Coorong decision-making framework

Supporting ecosystem based management

Department for Environment and Water
June 2022

DEW Technical report 2022/15

Government
of South Australia
Department for
Environment and Water

Department for Environment and Water
Government of South Australia
June 2022

81-95 Waymouth St, ADELAIDE SA 5000
Telephone +61 (8) 8463 6946
Facsimile +61 (8) 8463 6999
ABN 36702093234

www.environment.sa.gov.au

ISBN 978-1-922027-57-3

Preferred way to cite this publication

DEW (2022). *Coorong decision-making framework, supporting ecosystem based management*, DEW Technical report 2022/15, Government of South Australia, Department for Environment and Water, Adelaide.

Foreword

The Department for Environment and Water (DEW) is responsible for the management of the State's natural resources, ranging from policy leadership to on-ground delivery in consultation with government, industry and communities.

High-quality science and effective monitoring provides the foundation for the successful management of our environment and natural resources. This is achieved through undertaking appropriate research, investigations, assessments, monitoring and evaluation.

DEW's strong partnerships with educational and research institutions, industries, government agencies, Landscape Boards and the community ensures that there is continual capacity building across the sector, and that the best skills and expertise are used to inform decision making.

John Schutz
CHIEF EXECUTIVE
DEPARTMENT FOR ENVIRONMENT AND WATER

Respect and Reconciliation

Aboriginal people are the First Peoples and Nations of South Australia. The Coorong, connected waters and surrounding lands have sustained unique First Nations cultures since time immemorial.

The Healthy Coorong, Healthy Basin program acknowledges the range of First Nations' rights, interests and obligations for the Coorong and connected waterways and the cultural connections that exist between Ngarrindjeri Nations and First Nations of the South East peoples across the region and seeks to support their equitable engagement.

Aboriginal peoples' spiritual, social, cultural and economic practices come from their lands and waters, and they continue to maintain their cultural heritage, economies, languages and laws which are of ongoing importance.

The Department for Environment and Water works across the State with Aboriginal South Australians to conserve and sustain Country. Through this work we seek to improve the relationship between Aboriginal and non-Aboriginal Australians and build respect based on mutual understanding and acceptance of each other.

Acknowledgements

This project was developed as part of the Department for Environment and Water's (DEW) Healthy Coorong, Healthy Basin Program, which is jointly funded by the Australian and South Australian governments.

The work undertaken in the development of the Coorong decision-making framework was part of *Trials and Investigations project; Activity 7.3 – Evaluation of model outputs*.

Gareth Oerman was the primary author of this report. Thank you to Rebecca Quin, Claire Sims, Adrienne Rumbelow, Jody O'Connor and Michelle Waycott for their reviews, which improved the report.

A special thanks to the following technical experts from DEW, Flinders University, The University of Adelaide, The University of Western Australia and South Australian Research and Development Institute for their provision of expertise, research and knowledge that underpinned the development of the decision-making framework: Adrienne Rumbelow, Brendan Busch, Chris Bice, Claire Sims, Dan Paraska, Daniel Rogers, George Giatas, Jody O'Connor, Justin Brookes, Luciana Bucater, Luke Mosley, Matt Gibbs, Matt Hipsey, Micha Jackson, Michelle Waycott, Orlando Lam-Gordillo, Peisheng Huang, Qifeng Ye, Rowan Mott, Sabine Dittmann, Steven Delean and Thomas Prowse.

Contents

List of figures

List of tables

Summary

Ecosystem based management (EBM) is recognised as the new approach to managing the human activities that affect marine and estuarine ecosystems. This approach to management considers the interconnectivity of ecosystem components and highlights the importance of processes that provide services to humans and the environment. To implement EBM, managers require a decision-making framework in which ecological indicators, objectives and performance metrics are consistent and used to evaluate competing management strategies in order to provide a recommendation for management intervention.

To improve the long-term health of the Coorong ecosystem, the *Healthy Coorong, Healthy Basin* program was initiated, with one of the aims being to develop and improve knowledge, tools and products to better support management-decision making. One key tool that was further developed and improved was the Coorong Dynamics Model (CDM); a spatially resolved model to simulate the environmental conditions within the Coorong comprising of a core hydrodynamic model coupled to a water quality and habitat model (AED), collectively an ecosystem model.

The CDM simulates hydrodynamic and sediment conditions, water quality, nutrients, chlorophyll-a, macroalgae, and *Ruppia* and estuarine fish habitat suitability in the Coorong at high spatial and temporal resolution. As the CDM simulates an extensive range of parameters at time scales as frequent as sub-daily and at spatial scales of 20–50 m, each model run produces masses of results rather than knowledge of how the ecosystem is likely to respond to management. A challenge therefore remains in the assessment and evaluation of model inputs and outputs to inform ecosystem management in an accurate, timely and repeatable manner that accounts for uncertainty in predictions. This necessitates the need for a decision-making framework to facilitate the rapid evaluation of CDM inputs and outputs to support transparent and evidence-based management of the Coorong.

The aim of this report was to develop a decision-making framework for the Coorong that summarises and evaluates CDM inputs and outputs in a manner that documents the anticipated responses of critical ecosystem components, processes and services (CPS) and threats. Outcomes desired from the decision-making framework are:

- Rigorous and transparent decision-making using best available evidence, including capturing uncertainty.
- Accurate, timely and repeatable ecological interpretation of model scenario inputs and outputs.
- Clear communications around the likely outcomes of different management scenarios based on an understanding of benefits and trade-offs.

An ecosystem assessment approach to support EBM in the Coorong was developed, and adapted from the National Oceanic Atmospheric Administration (USA) Integrated Ecosystem Assessment approach. The ecosystem assessment approach to EBM in the Coorong is flexible and capable of supporting a range of decision-making objectives (infrastructure investigations, policy, and water of the environment management) of water managing authorities (DEW, Murray-Darling Basin Authority etc.) by following all or a subset of the following processes: (1) modelling management scenarios, (2) summarising and evaluating modelled scenarios with a decision-making framework, (3) assemble inputs to inform decision-making, including the decision-making framework, (4) deciding upon an action, (5) undertaking the action, and (6) monitoring and evaluation, including adaptive management loops whereby model configuration and the decision-making framework are updated based on new findings.

The development of the decision-making framework for the Coorong followed six steps. The *first step* was to define management objectives for the ecosystem, and the *second step* was to identify critical CPS and key threats. The first and second steps were already complete and described within the draft Ramsar Management Plan and Ecological Character Description 2015 for The Coorong, and Lakes Alexandrina and Albert Wetland (Yarluwar-Ruwe).

The *third step* is to identify indicators of critical CPS and threat status, where indicators are biological, chemical or physical factors that either influence or are proxies for critical CPS and threat status. In the *fourth step*, quantitative

measures, known as reference points, were developed for each indicator to consistently document the anticipated responses of critical CPS and threats to modelled scenarios. The third and fourth steps were informed by a literature review of existing management metrics and models for critical CPS, and additional indicators and reference points were identified for biotic CPS and threats through a series of workshops with technical experts.

The *fifth step* was held with modellers to evaluate our confidence in the model accurately simulating indicators of critical CPS and threat status. Expert judgement was used to translate validation statistics in to a readily interpretable measure of confidence, using the categories good, acceptable and caution.

The *sixth step* is the summary of model inputs and outputs using indicator reference points to provide quantitative, ecologically meaningful, transparent and repeatable information to demonstrate how critical CPS and threats may respond to management scenarios. Model inputs and outputs were summarised in results tables and supported by standardised visual outputs, such as time series and rasters, to provide greater granularity (temporally and/or spatially) of summarised data to support decision-making.

The Coorong decision-making framework is a tool capable of summarising model outputs in a manner that is ecologically meaningful, accurate, timely, transparent, repeatable, and that accounts for uncertainty in predictions. As the design of the decision-making framework enables iteration, it is anticipated that new research findings (e.g. including new indicators and updating reference points) and ecological models will be input as they become available. The decision-making framework presented in this report requires testing, however, serves as a foundation for continual improvement in evidence-based management of the Coorong ecosystem.

1 Introduction

1.1 Background

Ecosystem based management (EBM) is recognised as the new approach to managing the human activities that affect marine and estuarine ecosystems (Levin et al. 2009; Espinosa-Romero et al. 2011; Wasson et al. 2015). This approach to management considers the interconnectivity of ecosystem components and highlights the importance of processes that provide services to humans and the environment (Curtin and Prellezo 2010). To implement EBM, managers require a decision-making framework in which values of ecological indicators, objectives and performance metrics are consistent and used evaluate competing management strategies in order to provide a recommendation for management intervention (Espinosa-Romero et al. 2011; Polasky et al. 2011).

EBM of the Coorong, South Australia (Figure 1.1), is sought to be improved using the knowledge, tools and products gained and developed under the Trials and Investigations (T&I) project of Phase 1 of the *Healthy Coorong, Healthy Basin* (HCHB) program. As ecosystem models help support EBM by explicitly considering the interactions of ecosystem components within model algorithms (Hipsey et al. 2020a), research under the T&I project was conducted to improve and further develop an ecosystem model for the Coorong via the development of the Coorong Dynamics Model (CDM).

The CDM simulates hydrodynamic and sediment conditions, water clarity (light and turbidity), nutrients (organic and inorganic), chlorophyll-a, macroalgae, and *Ruppia* and estuarine fish habitat suitability in the Coorong at high spatial and temporal resolution (Hipsey et al. 2020b). However, as the CDM simulates an extensive range of parameters at time scales as frequent as sub-daily and at spatial scales of 20–50 m over the full spatial extent of the Coorong, a challenge remains in the assessment and evaluation of inputs and outputs to inform ecosystem management in an accurate, timely and repeatable manner that accounts for uncertainty in predictions. This necessitates the need for a decision making framework to facilitate the rapid evaluation of CDM inputs and outputs in order to support management of the Coorong.

A key activity in the Integration Component of the T&I project includes the development of a framework to support evidence-based management decisions in the Coorong. The aim of this report was to develop a framework that summarises and evaluates CDM inputs and outputs in a manner that documents the anticipated responses of critical ecosystem components, processes and services (CPS) and threats. Outcomes desired from the decision-making framework are:

- Rigorous and transparent decision-making using best available evidence, including capturing uncertainty
- Accurate, timely and repeatable ecological interpretation of model scenario inputs and outputs.
- Clear communications around the likely outcomes of different management scenarios based on an understanding of benefits and trade-offs.

The Coorong decision-making framework is intended to be one of a range of inputs to support a decision-making objectives of water management authorities (i.e. DEW, Murray-Darling Basin Authority etc.). Flexibility needs to be inherent within the decision-making framework to support a range of decision-making objectives, including long-term infrastructure options under the Coorong Infrastructure Investigations Project, policy and environmental water management.

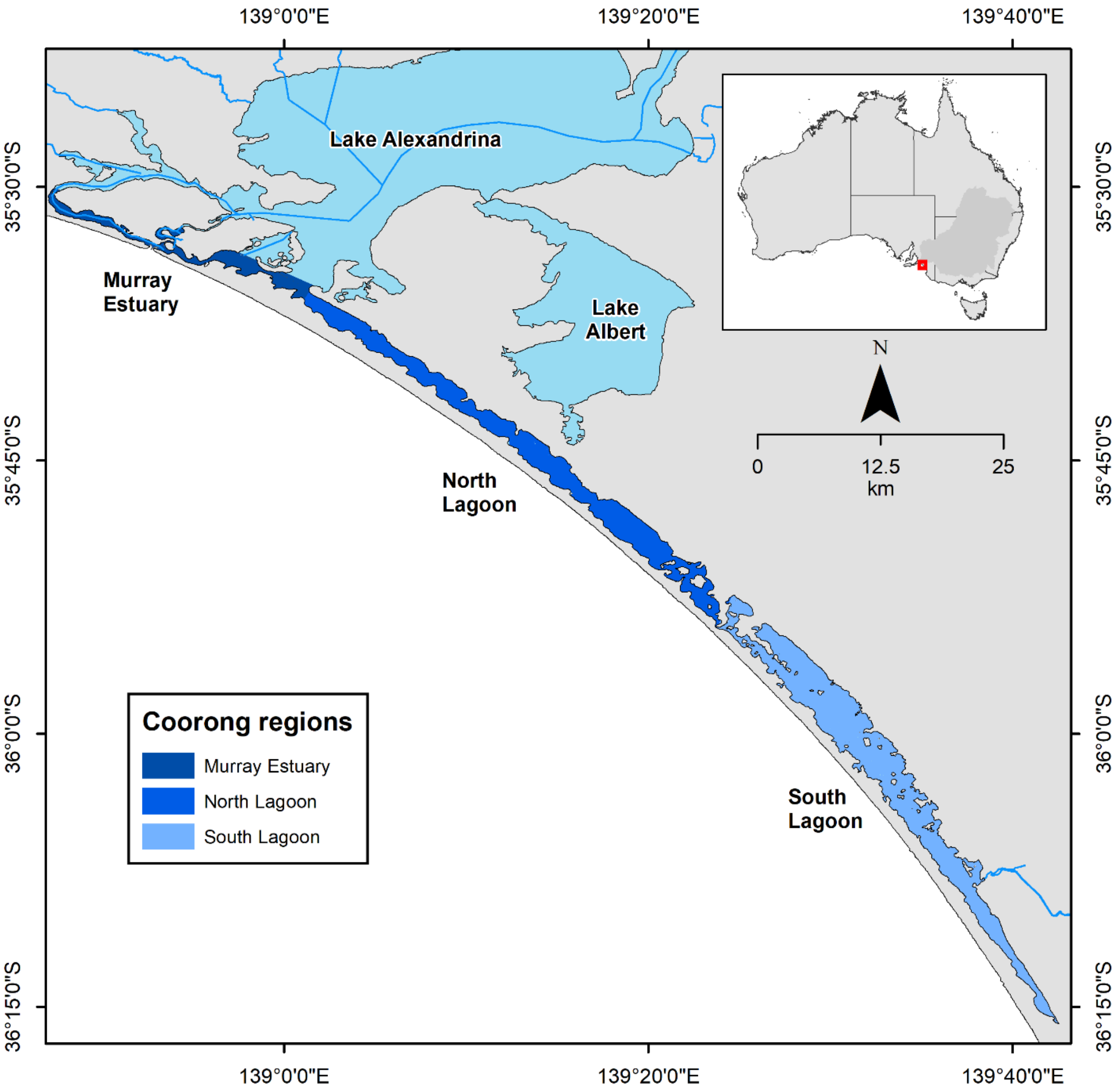

Figure 1.1. Location of the Coorong, South Australia, with respect the Murray-Darling Basin. The map delineates the inland waterbody below the Lake Alexandrina barrages into three regions: Murray estuary, Coorong North Lagoon and the Coorong South Lagoon.

1.2 Decision-making processes for ecosystem based management

The Integrated Ecosystem Assessment (IEA) developed by the US National Oceanic Atmospheric Administration (NOAA) (Levin et al. 2009; Monaco et al. 2021) is considered to be the most useful decision making framework to inform management of marine ecosystems (Espinosa-Romero et al. 2011). The IEA approach to EBM aims to summarise and analyse science in a manner that allows for environmental managers to balance trade-offs and determine what management action is most likely to meet the ecosystems fundamental social and ecological objectives (Levin et al. 2009; Montenero et al. 2021). NOAA is the agency that manages fisheries in the United States of America, and their IEA approach to ecosystem based fishery management is used throughout American waters, including Alaska and Hawaii (Samhouri et al. 2014; Williams et al. 2021). The NOAA IEA approach (Levin et al. 2009; Monaco et al. 2021) is comprised of five steps:

1. **Define goals and targets**: environmental managers, stakeholders and scientists are engaged to define goals (ecological, social or economic) for the system of interest. Goals provide a mechanism to measure progress, and it is recognised that to achieve set goals it is integral to understand how the ecosystem is structured and functions. To build this understanding, participants (environmental managers, stakeholders and scientists) are to define components that make up the ecosystem, and to consider the relationships, connections and feedbacks between those components. This is best represented by developing a conceptual model of the ecosystem.
2. **Develop indicators**: Identify and/or develop ecosystem indicators. Ecosystem indicators are quantitative biological, chemical, physical, social or economic measures that are proxies for the condition of ecosystem attributes.
3. **Assess ecosystem**: Assessment of ecosystem condition using selected indicators.
4. **Analyse uncertainty and risk**: Conduct a risk assessment across ecosystem components, which explicitly considers uncertainty with respect to our understanding and quantification of ecosystem dynamics. Risk considers the likelihood of crossing ecological thresholds or management benchmarks for indicators and how this may impact their resistance and resilience.
5. **Evaluate strategies**: Evaluate the potential outcomes of management actions on ecosystem components and identify trade-offs within management objectives.

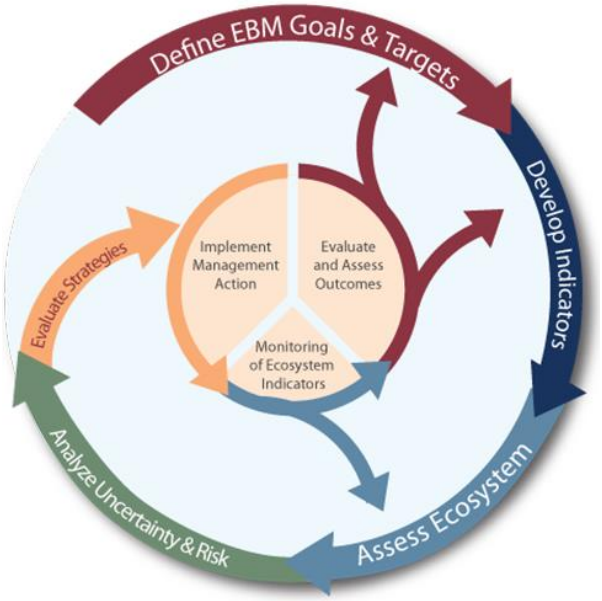

Figure 1.2. A schematic diagram illustrating the five steps to the NOAA Integrated Ecosystem Assessment (IEA), derived from Monaco et al. (2021).

2 Coorong ecological assessment approach

The ecosystem assessment approach to support EBM in the Coorong was adapted from the NOAA IEA approach to ensure it is fit-for-purpose. The Coorong EA takes a proactive and semi-quantitative approach to EBM by incorporating ecosystem modelling via the CDM in the assessment process. A key feature of the Coorong EA approach to EBM is the temporal resolution of ecologically meaningful information to support decision-making. The Coorong EA uses the high temporal and spatial resolution of ecosystem parameters simulated by the CDM to predict the response of critical ecosystem components, processes and services (CPS) and threats at different time scales (both within and between years). The inherent flexibility of the Coorong EA allows the assessment approach allows it to support a range of decision-making objectives by different users (DEW, Murray-Darling Basin Authority etc.) by completing all or a sub-set of the processes in Figure 2-1. For example, the Coorong EA could support:

- Evaluation of infrastructure options that aim to improve the ecological health of the Coorong (i.e. Coorong Infrastructure Investigations Project).
- Review of the Basin Plan; through a better understanding of water requirements for the restoration and protection of ecosystems and ecosystem functions under climate change.
- Annual water for the environment planning and short-term management operations.

The Coorong Ecosystem Assessment (EA) approach is comprised of six separate processes (Figure 2-1):

1. **Modelling**: Modelling includes model configuration, identifying a scenario to be simulated by the model, parameterising the model based upon the scenario to be run including boundary condition (tidal conditions, Salt Creek inflow, barrage flows, meteorology) definition, and providing a summarised output of the simulation to be evaluated using the decision-making framework. This modelling process is to be repeated for each model run of scenarios considered for selection.
2. **Decision-making framework**: Model inputs and outputs are evaluated in a decision-making framework to provide quantitative, ecologically meaningful, transparent and repeatable information to demonstrate how critical CPS and threats may respond to management scenarios. Steps 1-6 that outline the development of the decision-making framework are detailed in section 3.
3. **Assemble inputs to inform decision-making**: The decision-making framework is one of a range of inputs to inform decision-making. Inputs will differ between users and decision-making objectives, and can include management frameworks and processes, environmental outcomes from previous years, upstream processes, real-time data, consultation and site knowledge.
4. **Decision-making**: Selection of a preferred action that best aligns with objectives and legislative requirements.
5. **Undertake action**: Undertake the preferred action following required consultation and approval processes.
6. **Monitoring and evaluation**: Conduct monitoring of critical CPS status and threats in response to the initiated management action and evaluate the outcomes of management. The outcomes of monitoring and evaluation are incorporated in to the Coorong EA via adaptive management loops, where the new learnings can inform model configuration, indicators and associated reference points that influence critical CPS and threat status.

