	Population demographics	At specified* sites in RM, Lx, Lb & MM	Twice yearly (following high & low flow periods)	Demographics are likely to vary naturally intra-annually
	Murray hardyhead	Abundance	At specified* sites in RM, Lx & Lb	Twice yearly (following high & low flow periods)	
	Murray hardyhead, carp	Recruitment events	At specified* sites in RM, Lx, Lb & MM	Twice yearly (autumn/winter & spring/summer)	Recruitment is likely to vary naturally intra-annually
	Yarra pygmy perch, carp	Distribution	At specified* sites in RM, Lx, Lb, MM & T		
Tidal signal apparent	Common galaxias	Movements	At specified* sites in Lx, Lb & MM	Twice yearly (following high & low flow periods)	
	Common galaxias, bronze whaler	Distribution	At specified*	Twice yearly	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
	shark, sandy sprat		sites in Lx, Lb, MM, NL & O	(following high & low flow periods)	
	Mulloway, sandy sprat	Abundance	At specified* sites in Lx, Lb, MM, NL & O	Twice yearly (following high & low flow periods)	
	Mulloway	Fisheries take	At specified* sites in Lx, Lb, MM & O	Annually	
	Mulloway, sandy sprat	Population demographics	At specified* sites in Lx, Lb, MM, NL & O	Twice yearly (following high & low flow periods)	
Redundancy & appropriateness of ecological function					
Complex food webs present	Murray cod, golden perch, Australian smelt, congolli, common galaxias, Australian salmon, yellow-eyed mullet, mulloway, sandy sprat, black bream, small-mouthed hardyhead	Abundance	At specified* sites in RM, Lx, Lb, MM, NL, SL & O	Twice yearly (following high & low flow periods)	
	Golden perch, yellow-eyed mullet, mulloway, Murray cod, golden perch, black bream	Fisheries take	At specified* sites in RM, Lx, Lb, T, MM, NL & O	Annually	
	Murray cod, Australian smelt, congolli, Australian salmon, mulloway, sandy sprat, black bream	Population demographics	At specified* sites in RM, Lx, Lb, MM, NL & O	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Murray cod	Movements	At specified* sites in RM, Lx & Lb	Twice yearly (following high & low flow periods)	Strong correlation with river flow so could use campaign-based sampling following flow events
	Murray cod, golden perch, bony herring, Murray hardyhead, Yarra pygmy perch, congolli, common galaxias, Australian salmon, yellow-eyed mullet, mulloway, sandy sprat, black bream, small-mouthed hardyhead	Food web structure	At specified* sites in RM, Lx, Lb, MM, T, NL, SL & O	Twice yearly (following high & low flow periods)	
	Congolli, common galaxias	Recruitment events	At specified* sites in RM, Lx,	Twice yearly (autumn/winter &	Recruitment is likely to vary naturally intra-annually. Successful recruitment of congolli strongly correlated with barrage flow so could

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
			Lb, MM & NL	spring/summer)	use campaign-based sampling following flow events. Critical that common galaxias recruit annually or every second year
	Congolli, common galaxias	Distribution	At specified* sites in RM, Lx, Lb, MM & NL	Twice yearly (following high & low flow periods)	Congolli distribution dependent on barrage flow so could use campaign-based sampling following flow & likely adverse events
Functions performed by multiple species	Carp	Abundance	At specified* sites in RM, Lx, Lb &MM	Twice yearly (following high & low flow periods)	
	Carp	Fisheries take	At specified* sites in RM, Lx, Lb & MM	Annually	
	Carp	Distribution	At specified* sites in RM, Lx, Lb & MM	Twice yearly (following high & low flow periods)	
Efficient nutrient cycling	No taxa identified as relevant	NA	NA	NA	
Control of invasive species	Carp, bronze whaler shark	Abundance	At specified* sites in RM, Lx, Lb, MM & O	Twice yearly (following high & low flow periods)	
	Carp	Fisheries take	At specified* sites in RM, Lx, Lb & MM	Annually	
	Carp	Population demographics	At specified* sites in RM, Lx, Lb & MM	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Carp	Recruitment events	At specified* sites in RM, Lx, Lb & MM	Twice yearly (autumn/winter & spring/summer)	Recruitment is likely to vary naturally intra-annually
	Carp	Change in ratio of two groups	At specified* sites in RM, Lx, Lb & MM	Twice yearly (following high & low flow periods)	
Acid- & saline-tolerant & terrestrial	Bony herring, Australian smelt, Murray hardyhead, black bream	Change in ratio of two groups	At specified* sites in RM, Lx, Lb & MM	Twice yearly (following high & low flow periods)	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
species present					
	Bony herring, Australian smelt, Murray hardyhead, carp, common galaxias, bronze whaler shark, small-mouthed hardyhead	Abundance	At specified* sites in RM, Lx, Lb, MM, NL, SL & O	Twice yearly (following high & low flow periods)	
	Bony herring, carp	Fisheries take	At specified* sites in RM, Lx, Lb & MM	Annually	
	Australian smelt, Murray hardyhead, Australian salmon, mulloway, black bream, small-mouthed hardyhead	Population demographics	At specified* sites in RM, Lx, Lb, MM, NL, SL & O	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Murray hardyhead	Recruitment events	At specified* sites in RM, Lx & Lb	Twice yearly (autumn/winter & spring/summer)	Recruitment is likely to vary naturally intra-annually
	Common galaxias, Australian salmon, Murray cod, golden perch, bony herring, Yarra pygmy perch, black bream, small-mouthed hardyhead	Distribution	At specified* sites in RM, Lx, Lb, T, MM, T, NL, SL & O	Twice yearly (following high & low flow periods)	
	Golden perch, Yarra pygmy perch	Disease	At specified* sites in RM, Lx, Lb, MM & T	Twice yearly (following high & low flow periods)	Could use campaign-based sampling following likely adverse (e.g. low flow) conditions
	Golden perch, Yarra pygmy perch	Fish kills	At specified* sites in RM, Lx, Lb, MM & T	Following adverse conditions	
Aquatic-terrestrial connectivity					
Wide riparian & littoral zones supported	Murray hardyhead, Yarra pygmy perch, common galaxias, small-mouthed hardyhead	Abundance	At specified* sites in RM, Lx, Lb, MM, NL, SL & T	Twice yearly (following high & low flow periods)	
	Australian smelt, Murray hardyhead, Yarra pygmy perch, carp	Population demographics	At specified* sites in RM, Lx, Lb, MM & T	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Murray hardyhead, Yarra pygmy perch, common galaxias, carp	Recruitment events	At specified* sites in RM, Lx,	Twice yearly (autumn/winter	Recruitment is likely to vary naturally intra-annually. Critical that common galaxias recruit

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
			Lb, MM & T	& spring/summer)	annually or every second year
	Common galaxias, small-mouthed hardyhead	Distribution	At specified* sites in RM, Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	
Lateral connectivity of vegetation	Murray hardyhead, Yarra pygmy perch, common galaxias, small-mouthed hardyhead	Abundance	At specified* sites in RM, Lx, Lb, MM, NL, SL & T	Twice yearly (following high & low flow periods)	
	Murray hardyhead, Yarra pygmy perch	Population demographics	At specified* sites in RM, Lx, Lb & T	Twice yearly (autumn/winter & spring/summer)	Demographics are likely to vary naturally intra-annually
	Murray hardyhead, Yarra pygmy perch, common galaxias	Recruitment events	At specified* sites in RM, Lx, Lb, MM & T	Twice yearly (autumn/winter & spring/summer)	Recruitment is likely to vary naturally intra-annually. Critical that common galaxias recruit annually or every second year
	Common galaxias, small-mouthed hardyhead	Distribution	At specified* sites in RM, Lx, Lb, MM, NL & SL	Twice yearly (following high & low flow periods)	
Balance of aquatic & terrestrial species	Murray cod, golden perch, bony herring, Australian smelt, Murray hardyhead, Yarra pygmy perch, carp, congolli, common galaxias, Australian salmon, bronze whaler shark, short headed lamprey, yellow-eyed mullet, mulloway, sandy sprat, black bream, small-mouthed hardyhead	Distribution	At specified* sites in RM, Lx, Lb, MM, T, NL, SL & O	Twice yearly (following high & low flow periods)	
	Murray cod, golden perch, Australian smelt, Murray hardyhead, Yarra pygmy perch, carp, common galaxias, bronze whaler shark, short headed lamprey, yellow-eyed mullet, mulloway, sandy sprat, black bream, small-mouthed hardyhead	Abundance	At specified* sites in RM, Lx, Lb, MM, T, NL, SL & O	Twice yearly (following high & low flow periods)	
	Murray cod, golden perch, carp, yellow-eyed mullet, mulloway,	Fisheries take	At specified* sites in RM, Lx,	Annually	

Desired outcomes	Taxon/Assemblage	Metric	Spatial scale	Temporal scale	Notes
	black bream		Lb, MM, NL & O		
Exchange between aquatic & terrestrial systems	Golden perch, Australian smelt, Murray hardyhead, Yarra pygmy perch, carp, congolli, common galaxias, small-mouthed hardyhead	Food web structure	At specified* sites in RM, Lx, Lb, MM, T, NL & SL	Twice yearly (following high & low flow periods)	
Regular oxidation of sulfidic material	No taxa identified as relevant	NA	NA	NA	

* Use existing monitoring sites where possible

Table 19.5: Process indicator metrics for each of the objectives and outcomes provided in Chapter 3, including the relevant temporal and spatial scales

Lx = Lake Alexandrina, Lb = Lake Albert, MM = Murray Mouth & C = Coorong. Refer to Table 19.1 for definitions for each metric used and a description of the likely significance of changes in each.

Desired outcomes	Process	Metric	Spatial scale	Temporal scale	Notes
Self-sustaining populations					
Successful recruitment	Decomposition	Changes in the rate of an identified process – decomposition, colonisation of litter bags	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales are poorly understood & may need refinement
	Colonisation	Changes in recruitment patterns through space & time – number of taxa recruiting; Changes in population demographics – number of YoY, presence of seedlings, presence of tadpoles etc.; Changes in assemblage composition in time – terrestrial vs. aquatic taxa	At specified* sites in C, Lx, Lb & around the MM	Annually (e.g. post-summer)	Timing may vary among taxa/assemblages
Suitable habitat	Photosynthesis	Changes in photosynthetic activity in space & time – pigment composition	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Could also use campaign-based sampling during/after likely adverse or flooding events
	Nutrient cycling	Changes in the rate of an identified process – nutrient cycling by terrestrial plants; Changes in nutrient dynamics within the region	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales are poorly understood & may need refinement. Could also use campaign-based sampling during/after likely adverse events
	Response to water clarity	Changes in assemblage composition through space & time – vegetation & phytoplankton; Changes in population demographics – vegetation & phytoplankton; Changes in water quality – nutrients & suspended sediments; Changes in the structure or complexity of food webs through space & time – switching between clear- &	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Switching between states most relevant for Lx & Lb

Desired outcomes	Process	Metric	Spatial scale	Temporal scale	Notes
		turbid-water states			
	Terrestrialisation (re-wetting)	Changes in recruitment patterns through space & time; Changes in population demographics – mixture of terrestrial & aquatic taxa; Changes in ratio of two groups of taxa through space & time – terrestrial vs. aquatic	At specified* sites in C, Lx, Lb	Annually (following high flow period)	
	Bioaccumulation	Changes in population demographics – vegetation growth rates over time; Changes in assemblage distribution through space & time – vegetation cover; Changes in assemblage composition through time – diverse vegetation assemblage	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales may vary among taxa/toxins. Could also use campaign-based sampling during/after likely adverse events
	Food-web functionality	Changes in assemblage composition through space & time – presence of apex predators; Changes in recruitment patterns through space & time – range of FFGs; Changes in assemblage diversity through space & time – range of FFGs	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	
Suitable food resources	Decomposition	Changes in the rate of an identified process - decomposition, DOM & POM fractions	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales are poorly understood & may need refinement
	Nutrient cycling	Changes in nutrient dynamics within the region	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales are poorly understood & may need refinement
	Colonisation	Changes in recruitment patterns through time; Changes in population demographics	At specified* sites in C, Lx, Lb & around the MM	Annually (following high flow period)	Timing may vary among taxa/assemblages
	Food-web functionality	Changes in assemblage composition through space & time – presence of apex predators; Changes in the structure or complexity of food webs through space & time – relative proportions of FFGs, number of trophic	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	

Desired outcomes	Process	Metric	Spatial scale	Temporal scale	Notes
		levels, relative food chain lengths			
	Photosynthesis	Changes in photosynthetic activity in space & time			
Suitable water quality	Response to salinity dynamics	Changes in population demographics; Changes in the ratio of two groups of taxa through space & time – salinity tolerant vs. sensitive	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	
	Response to water clarity	Changes in assemblage composition through space & time – vegetation & phytoplankton; Changes in population demographics – vegetation & phytoplankton; Changes in assemblage distribution through space & time – vegetation & phytoplankton; Changes in water quality	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	
	Bioaccumulation	Changes in population demographics – age & size structure; Changes in recruitment patterns through space & time – number of eggs, YoY, tadpoles etc.	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales may vary among taxa/toxins. Could also use campaign-based sampling during/after likely adverse events
Population connectivity					
Species connectivity	Decomposition	Changes in the rate of an identified process – decomposition, Detritus composition & condition; Changes in assemblage diversity through space & time - decomposers	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales are poorly understood & may need refinement
	Functional connectivity	Changes in assemblage composition through space & time – mobile taxa, including migratory species; Changes in assemblage distribution through space & time – mobile taxa, including migratory species	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	For migratory taxa, annually may be a more appropriate temporal scale of sampling
Viable propagule bank	Functional connectivity	Changes in population demographics; Changes in recruitment patterns through space & time – arrival of ‘new’ individuals	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Scales may vary among taxa/assemblages
	Colonisation	Changes in assemblage distribution	At specified* sites in	Annually	Scales may vary among