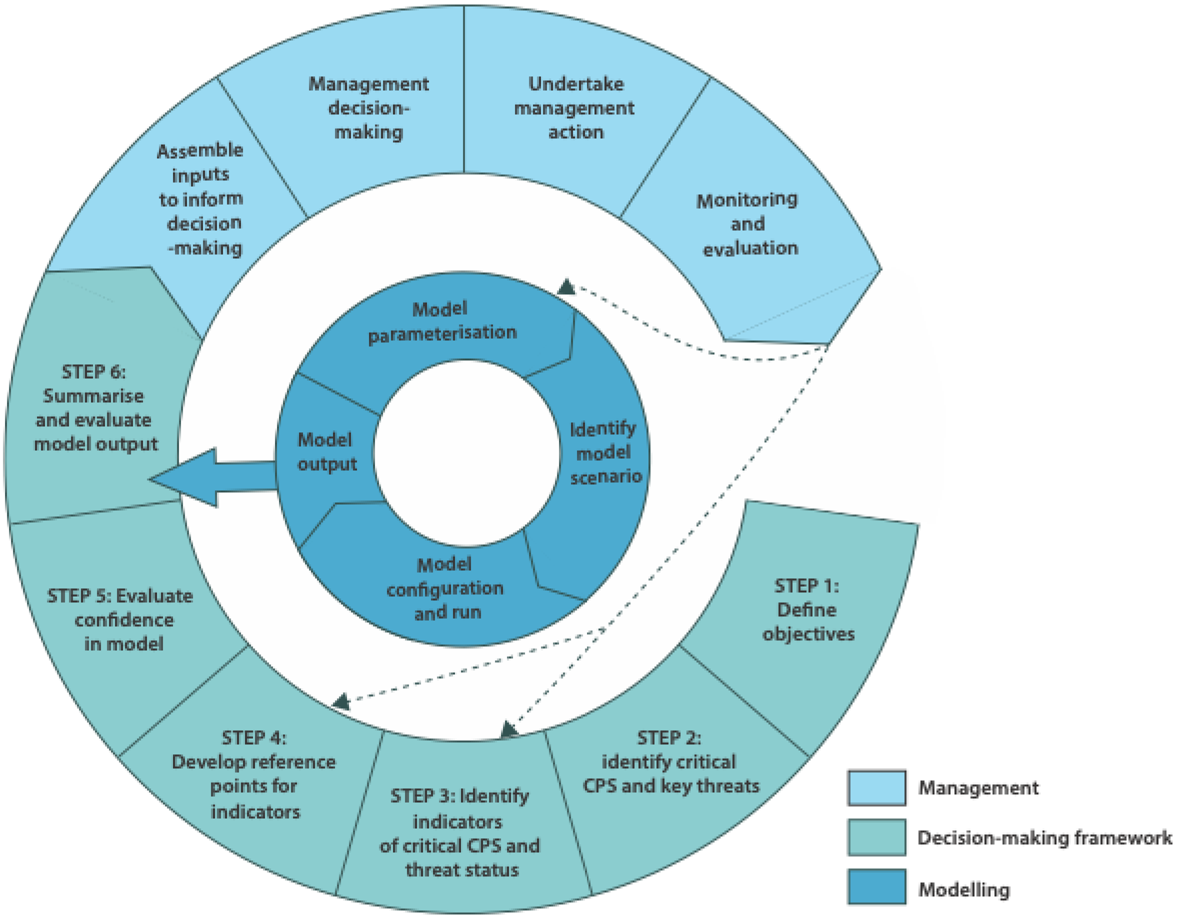

Figure 2-1. A schematic illustration of the ecosystem-based management cycle for the Coorong, which is comprised modelling, evaluation by the decision-making framework and management (decision-making, implementation, monitoring and evaluation). Inputs to inform decision-making will differ between users (i.e. water managing authorities) and decision-making objectives. Feedback loops to improve the ecosystem-based management cycle based on the outcomes of monitoring and evaluation are shown with a dashed line and arrow.

3 Decision-making framework

The steps of the Coorong EA considered in this report are those related to the decision-making framework, and therefore are:

1. **Define objective**: Objectives for management of the Coorong are described within the draft Ramsar Site Management Plan for The Coorong, and Lakes Alexandrina and Albert Wetland (Yarluwar-Ruwe) (DEW *in prep*.).
2. **Identify critical ecosystem components, processes and services (CPS) and key threats**: Critical CPS and key threats of the Coorong are detailed in the draft Ecological Character Description for The Coorong, and Lakes Alexandrina and Albert Wetland (Yarluwar-Ruwe) (DEW *in prep*.).
3. **Identify indicators of critical CPS and threat status**: Indicators are biological, chemical or physical factors that either influence or are proxies for critical CPS and threat status.
4. **Identify reference points for indicators of critical CPS and threat status**: Reference points are quantitative measures of an indicator that are used to consistently document the anticipated responses of critical CPS and threats.
5. **Evaluate confidence in the model simulating indicators**: Expert judgement of our confidence in the model accurately simulating indictors of critical CPS and threat status.
6. **Summarise and evaluate model output**: Model inputs and outputs are summarised and evaluated with indicator reference points to provide quantitative, ecologically meaningful, transparent and repeatable information to demonstrate how critical CPS and threats may respond to management scenarios.

4 Step 1: Define objectives

Objectives for management of the Coorong are described in the Ramsar Management Plan (RMP) (DEW *in prep*.) for the Coorong, and Lake Alexandrina and Albert Wetland (Yarluwar-Ruwe) Ramsar Site. The Ramsar site supports a number of ecological, economic (e.g. tourism and commercial fishing), social (e.g. recreation) and cultural values, which result from maintaining the sites ecological character (DEW *in prep*.). The RMP adopted the principle that by maintaining or enhancing the ecological character of the Ramsar site, the socio-economic and cultural values of the site will also be conserved (DEW *in prep*.), and therefore are not considered directly. As such, the primary objective for management of the Ramsar site, including the Coorong, is

> *to support the Coorong and Lakes Alexandrina and Albert Wetland Ramsar site to be a healthy, productive and resilient wetland system that maintains its international significance* (DEW *in prep*.).

5 Step 2: Identify ecosystem critical CPS and key threats

5.1 Ecosystem critical CPS

Ecological character is the combination of ecosystem components, processes and services (CPS) (see definitions of terms in Table 5.1) that characterise a wetland at a given point in time (Ramsar 2012). The draft ECD identified and described CPS of the Ramsar site and further classed CPS as either critical or non-critical, with critical CPS satisfying all four of the following criteria:

1. Be important determinants of the sites unique character
2. Be important for supporting the Ramsar criteria under which the site was listed
3. Be of a nature for which change is reasonably likely to occur over short to medium time scales (<100 years)
4. Be of a nature that will cause significant consequences if change occurs.

Table 5.1. Definitions for ecosystem components, processes and services used in the draft Ecological Character Description for the Coorong, and Lakes Alexandrina and Albert Wetland Ramsar site (DEW *in prep*.).

Term	Definition
Ecosystem components	The physical, chemical and biological parts of a wetland (from large scale to very small scale, for example habitat, species and genes) (Millennium Ecosystem Assessment 2005)
Ecosystem processes	The changes or reactions which occur naturally within wetland systems. They may be physical, chemical or biological. (Ramsar Convention 1996, Resolution VI.1 Annex A). They include all those processes that occur between organisms and within and between populations and communities, including interactions with the non-living environment that result in existing ecosystems and bring about changes in ecosystems over time (Australian Heritage Commission 2002).
Ecosystem services	The benefits that people receive or obtain from an ecosystem. The components of ecosystem services are provisioning (for example, food and water), regulating (for example, flood control), cultural (for example, spiritual, recreational) and supporting (for example, nutrient cycling, ecological value) (Millennium Ecosystem Assessment 2005).

Critical CPS and their sub-components that express our understanding of the structure and function of the Coorong are identified in Table 5.2. The wetland habitat and subtropical temperate saltmarsh critical CPS were not included in this decision-making framework. Wetland habitat in the ECD 2015 focuses on human mediated impacts to terrestrial environments within the Ramsar site, and therefore, is independent of freshwater management and occurs outside the spatial extent of the CDM. Subtropical and temperature coastal saltmarsh was also excluded, as the environmental drivers that affect its condition are a knowledge gap (DEW *in prep.*).

Table 5.2. The critical components, processes and services (CPS) (and their subcomponents) that characterise the structure and function of the Coorong. Critical CPS marked by an asterisk (*) are not considered within this framework.

Critical CPS	Subcomponent
Surface water regime	Inflows
Surface water regime	Coorong water levels
Salinity	Murray estuary and Coorong salinity
Vegetation	Submergent halophytes
Fish	Diversity (species richness)
Fish	Movement and recruitment
Waterbirds	Diversity
Waterbirds	Abundance
Waterbirds	Breeding
Waterbirds	Threatened species

Critical CPS	Subcomponent
Habitat*	Wetland habitat
Threatened ecological communities and species*	Subtropical and temperate coastal saltmarsh
Coorong food web	*Ruppia tuberosa* – primary producer
Coorong food web	Benthic macroinvertebrates – primary consumers
Coorong food web	Small-mouthed hardyhead – secondary consumer

Simplification of Waterbird critical CPS subcomponents

Waterbird critical CPS are comprised of waterbird diversity, abundance, breeding and threatened species sub-components. The waterbird communities and species considered in the ECD 2015 and draft RMP are extensive and add too much complexity for timely decision-making. As such, the decision-making framework considers habitat quality for shorebirds, waterfowl and piscivores to represent local-scale drivers influencing waterbirds at the site and to simplify the process. As waterbirds in the Coorong are highly diverse (Paton 2010), the decision-making framework focuses on the key waterbird species within each guild as identified for the HCHB program's T&I project; Component 4 – *Maintaining viable waterbird populations* (Table 5.3).

Table 5.3. Allocation of key waterbirds species to guilds considered within the decision-making framework.

Guild	Species
Shorebird	Curlew sandpiper
Shorebird	Sharp-tailed sandpiper
Shorebird	Red-necked stint
Shorebird	Common greenshank
Shorebird	Red-capped plover
Shorebird	Red-necked avocet
Waterfowl	Chestnut teal
Waterfowl	Black swan
Piscivore	Fairy tern
Piscivore	Australian pelican

Simplification of aquatic plant related critical CPS subcomponents

Two critical CPS sub-components relate to aquatic plants in the ECD 2015; *Ruppia tuberosa* as part of the Coorong foodweb critical CPS and submergent halophytes as part of the vegetation critical CPS. To reduce duplication in the decision-making framework, these sub-components were merged and considered via *R. tuberosa*, the dominated aquatic plant species in the system. It is considered that if conditions are beneficial to *R. tuberosa*, they will also benefit another important aquatic plant species; *Althenia cylindrocarpa*, due to presence of these species in mixed aquatic plant communities (Asanopoulous and Waycott 2020).

5.2 Threats

Threats and threatening activities described in the draft RMP include upstream water diversions, climate change, deteriorating water quality, invasive species and recreational activities. These threats are in part considered via the surface water regime and salinity critical CPS, however they do not adequately consider aspects of deteriorating water quality, such as nutrient enrichment. Nutrient enrichment threatens the Coorong, in particular the southern Coorong, which is in a hyper-eutrophic state due to reduced freshwater flushing and nutrient retention (Mosley et al. 2020). Hyper-eutrophication impairs the healthy functioning of the southern Coorong ecosystem through the promotion of anoxic and reduced sediments, and the shading and smothering effects of phytoplankton and macroalgae (Collier et al. 2017; Priestly et al. 2022), which reduce benthic habitat quality for macroinvertebrates (Sutula et al. 2014) and aquatic plants (Collier et al. 2017). As benthic macroinvertebrates and aquatic plants promote healthy nutrient cycling in the sediment (Mosley et al. 2022) and also underpin the food web (Giatas and Ye 2016), impacts to these biotic communities from eutrophication have flow on effects for the entire ecosystem. We therefore consider eutrophication to be a threatening ecosystem process. Trophic status is incorporated within the decision-making framework to evaluate the severity of the threat posed by eutrophication and to track whether the system is progressing towards a desired mesotrophic state.

5.3 Summary

A summary of the critical CPS and threats, and their sub-components, considered within the Coorong decision-making framework are shown in Table 5.4.

Table 5.4. Critical CPS and key threats of the Coorong. Sub-components for each critical CPS and threat are considered within the Coorong decision-making framework.

Critical CPS and threats	Sub-component
Surface water regime	Inflows
Surface water regime	Coorong water levels
Salinity	Murray estuary and Coorong salinity
Trophic status (threat: eutrophication)	Sediment and water quality
Aquatic plants	*Ruppia tuberosa*
Benthic macroinvertebrates	Benthic macroinvertebrates
Fish	Diversity (species richness)
Fish	Movement and recruitment (congolli and common galaxias)
Fish	Small-mouthed hardyhead
Waterbirds	Shorebirds
Waterbirds	Waterfowl
Waterbirds	Piscivores

6 Step 3 & 4: Identify indicators and reference points

Indicators and reference points provide a practical approach for measuring changes in the status of critical CPS and threats that relate to the management objective (Monaco et al. 2021). As the focus of the decision-making framework was to maintain or enhance the ecological character of the Ramsar site, indicators are defined as biological, chemical or physical factors that either influence or are proxies for critical CPS and threat status (Messer et al. 1991; Monaco et al. 2021). Reference points are quantified performance measures of an indicator that serve to consistently document the anticipated responses of critical CPS and threats to management scenarios.

Indicators and reference points for critical CPS and threats were identified through (1) a review of existing policy, management documents and ecological models (see section 6.1), and (2) a series of workshops with technical experts (see section 6.2).

To be fit-for-purpose for inclusion within the decision-making framework, indicators had to be an output of the CDM (see model manual, including inputs and outputs at https://aquaticecodynamics.github.io/cdm-science/index.html) and responsive to changes in environment conditions at the site.

6.1 Review

A review of policy and management documents was conducted to provide a *summary of Coorong management metrics and thresholds to evaluate hydrological and ecological model simulations* (DEW 2022). This consolidated site management targets, triggers and critical thresholds from existing policy, management documents and ecological models.

Key outcomes of the review that informed the decision-making framework were:

- Indicators and reference points for hydrology-related critical CPS (surface water regime and salinity) were documented and described within the draft RMP.
- A *Ruppia* habitat suitability index (HSI) is available (as detailed in Collier et al. 2017) and functions using the outputs of the Coorong Dynamics Model. Parameterisation of the *Ruppia* HSI was updated using the findings from Component 2 (aquatic plants and algae), and is presented in Hipsey et al. (2022).

As a result, a workshop to identify indicators and reference points for hydrology-related critical CPS was not required, and a workshop for *Ruppia* focused on identifying indicators and reference points not incorporated within the existing habitat suitability model.

6.2 Workshops

A workshop was held in October 2021 with researchers and government staff, including scientists and water managers, to detail our approach for identifying indicators and reference points for critical CPS. In this workshop, environmental stressors that influenced a subset of biotic critical CPS subcomponents were discussed and documented. A series of follow-up, targeted workshops were held in person and online via Microsoft Teams from November 2021 to March 2022 to identify indicators and reference points for the following critical CPS and threats:

- Trophic status (threat: eutrophication)
- Benthic macroinvertebrates

- *Ruppia*
- Fish
- Waterbirds

Attendees of each targeted workshop were reflective of their field of research and/or individual expertise (Table 6.1).

Table 6.1. Technical experts that contributed to targeted workshops that supported the development of the decision-making framework. An asterisk (*) denotes out of session contributions.

Workshop	Name	Affiliation
Trophic status (threat: eutrophication)	Matt Hipsey	University of Western Australia
	Michelle Waycott	University of Adelaide/Department for Environment and Water
	Claire Sims	Department for Environment and Water
	Luke Mosley	University of Adelaide*
Benthic macroinvertebrates	Sabine Dittmann	Flinders University
	Orlando Lam-Gordillo	Flinders University/Department for Environment and Water
Ruppia	Michelle Waycott	University of Adelaide/Department for Environment and Water
Fish (diversity, movement and recruitment, and smallmouth hardyhead)	Qifeng Ye	South Australian Research and Development Institute
	Chris Bice	South Australian Research and Development Institute
	Luciana Bucater	South Australian Research and Development Institute
	George Giatas	South Australian Research and Development Institute
Waterbirds (shorebirds, waterfowl and piscivores)	Thomas Prowse	University of Adelaide
	Micha Jackson	University of Adelaide
	Rowan Mott	University of Adelaide
	Steven Delean	University of Adelaide
	Justin Brookes	University of Adelaide
	Daniel Rogers	Department for Environment and Water
	Jody O’Connor	Department for Environment and Water

Identification and justification of indicators and reference points

To identify and justify indicators and reference points for critical CPS and threats from working session participants, a series of common questions were asked:

- What influences its status/condition?
- What are good proxies of its status?
- What does the indicator influence?
- What are the rules of thumb for management?
- How do we quantify an indicator to inform management?
- How do we align factors influencing the critical CPS with inputs and outputs of the model?

To ensure transparent and scientifically robust decision-making, indicators and reference points were justified using best-available science. Where available, research, investigations and site knowledge from the Coorong was used to justify indicators and reference points, and was supported by peer reviewed literature from other estuaries as required. Justifications for indicators and reference points were reflective of discussions and information derived from the workshop, and an opportunity was provided to technical experts to review, edit and contribute science to justifications within a paper that detailed workshop outcomes. For hydrology-related CPS, descriptions and rationale for indicators and reference points were reviewed by ecologists, hydrologists and policy representatives of DEW for use in the draft RMP. The draft RMP will be publically consulted on prior to its finalisation.

Indicators and reference points in space and time

Indicators and reference points for critical CPS and threats need to be appropriately applied in space and time to ensure model inputs and outputs are summarised in an ecologically meaningful manner. Within the workshop, participants helped to document the temporal and spatial range that indicators and reference points are relevant to a critical CPS or threat.

Indicators and reference points of a critical CPS or threat were applied in space using one or more of the following spatial units (Figure 1.1):

- Murray estuary (Goolwa barrage to Pelican Point)
- Coorong North Lagoon (Pelican Point to Parnka Point)
- Coorong South Lagoon (Parnka Point to southern end of the South Lagoon)
- System-wide (entire extent of the Murray estuary and Coorong lagoons).

Considerations that helped to apply indicators and reference points in space included:

- Distribution (or potential therefor) of the critical CPS (and life history stages therein) in the site
- Spatial extent that the indicator influences the status of the critical CPS
- Chemical gradient that runs north to south along the Coorong
- Geomorphological features of different spatial units.

The temporal range that an indicator and reference point were relevant to a critical CPS or threat were recorded as a range of months. Considerations that helped to apply indicators and reference points in time included:

- Time over which the critical CPS uses the site
- Time over which the indicator has direct influence over the status of the critical CPS
- Timing of critical CPS life stages (i.e. reproduction)
- Seasonal variability.

Importance of indicator to biotic critical CPS status

The importance of indicators to the status of biotic critical CPS were qualitatively assessed. For each indicator, attendees to workshops evaluated the importance of an indicator as either high, moderate or low based on criteria presented in Table 6.2. Criteria considered impacts to habitat quality and population condition of the critical CPS associated with potential strengthening or weakening of an indicator under current management.

To ensure the decision-making framework enables timely and accurate decision-making, it is important that it does not become over-fitted with indicators that add complexity to the framework but have minor influence on the status of biotic critical CPS. To avoid this issue, only indicators of ‘High’ and ‘Moderate’ importance are included within the decision-making framework. This importance ranking was incorporated within the decision-making framework to inform managers of the most important indicators affecting the status of each biotic critical CPS.

Table 6.2. Criteria used to categorise the importance of an indicator to the status of a critical CPS.

Importance	Habitat	Population condition
High	Potential to limit the extent of occurrence of the critical CPS under current management	Potential to limit the carrying capacity of the critical CPS (and constituents) under current management
Moderate	Potential to limit the area of occupation of the critical CPS under current management	Potential to significantly impact the demography or population size (i.e. reduced recruitment) of the critical CPS under current management
Low	Potential to reduce habitat suitability within the area of occupation of the critical CPS under current management	Potential to have a minor impact on the demography or population size of the critical CPS under current management

Measures

Indicator reference points require translation to a 'Measure' that can be used to post-process model inputs and outputs. Post-processing is the computation of highly detailed and complex inputs and outputs in to a summary value. Measures for critical CPS and threats were developed during targeted workshops (including one for hydrology-related CPS with Adrienne Rumbelow, DEW). Considerations when developing a 'Measure' included:

- Alignment with existing management targets and triggers in the Ramsar Management Plan
- How best to summarise spatial and temporal data to be relevant to the given critical CPS or threat.

Common spatial 'Measures' considered in workshops were:

- Lagoon-averages (via model output, spatial extent defined by a polygon)
- Lagoon-averages (via averaging across water stations within spatial extent defined by polygon)
- Total area (spatial extent defined by a polygon)
- Longitudinal extent (Km along the Coorong).

Common temporal 'Measures' considered in workshops were:

- Duration exceedance (i.e. days over reference point)
- Daily or monthly averages
- Total or balance value at a given date or over simulation duration.

To ensure that 'Measures' were fit-for-purpose for post-processing model inputs and outputs they were reviewed by modellers (Table 6.3).

Table 6.3. Modellers that reviewed 'Measures' to ensure they were fit-for-purpose for post-processing model inputs and outputs.

Name	Affiliation
Matt Hipsey	University of Western Australia
Brendan Busch	University of Western Australia
Peisheng Huang	University of Western Australia
Dan Paraska	University of Western Australia
Claire Sims	Department for Environment and Water

6.3 Results

The decision-making framework splits critical CPS and threats between two groups; hydrology and trophic status (see 6.3.1) and biota (see 6.3.2), to accommodate differences in the methodology and information gathered. Justifications for indicators and reference points developed for each critical CPS and threat are presented below.

6.3.1 Hydrology and trophic status

Indicators

Justifications for indicators of hydrological critical CPS and trophic status (threat: eutrophication) in the Murray estuary and Coorong are documented in Table 6.4.

Table 6.4. Indicators of hydrological critical CPS status and threats in the Murray estuary and Coorong.

Critical CPS	Indicator	Justification
Surface water regime	Flow (River Murray)	Flow from the River Murray is critical to the function and health of the Coorong (Kingsford et al. 2009; Webster 2010; Giatas and Ye 2016). In the Coorong, flow influences longitudinal and lateral connectivity, salinity and nutrient conditions (Webster 2010; Mosley et al. 2020) and drives the pelagic pathway of the ecosystem's food web (Giatas and Ye 2016). Water level and quality are assessed directly (see indicators below), and therefore, here flow relates to the ecosystem processes of connectivity between freshwater, estuarine and marine environments (Bice et al. 2021), primary productivity pulses (Bice et al. 2016; Giatas and Ye 2016) and environmental cues and conditions important to the life histories of a range of biota (Bice and Zampatti 2017; Ye et al. 2019a).
	Flow (Salt Creek)	Salt Creek flows into the South Lagoon. From 2001-2018, the average annual inflow volume was 15 GL (Gibbs et al. 2018). This inflow is critical to fishway operation (DEW 2019) and contributes to localise freshening within the South Lagoon (Mosley et al. 2017). High inflows from Salt Creek may contribute to local effects on fish recruitment and species richness (SARDI unpublished data).
	Water level	Water level is strongly associated with the condition of the Coorong ecosystem as it influences longitudinal and lateral

Critical CPS	Indicator	Justification
		connectivity (Webster 2010; Gibbs et al. 2018). The level of longitudinal and lateral connectivity subsequently the growth and reproduction of aquatic plants (Collier et al. 2017) and the extent and access to habitat for macroinvertebrates (Dittmann et al. 2018), fish (Q. Ye, personal communication, 6 December 2021) and waterbirds, in particular shorebirds (Paton and Bailey 2012; Paton et al. 2017).
Salinity	Salinity	A characteristic of the Coorong is the longitudinal salinity gradient (Paton 2010; Lam-Gordillo et al. 2022a). Salinity affects the structure and function of aquatic biota in estuaries (Telesh and Khlebovich 2010). In the Coorong, biotic communities are largely structured by salinity (Giatas and Ye 2016; Ye et al. 2020), with the occurrence and density of biota largely influenced by their salinity tolerance thresholds (McNeil et al. 2013; Collier et al. 2017; Dittmann et al. 2018) and the thresholds of their prey and predators (e.g. Paton et al. 2009; Ye et al. 2021). The tolerance thresholds of ecosystem engineers, such as bioturbating and bioirrigating macroinvertebrates and aquatic plants, also influence the physiochemical conditions and habitats that structure aquatic biotic communities (Lam-Gordillo et al. 2022b; Mosley et al. 2022).
Trophic status (threat: eutrophication)	Chlorophyll-a (Chl-a)	Chl-a is a proxy for the biomass of phytoplankton, and serves are an index for productivity and trophic condition (Boyer et al. 2008). Phytoplankton blooms in the Coorong lagoon are consequence of its hyper-eutrophic state (Mosley et al. 2020), and may cause light limitation for aquatic plants (Collier et al. 2017). These blooms are also the main source of nitrogen to the sediments of the Coorong lagoon (Priestly et al. 2022), which maintains high nutrient loads to fuel their blooms in future years.
	Light	Light availability is an important indicator that distinguishes aquatic systems between a clear water state dominated by submerged aquatic plants and a turbid state dominated by phytoplankton (Liu et al. 2015). The elevation distribution of *R. tuberosa* in the Coorong is limited by light (Kim et al. 2015), and experiments have shown that although tolerant of low light, shoot density and biomass can be significant reduced when extremely low light (6% natural light) is available for prolonged periods (>8 weeks) (Collier et al. 2017).
	Macroalgae	Macroalgae blooms form in the Coorong, particularly the central section, over spring and summer (Collier et al. 2017; Auricht et al. 2019). When macroalgae blooms develop they attach to submerged aquatic plants, *R. tuberosa* and *A. cylindrocarpa*, and adversely impact their reproduction and growth. Macroalgae can prevent flower-heads from reaching surface water where pollen is shed, break stalks with flower-heads or developing fruit and contribute to light limitation (Collier et al. 2017; Asanopoulous and Waycott 2020). When blooms decay, sediments become anoxic (poorly oxygenated)

Critical CPS	Indicator	Justification
		due to the depletion of oxygen by bacteria when decomposing organic material. Anoxic sediments subsequently impairs healthy nutrient cycling (Mosley et al. 2020) and reduces benthic habitat quality for aquatic plants (Pedersen et al. 2004; Holmer and Neilsen 2007) and macroinvertebrates (Kanaya et al. 2018).
	Oxygen penetration depth (OPD, sediment)	The OPD (also referred to as the redox potential discontinuity depth) marks the transition from oxidised to reduced (hypoxic/anoxic) conditions in a sediment profile (Gerwing et al. 2018). The depth of this transition is important as reduced sediments: support limited nitrogen removal through coupled nitrification-denitrification processes, flux inorganic nutrients to the water column fueling phytoplankton and macroalgae, and accumulate potentially toxic sulfides (Hallett et al. 2019). This in turn influences the benthic habitat quality for aquatic plants (Pedersen et al. 2004; Holmer and Neilsen 2007) and macroinvertebrates (Kanaya et al. 2018).
	Total Nitrogen (TN)	TN represents that maximum potential amount of bioavailable nitrogen, which is available for uptake and assimilation by phytoplankton, macroalgae and aquatic plants. Increased nitrogen loading of estuaries can alter the structure and function of their biological communities (Woodland et al. 2015). This has been observed in the southern Coorong, where nitrogen loading attributed to a lack of flushing flows has led its persistent hyper-eutrophic state (Mosley et al. 2020). Reductions in TN and TP concentrations can help shallow, coastal ecosystems, such as the Coorong, to recover (Riemann et al. 2016).
	Total Phosphorus (TP)	TP represents that maximum potential amount of bioavailable phosphorus that is available for uptake and assimilation by phytoplankton, macroalgae and aquatic plants. Phosphorus appears to be the nutrient limiting the growth of phytoplankton in the Coorong, however, this may be due to the oversupply of nitrogen (Mosley et al. 2020). Reductions in TN and TP concentrations can help shallow, coastal ecosystems, such as the Coorong, to recover (Riemann et al. 2016).
	Dissolved oxygen (DO, water column)	DO in the water column influences the suitability of habitat for biota and nutrient cycling in the sediment. Low DO negatively impact aquatic biota. Early life-stages of fish are particularly vulnerable to low DO, with moderately hypoxic conditions negatively affecting the eggs and larvae (Gillanders et al. 2011). Benthic macroinvertebrates are also impacted by low DO, with the blackwater event in the River Murray during flood in 2010 causing distinct change in the community present in the northern Coorong (Dittmann et al. 2021).

Reference points

Justifications for indicator reference points of hydrological critical CPS and trophic status (threat: eutrophication) in the Murray estuary and Coorong are documented in Table 6.5. Indicator reference points and their application in space and time are presented in the tabular decision-making framework presented in Appendix A and Section 9.9 of the Coorong Dynamics Model manual.

Table 6.5. Reference points of hydrology related critical CPS status in the Murray estuary and Coorong. Quantitative measures associated with Resources Condition Targets (RCT) and Management Triggers (MT) in the draft Ramsar Management Plan (DEW *in prep*.) are presented in brackets. Time and Space identify the temporal and spatial range that indicator reference points are relevant to a critical CPS or threat.

Critical CPS	Indicator	Reference Point	Justification
Surface water regime	Flow (River Murray discharge)	Null – continuous Time: year-round Space: Boundary condition	Flow is important to the ecosystem state of the Coorong (Lester et al. 2011). The Millennium Drought was associated with three consecutive years without River Murray discharge to the Coorong and caused significant degradation to the ecosystem (Paton 2010). Greater flows since the end of the Millennium Drought were critical to the recovery of ecosystem components (DEW 2020a).
	Flow (River Murray discharge)	>650 GL/year (RCT) Time: year-round Space: Boundary condition	An annual barrage flow of 650 GL is the minimum required to maintain Lake Alexandrina salinities below 1000 EC if delivered within a three year period where outflow exceeds 6000 GL (Lester et al. 2011). This flow is expected to provide a moderate positive contribution to key components of the Coorong food web including smallmouth hardyhead and macroinvertebrates, and the recruitment of congolli and common galaxias (O'Connor et al. 2015a).
	Flow (River Murray discharge)	Rolling >2,000 GL/year average (RCT) Time: year-round Space: Boundary condition	A 3-year rolling average annual flow of 2000 GL is the minimum required to maintain Lake Alexandrina salinities below 1000 EC (Lester et al. 2011). This flow is expected to provide a moderate positive contribution to key components of the Coorong food web including smallmouth hardyhead and macroinvertebrates, and the recruitment of congolli and common galaxias (O'Connor et al. 2015a).
	Flow (River Murray discharge)	>6,000 GL/year, 1 in 3 years (RCT) Time: year-round Space: Boundary condition	Flows of >6,000 GL/year at an annual return interval of three years are required to achieve a healthy ecosystem state (Lester et al. 2011). Such flows are expected to provide a large positive contribution to the condition of waterbirds, fish, macroinvertebrates and *R. tuberosa* distribution and recruitment (O'Connor et al. 2015a).
	Flow (River Murray discharge)	>10,000 GL/year, 1 in 7 years (RCT) Time: year-round	Flows of >10,000 GL/year at an annual return interval of seven years are required to achieve a healthy ecosystem state (Lester et al. 2011). Such flows are expected to provide a large positive

Critical CPS	Indicator	Reference Point	Justification
		Space: Boundary condition	contribution to the condition of waterbirds, fish, macroinvertebrates and *R. tuberosa* distribution, population vigour, area of occupancy and recruitment (O'Connor et al. 2015a).
	Flow (Salt Creek)	Null – continuous Time: year-round Space: Boundary condition (CSL)	Increased Salt Creek flow to the South Lagoon in spring 2021 may have contributed to local effects on fish recruitment and species richness (SARDI unpublished data). Flows from Salt Creek also influence fishway operation (DEW 2019) and the localised salinity environments of the South Lagoon (Mosley et al. 2017).
	Water level	>+0.2 m AHD (lower bound of RCT) Time: Sept–Dec Space: CSL	Target water levels in the South Lagoon from September to December were set between +0.4 m AHD and +0.2 m AHD, with the anticipation that water levels will recede from ≥+0.4 m AHD in September and be maintained above +0.2 m AHD until the end of the December. Maintenance of water levels above +0.2 m AHD from September to December are critical to successful *R. tuberosa* (and presumably *A. cylindrocarpa*) sexual (seed) and asexual (turions) reproduction (Collier et al. 2017).
	Water level	+0.15 m AHD (MT) Time: Sept–Dec Space: CSL	The upper bound of the core elevation range for *R. tuberosa* and *A. cyclindrocarpa* in spring 2020 was +0.15 m AHD (Oerman 2021). Water levels below +0.15 m AHD would subject plants within the core elevation range (-0.15 to +0.15 m AHD, Oerman 2021) to desiccation during periods critical for seed bank and turion production (August–December) (Collier et al. 2017; Asanopoulous and Waycott 2020).
	Water level	>+0.3 m AHD (RCT) Time: June-Aug Space: CSL	Target water levels in the South Lagoon from June to August were set at >0.30 m AHD. As the core elevation distribution of *R. tuberosa* and *A. cylindrocarpa* occurs between -0.15 and +0.15 m AHD in the South Lagoon (Oerman 2021), and *R. tuberosa* (and presumably *A. cylindrocarpa*) have their greatest shoot densities in water depths of 0.2 to 0.6 m (Kim et al. 2015), water levels in the South Lagoon of +0.35 m AHD over June and July should provide optimal growth conditions. Water levels above +0.3 m AHD would help facilitate connectivity and exchange of water between the North and South Lagoon, which is likely beneficial to the export of nutrients and the passage of fish.
	Water level	+0.2 m AHD (MT) Time: June-Aug Space: CSL	In winter, water levels above +0.2 m AHD enable connectivity between the North and South Lagoons (M Gibbs Pers. Comm. 2021), which would have water quality benefits (i.e. lower salinities) and enable the passage of fish between the lagoons.

Critical CPS	Indicator	Reference Point	Justification
	Salinity	<35 g/L (RCT) Time: Year-round Space: ME	Salinities below 35 g/L support high abundances of macroinvertebrates and fishes in the Murray Mouth and upper North lagoon (Dittmann 2015; Giatas and Ye 2016; Ye et al. 2019b); habitat for sandy sprat (Hossain et al. 2016) and the crab *Paragrapsus gaimardii* (Ye et al. 2019b) that are important prey for fish and waterbirds (Giatas and Ye 2016); and the recruitment of estuarine fishes, including black bream (Ye et al. 2019a) and gobies (Ye et al. 2015).
	Salinity	<45 g/L (RCT) Time: Year-round Space: CNL	Salinities below 45 g/L in the Coorong North Lagoon support common macroinvertebrate species with hypermarine salinity tolerances including: polychaete worms *Nephtys australiensis*, *Boccardiella limnicola* and *Australonereis ehlersi* and gastropod snails *Salinator fragilis* and *Hydrobiidae* (Dittmann et al. 2018); optimal conditions for greenback flounder egg fertilisation and survival (Hart and Purser 1995) and adult habitat (Earl et al. 2017); suitable conditions for the survival and growth of juvenile black bream (Partridge and Jenkins 2002); and optimal conditions for *Ruppia* flowering and seed bank formation mainly in the southern section of the North Lagoon (Collier et al. 2017; Asanopoulos and Waycott 2020).
	Salinity	<60 g/L (RCT) Time: June-Aug Space: CSL	Salinities <60 g/L in the Coorong South Lagoon in winter (June-Aug) support optimal conditions for *R. tuberosa* germination from seed, sprouting from turions and vegetative growth (Collier et al. 2017; Asanopoulos and Waycott 2020) and lower the potential for the South Lagoon to exceed upper salinity thresholds (100 g/L) for key biota in summer.
	Salinity	<60 g/L Time: Year-round Space: System-wide	Burrowing and bioturbating benthic macroinvertebrates are lost from the Coorong when salinities exceed 60 g/L (Lam-Gordillo et al. 2022a). These taxa are important in the remediating sediment condition, and therefore, provide critical ecological functions (Lam-Gordillo et al. 2022b). A species rich fish community is also considered to have an upper salinity of 60 g/L (Ye et al. 2020).
	Salinity	<100 g/L (RCT/MT) Time: Year-round Space: CSL	Salinities <100 g/L in the Coorong South Lagoon support suitable conditions for *R. tuberosa* flowering (leading to seed-set) between September and December (optimal: 40–63 g/L, suboptimal: 17–102 g/L; Collier et al. 2017; Asanopoulos and Waycott 2020); optimal salinity conditions (full range: 30–122 g/L) for *R. tuberosa* adult plant (vegetative) growth (Collier et al. 2017;

Critical CPS	Indicator	Reference Point	Justification
			Asanopoulos and Waycott 2020); suitable conditions for small-mouthed hardyhead recruitment and distribution (Ye et al. 2020), including avoiding lethal effects (i.e. the LC_{50} value is 108 g/L; Lui 1969); and suitable conditions for larvae of salt-tolerant chironomids (*Tanytarsus barbitarsis*) (Kokkinn 1986; Dittmann 2015).
Trophic status (threat: eutrophication)	Total Nitrogen (TN)	Balance, continuous Time: Year-round (includes splits: Apr-Sep, Oct-Mar) Space: CSL and CNL	No reference point was developed for TN and TP as balance is to be evaluated, where the balance is equal to import minus export. Tracking TN and TP balance is important as reduction can help shallow, coastal ecosystems to recover (Riemann et al. 2016). Long-term net export of nutrients is required to reach the desired mesotrophic nutrient condition for the Coorong (DEW 2021).
	Total Phosphorus (TP)	Balance, continuous Time: Year-round (includes splits: Apr-Sep, Oct-Mar) Space: CSL and CNL	
	Chl-a	<5 µg/L Time: Year-round (includes splits: Apr-Sep, Oct-Mar) Space: CNL	The reference point is the Australian Water Quality Guidelines (AWQG) trigger value for chl-a in an estuary (ANZECC 2000). This reference point is limited to the Murray estuary and North Lagoon where estuarine (<35 g/L) waters occur.
	Chl-a	<10 µg/L Time: Year-round (includes splits: Apr-Sep, Oct-Mar) Space: CSL	The reference point set was doubled from the AWQG trigger value for chl-a in an estuary to reflect a value suitable for hypersaline lagoon (L. Mosley, personal communication, 25 May 2021). As such, this reference point is only relevant to the South Lagoon.
	Light	Knowledge gap	The influence on light conditions (magnitude, attenuation and duration) on the function of the Coorong ecosystem is currently a knowledge gap.
	DO	>4 mg/L Time: Year-round (includes splits: Apr-Sep, Oct-Mar) Space: CSL	Tolerance thresholds for common benthic macroinvertebrates least sensitive to low DO is 4 mg/L (Dittmann et al. 2018). Key macroinvertebrate taxa with tolerance thresholds at 4 mg/L, includes *Simplisetia aequisetis*; a dwelling species key to promote the colonisation and remediation of reduced sediments (Lam-Gordillo et al. 2022b), and amphipods and chironomids, both of which are important prey items for shorebirds and fish (Ye et al. 2020; Giatas et al. 2022). Low DO concentrations

Critical CPS	Indicator	Reference Point	Justification
			(~4 mg/L) may also impact early life stages of fish, with larval black bream unable to survive under such conditions (Hassell et al. 2008).
	DO	>6.5 mg/L Time: Year-round (includes splits: Apr-Sep, Oct-Mar) Space: ME and CNL	The most intolerant common macroinvertebrate to low DO is *Australonereis ehlersi*, which has a lower tolerance threshold of 6.5 mg/L (Dittmann et al. 2018).
	OPD (sediment)	>3 cm Time: Year-round (includes splits: Apr-Sep, Oct-Mar) Space: System-wide (includes splits: ME and CNL, and CSL)	An OPD of 3 cm is considered to be sufficient to support a diverse macroinvertebrate community in the Coorong provided other environmental stressors are not limiting (e.g. hyper-salinity). Sampling conducted by Lam-Gordillo et al. (2022b) identified that diverse macroinvertebrate communities persisted at Pelican Point and Long Point where the depth of oxic sediment layers was 3 cm. OPD influences sediment colouration (Hallett et al. 2019), and sediment colouration is associated with the biomass of aquatic plants in the Coorong (Lewis et al. 2022). Biomass of aquatic plants was found to be significantly greater when growing in sediments where upper layers are yellow/brown rather than grey or black (Lewis et al. 2022).

6.3.2 Biotic

Over the series of workshops with technical experts, a total of 12 indicators were identified across all critical CPS. A visual guide to the indicators that are most important to the status of each critical CPS subcomponent is provided in Figure 6-1. Indicators that linked to the most biotic critical CPS subcomponents were salinity, water level and flow (River Murray), with seven, four and four links, respectively. *Ruppia* had the greatest number of indicators (six), while waterbirds (waterfowl) had the fewest (two). All other biotic critical CPS subcomponents had either three or four indicators.

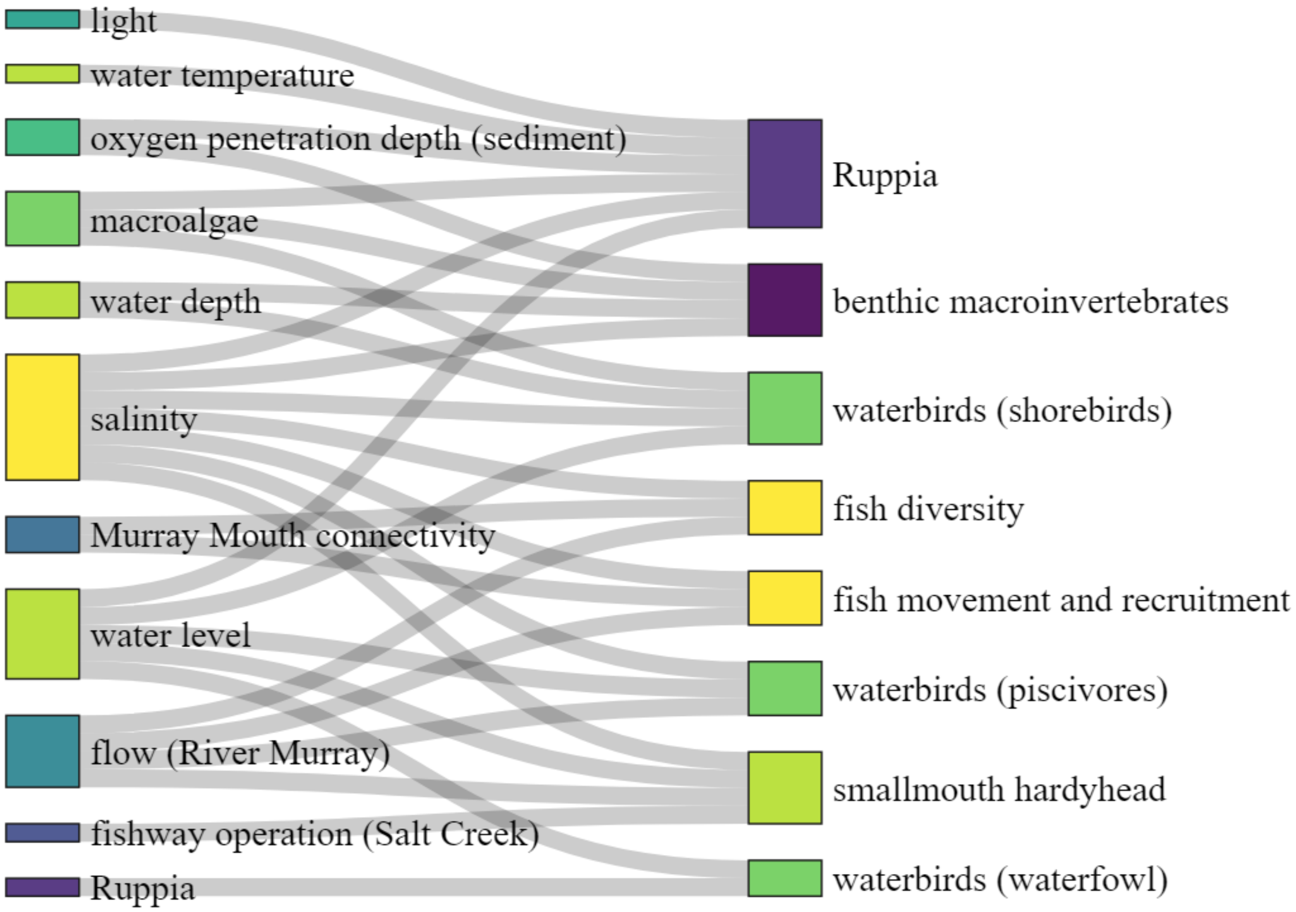

Figure 6-1. Links between important indicators (left) and the critical CPS subcomponent (right) that they influence.

Indicators

Justifications for indicators of biotic CPS subcomponents ranked as of High or Moderate importance are described in Table 6.6. The ranking of importance helps to identify the indicators that have the greatest influence over the status of critical biotic CPS from those which have less influence. This ranking of importance is presented in the biotic tabular decision-making framework (Appendix B).

Table 6.6. Indicators of biotic critical CPS subcomponent status in the Murray estuary and Coorong.