Desired outcomes	Process	Metric	Spatial scale	Temporal scale	Notes
		through time – propagules; Changes in assemblage abundance through time – number of viable propagules; Changes in assemblage diversity through time – viable insect & plant propagules	C, Lx, Lb & around the MM	(following high flow period)	taxa/assemblages
No barriers to recruitment	Nutrient cycling	Changes in nutrient dynamics within the region – across the hydrologic cycle	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales are poorly understood & may need refinement. Could also use campaign-based sampling during/after likely adverse events
	Colonisation	Changes in population demographics; Changes in recruitment patterns in time	At specified* sites in C, Lx, Lb & around the MM	Annually (following high flow period)	Timing may vary among taxa/assemblages
Hydraulic connectivity					
Lateral hydraulic connectivity	Decomposition	Changes in the rate of an identified process – decomposition; Detritus composition & condition – variability & diversity of OM sources	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales are poorly understood & may need refinement
	Terrestrialisation (re-wetting)	Changes in assemblage composition through space & time, changes in ratio of two groups of taxa through space & time – terrestrial vs. aquatic	At specified* sites in C, Lx, Lb	Annually (following high flow period)	
Water residence times finite	No processes identified as relevant	NA	NA	NA	
Regional hydraulically connected	Nutrient cycling	Changes in nutrient dynamics within the region – across the hydrologic cycle	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales are poorly understood & may need refinement. Could also use campaign-based sampling during/after likely adverse events
Longitudinal biological connectivity	Photosynthesis	Changes in photosynthetic activity in space & time; Changes in the rate of an identified process – photosynthesis	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Could also use campaign-based sampling during/after likely adverse events
	Decomposition	Changes in the rate of an identified	At specified* sites in	Twice yearly	Optimal scales are poorly

Desired outcomes	Process	Metric	Spatial scale	Temporal scale	Notes
		process – decomposition; Detritus composition & condition	C, Lx, Lb & around the MM	(following high & low flow periods)	understood & may need refinement
	Nutrient cycling	Changes in nutrient dynamics within the region – across the hydrologic cycle	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales are poorly understood & may need refinement. Could also use campaign-based sampling during/after likely adverse events
	Food-web functionality	Changes in the structure or complexity of food webs through space & time – diversity in the sources of nutrients, microbial C determination via BIOLOG plates	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	See Barton (2006) for details of BIOLOG plates
No accumulation of pollutants	Response to sediment dynamics	Toxins in environmental media – chemical properties in sediment	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Could also use campaign-based sampling during/after likely adverse events
	Terrestrialisation (re-wetting)	Changes in the level of toxins in tissues in space & through time – plant uptake of pollutants; Toxins in environmental media – heavy metal concentrations in sediment	At specified* sites in C, Lx, Lb	Annually (following high flow period)	Could also use campaign-based sampling during/after likely adverse events
	Bioaccumulation	Changes in the rate of an identified process – oxidation & decomposition; Changes in assemblage distribution through space & time – vegetation; Changes in the level of toxins in tissues in space & through time – heavy metal concentrations	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Could also use campaign-based sampling during/after likely adverse events
Habitat complexity					
Lateral habitat diversity	Decomposition	Changes in the rate on an identified process – decomposition; Detritus composition & condition; Changes in assemblage abundance through space & time – vegetation cover; Changes in assemblage diversity through space &	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales are poorly understood & may need refinement

Desired outcomes	Process	Metric	Spatial scale	Temporal scale	Notes
		time – vegetation			
	Response to sediment dynamics	Changes in assemblage composition through space & time – vegetation; Changes in assemblage abundance through space & time – vegetation cover; Changes in assemblage diversity through space & time - vegetation	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	
Habitat variability	Decomposition	Changes in the rate of an identified process – decomposition; Detritus composition & condition – variability	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales are poorly understood & may need refinement
Persistent salinity gradient across site					
Range of salinities with appropriate maxima	Response to salinity dynamics	Changes in the ratio of two groups of taxa through space & time – salinity tolerant vs. sensitive	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	
Temporal variability in salinity	Response to salinity dynamics	Changes in the ratio of two groups of taxa through space & time – salinity tolerant vs. sensitive	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	
Communities requiring varied salinities supported	Response to salinity dynamics	Changes in the ratio of two groups of taxa through space & time – salinity tolerant vs. sensitive	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	
Flow & water level variability					
Temporal variability in flow	No processes identified as relevant	NA	NA	NA	
Seasonal variability in flows	No processes identified as relevant	NA	NA	NA	
Seasonal variability in water levels	No processes identified as relevant	NA	NA	NA	
Communities requiring varied	Terrestrialisation (re-wetting)	Changes in population demographics; Changes in assemblage composition through space & time – proportion of	At specified* sites in C, Lx, Lb	Annually (following high	

Desired outcomes	Process	Metric	Spatial scale	Temporal scale	Notes
hydrology supported		terrestrial & aquatic taxa; Changes in ratio of two groups of taxa through space & time – terrestrial vs. aquatic		flow period)	
Communities requiring flooding supported	Terrestrialisation (re-wetting)	Changes in population demographics; Changes in ratio of two groups of taxa through space & time – taxa with differing flooding requirements	At specified* sites in C, Lx, Lb	Annually (following high flow period)	
Tidal signal apparent	No processes identified as relevant	NA	NA	NA	
Redundancy & appropriateness of ecological function					
Complex food webs present	Photosynthesis	Changes in photosynthetic activity in space & time – pigment composition	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	
	Decomposition	Changes in the rate of an identified process – decomposition; Detritus composition & condition; Changes in assemblage abundance through space & time – decomposers; Changes in assemblage diversity through space & time – decomposers	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales are poorly understood & may need refinement
	Food-web functionality	Changes in the structure or complexity of food webs through space & time – FFGs; Changes in assemblage diversity through space & time – FFGs; Changes in assemblage composition through space & time – FFGs	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	
Functions performed by multiple species	Photosynthesis	Changes in photosynthetic activity in space & time; Changes in the rate of an identified process - photosynthesis	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	
	Decomposition	Detritus composition & condition – POM vs. DOM concentrations & leaf litter; Changes in assemblage abundance through space & time – decomposers; Changes in assemblage diversity	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales are poorly understood & may need refinement

Desired outcomes	Process	Metric	Spatial scale	Temporal scale	Notes
		through space & time decomposers			
	Nutrient cycling	Changes in nutrient dynamics within the region – throughout the ecosystem	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	
	Food-web functionality	Changes in assemblage diversity through space & time – diversity within FFGs; Changes in the structure or complexity of food webs through space & time – multiple taxa in each trophic level	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	
Efficient nutrient cycling	Photosynthesis	Changes in photosynthetic activity in space & time - PAM fluorometry & NDVI scores	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales are poorly understood & may need refinement
	Decomposition	Changes in the rate of an identified process – decomposition; Detritus composition & condition; Changes in assemblage abundance through space & time – decomposers; Changes in assemblage diversity through space & time – decomposers	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales are poorly understood & may need refinement
	Nutrient cycling	Changes in the rate of an identified process – nutrient cycling; Changes in nutrient dynamics within the region – throughout the ecosystem	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales are poorly understood & may need refinement. Could also use campaign-based sampling during/after likely adverse events
	Food-web functionality	Changes in the structure or complexity of food webs through space & time – diversity in the sources of nutrients (e.g. identified via stable isotope analyses); Changes in assemblage diversity though space & time – FFGs	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Could also use campaign-based sampling during/after likely adverse events
Control of invasive species	Colonisation	Changes in ratio of two groups of taxa through space & time – invasive vs. non-invasive; Changes in recruitment patterns through space & time –	At specified* sites in C, Lx, Lb & around the MM	Annually (following high flow period)	Timing may vary among taxa/assemblages

Desired outcomes	Process	Metric	Spatial scale	Temporal scale	Notes
		colonisation rates of known invasive taxa; Changes in assemblage distribution through space & time – areal extent of invasive taxa; Changes in assemblage composition through space & time – proportion of invasive vs. non-invasive taxa			
Acid- & saline-tolerant & terrestrial species present	Response to salinity dynamics	Changes in assemblage composition through space & time – proportion of salt-tolerant & sensitive species; Changes in assemblage abundance through space & time – number of salt-tolerant & -sensitive individuals; Changes in the ratio of two groups of taxa through space & time – salinity tolerant vs. sensitive individuals; Changes in the ratio of two groups of taxa through space & time – salinity tolerant vs. sensitive	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	
	Response to acid/base dynamics	Changes in assemblage composition through space & time – proportion of acid- tolerant & sensitive species; Changes in the ratio of two groups of taxa through space & time – acid-tolerant vs. sensitive	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	Could also use campaign-based sampling during/after likely adverse events
	Response to sediment dynamics	Changes in assemblage composition through space & time – proportions of tolerant & sensitive taxa (i.e. to turbidity & sedimentation levels)	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	
	Response to water clarity	Changes in assemblage composition through space & time – proportions of turbidity-tolerant & turbidity-sensitive taxa	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Could also use campaign-based sampling during/after likely adverse events
Aquatic-terrestrial connectivity					
Wide riparian & littoral zones supported	No processes identified as relevant	NA	NA	NA	

Desired outcomes	Process	Metric	Spatial scale	Temporal scale	Notes
Lateral connectivity of vegetation	No processes identified as relevant	NA	NA	NA	
Balance of aquatic & terrestrial species	Photosynthesis	Changes in photosynthetic activity in space & time – pigment composition	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	
	Terrestrialisation (re-wetting)	Changes in ratio of two groups of taxa through space & time – terrestrial vs. aquatic; Changes in assemblage composition through space & time – proportion of terrestrial vs. aquatic taxa	At specified* sites in C, Lx, Lb	Annually (following high flow period)	
Exchange between aquatic & terrestrial systems	Decomposition	Changes in the rate of an identified process – decomposition; Detritus composition & condition; Changes in assemblage abundance through space & time – decomposers; Changes in assemblage diversity through space & time – decomposers	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales are poorly understood & may need refinement
	Nutrient cycling	Changes in nutrient dynamics within the region – throughout the ecosystem	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales are poorly understood & may need refinement
	Food-web functionality	Changes in the ratio of two groups of taxa through space & time – terrestrial vs. aquatic	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	
Regular oxidation of sulfidic material	Response to acid/base dynamics	Changes in assemblage composition through space & time – benthic infauna; Changes in the ratio of two groups of taxa through space & time – acid-tolerant vs. sensitive	At specified* sites in Lx & Lb	Twice yearly (following high & low flow periods)	Could also use campaign-based sampling during/after likely adverse events
	Terrestrialisation (re-wetting)	Changes in ratio of two groups of taxa through space & time – acid-tolerant vs. sensitive, & mobile terrestrial vs. aquatic taxa; Toxins in environmental media – sediment quality properties	At specified* sites in C, Lx, Lb	Annually (following high flow period)	Could also use campaign-based sampling during/after likely adverse events

Desired outcomes	Process	Metric	Spatial scale	Temporal scale	Notes
	Bioaccumulation	Changes in the level of toxins in tissues in space & through time – heavy metal concentrations; Toxins in environmental media – sediment quality properties	At specified* sites in C, Lx, Lb & around the MM	Twice yearly (following high & low flow periods)	Optimal scales may vary among taxa/toxins. Could also use campaign-based sampling during/after likely adverse events

* Use existing monitoring sites where possible

20. Appendix E: How to read figures

Rebecca E. Lester & Peter G. Fairweather

This appendix provides an introduction to each type of figure that has been presented in this report, and a summary of how to read each.

20.1 Boxplots

Boxplot figures were presented for each set of scenarios to represent the hydrodynamic model output for the variables that drive ecosystem states in the Coorong.

In a boxplot, the interquartile range is represented by a box (Figure 20.1). That is, the limits of the box show the range for which the variable in question falls for 50% of the time. The whiskers on the box show an interval which is 1.5 times the interquartile range and more extreme values (outliers) are represented by points. Finally, the median is represented by a line through the box at the relevant height. Boxplots are presented that compare each group of scenarios, in line with the research questions (Figure 20.1). There is no one order in which the boxes could be presented which would allow all comparisons to be easily made.

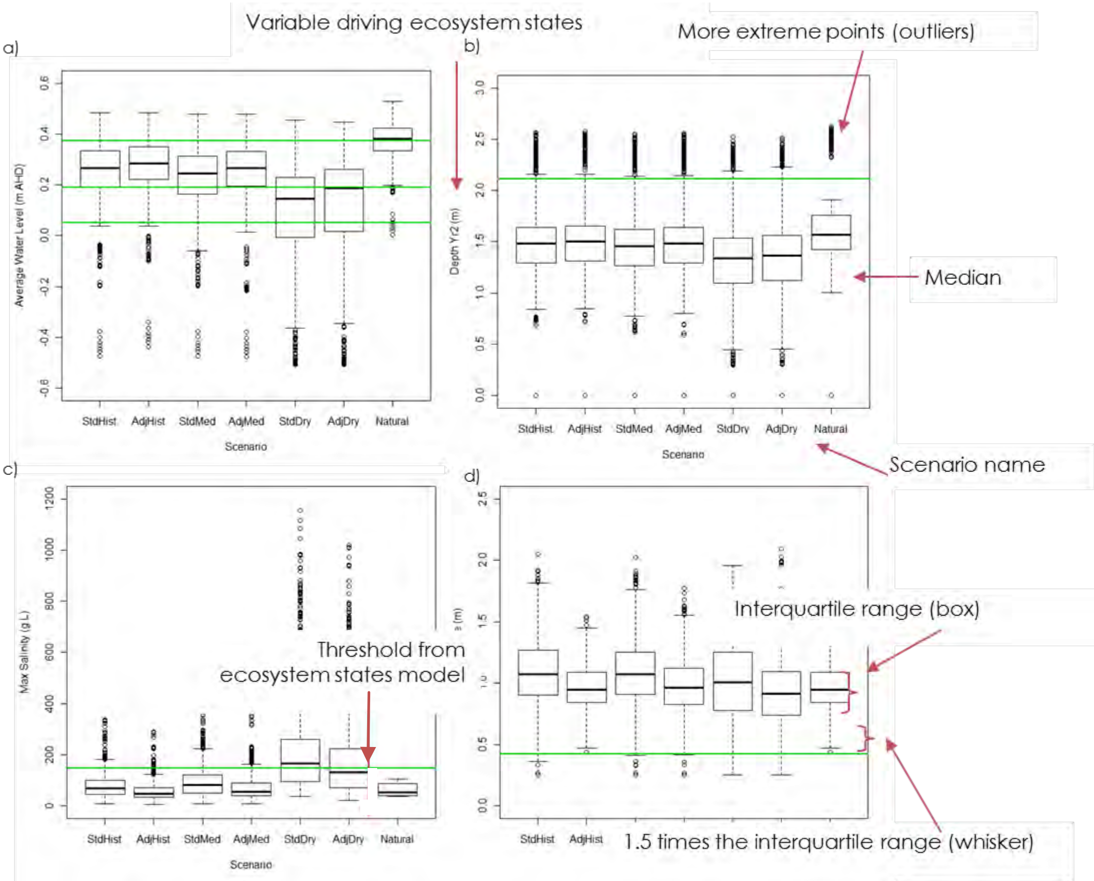

Figure 20.1: Example of boxplots from the climate change scenarios, highlighting points to note with red arrows

a) Average water levels (m AHD), b) water depths from the previous year (m), c) salinities (g L^{-1}), and d) annual tidal range (m). The green lines indicate the thresholds for each of the driving variables. StdHist is Standard Historical scenario, AdjHist is Adjusted Historical scenario, StdMed is Standard Median scenario, AdjMed is Adjusted Median scenario, StdDry is Standard Dry scenario and AdjDry is Adjusted Dry scenario.