Critical CPS subcomponent	Indicator	Importance	Justification
Ruppia tuberosa	Water level	High	Water level is a principal environmental driver of *R. tuberosa* distribution and reproduction (Kim et al. 2015; Collier et al. 2017; Asanopoulos and Waycott 2020). Water cover of varying depths is required for *R. tuberosa* to complete each life stage (Kim et al. 2015; Collier et al. 2017).
	Salinity	High	Salinity is a principal environmental driver of the abundance and distribution of *R. tuberosa* life stages (Kim et al. 2015; Collier et al. 2017). Extreme hyper-salinity can reduce germination, flower and seed production and biomass (Kim et al. 2015).
	Light	High	*R. tuberosa* is reasonably tolerant to low light levels, however, it is still sensitive to shading (Collier et al. 2017). The reduced abundances of *R. tuberosa* at water depths greater than 60 cm also suggest that the species is light limited (Kim et al. 2015).
	Macroalgae	Moderate	Macroalgae impacts *R. tuberosa* by preventing flower-heads from reaching surface water where pollen is shed, breaking stalks with flower-heads or developing fruit, contributing to light limitation and potentially causing senescence attributed to sulphide intrusion from sediments that become reduced when algae decay (Collier et al. 2017).
	Water temperature	Moderate	The influence of water temperature on *R. tuberosa* in the Coorong is a knowledge gap. However, changes in water temperature are expected to provide environmental cues to initiate flowering and form turions (Brock 1982; Collier et al. 2017). Water temperature strongly influences the growth rates and subsequently biomass of other Ruppia species and annual seagrass species from temperate habitats (Collier et al. 2017).
	OPD (sediment)	Moderate	The depth of oxygen penetration influences sediment colouration (Hallett et al. 2019), and sediment colouration is associated with biomass of aquatic plants in the Coorong (Lewis et al. 2022). Biomass of aquatic plants was found to be

Critical CPS subcomponent	Indicator	Importance	Justification
			significantly greater when growing in sediments where upper layers are yellow/brown rather than grey or black (Lewis et al. 2022).
Benthic macroinvertebrates	Salinity	High	Salinity is the primary driver of macroinvertebrate community composition, biomass and abundance (Dittmann et al. 2015; Lam-Gordillo et al. 2022). Salinity directly impacts macroinvertebrate communities via the physiological tolerance of taxa (Dittmann et al. 2018), and indirectly impacts macroinvertebrates through changes in habitat quality associated with ecosystem function (Lam-Gordillo et al. 2022a; Lam-Gordillo et al. 2022b).
	Water depth	Moderate	Mudflats become uninhabitable for benthic macroinvertebrates if they experience long-term exposure (Dittmann et al. 2015). Near-shore sediments are at greatest risk of long-term exposure, though can be recolonised if inundated or pulsed (i.e. tidal cycling or wind seiching) with water (Dittmann et al. 2018).
	Macroalgae	Moderate	Benthic macroinvertebrates are negatively impacted by mats of macroalgae that cover the sediment (Sutula et al. 2014). Macroalgal mats when decomposing increase the oxygen demand of the sediment leading to reduced sediments (Mosley et al. 2020) and potentially intolerable levels of DO and hydrogen sulphide (Kanaya et al. 2018). These mats also form a barrier that may impede recolonisation of underlying sediments (S. Dittmann & O. Lam-Gordillo, personal communication, 20 January 2022). Abundances of macroinvertebrates at Ewe Island in the Murray estuary were found to decline when blanketed by macroalgae (Dittmann et al. 2021) and to recover after macroalgal cover dislodgement during high flows (S. Dittmann & O. Lam-Gordillo, personal communication, 20 January 2022).
	OPD (sediment)	Moderate	Benthic macroinvertebrates both influence and are influenced by sediment condition. Reduced sediments caused by the bacterial breakdown of excessive organic matter (Mosley et al. 2020) can lead to intolerable levels of DO and hydrogen sulphide (Kanaya et al. 2018). Bioturbating and irrigating macroinvertebrates can remediate sediments with excessive organic matter under suitable conditions (Lam-Gordillo et al. 2022a; Lam-Gordillo et al. 2022b). An informative

Critical CPS subcomponent	Indicator	Importance	Justification
			indicator of sediment condition, and therefore benthic habitat quality for macroinvertebrates, is OPD, which marks the transition from oxidised to reduced (hypoxic/anoxic) conditions in a sediment profile (Gerwing et al. 2018; Hallett et al. 2019).
Fish diversity (species richness/biodisparity)	Salinity	High	Salinity is the primary driver of fish species richness in the Murray estuary and Coorong (Ye et al. 2020). Salinity influences fish diversity directly via physical tolerances (osmoregulatory limit) of fish species at different life stages and in-directly via the physical tolerances of food resources and habitat forming species, and the formation of nursey habitats (i.e. salt wedges) (Bice et al. 2018a; Ye et al. 2020).
	Murray Mouth connectivity (water depth)	High	Connection between marine and estuarine habitats via an open Murray Mouth is required for the passage of diadromous species, marine opportunists and estuarine species (Gillanders et al. 2011; Bice et al. 2018a). The diadromous congolli spawn in the Southern Ocean and require an open Murray Mouth to move between marine and estuarine environments to complete their life history (Bice et al. 2018b). Marine estuarine-opportunist species also use the Murray estuary and Coorong particularly as juveniles. Marine estuarine-opportunists include mulloway, greenback flounder, yelloweye mullet and sandy sprat (Bice et al. 2018a).
	Flow (River Murray discharge)	High	River Murray discharge increases allochthonous input, which drives the pelagic productivity pathway of the Coorong food web (Giatas and Ye 2016). Freshwater derived zooplankton are selectively preyed upon by sandy sprat in the Murray estuary, and the proportion of their gut content comprised of freshwater zooplankton increases with River Murray discharge (Bice et al. 2016). In estuarine waters of the Coorong, sandy sprat are a key prey item for piscivorous fish, including Australian salmon and mulloway (Giatas and Ye 2015). Freshwater flow out estuary mouths provides olfactory cues that attract larval and juvenile estuary dependent marine fish species into estuaries (Whitfield et al. 1994; Teodosio et al. 2016), where recruitment is enhanced (Tweddle and Froneman 2017). River Murray discharge through open barrage gates and fishways provides connectivity between the freshwater and estuarine environments that

Critical CPS subcomponent	Indicator	Importance	Justification
			supports the movements of diadromous, estuarine and freshwater species (Bice et al. 2018b).
Smallmouth hardyhead	Salinity	High	Salinity is the key driver of population condition for smallmouth hardyhead (Wedderburn et al. 2016; Ye et al. 2021). In hypersaline waters, smallmouth hardyhead have an osmoregulatory advantage over other estuarine fish species (Noell et al. 2009; McNeil et al. 2013), likely reducing its competition with- and predation by other fish species (Ye et al. 2021). The abundance of this species is usually highest at approximately 80 g/L (Ye et al. 2020). As waters become extremely hypersaline (>100 g/L), the osmoregulatory threshold of smallmouth hardyhead (LD_{50} 108 g/L, Lui 1969) is approached and their distribution and recruitment may become limited (Ye et al. 2011).
	Flow (River Murray discharge)	High	Zooplankton are a food resource for smallmouth hardyhead (Hossain et al. 2017), and their transport via flow from the River Murray to the estuary likely promotes recruitment (Ye et al. 2021). Freshwater flow leads to seasonal reductions of salinity, which has been suggested as a partial cue to spawning in smallmouth hardyhead (Molsher et al. 1994).
	Water level (Connectivity between Coorong lagoons)	High	Connectivity between the North Lagoon and South Lagoon is thought to be important for smallmouth hardyhead, as it allows this species to escape if/when water quality worsens in the South Lagoon (i.e. extreme salinities) (Q. Ye, personal communication, 6 December 2021). Longitudinal connectivity across the Coorong lagoons also enables smallmouth hardyhead to access habitat with abundant *Ruppia*. Smallmouth hardyhead eggs adhere to *Ruppia*, which retains eggs within favourable salinities, improving egg survival and recruitment (Molsher et al. 1994). The relative importance of lagoon connectivity (influenced by water level) to the population condition of smallmouth hardyhead is considered to be a knowledge gap.
	Fishway operation (Salt Creek)	Moderate	During the height of the Millennium Drought, Salt Creek provided refugia for smallmouth hardyhead from the extremely hypersaline (>140 g/L) waters of the South Lagoon (Ye et al. 2011). More recent monitoring at Salt Creek and Morella fishways found high numbers of smallmouth hardyhead moving through fishways (SARDI unpublished data). The importance of connectivity between the Coorong and South East to the population

Critical CPS subcomponent	Indicator	Importance	Justification
			dynamics of smallmouth hardyhead is a knowledge gap.
Fish movement and recruitment (congolli and common galaxias)	Flow (River Murray discharge)	High	River Murray discharge through open barrage gates in winter and open fishways in spring–summer provides connectivity between freshwater and estuarine environments, which enables downstream migration of adults for spawning and upstream migration of juveniles from their spawning grounds (Bice et al. 2018b; Bice et al. 2021). Flow may also contribute to greater attraction and ingress of juvenile congolli from the ocean and productivity pulses that improve recruitment (Bice et al. 2018b). Populations of congolli and common galaxias collapsed during the Millennium Drought when there was no barrage flow for three consecutive years, resulting in the closure of barrage gates and fishways (Bice et al. 2018b; Bice et al. 2021).
	Murray Mouth connectivity (water depth)	High	Congolli spawn in the Southern Ocean and require an open Murray Mouth to move between marine and estuarine environments to complete their life history (Bice et al. 2018b).
	Salinity	Moderate	Laboratory trials found salinity to strongly affect the ability of common galaxias eggs to develop and produce viable larvae (Ye et al. 2010). Although congolli are highly tolerant to hypersaline conditions (LD_{50} 94 g/L at 23°C, McNeil et al. 2016), 96% of the catch (by number) in the Coorong from 2008–2021 were at salinities <60 g/L (SARDI unpublished data).
Waterbirds (Shorebirds)	Water depth	High	Water depth is well known to be the most important factor influencing the availability of habitat for shorebirds in wetland systems (Isola et al. 2000; Collazo et al. 2002). Shorebirds forage in areas of shallow water, as leg length limits foraging depths (Norazlimi and Ramli 2015). In the Coorong, the water depths at which key shorebirds species forage is well documented in Paton (2010).
	Water level	High	Shorebird prey samples from the Coorong from 2000-2020 showed higher densities when samples were collected at 30 cm or 60 cm water depths than when samples were collected at the waterline (Jackson et al. 2022). This suggests that prey availability is likely to be optimal when significant areas of bare mudflat are regularly wetted and dried, thus exposing the most productive sections of the mudflats to the birds regularly. Excessively low water levels may cause sites to dry out and

Critical CPS subcomponent	Indicator	Importance	Justification
			prey to die off. Conversely, excessively high water levels may reduce access to prey at the most productive mudflat areas thereby reducing foraging opportunities. In addition, shorebirds generally avoid proximity to tall vegetation as a predation avoidance technique, and are therefore unlikely to use sites where the waterline is too close to terrestrial vegetation, inhibiting sightlines.
	Salinity	Moderate	Salinity is expected to influence habitat quality for shorebirds via impacts on the density and distribution of aquatic food resources (Ye et al. 2020). As the food resources consumed by shorebirds varies between species (Ye et al. 2020), the distribution of shorebirds across the Murray estuary and Coorong is also species specific (Paton 2010; Mott et al. 2022; Prowse et al. 2022; Jackson et al. 2022). Generally speaking, shorebirds can tolerate a wide range of salinities from fresh to hypersaline, and can switch prey resources accordingly.
	Macroalgae	Moderate	Macroalgal mats can influence the foraging behaviour of certain shorebird species (Green et al. 2015). Investigations in the Coorong by Peters (2018) also found changes in foraging behaviour to be species specific. Mats of macroalgae are thought to adversely impact shorebirds in the Coorong by restricting access to mudflat for foraging (Paton et al. 2017), impeding the emergence of adult chironomid from aquatic environments that may subsequently reduce chironomid densities (Peters 2018), and causing sediment anoxia that negatively affects benthic habitat quality for benthic macroinvertebrates (Sutula et al. 2014).
Waterbirds (Waterfowl)	*Ruppia* (proxy for submerged halophytes)	High	*Ruppia tuberosa* (62%) and *Althenia* sp. (5%) comprised 67% of the plant material found within 34 teal scats (from mixed flocks of grey and chestnut teal) collected over the Murray estuary and Coorong in 2021 (Giatas et al. 2022). There is evidence that submerged halophytes were also important historically as gizzard and oesophagus contents of grey teal, chestnut teal and Australian shelduck in the Coorong in 1965 comprised of *Lamprothanium papulosum*, *Ruppia* sp. and *Althenia cylindrocarpa* (Delroy 1975). *Ruppia tuberosa* is an important food resource for black swan in the Coorong (Paton 2010), and their abundance is strongly correlated with the percentage cover of *R. tuberosa* (Rogers and Paton 2009).

Critical CPS subcomponent	Indicator	Importance	Justification
	Water level	High	High water levels can exclude waterfowl from accessing food resources around the shores of the Coorong (Paton and Bailey 2012), which may in part contribute to the low abundances of waterfowl recorded under such conditions (DEW 2020a). High summer water levels in the Coorong are associated with flood over the Murray-Darling Basin (DEW 2020a), which may contribute to the exodus of waterfowl to re-filling inland waterbodies (Bino et al. 2020).
Waterbirds (Piscivores)	Salinity	High	Salinity is a key driver of fish species richness, abundance and distributions in the Murray estuary and Coorong (Ye et al. 2016). As such, salinity has a strong influence over the energy density of fish throughout the system that are available for consumption by piscivorous waterbirds.
	Flow	High	River Murray discharge increases connectivity between Lake Alexandrina and the Murray estuary, the extent of estuarine waters and drives the pelagic productivity pathway of the Coorong food web (Giatas and Ye 2016). As a result, the recruitment of fish species, including smallmouth hardyhead, sandy sprat, bony herring and yellow-eye mullet is promoted, contributing to greater abundances of fish throughout the system (Giatas and Ye 2016). The density of fish in the Coorong was found to strongly correlate with the abundance of both fairy tern and Australian pelican (Rogers and Paton 2009).
	Water level	High	Water level influences the area of island habitat available to piscivorous waterbirds for breeding; and the accessibility of that habitat to foxes. Fairy tern are vulnerable to changes in water level, with high water levels in 2016/17 inundating islands that historically supported breeding (Paton et al. 2017). In the same year, a sudden drop in the South Lagoon water level by 60 cm re-connected an island supporting breeding to the mainland, which was subsequently decimated by foxes (Paton et al. 2017). Larger islands that support Australian pelican breeding remained isolated from the mainland even under very low water levels experienced during the Millennium Drought (DENR 2010).

Reference points

Justifications for indicator reference points of biotic critical CPS subcomponent status are described in Table 6.7. Reference points were developed in to a 'Measure' that can be used to post-process model inputs and outputs (see *Measure* methodology in section 6.2). Measures developed are presented in Appendix B and Section 9.9 of the Coorong Dynamics Model manual.

Table 6.7. Justification for indicators reference points that relate to the status of critical CPS. Time and Space identify the temporal and spatial range that indicator reference points are relevant to a critical CPS or threat.

Critical CPS subcomponent	Indicator	Reference point	Justification
Ruppia tuberosa	Hipsey et al. (2022) built upon a literature review by Collier et al. (2017) to determine thresholds for salinity, temperature, light, water depth and algal biomass for each life stage (Table 6.8) of the *R. tuberosa* lifecycle (Figure 6.2). See detail below table.		
	OPD (sediment)	>3 cm Time: Apr-July, June-Sept, Aug-Dec) Space: CNL and CSL (splits between lagoons)	The depth of oxygen penetration influences sediment colouration (Hallett et al. 2019), and sediment colouration is associated with biomass of aquatic plants in the Coorong (Lewis et al. 2022). Biomass of aquatic plants was found to be significantly greater when growing in sediments where upper layers are yellow/brown rather than grey or black (Lewis et al. 2022). A reference point of 3 cm is used as a proxy for an oxic upper layer of sediment.
Benthic macroinvertebrates	Salinity	<25 g/L Time: Year-round (includes splits: Apr-Sep, Oct-Mar) Space: System-wide	Threshold documented in the LINKTREE analysis differentiating the estuarine benthic macroinvertebrate community of the northern Coorong (Murray estuary and North Lagoon) between years of flow and extreme drought (Dittmann et al. 2021). Estuarine conditions are associated with higher community richness and abundances of benthic macroinvertebrates than elsewhere in the Coorong (Lam-Gordillo et al. 2022a).
	Salinity	<50 g/L Time: Year-round (includes splits: Apr-Sep, Oct-Mar) Space: System-wide	Threshold documented in the LINKTREE analysis for the diverse macroinvertebrate community of the northern Coorong (Murray estuary and North Lagoon) (Dittmann et al. 2021). A bioassay experiment by Remalli et al. (2018) that used hypersaline sediments from the St Kilda saltfields, South Australia, found that many bioturbating organisms try to avoid rather than reside

Critical CPS subcomponent	Indicator	Reference point	Justification
			in sediments with porewater salinities >50 g/L.
	Salinity	<105 g/L Time: Year-round (includes splits: Apr-Sep, Oct-Mar) Space: System-wide	Threshold documented in the LINKTREE analysis for the depauperate macroinvertebrate community in the southern Coorong that delineated years of extreme drought (2006–09) from other years of sampling (conducted since 2004). During this period, the key macroinvertebrate taxa; chironomid larvae, that supports the South Lagoon food web was in exceedingly low abundance (Paton 2010; Dittmann et al. 2021).
	Water depth	1 cm, daily inundation Time: Year-round (includes splits: Apr-Sep, Oct-Mar) Space: System-wide	Daily inundation of mudflats is considered to be adequate for benthic macroinvertebrates to remain within existing habitat and recolonise previously desiccated habitats (Dittmann et al. 2018).
	Macroalgae	Algae HSI >0.25 Time: Year-round (includes splits: Apr-Sep, Oct-Mar) Space: System-wide	Validation of the algae HSI has shown that values exceeding 0.25 have a high likelihood of algae being present or forming dense aggregations (Hipsey et al. 2021).
	Oxygen penetration depth (sediment)	>3 cm Time: Year-round (includes splits: Apr-Sep, Oct-Mar) Space: System-wide	An OPD of 3 cm is considered to be sufficient to support a diverse macroinvertebrate community in the Coorong provided other environmental stressors are not limiting (e.g. hyper-salinity). Sampling conducted by Lam-Gordillo et al. (2022a) identified that diverse macroinvertebrate communities persisted at Pelican Point and Long Point where the depth of oxic sediment layers was 3 cm.
Fish diversity (species richness/biodisparity)	Salinity	<30 g/L Time: Year-round (includes	Maintenance of brackish salinities downstream of the Tauwitchere and Goolwa barrages in spring and summer are associated with high species diversity, including a range of

Critical CPS subcomponent	Indicator	Reference point	Justification
		splits: Apr-Sep, Oct-Mar) Space: ME	freshwater, diadromous, estuarine and marine species (Bice et al. 2021).
	Salinity	<60 g/L Time: Year-round (includes splits: Apr-Sep, Oct-Mar) Space: System-wide	Fish species richness in the Coorong decreases significantly when salinities exceed 60 g/L, with no more than four species present at salinities >70 g/L (Ye et al. 2020).
	Salinity	Average daily salinity across ME is ≥40 g/L for ≥2 months Time: Year-round Space: ME	During the peak of the Millennium Drought, salinities in the Murray estuary increased from brackish to marine-hypersaline and species richness and diversity reduced (Zampatti et al. 2010). A LINKTREE analysis based on 15 years of fish monitoring data across the Coorong suggests that salinities <37 g/L maintain a distinct fish community in the Murray estuary (Ye et al. 2020).
	Murray Mouth connectivity (water depth)	>1 m Time: Year-round Space: ME	Minimum water depths at fishway entry and exit points suggested for large-bodied fish passage is 1 m (O'Connor et al. 2015b). A Murray Mouth depth of 1 m is considered adequate for the passage of large-bodied species.
	Flow (River Murray discharge)	Continuous, average monthly discharge Time: Year-round Space: ME	No reference point was developed for flow, with greater volumes of flow considered to be more beneficial. Zampatti et al. (2010) found that small volumes (~50 ML/day) of River Murray discharge from the barrages provide a limited estuarine refuge for the estuarine fish assemblage. Flow is also strongly associated with the population condition of black bream, greenback flounder, smallmouth hardyhead (Ye et al. 2021), mulloway (Ferguson et al. 2008) and catches of sandy sprat (Bice et al. 2021).
Smallmouth hardyhead	Salinity	<100 g/L Time: Year-round (includes splits: Apr-Sep, Oct-Mar)	The osmoregulatory threshold (LD_{50}) for smallmouth hardyhead is 108 g/L (Lui 1969), and their distribution and recruitment becomes limited as salinities surpass 100 g/L (Noell et al. 2009; Ye et al. 2011).

Critical CPS subcomponent	Indicator	Reference point	Justification
		Space: System-wide	
	Flow (River Murray discharge)	Continuous, average monthly discharge Time: Year-round (includes splits: Apr-Sep, Oct-Mar) Space: System-wide	No reference point was developed for flow, with greater volumes of flow considered to be more beneficial to the population condition of smallmouth hardyhead. The population condition of smallmouth hardyhead is strongly associated with flow, with high flow events leading to very good population condition (Ye et al. 2021).
	Water level (Connectivity between Coorong lagoons)	Water level >+0.3 m AHD Time: Year-round (includes splits: Apr-Sep, Oct-Mar) Space: CSL	The North and South lagoons of the Coorong become connected at ~+0.2 m AHD, and ≥10 cm water depth is considered to be adequate for the passage of the small-bodied smallmouth hardyhead (SARDI, personal communication, 6 December 2021).
	Fishway operation (Salt Creek)	Salt Creek flow is >3 ML/day and CSL is >+0.4 m AHD or flow is >2 ML/day and CSL is >+0.8 m AHD Time: Year-round (includes splits: Apr-Sep, Oct-Mar) Space: CSL	To achieve the minimum water depth (10 cm) within the fishway for passage of small-bodied fish, including smallmouth hardyhead, the reference point conditions regarding Salt Creek flow and Coorong South Lagoon water levels must be met (DEW 2019).
Fish movement and recruitment (congolli and common galaxias)	Flow (River Murray discharge)	River Murray discharge is >200 ML/day Time: Oct-Jan Space: Boundary condition	In the assumption of Lake levels >+0.4 m AHD (not accounted for the in CDM), River Murray discharge of 200 ML/day from the barrages is considered to be adequate to operate all barrage fishways (C. Bice, personal communication, 6 December 2021) for the upstream migration of congolli and common galaxias (Bice et al. 2018b; Bice et al. 2021). This reference point assumes that fishways will be prioritised for barrage discharge over open bays under low flow conditions.