20.2 Deviations from Standard Historical scenario

The second output displaying the hydrodynamic results of the various scenarios compares the deviances of values for key variables from the values obtained in the Standard Historical scenario, here used as a baseline (Figures 20.3 & 20.3). This was divided into two figures, one for the two key variables in the marine (or northern) basin (i.e. water level and depth from two years previous) (Figure 20.2) and one for two key variables in the hypersaline (or southern) basin model (i.e. water level and salinity) (Figure 20.3). The hypersaline basin also had a third driving variable (i.e. annual range) but this threshold was only relevant for a few site-years, and so, in the interests of two-dimensional display, was omitted from this analysis.

In these figures, the vertical and horizontal lines represent the values of each variable seen in the Standard Historical scenario. That is, scenarios that fall on the lines had a zero sum deviation compared with the Standard Historical for that variable and were not different. The figure for the North Lagoon plots the sum of deviations for water levels and depths without flow for site-years in the North Lagoon (Figure 20.2). Here, an increase in water level and an increase in depth could be considered an improvement, compared with the Standard Historical. Thus, scenarios where the vector ends in the upper-right quadrant (which is shaded grey) represent an improvement on both variables. Scenarios with vectors ending in the opposite quadrant (the bottom-left) represent a deterioration relative to both variables. The other two quadrants are an improvement for one variable, but not the other.

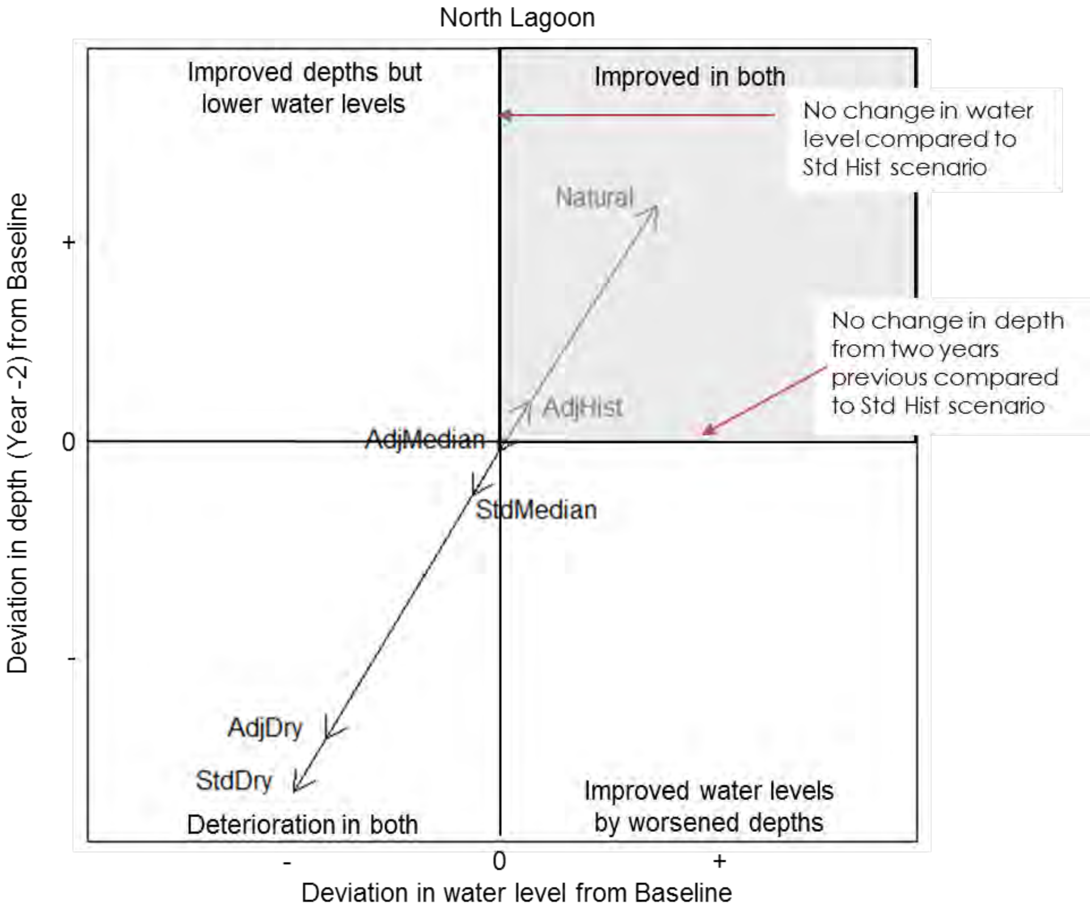

Figure 20.2: Example of comparison of the timing of flow and climate change scenarios to the Standard Historical scenario for key variables in the North Lagoon, highlighting points to note in red

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Standard Historical scenario with respect to water levels and depths (with depths from two years previously). The length of each vector is proportional to the strength of the deviation from the Standard Historical condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). AdjHist is Adjusted Historical scenario, StdMed is Standard Median scenario, AdjMed is Adjusted Median scenario, StdDry is Standard Dry scenario and AdjDry is Adjusted Dry scenario.

The second figure plots the sum of deviations for salinity and water level in the South Lagoon (Figure 20.3). As for Figure 20.2, scenarios falling on the horizontal and vertical lines indicate no deviation from the Standard Historical scenario for the variable in question. In this case, a decrease in salinity and an increase in water level constitutes an improvement. This corresponds to the bottom-right quadrant (shaded grey). Scenarios falling in the opposite quadrant (i.e. the upper-left) showed a deterioration with respect to both variables.

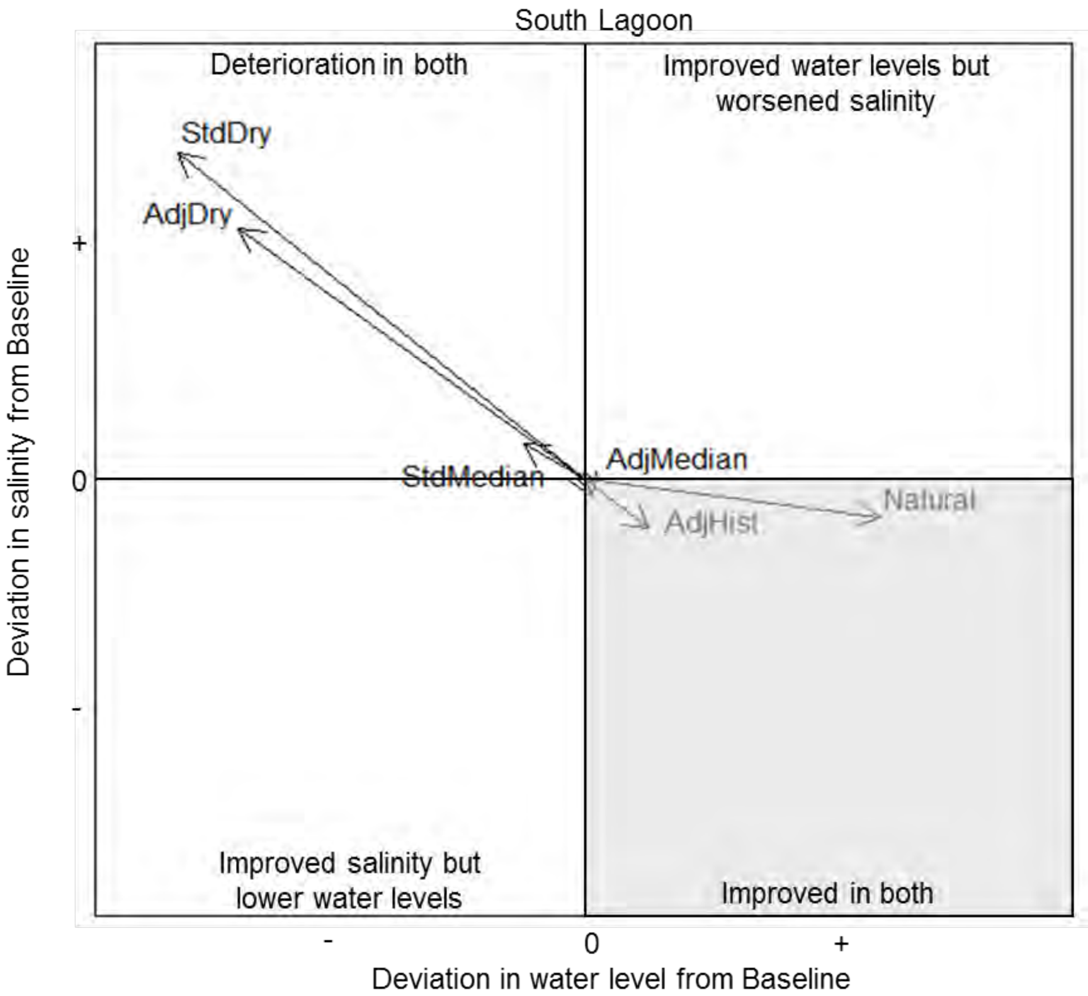

Figure 20.3: Example of comparison of the effect of the timing of flow and climate change scenarios relative to Standard Historical scenario for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Standard Historical scenario with respect to water levels and salinity. The length of each vector is proportional to the strength of the deviation from the Standard Historical condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). AdjHist is Adjusted Historical scenario, StdMed is Standard Median scenario, AdjMed is Adjusted Median scenario, StdDry is Standard Dry scenario and AdjDry is Adjusted Dry scenario.

20.3 Distribution of ecosystem states in space and time

The distribution of ecosystem states for each site in each year is presented in Figure 20.4. Sites are numbered from north to south, seven sites occurring in each lagoon, approximately evenly spaced. All 114 years of a simulation run are shown from left to right. Each site-year is represented by a circle, the colour of which indicates the relevant ecosystem state. A key outlining the colour-coding for each of the eight ecosystem states is given below the figure.

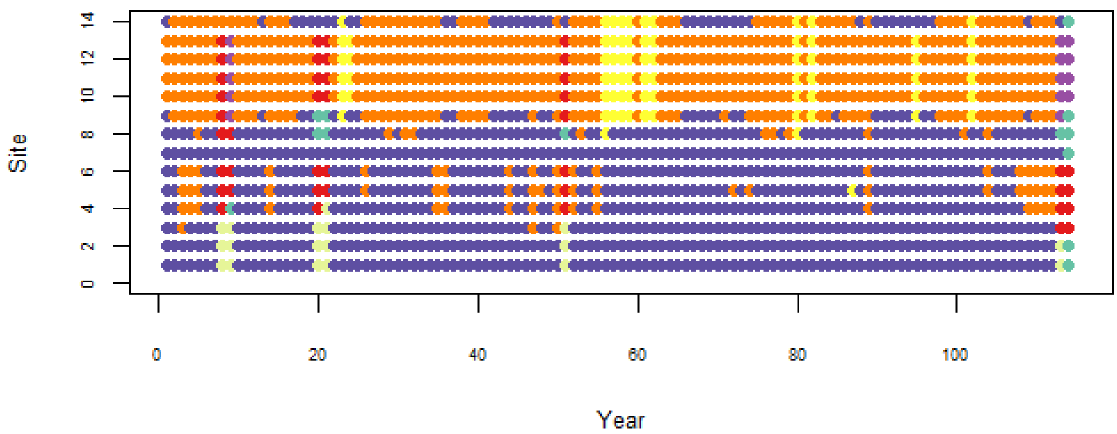

Figure 20.4: Example of distribution of ecosystem states for each site-year under the Standard Historical scenario

Each sequence of dots shows the distribution of the states for one site across the 114-year model run. The changes in the dot colours represent the transitions between states. For each dot, colours represent the following states: dark blue = Estuarine/Marine, light blue = Marine, light green = Unhealthy Marine, dark green = Degraded Marine, yellow = Healthy Hypersaline, orange =Average Hypersaline, red = Unhealthy Hypersaline and purple = Degraded Hypersaline.

20.4 Comparison of the proportion of site-years in each ecosystem state among scenarios

The next figure compares the proportion of site-years in each of the ecosystem states amongst groups of scenarios (Figure 20.5). This figure shows the distribution of ecosystem states for the Standard Historical scenario across the site-years, and compares it with other relevant scenarios, in combinations according to the research questions. A legend with abbreviated ecosystem state names is given, with a key below the figure explaining each of the abbreviations. Colour-coding is consistent with Figure 20.4.

This figure gives the total proportion of site-years that were found in each ecosystem state, across the entirety of the model run (114 years). Note that not all states are seen in every scenario. Also the number of colours is not an indicator of 'diversity' because the usually less-common colours represent degraded states (not necessarily a good thing).