Critical CPS subcomponent	Indicator	Reference point	Justification
	Flow (River Murray discharge)	Continuous, average monthly discharge Time: May-Aug Space: Boundary condition	No reference point was developed for flow between May and August, with greater volumes of flow associated with increases in the number of open barrage gates, which are critical for the downstream passage of congolli and common galaxias to spawn (Bice et al. 2018b; Bice et al. 2021).
	Murray Mouth connectivity (water depth)	>30 cm Time: May-Jan Space: ME	Minimum water depths at fishway entry and exit points suggested for small to medium-bodied fish passage is 30 cm (O'Connor et al. 2015b). A Murray Mouth depth of 30 cm is considered adequate for the passage of small-bodied species.
	Salinity	<35 g/L Time: Oct-Jan Space: ME	Salinities exceeding seawater (35 g/L) resulted in common galaxias egg retardation and 100% mortality (Ye et al. 2010).
Waterbirds (Shorebirds)	Water depth	<10 cm Time: Sep-Apr Space: System-wide	Location occupancy and abundance of red-necked stint and common greenshank based on counts from 2000-2020 increased with greater availability of habitat within 0-20 cm water depth (Prowse et al., 2021). Key shorebird species; common greenshank, curlew sandpiper, red-capped plover, red-necked stint and sharp-tailed sandpiper forage in water depths of <10 cm (Paton 2010).
	Water depth	<20 cm Time: Sep-Apr Space: System-wide	Foraging observations of red-necked avocet and banded stilt largely (>90%) occur in water depths of <20 cm (Paton 2010). Mott et al. (2022) also documented that tagged red-necked avocets favoured locations known to have significant areas of shallow water (~5-20cm) available when they were present.
	Water level	>+0.4 m AHD Time: Sep-Apr Space: CSL	Jackson et al. (2022) found that shorebird abundance across seven sample sites in 2021-2022 was positively associated with the combined area of exposed mudflat and shallow water, which are directly related to water level. There is a significant decline in mudflat area when water levels exceed +0.4 m AHD (Hobbs et al. 2019), and shorebirds may be deterred from using mudflat at higher elevations due to the lower line-

Critical CPS subcomponent	Indicator	Reference point	Justification
			of-sight distance from terrestrial vegetation (Jackson et al. 2022).
	Salinity	<140 g/L Time: Sep-Apr Space: System-wide	Chironomids dominated the diets of red-capped plovers, red-necked stint and sharp-tailed sandpipers in the South Lagoon in 2021 (Giatas et al. 2022). Chironomids are the most salt-tolerant of the common benthic macroinvertebrates found in the Murray estuary and Coorong, and have a salinity tolerance threshold of 140 g/L (Dittmann et al. 2018). When salinities were around 140 g/L in the South Lagoon during the Millennium Drought, chironomids were not recorded (Paton 2010).
	Macroalgae	Algae HSI >0.25 Time: Sep-Apr Space: System-wide	Validation of the algae HSI found that when measures exceed a mean of 0.25 there is a high likelihood of algae presence or dense formations (Hipsey et al. 2021). The extent of the Coorong where the algae HSI exceeds 0.25 is therefore a proxy for the severity of impacts associated with macroalgal mats on shorebirds.
Waterbirds (Waterfowl)	Ruppia (HSI: adult growth and precursor stages)	Continuous Time: Sep-Apr Space: CNL and CSL (splits between lagoons)	No reference point was developed for *Ruppia* HSI (adult growth), with greater extents of habitat area considered more likely to increase the provisions of forage for herbivorous waterfowl. The abundances of black swan are strongly positively correlated with the percentage cover of *R. tuberosa* (Rogers and Paton 2009).
	Ruppia (HSI: turion and precursor stages)	Continuous Time: June-Dec Space: CNL and CSL (splits between lagoons)	No reference point was developed for *Ruppia* HSI (turion), with greater extents of habitat area considered more likely to increase the provisions of turions for herbivorous waterfowl.
	Water level	>+0.35 m AHD Time: Sep-May Space: CSL	*Ruppia tuberosa* and *Althenia cylindrocarpa* plants in spring 2020 were identified to primarily (88%) be found between -0.15 and +0.15 m AHD in the South Lagoon, with 1% of plants found above +0.15 m AHD (Oerman 2021). Given the above threshold of +0.15 m AHD for aquatic plants in the CSL

Critical CPS subcomponent	Indicator	Reference point	Justification
			(Oerman 2021), and noting that chestnut teal are expected to have poor foraging ability when water depths are >20 cm (O'Connor et al. 2013), forage for teal and other waterfowl is expected to be highly limited above +0.35 m AHD.
Waterbirds (Piscivores)	Salinity	<40 g/L Time: Sep-Apr Space: System-wide	Estimated fish biomass density (kg/seine) based on SARDI fish sampling in the Coorong from 2008/09 to 2020/21 was greatest when salinities averaged over the Murray estuary and North lagoon were below 40 g/L (SARDI unpublished data).
	Salinity	<100 g/L Time: Sep-Apr Space: System-wide	Smallmouth hardyhead are the most salt tolerant fish in the Coorong and a key food resource for piscivorous waterbirds (Paton 2010; Giatas and Ye 2016). The osmoregulatory threshold (LD_{50}) for smallmouth hardyhead is 108 g/L (Lui 1969), and their distribution and recruitment becomes limited as salinities surpass 100 g/L (Ye et al. 2011). Therefore, salinities above 100 g/L may limit the extent and abundance of a particularly important piscivorous food resource.
	Flow (River Murray discharge)	Continuous, average monthly discharge Time: Sep-Apr Space: Boundary condition	No reference point was developed for flow, with greater volumes of flow considered to be more beneficial to the food resource provision for piscivorous waterbirds. Coorong studies have shown that fish species richness and abundance decline during drought and increase following high flows (Ye et al. 2020).
	Water level	<-0.5 m AHD Time: Sep-Apr Space: CSL	Fairy terns successfully bred in the South Lagoon in the 2015/16 breeding season when the lagoon-averaged water levels reached -0.42 m AHD. It is expected that the risk of foxes accessing and predating nesting colonies on South Lagoon islands would increase as water levels decline below -0.5 m AHD. A digital elevation model investigation determined that the extent of island habitat with a minimum of 150 m^3 of water protection declined significantly below -0.5 m (T Hobbs, unpublished data).

Ruppia Habitat Suitability Model

Hipsey et al. (2022) built upon a literature review by Collier et al. (2017) to determine thresholds for salinity, temperature, light, water depth and algal biomass for each life stage (Table 6.8) of the *R. tuberosa* lifecycle (Figure 6.2). These ecological thresholds were used to parameterise the *Ruppia* HSI, which can be coupled with the CDM (DEW 2020b) to determine the habitat suitability for each *R. tuberosa* life stage and across the life cycle under different management scenarios.

Table 6.8. Parameterisation of the Ruppia Habitat Suitability Index based upon a literature review that determined thresholds for salinity, temperature, light, water depth and algal biomass (Hipsey et al. 2022).

Life stage	Salinity (g/L)	Water depth (m)	Temperature (°C)	Light (% SI)	Algal biomass (g DW m^{-2})
Turion viability (1 January to 31 March)	<135: Optimal 135-165: Sub-optimal ≥165: Unsuitable				
Seed germination (1 April to 30 June)	<0.1: Unsuitable 0.1-40: Optimal 40-85: Sub-optimal >85: Unsuitable	Permanently dry: Unsuitable <15 days wet (>95% of time): Unsuitable 15-42 days wet (>95% of time): Sub-optimal* >42 days wet (>95% of time): Optimal*			
Turion sprouting (1 April to 30 September)	≤0.1: Unsuitable 0.1-20: Sub-optimal 20-75: Optimal 75-125: Sub-optimal >125: Unsuitable	≤0.01: Unsuitable 0.01-0.02: Sub-optimal >0.2: Optimal			
Adult growth (1 June to 30 September)	<10: Unsuitable 10-19: Sub-optimal 19-124: Optimal 124-230: Sub-optimal >230: Unsuitable	<0.1: Unsuitable 0.1-0.2: Sub-optimal 02-0.6: Optimal 0.6-0.9: Sub-optimal >0.9: Unsuitable	<4: Unsuitable 4-20: Sub-optimal 20-23: Optimal 23-30: Sub-optimal >30: Unsuitable	≤5: Unsuitable 5-36: Sub-optimal ≥36: Optimal	<25: Optimal 25-100: Sub-optimal >100: Unsuitable
Flowering and seed set (1 August to 31 December)	<12: Unsuitable 12-47: Sub-optimal 47-62: Optimal	<0.1: Unsuitable 0.1-0.4: Optimal 0.4-0.9: Sub-optimal >0.9: Unsuitable	<4: Unsuitable 4-20: Sub-optimal 20-23: Optimal	≤5: Unsuitable 5-36: Sub-optimal	<25: Optimal 25-100: Sub-optimal >100: Unsuitable

Life stage	Salinity (g/L)	Water depth (m)	Temperature (°C)	Light (% SI)	Algal biomass (g DW m^{-2})
	62-100: Sub-optimal >100: Unsuitable		23-30: Sub-optimal >30: Unsuitable	≥36: Optimal	
Turion formation (1 August to 31 December)	<70: Unsuitable 70-124: Sub-optimal 124-160: Optimal 160-230: Sub-optimal >230: Unsuitable	<0.1: Unsuitable 0.1-0.4: Optimal 0.4-0.9: Sub-optimal >0.9: Unsuitable	<4: Unsuitable 4-20: Sub-optimal 20-23: Optimal 23-30: Sub-optimal >30: Unsuitable	≤5: Unsuitable 5-36: Sub-optimal ≥36: Optimal	

*Provided that the wet days are not followed by >8 dry days (= Unsuitable)

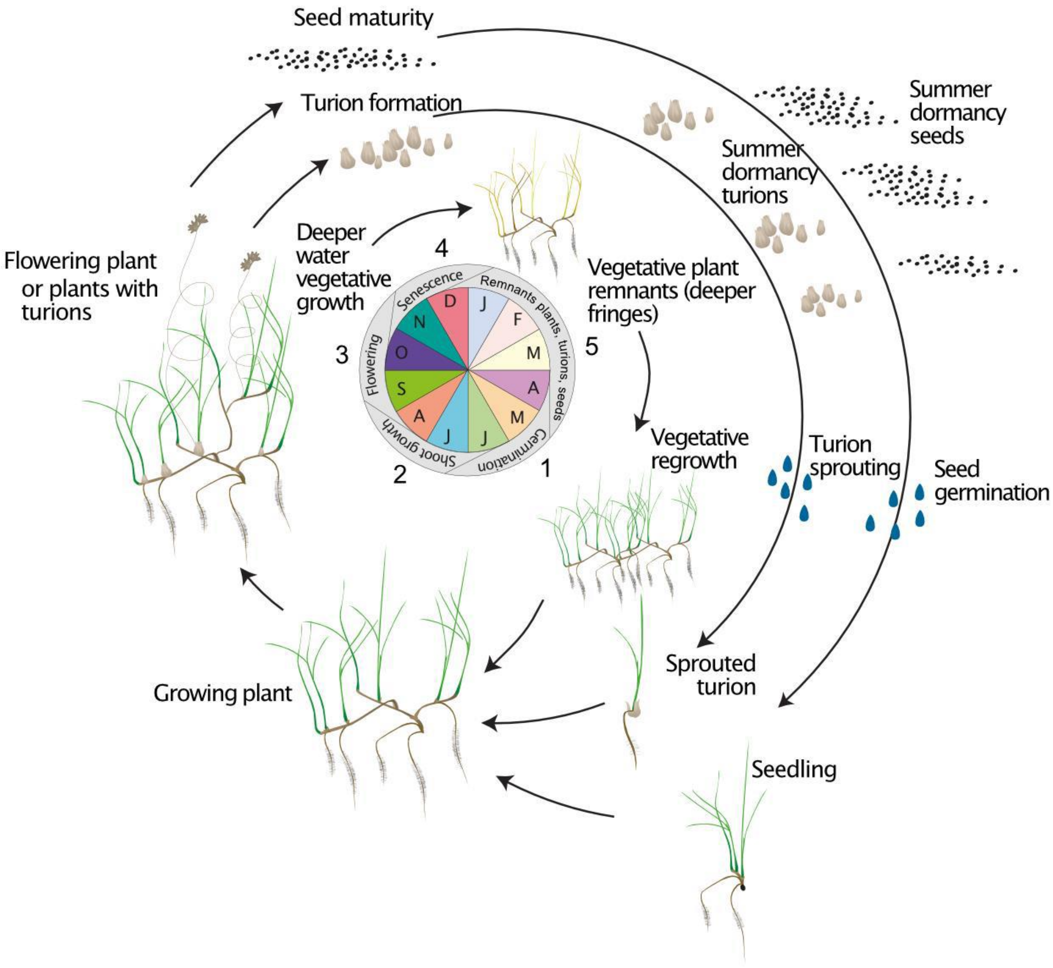

Figure 6.2. Conceptual diagram of *R. tuberosa* life cycle showing the five life stage and three possible life cycle pathways; whole plants, seeds and turions (Asanopoulos and Waycott 2020).

7 Step 5: Confidence in model

Addressing uncertainty is a fundamental part of the environmental decision-making process (Ascough et al. 2008). To successfully account for uncertainty within decision-making, it is important to identify the sources of uncertainty and quantify their level (Ascough et al. 2008; Geary et al. 2020). However, for complex systems such as the Coorong, the heavy computational cost related to the high-resolution mesh and numerous factors in external loads (e.g. barrage flows and their nutrient concentrations) and internal processes (e.g. biogeochemical controlling parameters) make it unrealistic to perform such an uncertainty analysis (Doherty 2015; Kavetski et al. 2018; Huang et al. 2022). Instead, as this decision-making framework focuses on summarising inputs and outputs of the CDM, we consider uncertainty as the level of confidence we have in the model accuracy simulating indicators of the status of critical CPS and threats.

In modelling, certainty is quantified through validation, and statistics are produced to demonstrate the goodness-of-fit and error between observed and modelled data. Due to the technical knowledge required to interpret such statistics, decision-makers may make decisions without appropriately considering uncertainty. To resolve this, we described a methodology that translates validation statistics to readily interpretable measures of confidence (see section 7.1). A confidence evaluation for each indicator of critical CPS and threat status has not been undertaken in this report, however, will take place when the Coorong decision-making framework is updated and tested (see recommendation in section 10).

7.1 Method

To demonstrate the level of confidence in the CDM accurately simulating indicators within the decision-making framework, a workshop was held with Matt Hipsey (UWA) and Peisheng Huang (UWA), whom led the model development and validation. The workshop intended to develop a process for the conversion of validation statistics; coefficient of determination, bias, root mean squared error, normalised root mean square error (*see descriptions in* Table 7.1), in to a more readily interpretable measure of confidence.

Table 7.1. Description of statistics used in validation of CDM parameters. The performance metrics were defined and calculated following the methods in Jackson et al. (2019).

Statistic	Description
Coefficient of determination (R^2)	A measure of how close the model and observed data can be represented by a linear regression line. The R-squared value is always between 0 and 1.0 with the higher R-squared value indicating a better model fit.
Bias	A measure of the tendency for a modelled parameter to systematically over- or under-estimate the observed value.
Root Mean Square Error (RMSE)	A measure of error in the model based upon the comparison of modelled and observed values. A value of zero indicates a perfect match between modelled and observed values, and greater differences between modelled and observed values will be reflected in greater RMSE values.
Normalised Root Mean Square Error (NRMSE)	Normalising the RMSE by the mean of the observed data; this allows comparison between data sets with different scales.

Modelers will subjectively evaluate confidence in the CDMs ability to simulate indicators of critical CPS and threat status in to one of the following categories:

- Good
- Acceptable, and
- Caution.

In the confidence evaluation, modelers will consider the:

- Quality of observed data, which is influenced by field and laboratory data limitations, methodologies, processes and protocols.
- Performance score relative to what is typically reported in the literature for water quality models (Arhonditsis and Brett 2004).
- Ability of the CDM to capture the mean of an indicator and its spatial gradient and seasonality.
- Partitioning of water quality constituents within different ecosystem pools (i.e. storages of energy, such as the water column and sediment).
- Natural variability of the indicator at different temporal scales (i.e. sub-daily to seasonal).

8 Step 6: Summarise and evaluate model output

Model inputs and outputs are to be summarised and evaluated in results tables, and supported by standardised visual model outputs that provide greater granularity (temporal or spatial) to the tabular results of the decision-making frameworks. Example, metadata on the results tables and standardised outputs of the decision-making framework are presented in section 8.1 and 8.2, respectively.

8.1 Results tables

A description of all the metadata fields of the results tables supporting the decision-making framework are provided in Table 8.1. A worked example of how information is applied for an indicator of the status of small-mouthed hardyhead; a sub-component of the food web critical CPS is shown in Table 8.1. Complete tabular abiotic and biotic decision-making frameworks are presented in Appendix A and B, and document the full suite of indicator reference points that can be used to summarise model inputs and outputs.

The decision-making framework provides quantitative measures associated with indicator reference points to document the anticipated responses of critical CPS subcomponents and threats. However, it is recognised that decision theory holds that it is easier to rank outcomes than it is to accurately predict outcomes (Geary et al. 2020). Therefore, to help select the best management option, the tabular results have been designed to be comparative, by displaying the summarised results for each management scenario in adjacent columns (as shown in Table 8.3).

Table 8.1. Metadata of the tabular results of the decision-making framework.

Key	Description	Example
Critical CPS subcomponent/threat	Critical CPS subcomponents or key threats identified in the ECD and RMP.	Small-mouthed hardyhead: a sub-component of the food web critical CPS.

Key	Description	Example
Indicator	Biological, chemical or physical factors that either influence or are proxies for critical CPS and threat status.	Salinity (see justification in Table 6.6).
Importance (biotic CPS only)	Importance (High or Moderate) of the indicator in causing change to the status of the critical CPS subcomponents or threat based on criteria presented in Table 6.2.	High (see justification in Table 6.6).
Reference Point	Reference points are quantitative measures of an indicator that are used to consistently document the anticipated responses of critical CPS subcomponents and threats.	100 g/L (see justification in Table 6.7).
Time	The temporal range that an indicator and reference point were relevant to a critical CPS or threat.	October to March: Aligns with the spawning and recruitment stages of the smallmouth hardyhead lifecycle.
Space	Relevance of the indicator reference point in space, using the discrete units shown in Figure 1.1.	System-wide: species is known to occur throughout the entire system (Ye et al. 2020).
Measure	Indicator reference points were translated to a 'Measure' suitable for summarising data in space and time in an ecologically meaningful manner. Post-processing is the computation process for calculating a single summary value based on the 'Measure' from highly detailed and complex model inputs and outputs.	Mean daily longitudinal extent (km) below 100 g/L
Confidence	Translation of validation statistics to a readily interpretable measure of confidence, using a scale of good, acceptable and caution.	Good: Confidence in modelled salinities is good in the South Lagoon, where there is a likelihood of salinities exceeding 100 g/L.
Benefit/Risk	Critical CPS: benefit distinguishes a positive relationship between the 'Measures' and beneficial conditions to the critical CPS subcomponent, and vice versa for risk. Threat: benefit is distinguishes where increases in a 'Measure' reduce ecosystem risk, and vice versa for risk.	Benefit: increases in the mean daily longitudinal extent of the Murray estuary and Coorong below 100 g/L is beneficial to small-mouthed hardyhead recruitment and distribution.

Table 8.2. Example layout of the tabular results of the decision-making framework, showing the summarised model inputs and outputs of two potential management scenarios (Scen 1 and Scen 2) for one indicator reference point (i.e. salinity) of the smallmouth hardyhead CPS subcomponent.

Critical CPS subcomponent	Indicator	Importance	Reference Point	Time	Space	Measure	Confidence	Benefit/ Risk	Scen 1.	Scen 2.
Smallmouth Hardyhead	Salinity	High	100 g/L	Oct-Mar	System-wide	Mean daily longitudinal extent (Km) below 100 g/L	Good	Benefit	80	100

8.2 Standardised outputs

Water managers rely upon visual model outputs at high spatial and temporal resolution to demonstrate the anticipated influence of alternative management scenarios. These visual model outputs are presented for Annual Operation Outlooks, which explore potential operating strategies and water availability scenarios for an up-coming water year based upon climate projections. Visual model outputs support communication with researchers and the community to inform and be informed on proposed management interventions and desired outcomes. Standardised visual outputs are intended to support annual water planning by supplementing and provide greater granularity (temporal or spatial) to the tabular results of the decision-making framework. It is recognised that specific outputs may be required for targeted management interventions and operations that are not considered here.

8.2.1 Method

A workshop was held with a DEW environmental water manager (Adrienne Rumbelow) and DEW hydrologist/modeler (Claire Sims) to identify standardised visual model outputs (time series, rasters etc.). To support the workshop, visual outputs from the CDM produced for the Coorong Infrastructure Investigations project and from the 1-D Coorong Hydrodynamics Model for Annual Operations Outlooks were presented to help select the most informative outputs. Presented model outputs included:

- Time (daily) series at water stations along the Coorong
- Time (daily) series using lagoon-averages
- Daily longitudinal extent of the Coorong meeting an environmental condition
- Longitudinal plots: average value for time period longitudinally along the Coorong
- Rasters of an environmental condition(s) over the system.

For each indicator of critical CPS and threat status, the following information was recorded within the workshop to inform post-processing of model simulations to develop visual outputs:

- Need: Whether an output supplementary to the tabular results was required.
- Style: Style of output that best supports decision-making, i.e. time series, raster, other
- Time step: Time step (daily or monthly etc.) for graphing (if output is a time series)
- Space: Spatial bounds considered for the output, i.e. how total space will be divided for an output
- Measure: How the measure of an indicator is to be post-processed

- Duration: Maximum time period to be output for a time series before another graph facet is required to ensure outputs are easily interpretable, i.e. two facets would be needed if two years' worth of data were to be graphed to improve readability.