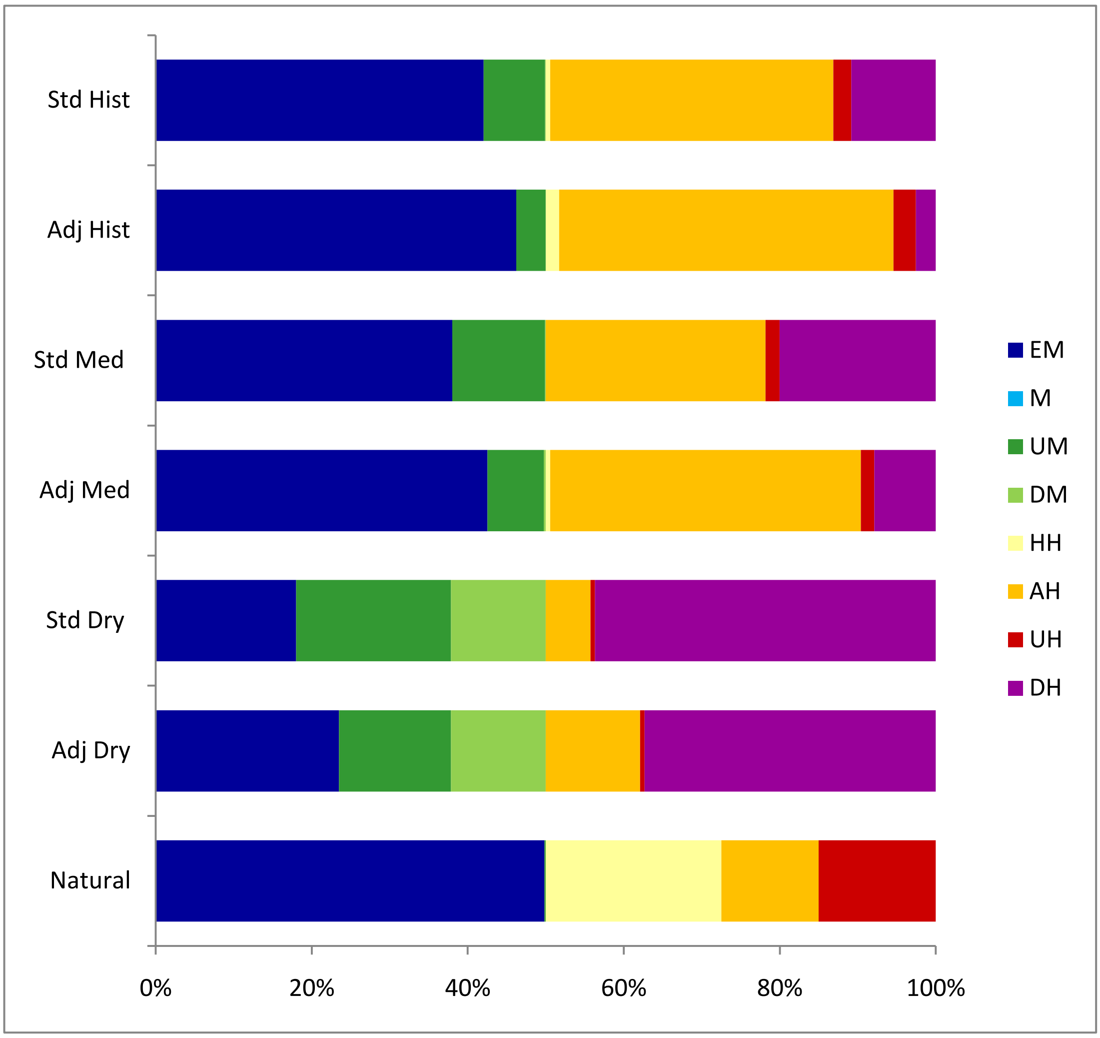

Figure 20.5: Example of comparing the proportion of site-years in each ecosystem state for the timing of flow and climate change scenarios

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DM = Degraded Hypersaline. Std Hist is Standard Historical scenario, Adj Hist is Adjusted Historical scenario, Std Med is Standard Median scenario, Adj Med is Adjusted Median scenario, Std Dry is Standard Dry scenario and Adj Dry is Adjusted Dry scenario.

20.5 Comparing the deviation in the proportion of site-years in each ecosystem state compared to the Standard Historical scenario

Figure 20.6 illustrates the percent change in the number of site-years predicted to be in each ecosystem state compared to the Standard Historical scenario. Increases in the incidence of an ecosystem state are shown as a positive change (i.e. above the x-axis), while decreases in frequency are shown as a negative change (i.e. below the x-axis). The terms positive and negative are used in a mathematical sense and are not perjorative (i.e. do not imply improvement or deterioration, which will vary depending on the ecosystem state in question). A legend with abbreviated ecosystem state names is given, with a key below the figure explaining each of the abbreviations. Colour-coding is consistent with Figure 20.4.

The display of multiple scenarios along the x-axis allows the relative changes associated with different scenarios to be compared. For example, in Figure 20.6, the Adjusted Median scenario had a smaller decline in the incidence of the Estuarine/Marine state than the Adjusted Dry scenario did (consistent with expectations that a dry future climate would result in a more-degraded mix of ecosystem states).

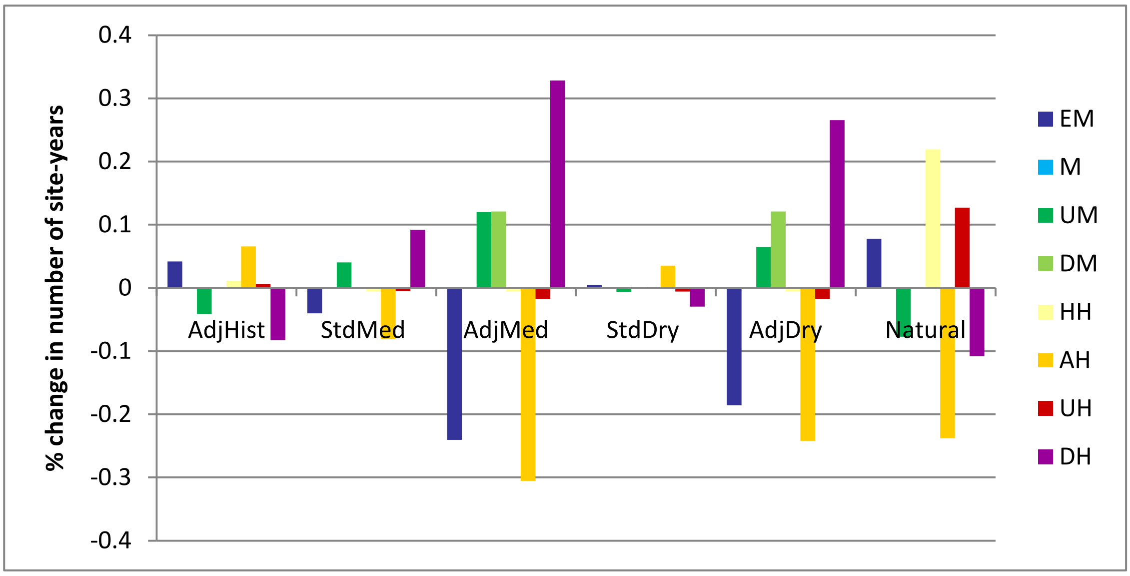

Figure 20.6: Example of the deviations in the proportion of site-years in each ecosystem state compared to the Standard Historical scenario for the rules-based flow delivery scenarios under a median future climate

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DM = Degraded Hypersaline. Std Hist is Standard Historical scenario, Adj Hist is Adjusted Historical scenario, Std Med is Standard Median scenario, Adj Med is Adjusted Median scenario, Std Dry is Standard Dry scenario and Adj Dry is Adjusted Dry scenario.

21. Appendix F: Conditions typical of each ecosystem state

Rebecca E. Lester & Peter G. Fairweather

The ERM model for the Coorong identified eight distinct ecosystem states. The states are presented as two linked logic trees (Figure 11.1a and b), one for each of two basins of attraction.

The northern basin consisted of four states, including those named Estuarine/Marine, Marine, Unhealthy Marine and Degraded Marine. These states had greater tidal ranges than those four of the southern basin: Healthy, Average, Unhealthy and Degraded Hypersaline. The biological and environmental characteristics of each state are shown in Table 21.1. Further information on the conditions and characteristic taxa of each state are presented in Lester & Fairweather (2010, 2011)

While the ecosystem state model performs well in describing the ecosystem states that have occurred in the nine years for which we had sufficient data, we acknowledge that other states are likely to (at least potentially) exist that are not adequately represented within this time frame. One that we have identified as likely to occur is an estuarine state, potentially requiring significant, ongoing freshwater inputs, such as have not occurred during the previous decade. Another is a state even less speciose than the Degraded Hypersaline state in the southern basin, or than the Degraded Marine state in the northern basin. The existence of both of these states is hinted at in anecdotal accounts of the system, either from the general public or researchers who have worked in the system for many years, and from the trends in data collected during 2008 after the development of these models, particularly in the South Lagoon. The possible existence of other states that fall outside the bounds of the data set is important to keep in mind when interpreting these results with a view to further management of the system.

Table 21.1: Relative biological and environmental characteristics of observed ecosystem states

Terms within the table are internally standardised from very low to very high. [a] Caution should be used in interpreting these results, as only one case for the Degraded Marine state exists in each of the long-term (1999-2007) and short-term analyses (2005-2007). [b] *Ruppia tuberosa* was only present in the long-term analyses because it was only monitored annually. NA indicates that no data was available for that state for the specified parameters. [TKN] represents concentration of total Kjeldahl nitrogen and [TP] represents concentration of total phosphate.

	Marine states				**Hypersaline states**			
Variable	**Estuarine/ Marine**	**Marine**	**Unhealthy Marine**	**Degraded Marine[a]**	**Healthy Hypersaline**	**Average Hypersaline**	**Unhealthy Hypersaline**	**Degraded Hypersaline**
Biological characteristics								
Fishing birds	High	Moderate	High	High	Very low	Low	Moderate	Very low
Shorebirds	Low	Very low	Low	Moderate	Moderate	Very high	Very high	High
Waterfowl	High	Moderate	Moderate	Moderate	Very high	Very high	Moderate	Very low
Estuarine fish	High	Very high	High	Low	Very low	Very low	Very low	Very low
Marine fish	High	Very high	Very high	Very low	Very low	Low	Moderate	Low
Benthic invertebrates	Very high	Moderate	High	Low	NA	Low	Very low	Very low
Ruppia tuberosa[b]	Very low	Very low	Low	NA	NA	Very high	High	NA
Environmental characteristics								
Days since flow	Low	High	High	High	High	Low	High	High
Flow volume	Moderate	Very low	Very low	Very low	Very low	Moderate	Very low	Very low
Salinity	Low	Very low	Moderate	Moderate	High	High	Very high	Very high
Tidal influence	High	High	High	High	Very low	Very low	Very low	Very low
[TKN]	Low	Very low	Very low	NA	Very high	High	High	High
[TP]	Low	Very low	Very low	NA	Moderate	High	High	Very high
Turbidity	Low	Very low	Low	NA	Very high	Moderate	High	Moderate

22. Appendix G: Comparison of predictions for the Natural flow scenario under the original versus the alternative ecosystem states model

Rebecca E. Lester & Peter G. Fairweather

In order to investigate the effects of different levels of environmental flows, the alternative ecosystem states model was used in this report (Lester & Fairweather 2009a). This model was developed using driving variables that did not include flow-related variables as potential predictors. The reason for this was that the original model included the maximum number of days without flow over the barrages as one of the main predictors of ecosystem states. This is likely to be due to the large stretches of time with no barrage flows that occurred during the period from which the calibration data was drawn (Lester & Fairweather 2009a, 2011). Therefore, the original model does not distinguish well between scenarios that have few periods of no flow, but where different volumes of flow are delivered.

However, this alternative model does not predict exactly the same mix of ecosystem states as the original model (Figure 22.1). The alternative model is divided into the two basins (i.e. marine and hypersaline basins), so the relative proportion of the Coorong that falls within each basin is fixed, which is not the case for the original model, where this is determined by the degree of tidal influence in the system. The relative proportions of each ecosystem state within each basin also changes depending on whether the original or the alternative ecosystem states model is used. This means that the choice of model needs to be considered carefully but, provided that model is consistently used for all scenarios investigated, comparisons between scenarios are valid. However, in this report, both the Natural and Adjusted Historical 700 scenarios showed higher proportions of site-years in the Unhealthy Hypersaline state than was expected. A detailed investigation of this behaviour indicated that this was a result of the decision node in the alternative ecosystem states model that classified site-years where water level from the previous year were over 0.37 m AHD as Unhealthy Hypersaline.

As has been highlighted above, the relationship between hydrodynamics and ecology is not linear, so increases in water levels will not always result in improvements in ecological condition. For example, very high water levels may completely flood mudflats, effectively making these unavailable as a food source for wading birds. However, this pattern of high water levels resulting in less-diverse ecosystem states was not observed in the original ecosystem states model and thus, represents a discrepancy between the two models.

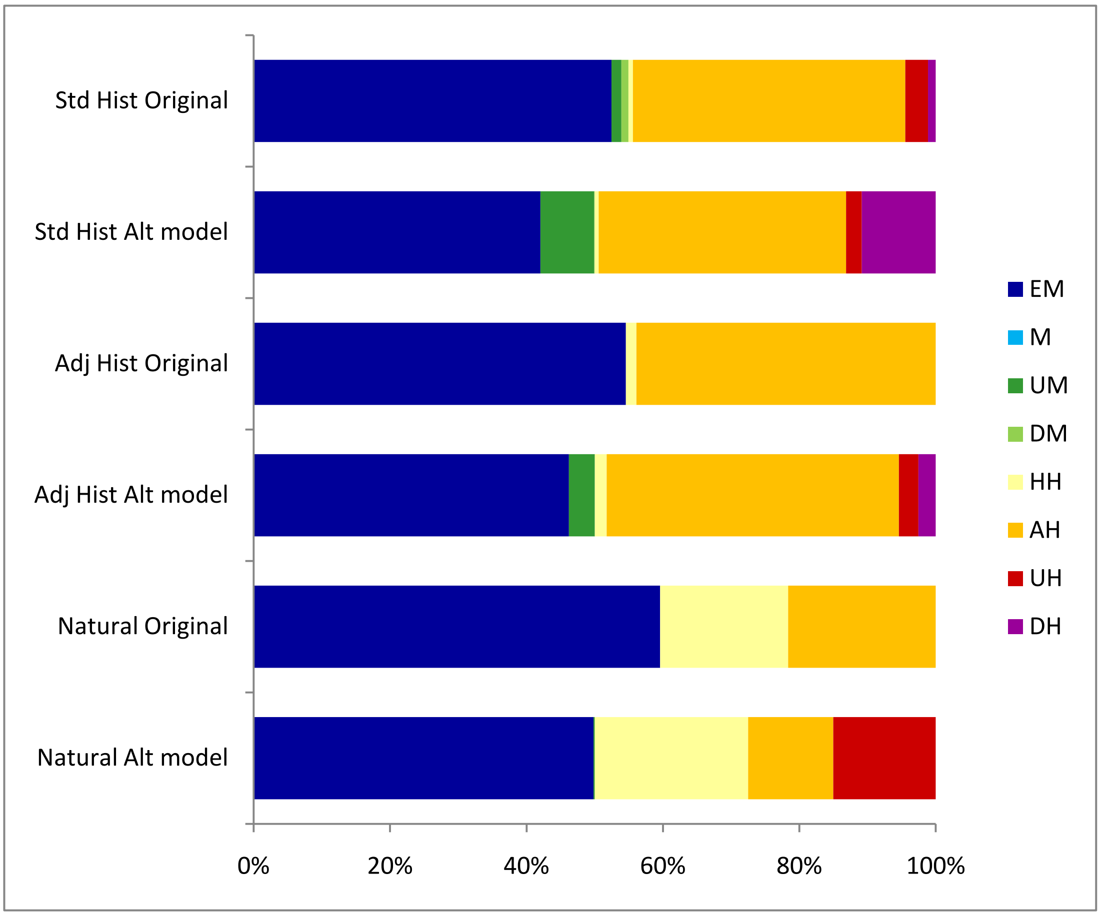

Figure 22.1: Comparing the proportion of site-years in each ecosystem state for scenarios investigated using the original versus the alternative ecosystem states model

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline. Std Hist Original is Standard Historical scenario using the original model, Std Hist Alt Model is Standard Historical scenario using the alternative model, Adj Hist Original is Adjusted Historical scenario using original model, Adj Hist Alt model is Adjusted Historical scenario using the alternative model, Natural Original is Natural scenario using the original model and Natural Alt model is Natural scenario using the alternative model.

It is possible that this discrepancy arises because the Natural scenario involves flow volumes that are well outside the experience of the ecosystem states model. This means that the flow volumes for the calibration period were much lower and we can have only a lower level of confidence that the model is capable of capturing behaviour outside that range of experience accurately. Figure 22.2 illustrates the range of experience of the model based on the average annual flows. It shows the average annual flow across the scenario run for all scenarios modelled within Chapter 10 and 11 and those that were included in Lester *et al.* (2009a). The vertical line indicates the average annual flow volume for the training data set used to develop the model, with the range of different annual flow volumes indicated by the shaded box. It is obvious that the far right point (corresponding to the Natural scenario) is well above the average flow volume for which the model was developed, and is higher even than any individual year within that data set. Thus, it is possible that the model does not accurately capture the behaviour of the system at that level of flow over the barrages.

Figure 22.2 also shows the non-linearity of the proportion of site-years predicted to be in degraded ecosystem states compared with the average annual flow over the barrages. The Natural scenario (the far right point) is substantially higher than any other scenario that had flows over 4000 GL year^{-1} on average.

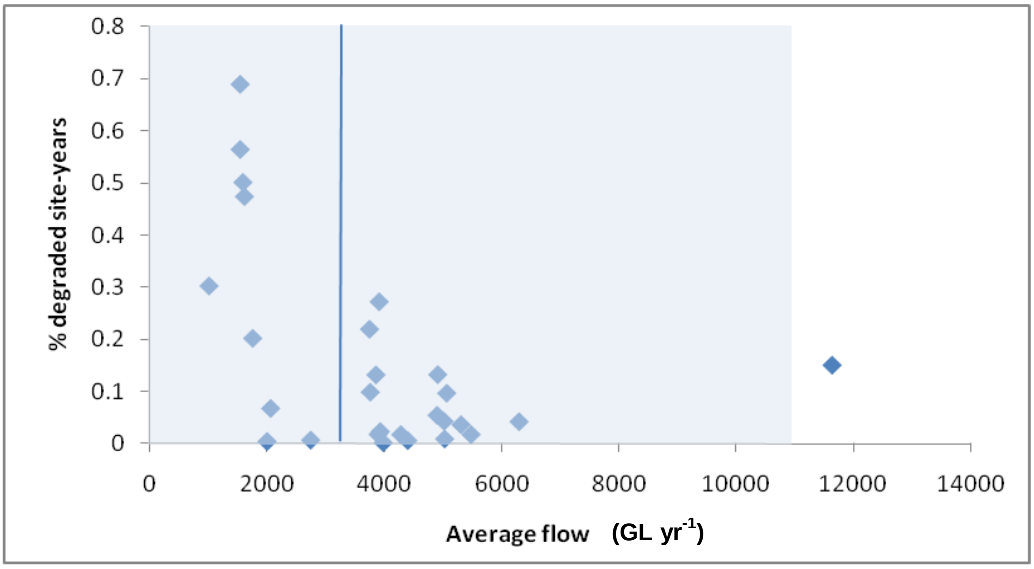

Figure 22.2: Comparison of the proportion of degraded ecosystem states against the average annual flow volume per scenario modelled

Note: The vertical blue line indicates the average annual flow volume for the training data set, with the shaded box showing the range of average annual flow volumes for each of the years within that training data set.

Closer examination indicates that this is due to the increased proportion of site-years predicted to be in the Unhealthy Hypersaline state, as a result of particularly high water levels (Figure 22.3).

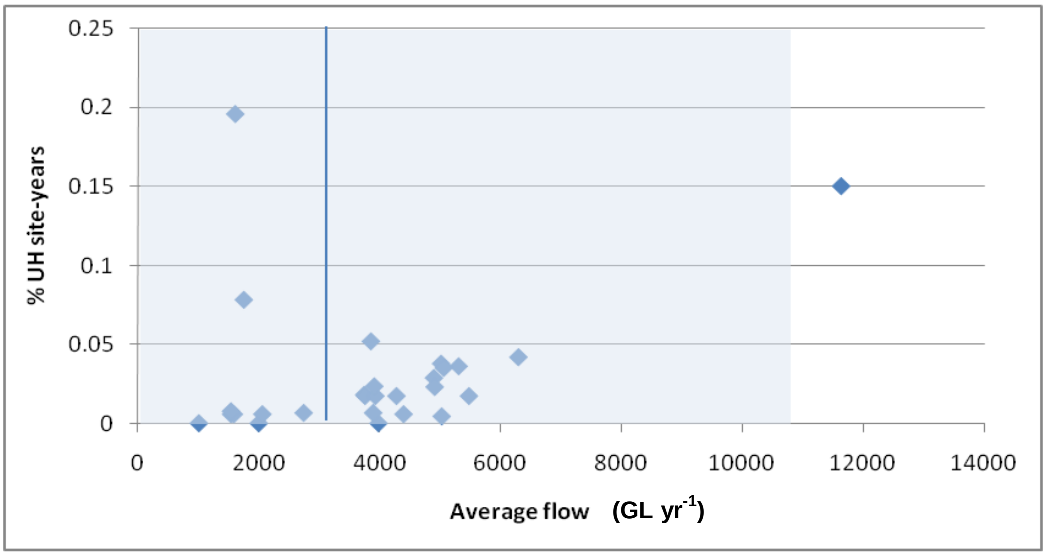

Figure 22.3: Comparison of the proportion of site-years in the Unhealthy Hypersaline state against the average annual flow volume per scenario modelled

Note: The vertical blue line indicates the average annual flow volume for the training data set, with the shaded box showing the range of average annual flow volumes for each of the years within that training data set. UH is Unhealthy Hypersaline.

While it is possible that this is a real effect, it is likely that this pattern is a result of the model's lack of experience at flow volumes of the magnitude seen in the Natural scenario. Thus, the results must be interpreted with care. As has been highlighted before, the relatively-poor and degrading condition of the Coorong over the years covered by the training data set means that the model is more adept at describing degradation within the system, rather than the intricacies associated with estuarine conditions (e.g. see Lester & Fairweather 2009a for a discussion of likely additional estuarine states in the marine basin). The lack of agreement between the two versions of the model suggests that this is, in fact, an artefact of the model, rather than a real finding. However, until this situation can be resolved by testing the predictions of the current model against observed data during high flow conditions, it is impossible to categorically resolve the discrepancy. Therefore, extreme caution should be exercised before using this model as a justification for providing only lower levels of flow because of the potential effect on the South Lagoon.

Instead, in this instance, it would be prudent to rely on the trade-offs that are apparent for the identified indicator taxa, assemblages and processes in the South Lagoon of the Coorong and use the ecosystem states model for comparisons between scenarios and for determining the likely extend of degradation under lower flow conditions.

23. Appendix H: Reproduction of Muller (2010b)

Kerri L. Muller

1. Background

The Lower Lakes (Lakes Alexandrina and Albert; the lakes) are situated at the terminus of the River Murray in South Australia. The River Murray channel empties into Lake Alexandrina (which also receives relatively small inflows from the Eastern Mount Lofty Ranges) and through it connects to the Murray Mouth region, the Coorong and Southern Ocean when the barrages at the southern end of the lake are open. Lake Albert is a terminal lake that lies to the south-east of Lake Alexandrina from which it receives its surface water inflows (i.e. receives water/exchanges water with Lake Alexandrina but does not have surface outflow to another water body downstream). The Lakes are also discharge points for regional groundwater although inflow volumes are thought to be negligible compared with surface inflows (Zulfic and Barnett 2004). Given that the Murray-Darling Basin is currently experiencing drought conditions and is both highly regulated and developed, the Lower Lakes are subject to a highly modified inflow regime that may result in lake water levels that do not support a healthy, resilient wetland system (DEH 2009a). This paper is one in a set of papers being prepared to determine the environmental water requirements of the Coorong and Lakes Alexandrina and Albert from first ecological principles (referred to as the upcoming environmental water requirements report to be finalised early in 2010). It describes ideal water level envelopes for the two lakes that, if followed, would meet the consolidated requirements of the different ecosystem components and processes that would comprise a healthy, resilient wetland system. As such it does not investigate any environmental water requirement factors other than water levels in the lakes, which will be covered in other papers in the set. It also focuses on the ecological ideal and does not seek to solve operational constraints but rather identifies some of these for managers to consider. This work builds on the operational principles and guidelines developed as part of The Living Murray program for which this site is an Icon site (SAMDBNRMB 2009). That work was necessarily constrained by current operational and hydrological factors that have not been considered constraints in preparing this paper, which seeks to describe the ecological ideal.

Water levels are a key determinant of Ecological Character in Lakes Alexandrina and Albert, primarily because they have a strong influence on the plant community structure, inundate or expose acid sulfate soils and enable access to, or conversely disconnect, given habitats over space and time (Boulton & Brock 1999; Holt *et al.* 2005; Nicol *et al.* 2007; Phillips & Muller 2006; Fitzpatrick *et al.* 2008; DEH 2009a). This high degree of determination of Ecological Character by water levels is reflected in the focus of the 8 Objectives and 33 associated Outcomes for the site (Chapter 3), of which the following 23 Outcomes (70%) are directly linked to lake water levels or variations in lake water levels:

i., ii, iii, iv., v., vi., vii., viii., ix., x., xi., xii., xiii., xiv., xx., xxi., xxii., xxiv., xxviii., xxix., xxx., xxxi. and *xxxiii.*

Of these, five Outcomes; *xx., xxi., xxii., xxix.* and *xxxiii.* (15% of the 33 Outcomes), specifically refer to lake water levels and seek to mimic natural variations in these, thus it is important to develop an understanding of what natural water level variations are likely to have been and what the requirements of the indicators in the upcoming environmental water requirements report are for water levels and their variations. It should be noted that in the upcoming environmental water requirements report, each of the 56 identified biological and process indicators are assessed each of the 33 Outcomes for suitability as evidence that a particular Outcome has been met.

Given that this assessment work is being undertaken simultaneously, any relevant results have been utilised and are cross-referenced here.

2. Historical lake water levels

It is known that under natural conditions, the lakes were permanent and remained essentially fresh with occasional ingressions of seawater in the southern parts of Lake Alexandrina (i.e. south of Point Sturt; Sim and Muller 2004; Fluin *et al*. 2009). It is likely, therefore, that natural seasonal and inter-annual variations in average water levels in the lakes were in the order of 60 cm (i.e. from approximately +0.3 to +0.9 m AHD; DWBLC 2005) based upon evidence that:

- seawater incursion was extremely limited in time and space (sea level is approximately +0.2 m AHD within the Murray Mouth embayment; DEH 2009a);
- the lakes are located at the end of catchment as large as the Murray-Darling Basin;
- flow at this end of the catchment was essentially permanent under natural conditions (e.g. sufficient to prevent the Murray Mouth from closing; Bourman 2000);
- the lakes are broad and shallow (DEH 2009b);
- the fresh waters of the lakes drained around, through and over the barrier islands in the southern parts of Lake Alexandrina (Mundoo, Ewe and Tauwitchere islands), with overland flow occurring at approximately +0.83 m AHD (Sim and Muller 2004; Ngarrindjeri Nation 2007; DEH 2009b); and that
- climatic and hydrological conditions such as wind seches or floods result in water levels deeper than the theoretical maximum set by the sill levels of these islands and channels, with occasional flood peaks of +1.0 m AHD or higher (Heneker 2009).

These processes operated together to support dynamic, interconnected ecosystems of great physicochemical and biological diversity. Between 1935 and 1940, an abrupt disconnect in the exchange of fresh, estuarine and marine water was created when a series of five permanent barrages were built to hold fresh water in the lakes and raise the water levels thereby stopping the (anthropogenically-induced) ingress of seawater (Sim and Muller 2004). For the majority of time since then, the combined impacts of river regulation and barrage operation have resulted in a relatively static regime of water levels that varied between +0.5 and +0.83 m AHD most of the time, except in periods of significantly lowered water availability (e.g. 1967/68 when levels dropped to c. +0.1 m AHD) or when inflows were significantly greater than outflows (e.g. 1965/66 when levels were c. +0.95 m AHD; see Figure 1). Full supply level for the lakes is considered to be +0.75 m AHD (DWLBC 2009). Since 2006, the effects of reduced inflows and allocation of available resources within the Murray-Darling Basin have resulted in a sustained drawdown of lake levels to well below those previously experienced such that water levels are now approximately 1 m below sea level (i.e. -1 m AHD; see Figure 1). The evidence from acid sulfate soil studies suggests that the lakes have not been this low in the 7,000 years since they formed (Fitzpatrick *et al.* 2008).