8.2.2 Results

Outcomes of the workshop documented in Table 8.3 will inform post-processing of model inputs and outputs to develop standardised visual outputs that will support management decision-making.

Table 8.3. Information required to support post-processing of model inputs and outputs into standardised visual outputs.

Indicator	Output
Salinity	Need: Required Style: Time series Time step: Daily Space: Murray estuary, Coorong North Lagoon split into thirds, Coorong South Lagoon split into thirds. Measure: Average daily salinity over units of space Duration: 12-months
Murray Mouth connectivity	Need: Not required Comment: Daily cumulative flow (in or out) across the Murray Mouth may be useful to inform targeted operations.
Flow (River Murray discharge)	Need: Required Style: Time series Time step: Daily Measure: Flow (ML/day) across all barrages Duration: 12-months
Flow (Salt Creek discharge)	Need: Required Style: Time series Time step: Daily Measure: Flow (ML/day) at Salt Creek outlet Duration: 12-months
Water level (Coorong South Lagoon)	Need: Required Style: Time series Time step: Daily Space: Murray estuary, Coorong North Lagoon split into thirds, Coorong South Lagoon split into thirds. Measure: Average daily water level over units of space Duration: 12-months
Fishway operation (Salt Creek)	Need: Required Style: Time series Time step: Daily Space: Salt Creek/Coorong South Lagoon Measure: Salt Creek flow is >3 ML/day and CSL is >+0.4 m AHD or >2 ML/day and CSL is >+0.8 m AHD, 1=conditions met and 0 = conditions not met. Duration: 12-months
Water depth (inundation area)	Need: Not required.

Indicator	Output
	Comment: Adequately accounted for within the tabular results of the framework.
Water depth (<10 cm area)	Need: Required Style: Time series Time step: Daily Space: Murray estuary, Coorong North Lagoon split into thirds, Coorong South Lagoon split into thirds. Measure: Mean daily area (Ha) of water cover less than 10 cm over units of space Duration: 12-months
Macroalgae (Ulva HSI)	Need: Required Style (1): Raster Space (1): last third of the Coorong North Lagoon and first third of the Coorong South Lagoon Measure (1): HSI value over model period for each scenario or delta-map showing comparison of two scenarios. Style (2): Longitudinal plot Space (2): Longitudinal transect of the Coorong Measure (2): HSI value over model period
OPD	Need: Not required. Comment: Adequately accounted for within the tabular results of the framework.
Ruppia (HSI)	Need: Required Style (1): Raster Space (1): entire system Measure (1): HSI output for each life stage and the sexual lifecycle Style (2): Longitudinal plot Space (2): Longitudinal transect of the Coorong Measure (2): HSI value over model period
Chl-a	Need: Not required. Comment: Adequately accounted for within the tabular results of the framework.
TN & TP (balance)	Need: Not required. Comment: Adequately accounted for within the tabular results of the framework.
DO	Need: Not required. Comment: Adequately accounted for within the tabular results of the framework.

9 Discussion

New knowledge, tools and products were gained and developed under the T&I project of the HCHB program to support EBM of the Coorong. This wealth of information (data, knowledge and tools) to support management decision-making in the Coorong has created both new opportunities and challenges associated with an information-rich environment.

The collection of targeted information on the Coorong ecosystem via the HCHB T&I project has enhanced our knowledge of how the ecosystem functions and further improved the CDM. These improvements and enhancement of the CDM have resulted in a sophisticated and powerful tool to support decision-making. However, there are new challenges for decision-makers in information rich environments, with decision-makers finding themselves "drowning in data" due to the overwhelming mass of information (Levin et al. 2009; Bharadwaj 2018). Decision-makers in the Coorong also face this challenge, as the CDM simulates an extensive range of parameters at time scales as frequent as sub-daily and at spatial scales of 20–50 m, over the full spatial extent of the Coorong. The fine resolution of this spatio-temporal data results in masses of data, rather than knowledge of how the ecosystem is likely to respond to management. A challenge therefore remains in the assessment and evaluation of inputs and outputs to inform ecosystem management in an accurate, timely and repeatable manner that accounts for uncertainty in predictions.

We have sought to resolve this challenge through the development of the Coorong decision-making framework, which automates:

- the summary of model inputs and outputs using measures associated with indicator reference points to yield quantitative results tables that demonstrate how critical CPS and threats are likely to respond to management scenarios, and
- standardised visual outputs of ecosystem indicators that provide greater granularity (temporal or spatial) to the tabular results to further inform decision-making.

The Coorong decision-making framework was designed to be fit-for-purpose and flexible, and provide ecological interpretations of model scenarios based on best-available science in a timely, transparent and repeatable manner that accounts for uncertainty. The Coorong decision-making framework achieves each of these functions:

- *Fit-for-purpose*: The Coorong decision-making framework meets its purpose of supporting informed decision-making to support EBM as measures associated with indicator reference points provide insight into the expected response of critical CPS and threats. These measures align with CDM inputs and outputs and were co-developed with modelers to ensure they can be fulfilled by post-processing model outputs. Standardised outputs that support the tabular framework results were co-developed with both modelers and environmental managers to ensure that they supplement data summarised in the tables, and provided the granularity of spatiotemporal data often requested and used to inform decision-making.
- *Flexible*: The Coorong decision-making framework was designed to match the temporal flexibility of the CDM, and therefore can be used in hindcasts and forecasts, and at a range of temporal scales ranging from a month to decades. In addition, the framework captures seasonality in the ecosystem, with many indicators and reference points changing depending upon the time of year in order to be relevant to the critical CPS or threat. For example, the timing of life stages of diadromous fish are considered through temporal indicator reference points associated with the downstream migration of adults to spawn and the subsequent upstream migration of juveniles. The design of the decision-making framework also enables the science underpinning the summary of CDM inputs and outputs for a given critical CPS or threat to be iteratively updated as new research findings and ecological models become available.
- *Transparent*: Transparency is important to effective decision-making and engagement of people involved in or affected by a decision. To ensure transparency in the Coorong decision-making framework, we have documented the steps taken in its developed, justified all indicators and reference points for critical CPS

and threats, and shown the measures associated with indicator reference points to be used to summarise outputs of the CDM. This open and transparent documentation of the process and information underpinning the Coorong decision-making framework will support traceability of decisions and enable critique of the framework to be clearly documented, supporting continual improvement.

- *Timely and repeatable*: Information supporting decision-making needs to be delivered to match the timelines of decision-makers. To meet the timelines of decision-makers in the Coorong, code was written to automate the population and creation of the results tables and standardised outputs of the Coorong decision-making framework. The Coorong decision-making framework and associated code provides consistency in the information used to summarise CDM inputs and outputs to make it repeatable. Initial development of code to enable automation is time intensive, however, it will enable timely delivery of the Coorong decision-making framework following runs of the CDM.
- *Best-available science*: A participatory approach was used to develop the science that underpins the decision-making framework. This approach built trust with technical experts through the integration of their knowledge and research into the framework. Knowledge and research of technical experts from a range of research disciplines were used to identify indicators of critical CPS and threat status and associated reference points. Where available, research, investigations and site knowledge from the Coorong were used to justify indicators and reference points, and were supported by peer reviewed literature from other estuaries as required. Due to the parallel timelines of the T&I project with the development of the decision-making framework, not all findings and new ecological models could be incorporated. However, as detailed above, the flexibility of the decision-making framework enables it to continually be updated with the best-available science. Therefore, research findings and ecological models not included in the first iteration of the Coorong decision-making framework can be input in to future iterations.
- *Capturing uncertainty*: Decision-makers require an understanding the level of confidence in supporting information when making decisions to ensure they are aware of the likelihood of unintended outcomes. It is therefore important to identify sources of uncertainty and quantify their level (Ascough et al. 2008; Geary et al. 2020). As our decision-making framework focuses on summarising inputs and outputs of the CDM, we consider uncertainty as the level of confidence we have in the model accuracy simulating indicators of the status of CPS and threats. In modelling, certainty is quantified through validation, and statistics are produced to demonstrate the goodness-of-fit and error between observed and modelled data. Due to the technical knowledge required to interpret such statistics, decision-makers may make decisions without appropriately considering uncertainty. To resolve this, we described a methodology that translates validation statistics to readily interpretable measures of confidence using the categories good, acceptable and caution.

Modelling and the ecologically meaningful evaluation of model inputs and outputs using the Coorong decision-making framework fit within a broader approach to support ecosystem-based management of the Coorong. The Coorong EA approach uses the Coorong decision-making framework as an input to inform decision-making in concert with management frameworks and processes, environmental outcomes from previous years, upstream processes, real-time data, consultation and site knowledge. Using this information, a preferred action for management can be selected and undertaken following required consultation and approval processes. The final step in the Coorong EA approach is monitoring and evaluation which determines the ecological outcomes to management and provides a mechanism for these outcomes to inform model configuration and the science underpinning the Coorong decision-making framework through adaptive management loops.

Inputs to inform decision-making using the Coorong EA approach will depend upon the decision-making objective of the user. The inherent flexibility of the Coorong EA approach allows it to support a range of decision-making objectives (infrastructure investigations, policy, and water of the environment management) for water managing authorities (DEW, Murray-Darling Basin Authority etc.). It is anticipated the Coorong EA could support:

- evaluation of infrastructure options that aim to improve the ecological health of the Coorong (i.e. infrastructure options currently being investigated in the HCHB program)

- review of the Basin Plan; through a better understanding of water requirements for the restoration and protection of ecosystems and ecosystem functions under climate change, and
- annual water for the environment planning and short-term management operations.

10 Recommendations

To improve the Coorong decision-making framework, we recommend:

- Testing the framework's ability to summarise model inputs and outputs using potential management scenarios.

Real world management scenarios are recommended to be run by the CDM and summarised using the decision-making framework. Testing the ability of the decision-making framework to inform management decision-making, will help to identify issues limiting our confidence in ecological interpretation. Issues may include: inadequate sensitivity of 'Measures' to help differentiate between modelled management scenarios; and "wicked problems" where for a given management scenario, indicator reference points for a critical CPS or threat may be associated both with an increase in risk and benefit (e.g. lower salinity a maybe benefit, but may result in a greater risk of increased algal cover).

- Conducting a confidence evaluation for each indicator of critical CPS and threat status simulated by the CDM

An evaluation of our level of confidence in the CDM accurately simulating indicators of critical CPS and threat status is required before the decision-making framework is fit to support decision-making. The methodology described in section 7.1 is to be followed to support the confidence evaluation.

- Seeking feedback from environmental managers and advisory groups

Feedback from environmental managers and advisory groups is sought to determine how informative and useable the outputs of the decision-making framework are, and ways in which they could be improved to better inform or communicate management decision-making.

- A review of the sensitivity of 'Measures' for indicator reference points

Maximising the sensitivity of indicator reference points to environmental change helps managers to predict and evaluate the efficacy of management actions.

- Further development of habitat suitability indices or response models to account for the interactions of indicators directly or in-directly on the critical CPS subcomponent.

The development of habitat suitability indices or response models help to resolve "wicked problems" where under a given management scenario there are measures of indicator reference points for a given critical CPS or threat that were associated both with an increase in risk and an increase in benefit.

- New research findings and ecological models are input as they become available

The decision-making framework is designed to be iteratively updated and improved as new research findings and ecological models are developed, including those from HCHB Phase 1 T&I project.

- Trend and condition of critical CPS subcomponents and threats should be incorporated in to the framework to signal where targeted management may be required.

Selection of the most appropriate management action to achieve ecosystem objectives is dependent upon the need of critical CPS subcomponents and threats for targeted management. Trend and condition are two key parameters used to evaluate the need of critical CPS subcomponents for targeted management. It is therefore recommended that the trend and condition of critical CPS be included within the tabular results of the decision-making framework to further inform decision-makers.

11 Conclusion

The Coorong decision-making framework is a tool capable of summarising model inputs and outputs in a manner that is ecologically meaningful, accurate, timely, transparent, repeatable, and that accounts for uncertainty in predictions. Importantly, the design of the decision-making framework is flexible in time to accommodate different management questions, and enables iteration to facilitate the input new research findings and ecological models as they become available. The decision-making framework presented in this report serves as a tool for continual improvement in evidence-based management of the Coorong ecosystem.

12 References

Arhonditsis GB and Brett MT (2004) 'Evaluation of the current state of mechanistic aquatic biogeochemical modelling', *Marine Ecology Progress Series* 271, 13-26.

Asanopoulos C and Waycott M (2020) *The growth of aquatic macrophytes (Ruppia tuberosa spp. and Althenia cylindrocarpa) and the filamentous algal community in the southern Coorong*, Goyder Institute for Water Research Technical Report Series No. 20/13.

Ascough JC, Maier HR, Ravalico JK and Strudley MW (2008) 'Future research challengers for incorporation of uncertainty in environmental and ecological decision-making', *Ecological Modelling* 219 (3-4), 383-399.

Auricht H, Clarke K and Waycott M (2019) *Investigation of the application of remote sensing to estimate coverage of surface exposed (floating) filamentous algae in the Coorong, South Australia*, Goyder Institute for Water Research Technical Report Series No. 19/34.

Australian and New Zealand Environment and Conservation Council (2000) *Australian and New Zealand guidelines for fresh and marine water quality, volume 1, the guidelines, chapters 1–7*, ANZECC.

Bharardwaj N (2018) Strategic decision making an in information-rich environment: A synthesis and an organising framework for innovation research, *Innovation and Strategy (Review of Marketing Research, Vol. 15)*, Emerald Publishing Limited, Bingley, pp. 3-30.

Bice C and Zampatti B (2017) 'Crossing the threshold. Attention to diadromous fish', *RIPRAP* 40, 46–47.

Bice CM, Furst D, Lamontagne S, Oliver R, Zampatti BP and Revill A (2016) *The influence of freshwater discharge on productivity, microbiota community structure and trophic dynamics in the Murray estuary: evidence of freshwater derived trophic subsidy in the sandy sprat*, Goyder Institute for Water Research Technical Report Series No. 15/40, Adelaide, South Australia.

Bice CM, Schmarr DW, Zampatti BP and Fredberg J (2021) *Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes in 2020/21*, SARDI (Aquatic Sciences), SARDI Publications No. F2011/000186-11. Research Report Series No. 1177.

Bice CM, Wedderburn SD, Hammer MP, Ye Q and Zampatti BP (2018a) 'Fishes of the Lower Lakes and Coorong: A summary of life-history, population dynamics and management', in Mosley L, Ye Q, Shepherd S, Hemming S, Fitzpatrick R (eds), *Natural History of the Coorong, Lower Lakes, and Murray Mouth Region (Yarluwar-Ruwe)*, Royal Society of South Australia.

Bice CM, Zampatti BP, Morrongiello JR (2018b) 'Connectivity, migration and recruitment in a catadromous fish', *Marine and Freshwater Research* 69, 1733–1745.

Bino G, Brandis K, Kingsford R, Porter J (2020) 'Waterbird synchrony across Australia's highly variable dryland rivers – Risks and opportunities for conservation', *Biological Conservation* 243, 1-13.

Boyer JN, Kelbe CR, Ortner PB and Rudnik DT (2008) 'Phytoplankton bloom status: Chlorophyll a biomass as an indicator of water quality condition in the southern estuaries of Florida, USA', *Ecological indicators* 9(6) supplement, s56–67.

Collazo JA, O'Harra DA and Kellu CA (2002) 'Accessible habitat for shorebirds: Factors influencing its availability and conservation implications', *Waterbirds 25 (Special Publication 2),* 13–24.

Collier C, van Dijk K, Erftemeijer P, Foster N, Hipsey M, O'Loughlin E, Ticli K and Waycott M (2017) *Optimising Coorong Ruppia habitat, Strategies to improve habitat conditions for Ruppia tuberosa in the Coorong (South Australia) based on literature review, manipulative experiments and predictive modelling*, University of Adelaide, DEWNR, University of Western Australian and DAMCO Consulting.

Curtin R and Prellezo R (2011) 'Understanding marine ecosystem based management: A literature review', *Marine Policy* 34(5), 821–830.

Delroy LB (1975) 'The food of waterfowl (Anatidae) in the southern Coorong salt water habitat of South Australia', *South Australian Ornithologist*, 26, 157–163.

DENR (2010) *Breeding Australian pelican, Pelecanus conspicillatus, in the Coorong National Park, South Australia 2009–2010*, DENR.

DEW (2019) *South East Flows Restoration Project Operations Manual*, South Australian Government, Department for Environment and Water, Adelaide, South Australia.

DEW (2020a) *South Australian River Murray Basin Plan Environmental Outcome Evaluation: Coorong, Lower Lakes and Murray Mouth (CLLMM) Priority Environmental Asset*, DEW Technical report 2020/18, Government of South Australia, Department for Environment and Water, Adelaide.

DEW (2020b) *Summary of Coorong hydrological, biogeochemical and ecological models*, DEW Technical report 2020/39, Government of South Australia, Department for Environment and Water, Adelaide.

DEW (2021) *State of the Southern Coorong – discussion paper, building a shared understanding of current scientific knowledge, June 2021*, Department for Environment and Water, Government of South Australia.

DEW (in prep.) *Ecological Character Description 2015 Coorong and Lakes Alexandrina and Albert Wetland Ramsar site,* Department for Environment and Water, South Australia.

DEW (in prep.) *The Coorong and Lakes Alexandrina and Albert Wetland Ramsar Site Management Plan,* Department for Environment and Water, South Australia.

Dittmann S (2015) *Macroinvertebrate monitoring, analysis and synthesis for Coorong and Murray Mouth locations. Progress report and preliminary response to "Condition of the RAMSAR site since listing" July 2015,* Interim Report for the Department of Environment, Water and Natural Resources.

Dittmann S, Baring R, Baggalley S, Cantin A, Earl J, Gannon R, Keuning J, Mayo A, Navon N, Nelson M, Noble W and Ramsdale T (2015) 'Drought and flood effects on microbenthic communities in the estuary of Australia's largest river system', *Estuarine, Coastal and Shelf Science* 165, 36–61.

Dittmann S, Kent J and Lam-Gordillo O (2021) *Benthic macroinvertebrate survey 2020-2021 report. Coorong, Lower Lakes and Murray Mouth Icon Site*, Report for the Department for Environment and Water and the Murray-Darling Basin Authority, Flinders University, Adelaide.

Dittmann S, Rolston A and Baring R (2018) 'Estuarine and lagoon macro-invertebrates – patterns and processes', in Mosley L, Ye Q, Shepherd S, Hemming S, Fitzpatrick R (eds), *Natural History of the Coorong, Lower Lakes, and Murray Mouth Region (Yarluwar-Ruwe), Royal Society of South Australia*, 332–348.

Doherty J (2015) *Calibration and Uncertainty Analysis for Complex Environmental Models*, Brisbane, Australia, Watermark Numerical Computing.

Earl J, Fowler A, Ye Q and Dittmann S (2017) 'Complex movement patterns of greenback flounder (*Rhombosolea tapirina*) in the Murray River estuary and Coorong, Australia,' *Journal of Sea Research*, 122:1–10.

Espinosa-Romero MJ, Chan KMA, McDaniels T, Dalmer DM (2011) 'Structuring decision-making for ecosystem-based management', *Marine Policy* 575–583.

Ferguson GJ, Ward TM and Geddes MC (2008) ‘Do recent age structure and historical catches of mulloway, *Argyrosomus japonicus* (Sciaenidae), reflect freshwater inflows in the remnant estuary of the Murray River, South Australia?’, *Aquatic Living Resources* 21, 145–152.

Geary WL, Bode M, Doherty TS, Fulton EA, Nimmo DG, Tulloch AIT, Tulloch VJD and Ritchie EG (2020) ‘A guide to ecosystem models and their environmental applications’, *Nature Ecology and Evolution* 4, 1459–1471.

Gerwing TG, Cox K, Gerwing AMA, Carr-Harris CN, Dudas SE and Juanes F (2018) ‘Depth to the apparent redox potential discontinuity (aRPD) as a parameter of interest in marine benthic habitat quality models’, *International Journal of Sediment Research* 33(2), 149–156.

Giatas G and Ye Q (2016) *Conceptual food-web models for the Coorong: A focus on fishes and the influence of freshwater inflows*, SARDI (Aquatic Sciences), SARDI Publication No. F2016/000124-1, Research Report Series No. 892.

Giatas G, Catalano S, Dittmann S, Ye Q, Jackson M, Mott R and Markos K (2022) *Primary food resources for key waterbirds and benthic fish in the Coorong*, Goyder Institute for Water Research Technical Report Series No. 22/02.

Giatas GC and Ye Q (2015) *Diet and trophic characteristics of mulloway (Argyrosomus japonicus), congolli (Pseudaphritis urvillii) and Australian salmon (Arripis truttaceus and A. trutta) in the Coorong*, SARDI (Aquatic Sciences), SARDI Publications No. F2015/000479-1. Research Report Series No. 858, SARDI Publication No., SARDI Aquatic Sciences, Adelaide.

Gibbs M (2018) ‘Hydrology and hydrodynamics of the Lower Lakes, Coorong and Murray Mouth’, in Mosley L, Ye Q, Shepherd S, Hemming S, Fitzpatrick R (eds), *Natural History of the Coorong, Lower Lakes, and Murray Mouth Region (Yarluwar-Ruwe)*, Royal Society of South Australia.

Gillanders BM, Elsdon TS, Halliday IA, Jenkins GP, Robins JB and Valesini FJ (2011) ‘Potential effects of climate change on Australian estuaries and fish utilising estuaries: a review’, *Marine and Freshwater Research* 62, 1115–1131.

Green L, Blumstein DT, Fong P (2015) ‘Macroalgal mats in a eutrophic estuary obscure visual foraging cues and increase variability in prey availability for some shorebirds’, *Estuaries and Coasts* 38, 917–926.

Hallett CS, Valesini FJ, Kilminster K, Wells NS and Eyre BE (2019) ‘A rapid protocol for assessing sediment condition in eutrophic estuaries’, *Environmental Science Processes and Impacts* 21, 1021–1037.

Hart P and Purser G (1995) ‘Effects of salinity and temperature on eggs and yolk sac larvae of greenback flounder *(Rhombosolea tapirina* Günther, 1862)’, *Aquaculture* 136, 221-230.