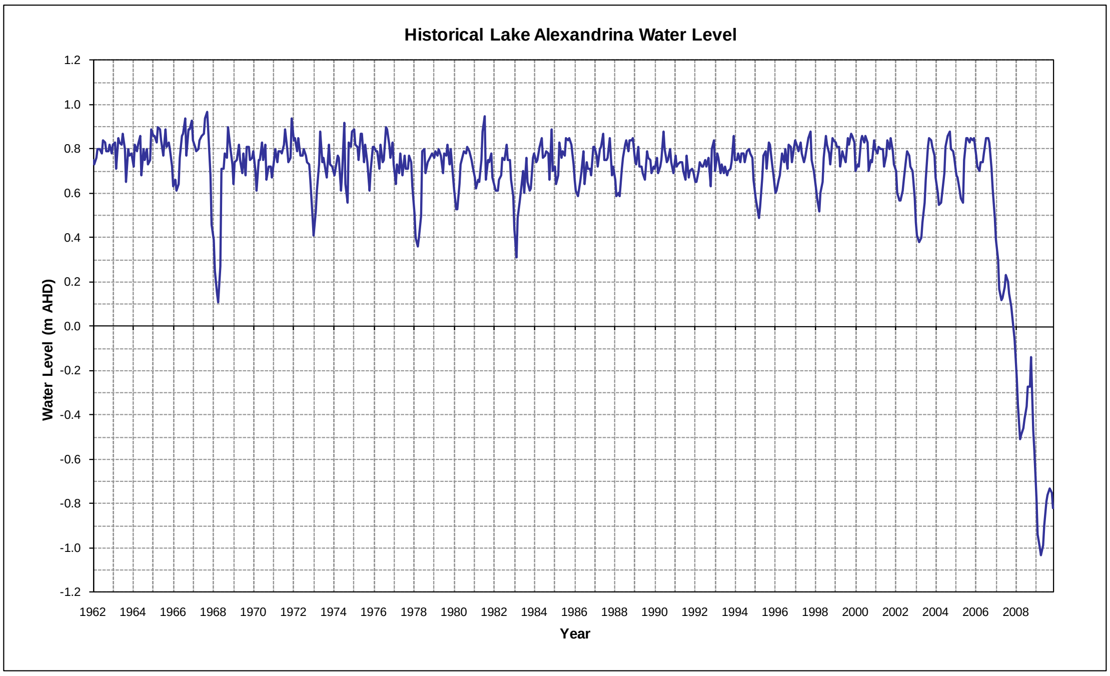

Figure 1: Average end-of-month water levels from 5 stations across Lake Alexandrina between 1962 and 2009

Note that Full Supply Level is +0.75 m AHD and 0 m AHD which is nominally sea level is shown as a black line (DWLBC 2009)

3. Environmental needs for lake level variation

It is evident that the regulation and homogenisation of the water regime in the lakes, described above, has led to a contraction and/or losses of plants suited to more variable water regimes that would have occurred prior to regulation (Walker *et al.* 1994; Blanch *et al.* 1999; Norris *et al.* 2001; Holt *et al.* 2005; Nicol *et al.* 2007). In particular the riparian zone became dominated by two species: common reed (*Phragmites australis*) and bullrush (*Typha domingensis*) under the regulated static regime rather than the diverse communities of reeds that were supported by the natural variation in water levels and the littoral zone became lower in diversity and contracted to less than 25 m wide (see Vegetation Indicators in upcoming environmental water requirements report). Given that vegetation patterns structure the wetland ecosystem and determine the trophic interactions that can be supported, to a large extent (Boulton & Brock 1999), this simplification and contraction has in turn led to a simplification and contraction of the ecosystem as a whole (see Phillips & Muller 2006 for review of changes in Ecological Character over time).

A more variable water level regime in the lakes, as proposed here, seeks to:

- Support self-sustaining littoral, riparian and floodplain vegetation communities that are wide and diverse that in turn will support productive and diverse ecological communities (Holt *et al.* 2005; Mondon *et al.* 2009);
- Promote temporal and spatial variation in habitat availability and ecological processes (e.g. Outcome xiii. and xiv.);
- Support life cycles of plants and animals that depend on spatial and temporal variability in habitat provision (e.g. congolli; Bice & Ye 2009; Bice 2010a); and
- Minimise lakeshore erosion, which is greatest at a lake level of +0.55 m AHD which coincides with the highly-erodible vertical transition from clays to Polltollach Sands (Muller 2008).

Re-instatement of variation in water regime that mimics the natural regime is both an outcome in itself (e.g. Outcome xx.) as well as being required evidence for meeting 23 of the possible 33 Outcomes (70%, see Section 2 and Chapter 3 for descriptions of Outcomes) and thus is considered a fundamental management action to achieve the vision of a healthy, resilient wetland.

3.1 Annual lake level envelope

If the environmental water needs of the 56 biological and process indicators (see upcoming environmental water requirements report) are used to construct an ideal envelope for lake level variation, average lake levels would vary between +0.35 and +0.7 m AHD in most years (Annual Return Interval of 1, ARI = 1), with fill occurring in late winter and spring and drawdown in summer and autumn to mimic the natural patterns and thus accommodate lifecycle processes. The ideal envelope for lake levels is shown in Figure 2 and Table 1 gives the rationale for the level changes over the months of the year. It should be noted that average lake levels are shown. Water levels at any one location can vary around this average depending on wind speed and direction (which drives seches of water and changes in water levels across the axis of the prevailing wind; see Figure 3) as well as local topographical variance at the sub-lake-basin scale.

The lower limit of +0.35 m AHD allows for fringing wetlands around the lakes and aquatic habitats on Hindmarsh and Mundoo Islands to remain connected to the permanently inundated habitats of the lakes for the vast majority of time (NB: disconnection at this water level may occur during some wind conditions), whilst promoting wide and diverse littoral and riparian vegetation through water level variation. It is critical that these habitats remain interconnected given that they provided irreplaceable and essential niches within the ecosystem, particularly the former permanently-flowing stream-like anabranches on the islands. Key components of these habitats were freshwater submerged aquatic plants and thus they were strongholds for small-bodied threatened fish such as Murray hardyhead and Southern and Yarra pygmy perch (see Bice 2010a), prior to the sustained drawdown that began in 2006. Additionally, these habitats provided permanent passage for fish and other biota hat has been otherwise interrupted by the construction and operation of the barrages.

Latest advice (DEH 2009b) indicates that the two Hindmarsh Island anabranches disconnect from the main body of Lake Alexandrina at +0.1 $\pm$ 0.15 m AHD (i.e. somewhere in the order of -0.05 and +0.25 m AHD accounting for error in Lidar data). The sill levels for these anabranches and other significant aquatic habitats (e.g. fringing wetlands) are being verified thus a precautionary approach has been taken in setting the minimum at +0.35 m AHD which is wise in terms of maintaining functional connectivity with the island anabranches and fringing wetlands (i.e. the latter may disconnect at higher elevations than +0.1 m AHD) across a range of short-term climatic conditions (e.g. wind direction and speed) that otherwise may disconnect these critical habitats if average lake water levels were actively managed to drop lower than +0.35 m AHD. If the lower limit was set below +0.35 m AHD there is also a higher risk of not receiving enough water in the subsequent year to fill the lakes to within the target envelope. If the lower limit were set higher than +0.35 m AHD, then the benefits of drawdown such as promoting wide and diverse littoral and riparian vegetation (i.e. Outcome xxix.) or supporting appropriate biogeochemical cycling (i.e. Outcome xxvi.) may not be maximised. Thus a lower limit of +0.35 m AHD is a consolidated position that seeks to optimise ecological needs for a variety of lake ecosystem components and processes.

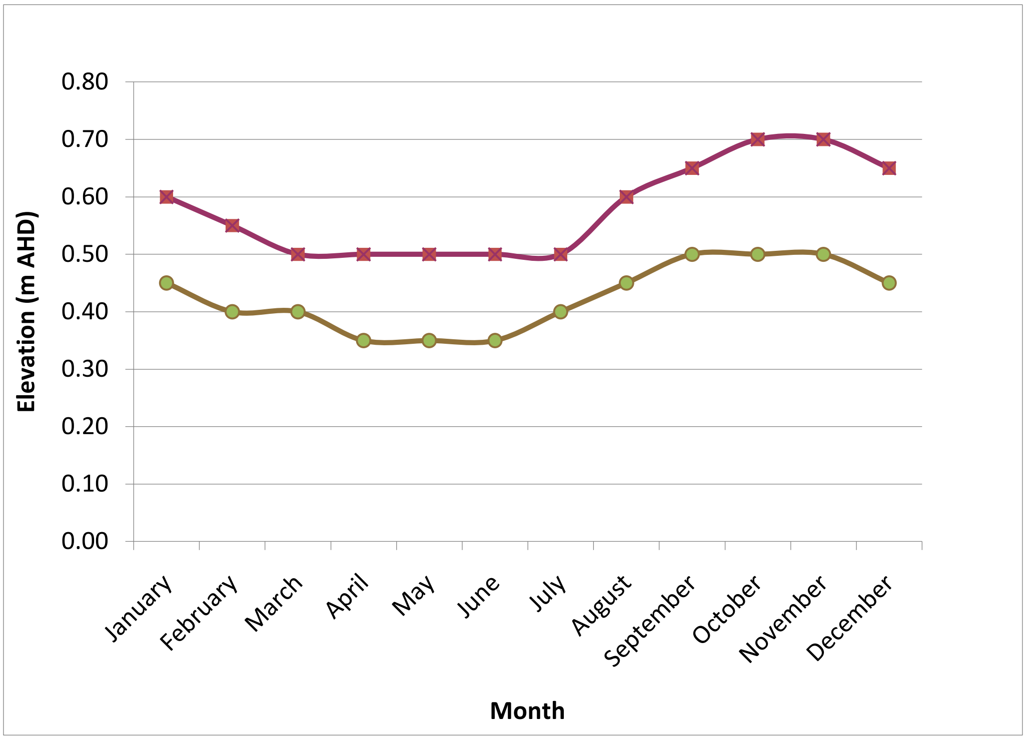

Figure 2: Proposed ideal envelope for the lakes at an Annual Return Interval of 1 (every year), showing upper and lower limits

There is a very low likelihood of re-establishing and sustaining all parts of the Ecological Character described by Phillips & Muller (2006) if the island anabranches and fringing wetlands are not reinstated and do not remain hydraulically connected at all times. It is therefore considered critical from the perspective of providing an envelope of lake levels that is optimal for lakes ecology, to keep average lake levels higher than +0.35 m AHD at all times. In order to make sure the stream-like habitats across Hindmarsh and Mundoo islands are functional during various climatic conditions when needed by migrating diadromous fish such as congolli and other biota, it is also critical that lake levels are never lower than +0.4 m AHD between May and February (Bice & Ye 2009; C. Bice pers. comm.). If it is found that this regime does not provide functional connectivity between the lakes, anabranches on the islands and the estuarine/marine components, then the minimum water levels should be raised to support those processes. Minimum lake levels of this order (+0.35 m AHD) would also sustain connectivity between the River Murray, tributaries and both lakes, thus maintaining functional connectivity between all the different freshwater components (See Outcomes *v.* to *xii.* in Chapter 3). It should also be noted that the upcoming environmental water requirements report gives indicators for assessing whether *Functional Connectivity* is supported.

Table 1: Rationale ideal envelope for the lakes at an Annual Return Interval of 1 (every year)

Month	Upper (m AHD)	Lower (m AHD)	Rationale
January	0.60	0.45	Gradual drawdown over late summer to expose mudflats and promote diverse vegetation, whilst supporting completion of life cycles for vegetation and dependent fauna.
February	0.55	0.40	February drawdown not to drop below +0.4 m AHD to ensure upstream migration of congolli (and common galaxias) juveniles from estuarine to fresh waters.
March	0.50	0.40	Summer/autumnal drawdown to expose mudflats and promote diverse vegetation but still support biotic movement between fresh and estuarine waters.
April	0.50	0.35	Autumnal drawdown to promote diverse vegetation can drop to +0.35 m AHD assuming that functional connectivity between the lakes and the island anabranches.
May	0.50	0.35	Autumnal drawdown to promote diverse vegetation but maintain connectivity to islands and fringing wetlands.
June	0.50	0.35	Winter low point prior to inflows commencing, supports over-wintering reeds which die-off and need their new shoots to grow at a rate that matches rising water levels in spring.
July	0.50	0.40	Fill typically begins in mid- to late winter. It may naturally have occurred very quickly but this proposed rate of fill would allow growth of new shoots of reeds and other vegetation to match rising water levels and thus promote diversity.
August	0.60	0.45	Highest rate of fill in late winter and early spring. Native fish, frogs and other fauna need access to vegetation from now onwards into spring/summer to obtain food and shelter for recruitment and protection from predation.
September	0.65	0.50	High water in spring for native fish, frogs and other fauna to access habitats and successfully recruit.
October	0.70	0.50	High water in spring for native fish, frogs and other fauna to access habitats and successfully recruit.
November	0.70	0.50	High water in spring for native fish, frogs and other fauna to access habitats and successfully recruit.
December	0.65	0.45	Commencement of summer drawdown to expose mudflats and promote diverse vegetation.

The upper limit of the ideal envelope is set at +0.7 m AHD in order to inundate the riparian vegetation and parts of the floodplain every year; provide faunal access to riparian and littoral vegetation; and create seasonal variation in water levels, without flooding the whole floodplain which only needs to occur on a 3-yearly cycle (see Section 4.2 below). It is not set higher than that because temporal and spatial variability in the extent of floodplain inundated is important and this envelope of lakes levels (ARI =1) is not intended to provide occasional flooding needs of floodplain biota but rather to sustain the littoral and riparian vegetation, although it is acknowledged that at +0.7 m AHD, some parts of the floodplain will be inundated particularly at a sub-lake-basin scale where wind seches and topographical changes can induce higher water levels than the average lake levels suggested in the ideal envelope.

In between the lower and upper limits, the rates of filling and drawdown are designed to create spatial and temporal variation in habitats; promote diversity in littoral, riparian and floodplain vegetation; maintain functional connectivity and ensure that rates of change in water level are not too great that vegetation is desiccated before both vegetative and dependent faunal life cycles are completed. See upcoming environmental water requirements report for species-specific needs for water levels on an annual basis.

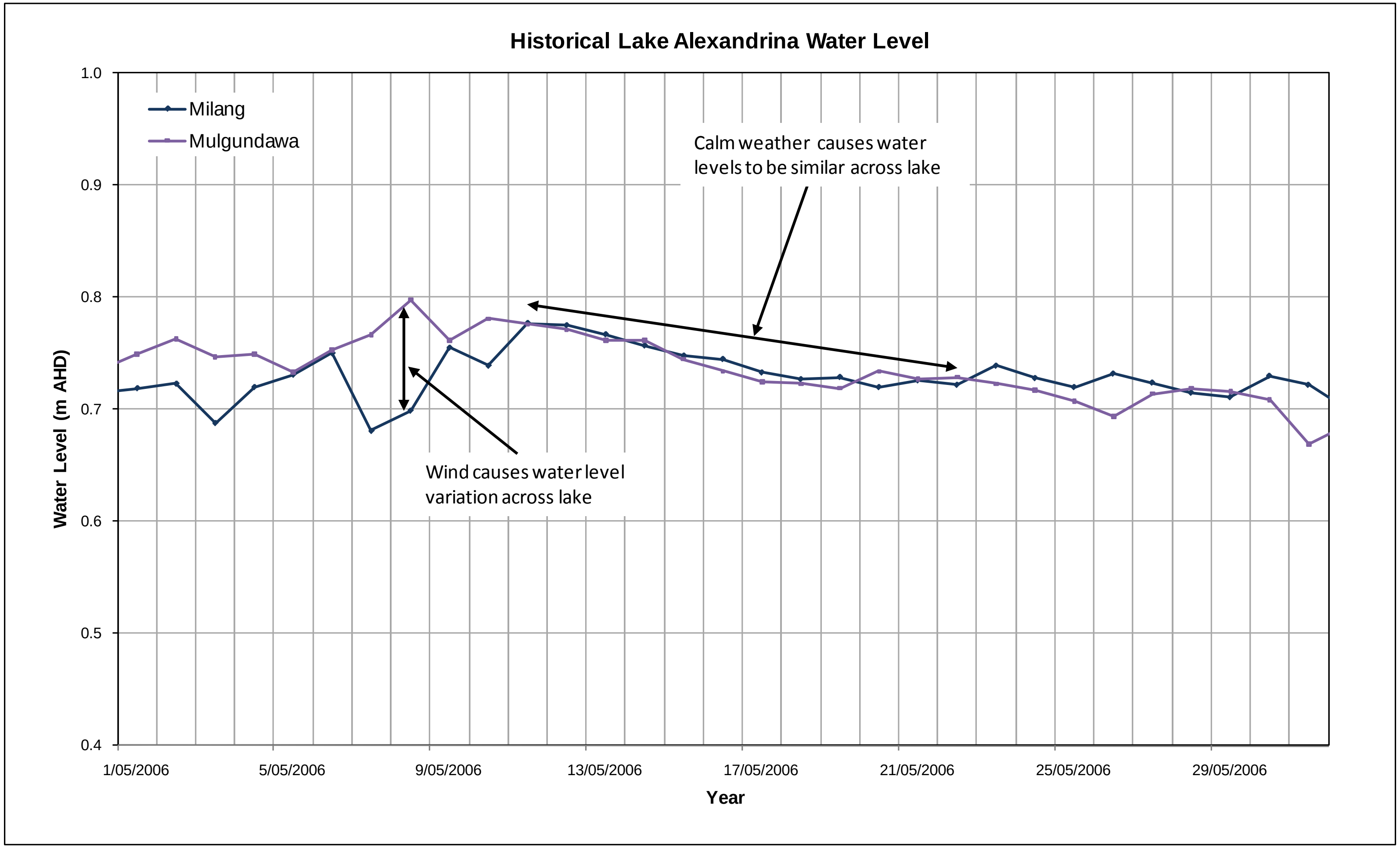

Figure 3: A comparison of fluctuations in Lake Alexandrina water levels at Milang and Mulgundawa stations showing the relative differences in lake water levels in calm vs windy weather (Heneker 2009)

3.2 Occasional flooding requirements (ARI = 3)

The annual lake level envelope (ARI = 1) described above would provide for seasonal variation in water levels (i.e. Outcome xx.) but it is not likely to provide adequate interannual variation or lake levels of sufficient height to support those biological and process indicators that require occasional flooding of the whole floodplain (e.g. Outcome xxi. and xxii.). Therefore it would also be ideal from an ecological perspective to have occasional flooding occur to lake levels greater than +0.7 m AHD with variable peak heights up to at least the historical maximum of an average lake level of +0.95 m AHD (see Figure 1). It is assumed that at approximately +0.83 m AHD, flow commences across flood runners on the islands between the barrages causing water to be released to the Coorong and Murray Mouth areas and lake levels to no longer continue to rise within a contained system (NB: at least some barrage gates would historically have been opened at a level of +0.83 m AHD, increasing discharges from the lakes above the flood runner capacity; Harvey pers. comm.). However average lake levels can exceed this theoretical maximum due to differential rates of inflow and outflow, wind seches and other factors. Water levels across the lakes historically peaked at +0.95 m AHD or more (Figure 1). Water levels greater than c. +0.85 m AHD were typically only achieved when River Murray inflows were in the order of 50,000 ML/d, although it may be possible to achieve peaks of +0.95 m AHD at lower inflow rates if barrage gates remain closed (Harvey pers. comm.).

The period for return of inundation events greater than +0.7 m AHD, has been set at 3 years in the ideal lake level envelope (ARI =3) based upon pre-regulation patterns (DWLBC 2005) and the needs of long-lived high elevation plant species such as samphires, lignum and paperbarks to have freshes every 3 years to promote seed production and recruitment to flowering adults (see Vegetation indicators in upcoming environmental water requirements report). These plant species are considered to act as surrogate indicators for the full suite of floodplain biota and processes and thus if their needs are met it is likely that the needs of EPBC-listed species such as Orange-bellied parrot (*Neophema chrystogaster*) will also be met (e.g. samphire plants need to produce plentiful seed to for Orange-bellied parrots to eat as well as recruit new individuals into their population; Mondon *et al.* 2009). Floodplain inundation every 3 years would also support EPBC-listed Metallic sun-orchid, *Thelmitra epipactoides* which associates with paperbark woodlands; diverse reed beds containing relatively rare but important plants such as Water ribbons (*Triglochin procerum*); and wide littoral and riparian vegetation (e.g. Outcome xxix.). Consequently, the habitat needs of a wide range of waterbirds (Jensen *et al.* 2000) and the EPBC-listed Southern bell frog (*Litoria raniformis*) are also likely to be met (see upcoming environmental water requirements report).

These occasional floodplain inundation events will also inundate fringing wetlands, the edges of the lakes and channel habitats on Hindmarsh Island and will thus supporting wide bands of littoral, riparian and floodplain vegetation (e.g. Outcome xxix.). In turn, these floods will support successful recruitment of endangered small-bodied native fish such as Murray hardyhead (*Craterocephalus fluviatilis*) and Southern (*Nannoperca obscura*) and Yarra Pygmy Perch (*Nannoperca australis*; Fish Indicator species in upcoming environmental water requirements report). One of the best recent years for breeding of these fishes occurred in 2005 and early 2006, following a prolonged period of inundation of lake edge habitats at water levels of +0.8 m AHD or greater from June 2005 to January 2006 (Bice, pers. comm.). Water was being released through the barrages during part of this period as well and thus this time period represented a period with a high degree of functional connectivity between different management units as well as between open water and floodplain habitats (e.g. Outcomes v. to xii.). While this observation may be seen as anecdotal, it provides a basis for determining the upper limits of the ideal water level envelope for the occasional flooding requirement.

It is important to note that the ideal envelope for floodplain inundation still contains seasonal variation and the lower level is set such that drawdown in summer could occur to a level of +0.50 m AHD to promote floodplain diversity (see Figure 4 and the rationale recorded in Table 2), although the qualitative evidence from Bice above would suggest that the optimal outcomes for fish would be achieved if the higher end of the envelope were followed and the floodplain remained inundated above +0.8 m AHD for the period June to January.

Such an envelope of lake levels would support the ecological needs for occasional flooding without sacrificing seasonal variation that promotes wide littoral and riparian vegetation and thus would maximise the ecological outcomes in the freshwater vegetation and associated aquatic communities of the Lakes. There is a risk, however, by sustaining water levels greater than +0.8 m AHD from August to February (if the upper limit was followed) of drowning-out littoral vegetation that is not able to grow to match the high water levels in spring and this would need to be monitored and used as an indicator of whether water levels need to be decreased earlier in summer or not raised as quickly or as high in early spring.

Setting the upper limit for the lake levels envelope with an Annual Return Interval of 3 (ARI = 3) at +0.95 m AHD is intended as a guide to managers and to encourage occasional flooding above the theoretical maximum of +0.85 m AHD rather than as a specific target and thus the upper limit for September to December, in Figure 3, could be read as > +0.85 m AHD (cf. up to +0.95 m AHD).

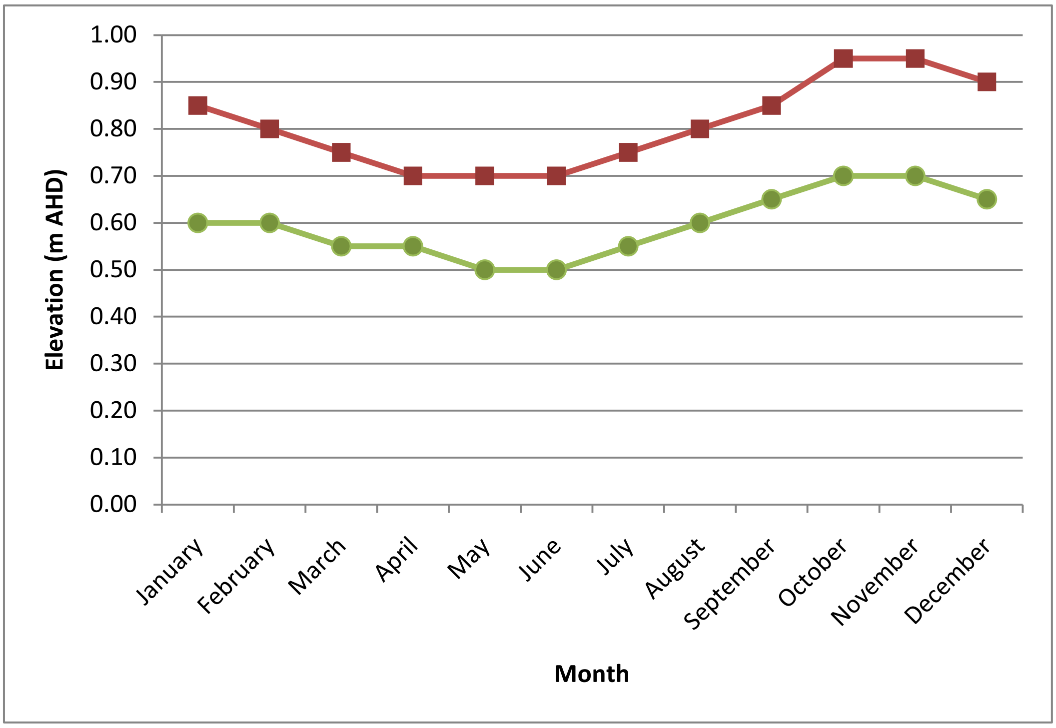

Figure 4: Proposed ideal envelope for lake levels at an Annual Return Interval of 3, showing upper and lower limits

Table 2: Rationale for ideal envelope for lake levels that would occur at an Annual Return Interval of 3, showing upper and lower limits

Month	Upper (m AHD)	Lower (m AHD)	Rationale ARI = 3
January	0.85	0.60	Gradual drawdown over late summer to expose mudflats and promote diverse vegetation, whilst supporting completion of life cycles for floodplain vegetation and dependent fauna. Optimal outcomes for small-bodied native fish if water levels are ≥ +0.8 m AHD from August to February (Bice pers. comm.).
February	0.80	0.60	Summer drawdown to expose part of the mudflats and promote diverse vegetation but stay above +0.6 m AHD so as to support faunal access to littoral vegetation and upstream migration of congolli (and common galaxias) juveniles from estuarine to fresh waters.
March	0.75	0.55	Summer/autumnal drawdown to expose mudflats and promote diverse vegetation, whilst still supporting high levels of connectivity between lakes, island anabranches and the Coorong.
April	0.70	0.55	Autumnal drawdown to promote diverse vegetation but maintain connectivity to islands and fringing wetlands.
May	0.70	0.50	Autumnal drawdown can drop to +0.50 m AHD to promote diverse vegetation but maintain connectivity to islands and fringing wetlands
June	0.70	0.50	Winter low point prior to inflows commencing, supports over-wintering reeds which die-off and need their new shoots to grow at a rate that matches rising water levels in spring.
July	0.75	0.55	Fill typically begins in mid- to late winter. It may naturally have occurred very quickly but this proposed rate of fill would allow growth of new shoots of reeds and other vegetation to match rising water levels.
August	0.80	0.60	Highest rate of fill in late winter and early spring. Native fish, frogs and other fauna need access to vegetation from now onwards into spring/summer to obtain food and shelter for recruitment and from predation.
September	0.85	0.65	Some species require occasional inundation of whole floodplain (e.g. long-lived vegetation), which is assumed to occur at average water levels of +0.83 m AHD given that is when flow commences over the islands and into the Coorong. NB: water levels can exceed +1.0 m AHD in some areas.
October	0.95	0.70	Some species require occasional inundation of whole floodplain (e.g. long-lived vegetation) at lake levels of ≥+0.85 m AHD.
November	0.95	0.70	Some species require occasional inundation of whole floodplain (e.g. long-lived vegetation) at lake levels of ≥+0.85 m AHD. Extended floodplain inundation compared to ARI = 1 to allow fish and plants to complete life cycles.
December	0.90	0.65	Commencement of summer drawdown to expose mudflats and promote diverse vegetation.

These two ideal lake level envelopes (Figures 2 and 4) are designed to meet the environmental needs of the lakes ecosystem for seasonal and interannual variation and thus are described as having Annual Return Intervals of 1 and 3, respectively. Given that water depth and elevation are interdependent (i.e. higher bed elevation has a lower water depth), these changes in water level will provide spatial variability as well as temporal variability (i.e. Outcome *xiv*.). That is, at different water levels, different habitats will be exposed, connected or disconnected and thus different ecological components and processes will be supported (see upcoming environmental water requirements report). It is important therefore that if managers operate within these envelopes at Annual Return Intervals of 1 and 3, that temporal and spatial patterns eventuate in the lakes. A comparison of the upper limit for the envelope with an Annual Return Interval of 1 and the lower limit for the occasional flooding envelope (ARI = 3) shows that the two envelopes overlap for large parts of the year (Figure 5), with the main difference being that the lower limit of ARI = 3 stays higher for longer in late summer and autumn to provide sustained floodplain inundation and to support completion of life cycles of species dependent on floodplain inundation. It is important though that managers seek to ensure that there is interannual variability by not directly mimicking water level changes in consecutive years even if to do so would comply with the frequency and variations described in the two envelopes.