Hassell KL, Coutin PC and Nugegoda D (2008) ‘Hypoxia impairs embryo development and survival in black bream (*Acanthopagrus butcheri*)’, *Marine Pollution Bulletin* 57(6–12), 302–306.

Hipsey H, Huang P, Busch B, Paraska D, Zhai S, Sims C and Gibbs M (2021) Coorong Dynamics Model manual. Aquatic Ecodynamics, The University of Western Australia. Available at: https://aquaticecodynamics.github.io/CDM/cdm-habitat-modelling.html

Hipsey MR, Huang P, Paraska D, Busch BD and Zhai S (2022) *The Coorong Dynamics Model: Resolving nutrient cycling and habitat dynamics in the Coorong Lagoon, South Australia*, Progress Report, University of Western Australia.

Hipsey MR, Busch BD, Huang P, Gibbs M (2020b) *Coorong Dynamics Model sensitivity tests and gap identification*, Goyder Institute for Water Research Technical Report Series No. 19/35.

Hipsey MR, Gal G, Arhonditsis GB, Carey CC, Elliott JA, Frassl MA, Janse JH, de Mora L, Robson BJ (2020a) ‘A system of metrics for assessment and improvement of aquatic ecosystem models’, *Environmental Modelling and Software* 128, 104697.

Holmer M and Nielsen R (2007) 'Effects of filamentous algal mats on sulfide invasion in eelgrass (*Zostera marina*)' *Journal of Experimental Marine Biology and Ecology* 353(2), 245–252.

Hossain M, Ye Q, Leterme S and Qin J (2016) 'Spatial and temporal changes of three prey-fish assemblage structure in a hypersaline lagoon: the Coorong, South Australia', *Marine and Freshwater Research* 68(2):282–292.

Huang P, De Sousa ER, Wells NS, Eyre BD, Gibbes B and Hipsey MR (2022) 'A modelling approach for addressing sensitivity and uncertainty of estuarine greenhouse gas (CO_2 and CH_4) dynamics', *Journal of Geophysical Research: Biogeosciences* 127, e2021JG006722.

Isola CR, Colwell MA, Taft OW and Safran RJ (2000) 'Interspecific differences in habitat use of shorebirds and waterfowl foraging in managed wetlands of California's San Joaquin Valley', *Waterbirds* 23(2), 196–208.

Jackson EK, Roberts W, Nelsen B, Williams GP, Nelson EJ and Ames EJ (2019) 'Introductory overview: Error metrics for hydrologic modelling – A review of common practices and open source library to facilitate use and adoption', *Environmental Modelling and Software* 119, 32-48.

Jackson MV, Mott R, Prowse TAA, Delean S, Shu Y, Brookes J and Cassey P (2022) *Recommended habitat quality measures for key waterbird species in the Coorong*, Goyder Institute for Water Research Technical Report Series No. 21/05.

Kanaya G, Nakamura Y and Koizumi T (2018) 'Ecological thresholds of hypoxia and sedimentary H_2S in coastal soft-bottom habitats: A macroinvertebrate-based assessment', *Marine Environmental Research* 136, 27–37.

Kavetski D, Qin Y and Kuczera G (2018) 'The fast and the robust: trade-offs between optimization robustness and cost in the calibration of environmental models', *Water Resources Research* 54(11), 9432–9455.

Kim D, Aldridge KT, Ganf GG and Brookes JD (2015) '*Physiochemical influences on Ruppia tuberosa abundance and distribution mediated through life cycle stages*', Inland Waters 5(4), 451–460.

Kingsford RT, Walker KF, Lester RE, Young WJ, Fairweather PG, Sammut J and Geddes MC (2010) 'A Ramsar wetland in crisis – the Coorong, Lower Lakes and Murray Mouth, Australia', *Marine and Freshwater Research* 62(3), 255–265.

Kokkinn M (1986) *A control strategy for 'Tanytarsus barbitarsis' Freemann (Diptera, Chironomidae), a small-scale pest organism / M. J. Kokkinn,* PhD thesis, Department of Zoology, University of Adelaide.

Lam-Gordillo O, Huang J, Barcelo A, Keny J, Mosley LM, Welsh DT, Simpson SL and Dittmann S (2022b) 'Restoration of benthic macrofauna promotes biogeochemical remediation of hostile sediments; An in situ transplantation experiment in a eutrophic estuarine-hypersaline lagoon system', *Science of the Total Environment* 833, 155201.

Lam-Gordillo O, Mosley LM, Simpson SL, Welsh DT and Dittmann S (2022a) 'Loss of benthic macrofauna functional traits correlates with changes in sediment biogeochemistry along an extreme salinity gradient in the Coorong lagoon, Australia', *Marine Pollution Bulletin* 174, 113202.

Lester R, Fairweather P, Heneker T, Higham J and Muller K (2011) *Specifying an environmental water requirement for the Coorong and Lakes Alexandrina and Albert: A first iteration*, Department for Environment and Natural Resources, South Australia.

Levin PS, Fogarty MJ, Murawski SA, Fluharty D (2009) 'Integrated ecosystem assessments: Developing the scientific basis for ecosystem-based management of the ocean', *PLoS Biol* 7(1): e1000014.

Lewis R, Waycott M, O'Loughlin EJ, Urgl C, van Dijk KJ, Calladine A and Nicol J (2022) *Distribution and seasonality of the Ruppia dominated aquatic macrophyte community and filamentous algae in the southern Coorong*, Goyder Institute for Water Research Technical Report Series No. 21/xx.

Lui LC (1969) 'Salinity tolerance and osmoregulation of *Taeniomembers microstomus* (Gunther, 1861) (Pisces: Mugiliformes: Atherinidae) from Australian salt lakes', *Australian Journal of Marine and Freshwater Research* 20(2) 157–162.

McNeil D, Westergaard S, Cheshire K, Noell C and Ye Q (2013) *Effects of hyper-saline conditions upon six estuarine fish from the Coorong and Murray Mouth*, SARDI (Aquatic Sciences), SARDI Publication No. F2009/000014-4, Research Report Series No. 700.

Messer JJ, Linthurst RA and Overton SW (1991) 'An EPA program for monitoring ecological status and trends', *Environmental Monitoring and Assessment* 17, 67-78.

Molsher R, Geddes M and Paton D (1994) 'Population and reproductive ecology of the small-mouthed hardyhead, *Antherinosoma microstoma* (Gunther) (Pisces: Atherinidae) along a salinity gradient in the Coorong, South Australia', *Transactions of the Royal Society of South Australia* 118(4), 207–216.

Monaco ME, Spooner E, Oakes SA, Harvey CJ and Kelble CR (2021) 'Introduction to the NOAA integrated ecosystem assessment program: advancing ecosystem based management', *Coastal Management* 49(1), 1-8.

Montenero J, Kelbe C and Broughton K (2021) 'A quantitative and qualitative decision-making process for selecting indicators to track ecosystem condition', *Marine Policy* 129, 104489.

Mosley LM, Hamilton B, Busch B, Hipsey M and Taylor B (2017) *Assessment and modelling of the effects of the 2013-2016 Morella Basin releases on Coorong water quality*, Report to the Department of Environment, Water and Natural Resources (DEWNR), University of Adelaide, South Australia.

Mosley LM, Brookes J, Dittmann S, Huang L, Lam-Gordillo O, Priestly S, Simpson S, Welsh D, and Waycott M (2022) *Coorong nutrient removal options,* Goyder Institute for Water Research Technical Report Series No. 21/xx.

Mosley LM, Priestley S, Brookes J, Dittmann S, Farkaš J, Farrell M, Ferguson AJ, Gibbs M, Hipsey M, Huang J, Lam-Gordillo O, Simpson SL, Teasdale PR, Tyler JJ, Waycott M and Welsh DT (2020) *Coorong water quality synthesis with a focus on the drivers of eutrophication*, Goyder Institute for Water Research Technical Report Series No. 20/10.

Mott R, Jackson M, Sanchez-Gomez S, Hunt B, Prowse T, Brookes J and Cassey P (2022*) Spatial and temporal habitat use by key waterbird species in the Coorong*, Goyder Institute for Water Research Technical Report Series No. 21/xx.

Noell C, Ye Q, Short D, Bucater L and Wellman N (2009) *Fish assemblages of the Murray Mouth and Coorong region, South Australia, during an extended drought period*, CSIRO: Water for a Health Country National Research Flagship, Canberra.

Norazlimi NA and Ramli R (2015) 'The relationships between morphological characteristics and foraging behaviour in four selected species of shorebirds and water birds utilising tropical mudflats', *The Scientific World Journal* 105296.

O'Connor J, Mallen-Cooper M and Stuart I (2015b) *Performance, operation and maintenance guidelines for fishways and fish passage works,* Arthur Rylah Institute for Environmental Research Technical Report No. 262 for the Water and Catchments Group, Department of Environment, Land, Water and Planning. Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

O'Connor J, Rogers D, Pisanu P (2013) *Modelling waterbird responses to ecological conditions in the Coorong, Lower Lakes, and Murray Mouth Ramsar site*, South Australian Department for Environment, Water and Natural Resources, Adelaide.

O'Connor J, Steggles T and Higham J (2015a) *Ecological objectives, targets and environmental water requirements for the Coorong, Lower Lakes and Murray Mouth*, DEWNR Technical Report 2015/45. Department of Environment, Water and Natural Resources, South Australia.

Oerman G (2021) *Elevation distribution of Ruppia tuberosa and Althenia cylindrocarpa in the southern Coorong,* Department for Environment and Water, Government of South Australia.

Partridge G and Jenkins G (2002) 'The effect of salinity on growth and survival of juvenile black bream (*Acanthopagrus butcheri*)', *Aquaculture* 210(1), 219–230.

Paton D (2010) *At the End of the River. The Coorong and Lower Lakes*, ATF Press, Hindmarsh.

Paton DC and Bailey CP (2012) *Condition monitoring of the Lower Lakes, Coorong and Murray Mouth icon site: waterbirds using the Coorong and Murray estuary in 2012*, University of Adelaide, Adelaide.

Paton DC, Paton FL and Bailey CP (2017) *Condition monitoring of the Coorong, Lower Lakes and Murray Mouth Icon Site: Waterbirds in the Coorong and Lower Lakes 2017*, University of Adelaide, Adelaide.

Paton DC, Rogers DJ, Hill BM, Bailey CP and Ziembicki M (2009) 'Temporal changes to spatially stratified waterbird communities of the Coorong, South Australia: implications for the management of heterogeneous wetlands', *Animal Conservation* 12, 408–417.

Pedersen O, Binzer T and Borum J (2004) 'Sulphide intrusion in eelgrass (*Zostera marina* L.)', *Plant, Cell and Environment* 27, 595–602.

Peters M (2018) *The influence of algal cover on two key biota of the southern Coorong: shorebirds and the chironomid Tanytarsus barbitarsis*, Honours thesis, University of Adelaide, Adelaide.

Polasky S, Carpenter SR, Folke C and Keeler B (2011) 'Decision-making under great uncertainty: environmental management in an era of global change', *Trends in Ecology and Evolution* 26(8), 398–404.

Priestly SC, Tyler J, Liebelt SR, Mosley LM, Wong WW, Shao Y, Woolston Z, Farrell M, Welsh DT, Brookes JD, Collins AS, Keneally C and Farkas J (2022) 'N and C isotope variations along an extreme eutrophication and salinity gradient in the Coorong lagoon, South Australia', *Frontiers in Earth Science* 9:727971.

Prowse T, Delean S, Mott R, Jackson M, Hunt B, Brookes J and Cassey P (2022) *Response models for key waterbird species of the Coorong,* Goyder Institute for Water Research Technical Report Series No. 22/04.

Remalli TM, Simpson SL, Bennett WW, King JJ, Mosley LM, Welsh DT and Jolley DF (2018) 'Assisted natural recovery of hypersaline sediments: salinity thresholds for the establishment of a community of bioturbating organisms', *Environmental Science Processes and Impacts* 20, 1244–1253.

Rogers DJ and Paton DC (2009) *Spatiotemporal variation in the waterbirds communities of the Coorong*, CSIRO, Water for a Healthy Country National Research Flagship, Canberra.

Samhouri JF, Haupt AJ, Levin PS, Link JS and Shuford R (2014) 'Lessons learned from developing integrated ecosystem assessment to inform marine ecosystem-based management in the USA', *ICES Journal of Marine Science* 71(5), 1205–1215.

Sutula M, Green L, Cicchetti G, Detenbeck N and Fong P (2014) 'Thresholds of adverse effects of macroalgal abundance and sediment organic matter on benthic habitat quality in estuarine intertidal flats', *Estuaries and Coasts* 37, 1532–1548.

Telesh IV and Khlebovich VV (2010) 'Principal processes within the estuarine salinity gradient: A review', *Marine Pollution Bulletin* 64(4-6), 149–155.

Teodosio MA. Paris CB, Wolanski E and Morais P (2016) 'Biophysical processes leading to the ingress of temperate fish larvae into estuarine nursey areas: A review', *Estuarine, Coastal and Shelf Science* 183, 187–202.

Tweddle GP and Froneman PW (2017) 'Fish recruitment Fish recruitment into a South African temporarily open/closed temperate estuary during three different hydrological mouth phases', *African Journal of Marine Science* 39:2, 203-209.

Wasson K, Suarez B, Akhavan A, McCarthy E, Kildow J, Johnson KS, Fountain MC, Woolfolk A, Silberstein M, Pendleton L and Feliz D (2015) 'Lessons learned from an ecosystem-based management approach to restoration of a California estuary', *Marine Policy* 58, 60–70.

Webster IT (2010) 'The hydrodynamics and salinity regime of a coastal lagoon – The Coorong, Australia – Seasonal to multi-decadal timescales', *Estuarine, Coastal and Shelf Science* 90(4), 264–274.

Wedderburn S, Bailey C, Delean S and Paton D (2016) 'Population and osmoregulatory responses of a euryhaline fish to extreme salinity fluctuations in coastal lagoons of the Coorong, Australia', *Estuarine, Coastal and Shelf Science* 165(5):50–57.

Whitfield AK (1994) 'Abundance of larval and 0+ juvenile marine fishes in the lower reaches of three southern African estuaries with differing freshwater inputs', *Marine Ecology Progress Series* 105 257-267.

Williams GD, Andrews KS, Brown JA, Gove JM, Hazen EL, Leong KM, Montenero KA, Moss JH, Rosellon-Druker JM, Schroeder ID, Siddon E, Szymkowiak M, Whitehouse GA, Zador SG and Harvey CJ (2021) 'Place-based ecosystem management: adapting integrated ecosystem assessment processes for developing scientifically and socially relevant indicator portfolio', *Coastal Management* 49(1), 46–71.

Woodland RJ, Thompson JR, Mac Nally R, Eigh P, Evrard V, Wary FY, Walker JP and Cook PLM (2015) 'Nitrogen loads explain primary productivity in estuaries at the ecosystem scale', *Limnology and Oceanography* 60, 1751–1762.

Ye Q, Bice CM, Bucater L, Ferguson GJ, Giatas GC, Wedderburn SD and Zampatti BP (2016) *Fish monitoring synthesis: understanding responses to drought and high flows in the Coorong, Lower lakes and Murray Mouth*, South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2016/000348-1. SARDI Research Report Series No. 909. 39pp.

Ye Q, Bucater L and Short D (2011) *Condition fish condition monitoring 2008-2011: the black bream (Acanthopagrus butcheri), greenback flounder (Rhombosolea tapirina) and smallmouthed hardyhead (Atherinosoma microstoma) populations*, SARDI (Aquatic Sciences), SARDI Publication No. F2011/000471-1, SARDI Research Report Series No. 582.

Ye Q, Bucater L and Short D (2015) *Fish response to flows in the Murray estuary and Coorong during 2013/14*, South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2014/000786-1, SARDI Research Report Series No. 884. 91pp.

Ye Q, Bucater L, Lorenz Z, Giatas G and Short D (2019a) *Monitoring salt wedge conditions and black bream (Acanthopagrus butcheri) recruitment in the Coorong during 2017-18,* South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. 2018/000425-1. SARDI Research Report Series No. 1012. 42 pp.

Ye Q, Bucater L, Short D and Giatas G (2021) *Coorong fish condition monitoring 2008–2020: Black bream (Acanthopagrus butcheri), greenback flounder (Rhombosolea tapirinia) and smallmouth hardyhead (Atherinosoma microstoma) populations*, SARDI (Aquatic Sciences), SARDI Publications No. F2011/000471-8. Research Report Series No. 1091.

Ye Q, Cheshire KJ and McNeil DG (Eds) (2010) *Influences of salinity, water quality and hydrology on early life stages of fishes in the Lower River Murray, South Australia*, South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2009/000470-1-6. SARDI Research Report Series No. 446. 179 p.

Ye Q, Dittmann S, Giatas G, Baring R, Nitschke J, Bucater L and Furst D (2019b*) The current state of food resources supporting waterbird and fish populations in the Coorong*, Goyder Institute for Water Research Technical Report Series No. 19/33.

Ye Q, Giatas G, Dittmann S, Baring R, Bucater L, Deane D, Furst D, Brookes J, Rogers D and Goldsworthy S (2020) *A synthesis of current knowledge of the food web and food resources for waterbird and fish populations in the Coorong*, Goyder Institute for Water Research Technical Report Series No. 20/11.

Zampatti BP, Bice CM and Jennings PR (2010) 'Temporal variability in fish assemblage structure and recruitment in freshwater-deprived estuary: The Coorong, Australia', *Marine and Freshwater Research* 61, 1298–1312.

13 Glossary

Allochthonous	Organic matter, nutrients and biota derived from upstream that are transported to the Murray estuary and Coorong.
Anoxic sediment	Sediment that is poorly oxygenated due to the depletion of oxygen by bacteria when decomposing organic matter, and which leads to unhealthy biogeochemical cycling.
Area of occupation	Area within a taxon's extent of occurrence that is occupied.
Australian Height Datum (AHD)	The vertical height of 0.0 m (sea level) in Australia as defined by taking the mean sea level of 30 tide gauges around the Australian coastline from 1966 to 1968.
Benthic macroinvertebrates	Bottom dwelling aquatic animals without a backbone that can be seen without magnification, such as worms, insects and bivalves.
Coorong Dynamics Model (CDM)	An ecosystem model of the Coorong that simulates hydrodynamic and sediment conditions, water clarity, nutrients, chlorophyll-a, macroalgae, and *Ruppia* and estuarine fish habitat suitability in the Coorong at high spatial and temporal resolution.
Decision-making framework	An evidence based document that summarises science in a manner that supports environmental managers to make management decisions.
Diadromous fish	A fish that travels between salt water and fresh water as part of its life cycle
Dissolved oxygen (DO)	Oxygen present within the water of the waterbody that influences its habitability for aquatic fauna.
Ecological Character Description (ECD)	A report that identifies and describes the critical components, processes and services (CPS) that determine the ecological character of the Ramsar site.
Ecosystem based management (EBM)	An approach to management that considers the interconnectivity of ecosystem components and highlights the importance of processes that provide services to humans and the environment.
Ecosystem components	The physical, chemical and biological parts of a wetland (from large scale to very small scale, for example habitat, species and genes).
Ecosystem components, processes and services (CPS)	Criteria (see *Ecosystem components, Ecosystem processes and Ecosystem Services*) that determine the ecological character of the Ramsar site.
Ecosystem processes	The changes or reactions which occur naturally within wetland systems. They may be physical, chemical or biological. They include all those processes that occur between organisms and within and between populations and communities, including interactions with the non-living environment that result in existing ecosystems and bring about changes in ecosystems over time.
Ecosystem services	The benefits that people receive or obtain from an ecosystem. The components of ecosystem services are provisioning (for example, food and water), regulating (for example, flood control), cultural (for example, spiritual, recreational) and supporting (for example, nutrient cycling, ecological value).

Extent of occurrence	Area contained within the shortest continuous boundary surrounding all known occurrences the taxon.
Habitat suitability	Capacity of a given habitat to support a selected taxon.
Healthy Coorong, Healthy Basin (HCHB) program	A program jointly funded by the Australian and South Australian governments aimed at improving the long-term management of the Coorong via on-ground works, management tools, research and trials and investigations.
Indicator	Biological, chemical or physical factors that either influence or are proxies for critical CPS and threat status.
Integrated Ecosystem Assessment (IEA)	An approach to ecosystem based management that aims to summarise and analyse science in a manner that allows for environmental managers to balance trade-offs and determine what management action is most likely to meet the ecosystems fundamental social and ecological objectives.
Macroalgae	Marine and multi-cellular algae that are visual with the naked eye.
Management Trigger	A pre-defined condition or value used to identify decision points to initiate a management response.
Murray estuary	The body of water below the Lakes barrages, which runs from the Goolwa Barrage to Pelican Point.
Murray Mouth	The point of connection between the River Murray and the ocean.
North Lagoon	The extent of the Coorong waterbody that runs from Pelican Point to Parnka Point.
Oxygen Penetration Depth (OPD)	The depth of oxygen penetration in to a sediment profile, which has implications for biogeochemical cycling and habitat suitability for benthic macroinvertebrates and aquatic plants.
Pelagic productivity pathway	Energy (phytoplankton) within the water column provided to the Coorong food-web.
Piscivore (waterbird)	A group of waterbirds that primarily feed upon fish.
Ramsar Management Plan (RMP)	A management plan that clearly specifies intended objectives for the Ramsar site, including clearly defined responsibilities, timelines, and milestones for accomplishing project tasks and management actions to maintain the ecological character of the Ramsar site.
Ramsar site	Refers to the Coorong and Lakes Alexandrina and Albert Wetland Ramsar site.
Reference point	Quantitative measures of an indicator that are used to consistently document the anticipated responses of critical CPS and threats.
Resource Condition Target	A typical and contemporary (21st century) state for the Ramsar site's critical CPS that takes into account variation under the current management.
***Ruppia* habitat suitability index (HSI)**	A model that predicts habitat suitability at a fine spatial resolution based upon quantified unsuitable, suitable and optimal salinity, temperature, light, water depth and algal conditions across life stages and the life cycle of *Ruppia tuberosa*.