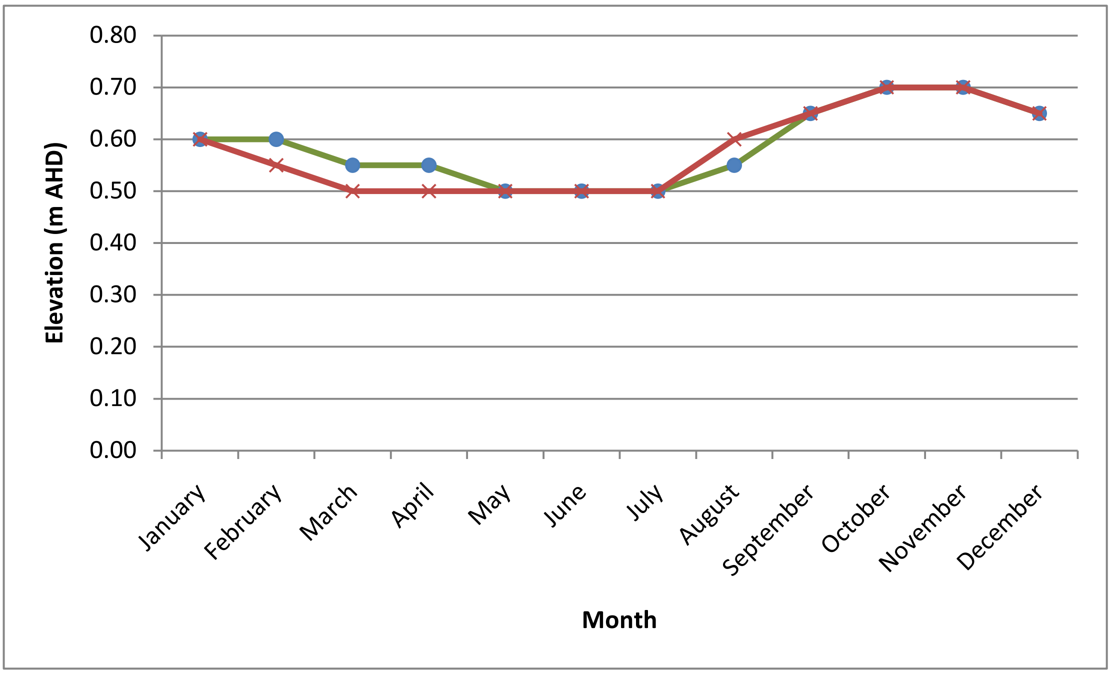

Figure 5: A Comparison of the ideal hydrograph Annual Return Interval (ARI) of 1 and the lower limit of the ARI = 3 hydrograph

4. Operational considerations and the ecological implications of compliance and non-compliance with these optimal lake level envelopes

The proposed envelopes for water levels with Annual Return Intervals of 1 and 3, above, should be considered as the ideal envelopes of lake levels for the ecological components and processes at the site (based on biological and process needs for water levels described in the upcoming environmental water requirements report). However, this site is both highly modified in itself as well as sitting within a highly modified catchment. River Murray operations often differ from natural seasonal flow patterns because the delivery pattern for entitlement flow to South Australia (as defined under the Murray-Darling Basin Agreement) is targeted primarily for irrigated agriculture. In a year when there is only enough water to supply South Australia with entitlement flow (1850 GL), then the monthly distribution of annual flow at the border should follow the pattern shown in Figure 6 (diamond markers). However, a large proportion of flow to South Australia has historically come from unregulated or flood events, the peaks of which generally occur between July and October, thus the observed flow to South Australia differs from that proposed in MDB Agreement (see Figure 6). The capacity to deliver flows to the Lower Lakes and Coorong depend in part on the ability for the unregulated events to continue or, if in times of low water availability, for water to be delivered in a pattern that replicates the historical distribution which best mimics the natural distribution (Heneker 2009). Delivering environmental water as per the entitlement flow distribution will not appropriately mimic natural distribution and is not likely to be possible without significant losses due to channel constraints over summer.

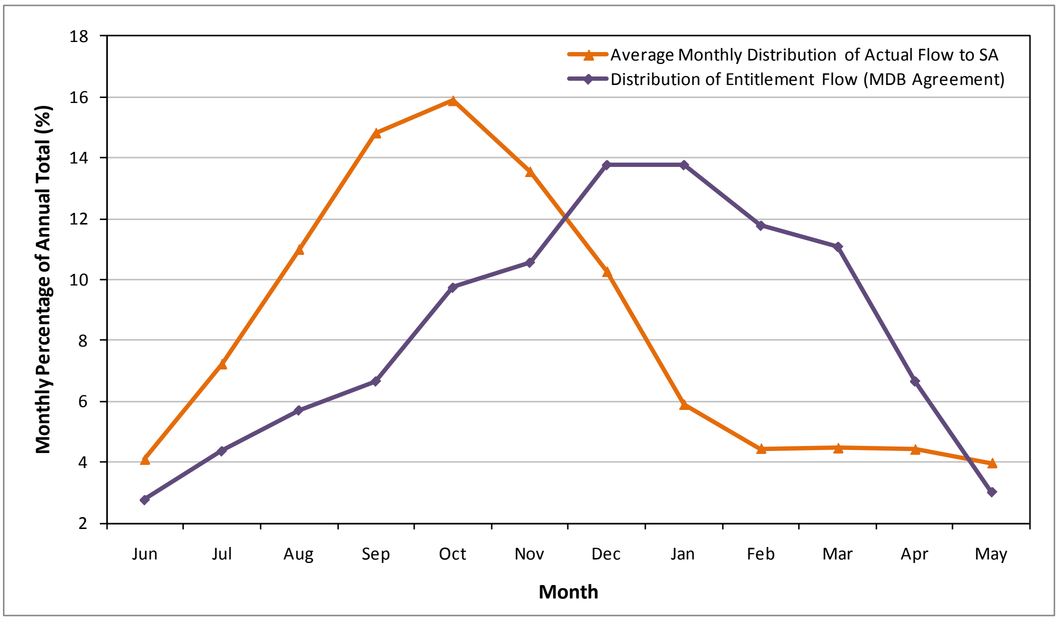

Figure 6: A Comparison of the average monthly distribution of actual flow into South Australia and the distribution of Entitlement Flow proposed in the Murray-Darling Basin Agreement (Heneker 2009)

There are also like to be operational constraints on delivery of the ideal lake level envelope at the site scale. For example, at lake levels of +0.4 m AHD of less, wind seches and high tides can combine or operate independently to create negative head (also known as reverse head) on the upstream side of the barrages which can result in the intrusion of seawater into the lakes if any parts of the barrage structure are opened to facilitate biopassage or water releases from the lakes (particularly if strong southerly winds are blowing). The amount of salt that enters the lakes during any one opening event at these low lake levels may only be small but it is likely to cause salinity levels to at least temporarily exceed targets for the lakes (see upcoming environmental water requirements report for salinity targets), if only in the southern parts of Lake Alexandrina.

The current rock ramp fishway (biopassage) in the Tauwitchere barrage ceases to operate below lake levels of +0.65 m AHD. Vertical slot fishways installed in Goolwa, Tauwitchere and Boundary Creek barrages can operate significantly lower than +0.35 m AHD (i.e. at the proposed lower limit for average lake levels, see Section 3) but they may need to be replaced or modified to allow free biopassage of small-bodied native fish (e.g. congolli; Fish Indicator in upcoming environmental water requirements report) and other fauna at such low lake levels without resulting in saltwater intrusion. It is highly preferable for catadromous fish such as congolli to have free movement between fresh, estuarine and marine habitats but it is recognised here that this may not be operationally possible at all times. It is essential however that fishways (biopassages) are not closed before March to allow for upstream migrations of juveniles and are open again by late May or early June to allow for downstream migrations of adult congolli (see Fish Indicators in upcoming environmental water requirements report; Bice pers. comm.).

There is also a risk by allowing lake levels to drop as low as +0.35 m AHD to maximise benefits to vegetation that require variable water levels, that not enough water will be available the following year to refill the lakes. Thus seeking a summer drawdown as low as +0.35 m AHD may compromise the capacity to meet the targets in the following year(s) and may result in untimely disconnection of habitats because water levels remain too low. Therefore it may be that the summer drawdown target needs to be higher than +0.35 m AHD in most years and can only be drawn-down to +0.35 m AHD in years with high water security when managers will be certain that water will be available to refill the lakes to meet the following years lake level targets. It is likely that modelling of the frequency of failure to refill in a subsequent year can be readily undertaken to assess this risk. Delivery of the ideal regime proposed in Sections 3.1 and 3.2, is thus likely to be subject to trade-offs in how best to deliver water within the site (e.g. low water levels in autumn may lead to disconnection of Lakes from Murray Mouth region and the Coorong as well as possible salinisation).

The ideal lake level envelopes proposed above (Sections 4.1 and 4.2) are based on ecological requirements only and thus may be subject to further operational constraints from outside of the site such as upstream channel capacity, access to water held in storage for environmental water provision and the need to deliver environmental outcomes at a range of ecosystems across the Murray-Darling Basin upstream of the site. There is a risk that if water is stored or traded for delivery to the Lakes and Coorong in summer to prevent water levels dropping too low, for example, that upstream ecosystems would be compromised by running water through in summer which is a time that their environmental water needs may be calling for a drawdown, which could not be facilitated if water was concurrently being delivered to the Lakes. As such it may be necessary to increase winter lake levels in some years to ensure that sufficient water is available at the site to account for evaporation and prevent summer water levels dropping to lower than +0.35 m AHD. Risks of failure to supply water to consumptive users also exist if the ideal lake levels for ecological benefit were to be followed. Opportunities to manage water levels in the Lower Lakes by upstream water management and intra-site distribution are thus limited by competing needs of other users, including other ecological assets, and managers need to be aware of these constraints and make trade-offs in a transparent and traceable manner such that robust adaptive management principles can be applied and water delivery to meet ecological needs improves over time.

The constraints above are included for consideration by managers and are not intended to be exhaustive. It will be necessary to undertake whole-of-basin modelling to better understand these risks and how to optimise water delivery. Following is a table of operational guidelines for managers that should be met as best as possible to optimise ecological outcomes at the site (Table 4). SAMDBNRMB (2009) should be referred to for the revision of targets, principles and philosophies for the site under *The Living Murray* Initiative.

Table 3: Operational guidelines for optimising water level management in the Lower Lakes

Refer to indicators sections in upcoming environmental water requirements report for details on indicators and metrics identified in risks columns.

Operational guidelines	Rationale	Risks of non-compliance	Risks of compliance
Do not flood above +0.7 m AHD for more than 3 years in a row.	Floodplain requires intermittent and variable flooding to maximise the representation of a diverse floral community (Outcomes *xiv. xx. xxix.* and *xxx.*).	Promotes monocultures of *Phragmites australis* and *Typha domingensis* rather than diverse riparian and emergent vegetation communities (Blanch *et al.* 1999; Holt *et al.* 2005; Gehrig & Nicol 2010).	Low maximum water levels could result in increased risk of falling below target lower limits because of evaporative losses (DEH 2009b).
Do inundate the floodplain to at least +0.83 m AHD at least once in every 3 years.	Long-lived vegetation requires occasional flooding to trigger recruitment, sustain existing adult vegetation and dependent fauna (Outcome *xxii*.).	Decline in long-lived, high-elevation vegetation and likely decline in associated assemblages.	Drowning of littoral vegetation at low elevations. Farmland may be inundated and erosion may occur if levels >+0.85 m AHD are sustained. Trade-offs between barrage releases and increased lake levels.
Do not allow average lake levels to drop below +0.35 m AHD at any time if possible, or at any time between June and March.	Maintain functional connectivity between all units and permanence of Hindmarsh Island streams at least at times that are critical to migrating congolli (i.e. June to March; Bice & Ye 2009).	Loss of flowing habitats and dependent species. Loss of functional connectivity (Outcomes *v.* to *xii.).* To prevent water levels exposing sufficient sulfidic material to result in water quality threats	No identified ecological risk provided island streams and fringing wetlands remain connected.
Do mimic natural patterns of rise and fall such that the lowest water level occurs in autumn (prior to winter fill commencing) and the highest in late spring/early summer.	Ecological components and processes are adapted to natural patterns of change (Jensen *et al.* 2000; Walker *et al.* 2004; Outcome *xix*. and *xx*.)	Ecological processes dependent on seasonal patterns (e.g. fish spawning; Bice & Ye 2009) will not be supported.	No identified ecological risk to this site although delivery through the modified system may compromise ecological targets at upstream sites.
Do not flood at a rate of greater than 2 cm per day (when possible).	Some submerged aquatic plants are unable to match very fast rates of water level rise (Blanch and Ganf 1999) and therefore the greatest diversity in littoral vegetation would be achieved with increases of not more than 2 cm/day. Slow inundation of parched, sulfuric materials (ASS) would minimise risk of	Submerged aquatic plants do not extend to edge of euphotic zone and thus littoral zone is not as wide as it could be. Favouring those that can withstand rapid increases in water levels i.e. fluctuation responders or those with floating leaf structures, reduces diversity of plants.	No identified ecological risk provided this guideline is not used to prevent floods. Floods are necessary and should be modified as little as possible. This principle is intended for use when refill is regulated.

Operational guidelines	Rationale	Risks of non-compliance	Risks of compliance
	transfer of acid and other oxidation products to water column.	Acidification and mobilisation of ASS oxidation products would be rapid and may pose water quality risk.	
Do drawdown the lakes to +0.35 m AHD during summer/autumn at least one year in 3.	Water level variation in the riparian and littoral zone will promote diverse and wide vegetation (Outcome *xxix*.). Regular oxidation of sulfidic materials would also be promoted which would reduce the risk of water quality impacts in years with drawdown to +0.35 m AHD or lower (Fitzpatrick *et al.* 2008).	Ecological processes requiring variable water levels and exposure of sediments will be best supported if lake levels drop as low as possible without compromising other ecological components and processes (e.g. functional connectivity).	Temporary loss of connection between lakes and island anabranches if lake levels around the freshwater inlets to the anabranches drop below sill level (c. +0.35 m AHD). Risk that levels will drop lower than +0.35 m AHD due to higher than predicted evaporation or other factors.
Do aim for flow through the biopassages (fishways) in the barrages at all times.	Fish and other biota ultimately need free passage through the barrages.	Barrage will be unpassable at critical ecological times. It is imperative that biopassage is facilitated from June to March at least (Bice, pers. comm.).	Increased predation (e.g. by seals and sharks) around biopassages. May decrease water levels in lakes through loss of water. May increase salinity in Lake Alexandrina through reverse flow.
Do not allow pH to drop to below 6 at any time unless the water is disconnected and can be treated prior to reconnection.	Fish need pH above 5	Fish and other fauna kills.	No identified ecological risk
Do release sufficient water through the barrages to meet water quality and ecosystem state targets.	Met water quality targets, primarily salinity targets, in lakes, Murray Mouth region and the Coorong. also need to provide sufficient water to support target ecosystem states in Murray Mouth region and the Coorong (see upcoming environmental water requirements report).	Loss of or severe contraction of estuarine conditions in dry years. Lakes salinities above targets and subsequent flows are insufficient to reduce to within targets which will adversely impact on a range of species and processes (see upcoming environmental water requirements report).	No identified ecological risk provided that lake levels remain within the ideal water level envelopes. Trade-offs within site and between sites will exist in terms of using water to flood or to release through the barrages.

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