***Ruppia tuberosa* (Ruppia)**	An aquatic plant that is the dominant species in the Coorong South Lagoon and an important habitat and food resource for fish and waterbirds.
Shorebird	A group of waterbirds with long legs and bills relative to their body size, which forage in shallow water habitats.
South Lagoon	The extent of the Ramsar site that runs from near Parnka Point to 42 Mile Crossing.
Standardised model output	Visual presentations (time series, rasters etc.) of data intended to support annual water planning by supplementing and provide greater granularity (temporal or spatial) to the tabular results of the decision-making framework.
Submergent halophyte	A salt-tolerant aquatic plants that has most of its structure below the water's surface.
Total Chlorophyll-a (T Chl-a)	The form of cholorphyll used in oxygenated photosynthesis, which is a proxy for phytoplankton biomass, and serves are an index for productivity and trophic condition.
Total Nitrogen (TN)	Total Nitrogen represents that maximum potential amount of bioavailable N, which is available for uptake and assimilation by phytoplankton, macroalgae and aquatic plants.
Total Phosphorus (TP)	Total Phosphorus represents that maximum potential amount of bioavailable P, which is available for uptake and assimilation by phytoplankton, macroalgae and aquatic plants.
Trials and Investigations (T&I) project	A scientific project working to fill critical knowledge gaps and provide the evidence-base to inform management actions to improve the long-term health of the Coorong.
US National Oceanic Atmospheric Administration (NOAA)	An American scientific and regulatory agency that is tasked with managing coastal and marine environments.
Validation statistics	Statistics that represent the goodness-of-fit and error between observed and modelled data.
Waterfowl	Waterbirds belonging to the order Anseriformes that includes ducks, geese and swans. Most species have webbed feet.

14 Appendices

A. Abiotic tabular decision-making framework. Metadata of the framework is described in Table 8.1.

Critical CPS	Indicator	Reference point	Time	Space	Measure	Benefit/risk
Surface water regime	Flow (River Murray barrages)	N/A - continuous	Year-round	System-wide	Total barrage release volume (GL)	Benefit
Surface water regime	Flow (River Murray barrages)	650 GL/year (RCT/MT)	Year-round	System-wide	Δ from 650 GL/year	Benefit = positive/Risk = negative
Surface water regime	Flow (River Murray barrages)	2,000 GL (RCT, rolling 3-year average)	Year-round	System-wide	Δ from 2000 GL/year rolling annual average	Benefit = positive/Risk = negative
Surface water regime	Flow (River Murray barrages)	6,000 (RCT, 1 in 3 years)	Year-round	System-wide	Δ from 6,000 GL/year	Benefit = positive/Risk = negative
Surface water regime	Flow (River Murray barrages)	10,000 (RCT, 1 in 7 years)	Year-round	System-wide	Δ from 10,000 GL/year	Benefit = positive/Risk = negative
Surface water regime	Flow (Salt Creek)	NA - Continuous	Year-round	CSL	Total flow from Salt Creek (GL)	Benefit
Surface water regime	Water level	+0.3 m AHD (RCT)	June-Aug	CSL	% of days CSL lagoon-averaged mean-daily water levels (via CSL stations A4260633, A4261209 and A4261165) are ≥+0.3 m AHD	Benefit
Surface water regime	Water level	+0.3 m AHD (RCT)	June-Aug	CSL	Maximum duration (days) of CSL lagoon-averaged	Risk

Critical CPS	Indicator	Reference point	Time	Space	Measure	Benefit/risk
					mean-daily water levels (via CSL stations A4260633, A4261209 and A4261165) are <+0.3 m AHD	
Surface water regime	Water level	+0.2 m AHD (MT)	June-Aug	CSL	% of CSL lagoon-averaged mean-daily water levels (via CSL stations A4260633, A4261209 and A4261165) are <+0.2 m AHD	Risk
Surface water regime	Water level	+0.2 m AHD (lower bound of RCT)	Sep-Dec	CSL	% of days CSL lagoon-averaged mean-daily water levels (via CSL stations A4260633, A4261209 and A4261165) are ≥+0.2 m AHD	Benefit
Surface water regime	Water level	+0.15 m AHD (MT)	Sep-Dec	CSL	% CSL lagoon-averaged mean-daily water levels (via CSL stations A4260633, A4261209 and A4261165) are <+0.15 m AHD	Risk
Surface water regime	Salinity	35 g/L (RCT/MT)	Year-round	ME	% of months that the mean monthly estuary-averaged	Benefit

Critical CPS	Indicator	Reference point	Time	Space	Measure	Benefit/risk
					salinity (via stations A4261036 A4261039, A4261128, A4261043) is <35 g/L	
Surface water regime	Salinity	45 g/L (RCT/MT)	Year-round	CNL	% of months that the mean monthly lagoon-averaged salinity (via A4261134, A4261135 and A4260572) is <45 g/L	Benefit
Surface water regime	Salinity	60 g/L (RCT/MT)	June-Aug	CSL	% of months that the mean monthly lagoon-averaged salinity (via A4261134, A4261135 and A4260572) is <60 g/L	Benefit
Surface water regime	Salinity	60 g/L	Year-round	System-wide	Mean daily longitudinal extent of the Coorong (Km) below 60 g/L	Benefit
Surface water regime	Salinity	100 g/L (RCT)	Year-round	CSL	% of days that the mean daily Lagoon average salinity (via A4261134, A4261135 and A4260572) is <100 g/L	Benefit

Critical CPS	Indicator	Reference point	Time	Space	Measure	Benefit/risk
Surface water regime	Salinity	100 g/L (MT)	Year-round	CSL	% of months that the mean monthly lagoon-averaged salinity (via A4261134, A4261135 and A4260572) is >100 g/L	Risk
Trophic status (threat: eutrophication)	Total Nitrogen	Continuous – N/A	Apr-Sep	CNL	Balance (import – export) (g/kg) at 30 September (or simulation end date) from 1 April (or simulation start date).	Benefit = positive/Risk = negative
Trophic status (threat: eutrophication)	Total Nitrogen	Continuous – N/A	Apr-Sep	CSL	Balance (import – export) (g/kg) at 30 September (or simulation end date) from 1 April (or simulation start date).	Benefit = positive/Risk = negative
Trophic status (threat: eutrophication)	Total Nitrogen	Continuous – N/A	Oct-Mar	CNL	Balance (import – export) (g/kg) at 31 March (or simulation end date) from 1 October (or simulation start date).	Benefit = positive/Risk = negative
Trophic status (threat: eutrophication)	Total Nitrogen	Continuous – N/A	Oct-Mar	CSL	Balance (import – export) (g/kg) at 31 March (or	Benefit = positive/Risk = negative

Critical CPS	Indicator	Reference point	Time	Space	Measure	Benefit/risk
					simulation end date) from 1 October (or simulation start date).	
Trophic status (threat: eutrophication)	Total Phosphorus	Continuous – N/A	Apr-Sep	CNL	Balance (import – export) (g/kg) at 30 September (or simulation end date) from 1 April (or simulation start date).	Benefit = positive/Risk = negative
Trophic status (threat: eutrophication)	Total Phosphorus	Continuous – N/A	Apr-Sep	CSL	Balance (import – export) (g/kg) at 30 September (or simulation end date) from 1 April (or simulation start date).	Benefit = positive/Risk = negative
Trophic status (threat: eutrophication)	Total Phosphorus	Continuous – N/A	Oct-Mar	CNL	Balance (import – export) (g/kg) at 31 March (or simulation end date) from 1 October (or simulation start date).	Benefit = positive/Risk = negative
Trophic status (threat: eutrophication)	Total Phosphorus	Continuous – N/A	Oct-Mar	CSL	Balance (import – export) (g/kg) at 31 March (or simulation end date) from 1 October (or	Benefit = positive/Risk = negative

Critical CPS	Indicator	Reference point	Time	Space	Measure	Benefit/risk
					simulation start date).	
Trophic status (threat: eutrophication)	Total Chlorophyll-a	5 µg/L	Apr-Sep	CNL	Average daily Δ from the mean daily lagoon-averaged T Chl-a concentration	Benefit = positive/Risk = negative
Trophic status (threat: eutrophication)	T Chl-a	5 µg/L	Oct-Mar	CNL	Average daily Δ from the mean daily lagoon-averaged T Chl-a concentration	Benefit = positive/Risk = negative
Trophic status (threat: eutrophication)	T Chl-a	10 µg/L	Oct-Mar	CSL	Average daily Δ from the mean daily lagoon-averaged T Chl-a concentration	Benefit = positive/Risk = negative
Trophic status (threat: eutrophication)	T Chl-a	10 µg/L	Apr-Sep	CSL	Average daily Δ from the mean daily lagoon-averaged T Chl-a concentration	Benefit = positive/Risk = negative
Trophic status (threat: eutrophication)	Dissolved oxygen	6.5 mg/L	Apr-Sep	ME, CNL	Average daily area (HA) that minimum DO is ≥6.5 mg/L	Benefit
Trophic status (threat: eutrophication)	Dissolved oxygen	6.5 mg/L	Oct-Mar	ME, CNL	Average daily area (HA) that minimum DO is ≥6.5 mg/L	Benefit
Trophic status (threat: eutrophication)	Dissolved oxygen	4 mg/L	Apr-Sep	CSL	Average daily area (HA) that minimum DO is ≥4 mg/L	Benefit

Critical CPS	Indicator	Reference point	Time	Space	Measure	Benefit/risk
Trophic status (threat: eutrophication)	Dissolved oxygen	4 mg/L	Oct-Mar	CSL	Average daily area (HA) that minimum DO is ≥4 mg/L	Benefit
Trophic status (threat: eutrophication)	Oxygen penetration depth	3 cm	Apr-Sep	ME, CNL	Average daily area (Km^2) where OPD is ≥3 cm using shallow sediment zones	Benefit
Trophic status (threat: eutrophication)	Oxygen penetration depth	3 cm	Apr-Sep	CSL	Average daily area (Km^2) where OPD is ≥3 cm using shallow sediment zones	Benefit
Trophic status (threat: eutrophication)	Oxygen penetration depth	3 cm	Oct-Mar	ME, CNL	Average daily area (Km^2) where OPD is ≥3 cm using shallow sediment zones	Benefit
Trophic status (threat: eutrophication)	Oxygen penetration depth	3 cm	Oct-Mar	CSL	Average daily area (Km^2) where OPD is ≥3 cm using shallow sediment zones	Benefit

B. Biotic decision-making framework. Metadata of the framework is described in Table 8.1.

Critical CPS	Indicator	Importance	Reference point	Time	Space	Measure	Benefit/risk
Ruppia	Life stage: turion viability	N/A	N/A - continuous	Jan-Mar	CNL	HSI × Area	Benefit
Ruppia	Life stage: turion viability	N/A	N/A - continuous	Jan-Mar	CSL	HSI × Area	Benefit

Critical CPS	Indicator	Importance	Reference point	Time	Space	Measure	Benefit/risk
Ruppia	Life stage: seed germination	N/A	N/A - continuous	Apr-July	CNL	HSI × Area	Benefit
Ruppia	Life stage: seed germination	N/A	N/A - continuous	Apr-July	CSL	HSI × Area	Benefit
Ruppia	Life stage: Turion sprouting	N/A	N/A - continuous	Apr-July	CNL	HSI × Area	Benefit
Ruppia	Life stage: Turion sprouting	N/A	N/A - continuous	Apr-July	CSL	HSI × Area	Benefit
Ruppia	Life stage: Adult plant growth	N/A	N/A - continuous	June-Sept	CNL	HSI × Area	Benefit
Ruppia	Life stage: Adult plant growth	N/A	N/A - continuous	June-Sept	CSL	HSI × Area	Benefit
Ruppia	Life stage: Flowering	N/A	N/A - continuous	Aug-Dec	CNL	HSI × Area	Benefit
Ruppia	Life stage: Flowering	N/A	N/A - continuous	Aug-Dec	CSL	HSI × Area	Benefit
Ruppia	Life stage: Turion production	N/A	N/A - continuous	Aug-Dec	CNL	HSI × Area	Benefit
Ruppia	Life stage: Turion production	N/A	N/A - continuous	Aug-Dec	CSL	HSI × Area	Benefit
Ruppia	Life stage: Seedbank production	N/A	N/A - continuous	Aug-Dec	CNL	HSI × Area	Benefit

Critical CPS	Indicator	Importance	Reference point	Time	Space	Measure	Benefit/risk
Ruppia	Life stage: Seedbank production	N/A	N/A - continuous	Aug-Dec	CSL	HSI × Area	Benefit
Ruppia	Lifecycle	N/A	N/A - continuous	June-Dec	CSL	HSI × Area	Benefit
Ruppia	Lifecycle	N/A	N/A - continuous	June-Dec	CNL	HSI × Area	Benefit
Ruppia	Oxygen penetration depth (sediment)	Moderate	>3 cm	Apr-July	CNL & CSL	Average daily area (Km^2) where OPD is ≥3 cm using shallow sediment zones	Benefit
Ruppia	Oxygen penetration depth (sediment)	Moderate	>3 cm	June-Sept	CNL & CSL	Average daily area (Km^2) where OPD is ≥3 cm using shallow sediment zones	Benefit
Ruppia	Oxygen penetration depth (sediment)	Moderate	>3 cm	Aug-Dec	CNL & CSL	Average daily area (Km^2) where OPD is ≥3 cm using shallow sediment zones	Benefit
Macroinvertebrates	Water depth and salinity	High	Daily inundation and salinity <25 g/L	Apr-Sep	System-wide	Average daily area (Km^2) with water cover and <25 g/L	Benefit
Macroinvertebrates	Water depth and salinity	High	Daily inundation and salinity <25 g/L	Oct-Mar	System-wide	Average daily area (Km^2) with water cover and <25 g/L	Benefit

Critical CPS	Indicator	Importance	Reference point	Time	Space	Measure	Benefit/risk
Macroinvertebrates	Water depth and salinity	High	Daily inundation and salinity <50 g/L	Apr-Sep	System-wide	Average daily area (Km^2) with water cover and <50 g/L	Benefit
Macroinvertebrates	Water depth and salinity	High	Daily inundation and salinity <50 g/L	Oct-Mar	System-wide	Average daily area (Km^2) with water cover and <50 g/L	Benefit
Macroinvertebrates	Water depth and salinity	High	Daily inundation and salinity <105 g/L	Apr-Sep	System-wide	Average daily area (Km^2) with water cover and <105 g/L	Benefit
Macroinvertebrates	Water depth and salinity	High	Daily inundation and salinity <105 g/L	Oct-Mar	System-wide	Average daily area (Km^2) with water cover and <105 g/L	Benefit
Macroinvertebrates	Macroalgae	Moderate	Algae HSI 0.25	Apr-Sep	System-wide	Area (Km^2) of mean Algae HSI >0.25	Risk
Macroinvertebrates	Macroalgae	Moderate	Algae HSI 0.25	Oct-Mar	System-wide	Area (Km^2) of mean Algae HSI >0.25	Risk
Macroinvertebrates	Oxygen penetration depth (sediment)	Moderate	3 cm	Apr-Sep	System-wide	Average daily area (Km^2) where OPD is ≥3 cm using shallow sediment zones	Benefit
Macroinvertebrates	Oxygen penetration depth (sediment)	Moderate	3 cm	Oct-Mar	System-wide	Average daily area (Km^2) where OPD is ≥3 cm using shallow sediment zones	Benefit

Critical CPS	Indicator	Importance	Reference point	Time	Space	Measure	Benefit/risk
Fish diversity (species richness/biodisparity	Salinity	High	<30 g/L	Apr-Sep	ME	Mean daily longitudinal extent (km) below 30 g/L	Benefit
Fish diversity (species richness/biodisparity	Salinity	High	<30 g/L	Oct-Mar	ME	Mean daily longitudinal extent (km) below 30 g/L	Benefit
Fish diversity (species richness/biodisparity	Salinity	High	<60 g/L	Apr-Sep	System-wide	Mean daily longitudinal extent (km) below 60 g/L	Benefit
Fish diversity (species richness/biodisparity	Salinity	High	<60 g/L	Oct-Mar	System-wide	Mean daily longitudinal extent (km) below 60 g/L	Benefit
Fish diversity (species richness/biodisparity	Salinity	High	Average daily salinity across ME is ≥40 g/L for ≥2 months	Year-round	ME	No. of events that mean monthly estuary-averaged salinity (via stations A4261036, A4261039, A4261128, A4261043) is >40 g/L for ≥2 months	Risk
Fish diversity (species richness/biodisparity	Flow (River Murray discharge)	High	N/A	Year-round	Boundary condition	Average monthly River Murray (barrages) discharge (GL)	Benefit

Critical CPS	Indicator	Importance	Reference point	Time	Space	Measure	Benefit/risk
Fish diversity (species richness/biodisparity	Murray Mouth morphology	High	Murray Mouth ≥1 m deep	Year-round	ME	% of days where Murray Mouth depth is ≥ 1 m	Benefit
Smallmouth hardyhead (Foodweb)	Salinity	High	<100 g/L	Apr-Sep	System-wide	Mean daily longitudinal extent (km) below 100 g/L	Benefit
Smallmouth hardyhead (Foodweb)	Salinity	High	<100 g/L	Oct-Mar	System-wide	Mean daily longitudinal extent (km) below 100 g/L	Benefit
Smallmouth hardyhead (Foodweb)	Flow (River Murray discharge)	High	N/A - continuous	Sep-Mar	Boundary condition	Average monthly River Murray discharge (GL)	Benefit
Smallmouth hardyhead (Foodweb)	Water level	High	CSL, +0.3 m AHD	Apr-Sep	CSL	% of days when CSL average water level is >0.3 m AHD	Benefit
Smallmouth hardyhead (Foodweb)	Water level	High	CSL, +0.3 m AHD	Oct-Mar	CSL	% of days when CSL average water level is >0.3 m AHD	Benefit
Smallmouth hardyhead (Foodweb)	South East connectivity (fishway operation)	High	Salt Creek flow is >3 ML/day and CSL is >+0.4 m AHD or Salt Creek flow >2 ML/day and CSL is >+0.8 m AHD	Apr-Sep	CSL	% of days where Salt Creek flow is >3 ML/day and average CSL is >+0.4 m AHD or Salt Creek flow is >2 ML/day and average CSL is >+0.8 m AHD	Benefit

Critical CPS	Indicator	Importance	Reference point	Time	Space	Measure	Benefit/risk
Smallmouth hardyhead (Foodweb)	South East connectivity (fishway operation)	High	Salt Creek flow is >3 ML/day and CSL is >+0.4 m AHD or Salt Creek flow >2 ML/day and CSL is >+0.8 m AHD	Oct-Mar	CSL	% of days where Salt Creek flow is >3 ML/day and average CSL is >+0.4 m AHD or Salt Creek flow is >2 ML/day and average CSL is >+0.8 m AHD	Benefit
Fish movement and recruitment (congolli and common galaxias)	Flow (River Murray discharge)	High	N/A	May–Aug	Boundary condition	Average monthly River Murray discharge (GL).	Benefit
Fish movement and recruitment (congolli and common galaxias)	Flow (River Murray discharge)	High	200 ML/day (assumes Lake level is >+0.4 m AHD)	Oct–Jan	Boundary condition	% of days when barrage flow are ≥ 200 ML/day.	Benefit
Fish movement and recruitment (congolli and common galaxias)	Murray Mouth morphology	High	Murray Mouth ≥30 cm deep	May–Jan	ME	% of days where Murray Mouth depth is ≥ 30 cm	Benefit
Fish movement and recruitment (congolli and common galaxias)	Salinity	Moderate	35 g/L	Oct–Jan	ME	% of days where average daily Murray estuary salinity is <35 g/L	Benefit
Waterbirds (Shorebirds)	Water depth	High	<10 cm	Sept-Apr	System-wide	Mean average daily Ha of water cover from <10 cm	Benefit
Waterbirds (Shorebirds)	Water depth	High	<20 cm	Sept-Apr	System-wide	Mean average daily Ha of water	Benefit

Critical CPS	Indicator	Importance	Reference point	Time	Space	Measure	Benefit/risk
						cover from <20 cm	
Waterbirds (Shorebirds)	Water level	High	>+0.4 m AHD	Sept-Apr	CSL	% of days that CSL lagoon-averaged water levels are >+0.4 m AHD	Risk
Waterbirds (Shorebirds)	Salinity	Moderate	<140 g/L	Sept–Apr	System-wide	Mean daily longitudinal extent (km) below 140 g/L	Benefit
Waterbirds (Shorebirds)	Macroalgae	Moderate	HSI >0.25	Sept–Apr	System-wide	Mean average daily Ha of algae mean HSI >0.25	Risk
Waterbirds (Waterfowl)	Ruppia (adult growth)	High	N/A – continuous	Apr–Sept (model period with precursor stages)	CNL	HSI × Area	Benefit
Waterbirds (Waterfowl)	Ruppia (adult growth)	High	N/A – continuous	Apr–Sept (model period with precursor stages)	CSL	HSI × Area	Benefit
Waterbirds (Waterfowl)	Ruppia (turion) - asexual lifecyle	High	N/A – continuous	Turion production: June-Dec (model period with precursor stages)	CNL	HSI × Area	Benefit
Waterbirds (Waterfowl)	Ruppia (turion) - asexual lifecyle	High	N/A – continuous	Turion production: June-Dec (model period with precursor stages)	CSL	HSI × Area	Benefit
Waterbirds (Waterfowl)	Water level	High	+0.35 m AHD	Sept-May	CSL	% of days when the lagoon-	Risk

Critical CPS	Indicator	Importance	Reference point	Time	Space	Measure	Benefit/risk
						averaged water level in the CSL is above +0.35 m AHD	
Waterbirds (Piscivores)	Salinity	High	<45 g/L	Sept-Apr	System-wide	Mean daily longitudinal extent (km) below 45 g/L	Benefit
Waterbirds (Piscivores)	Salinity	High	<100 g/L	Sept-Apr	System-wide	Mean daily longitudinal extent (km) below 100 g/L	Benefit
Waterbirds (Piscivores)	Flow (River Murray discharge)	High	N/A – continuous	Sept-Apr	System-wide	Average monthly River Murray discharge (GL)	Benefit
Waterbirds (Piscivores)	Water level	High	-0.5 m AHD	Sept-Apr	CSL	% of days when the lagoon-averaged water level in the CSL is below -0.5 m AHD	Benefit