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Where to from here? A review of reports on the microalgae and nutrient conditions within the Coorong and Lower Lakes

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This report was prepared for the South Australian Department of Environment, Water and Natural Resources as part of the South Australian Government's $610 million Murray Futures program funded by the Australian Government's Water for the Future Initiative.

Executive summary

This report assesses the potential to make greater use of nutrient and microalgae monitoring data in the Coorong, Lower Lakes and Murray Mouth (CLLMM) region to strengthen the links between the physical-chemical conditions and food web dynamics. Efforts in past research programs have established effective frameworks for integrating knowledge of river flows, water level, salinity and ecological response dynamics in the Coorong, and for integrating hydrodynamic and biogeochemical knowledge in the Lower Lakes. There are significant challenges in making more use of nutrient and microalgae monitoring data in such frameworks, and it remains an open question as to whether these data can be more effectively included in integrated assessments.

Priorities identified in this review reflect well-identified principles for good ecosystem monitoring and research:

- A focus on question-driven monitoring and research;
- Build upon the existing capacity for whole-of-system integrated assessment;
- Conduct this work within an adaptive management and adaptive monitoring framework.

This review suggests the following general strategy:

1. Maintain a set of clear, well evaluated, clearly communicated monitoring objectives and review these objectives regularly.
2. Identify those monitoring objectives that are amenable to opportunistic funding arrangements, and commission field campaigns to address these as and when funding allows.
3. Ensure any investments in interpretation of monitoring data place a high priority on maintaining and building upon the existing capacity for system-wide integrated assessment.
4. Monitoring site locations and parameters into the future:
    a. As much as practicable, maintain consistency with sites and parameters monitored in the past: regular, repeated measurements over a long time are more readily incorporated into long-term, integrated assessments.
    b. When locations or parameters are changed, ensure a period of overlap so the effects of the changes can be discerned.
    c. Where possible, measure concentrations and exchange rates at input locations (ocean, barrages, drains and creeks), particularly during flow events, as these are key determinants of biogeochemical budgets.
    d. When selecting site locations, a greater spatial extent is more informative than dense spatial coverage of a more limited extent.
    e. Ongoing review of monitoring in light of new data and insights as part of the adaptive management for the region.

Specific steps consistent with this strategy include:

1. Maintain and extend existing frameworks for integration of multiple knowledge sources to make whole-of-system assessments. These are valuable research infrastructure and allow the most value to be derived from monitoring data. Such frameworks include: hydrodynamic modelling in the Coorong, nutrient budgets in the Coorong, state and transition modelling in the Coorong and hydro-biogeochemical modelling in the Lower Lakes.

2. Link existing knowledge of *Ruppia* physical requirements to the existing hydrodynamic model and generate habitat suitability maps.
3. Calculate post-flood nutrient budgets using the updated hydrodynamic modelling.
4. Undertake a small field program aimed at testing whether shoreline measurements are representative of centreline concentration measurements.
5. Make continuous measurements of water level in the North and South Lagoon simultaneously with flow at Parnka Point to better inform the relationship between water level and flow between the two Lagoons.

Nutrient and microalgae monitoring in the Coorong and Lower Lakes

Background

With legislative and governance mechanisms in place to secure and deliver environmental water in the Murray-Darling Basin, there is an imperative to provide evidence for the ecological responses enabled by environmental flows. Such evidence underpins the characterisation of multiple benefits and trade-offs associated with ecosystem services (CSIRO 2010). One region of considerable importance is the Coorong, Lower Lakes and Murray Mouth (CLLMM) complex, where information on ecological responses to changing environmental conditions is required to inform site management.

For the Coorong there have been significant efforts to bring together monitoring data from many sources to create evidence-based models of ecological response to flow, water level and salinity (Lester and Fairweather 2009; Lester and Fairweather 2011; Lester, Webster *et al.* 2009; Lester, Webster *et al.* 2011). The work has demonstrated the powerful potential of integrating knowledge of physical processes with knowledge of species distribution and abundance over time. Understanding the links between physical, biogeochemical and ecological processes provides a valuable whole-of-ecosystem perspective. Biogeochemical processes and primary production mediate the higher trophic level responses, however integrating nutrient and microalgae monitoring data into such models has proved challenging (Lester, pers. comm).

Much of the monitoring data used previously in integrated modelling frameworks was collected during the drought years of 2000-2010 as little regular data was collected prior to this period. The Murray-Darling Basin saw its wettest year on record in 2010 and has continued to experience high rainfalls since, leading to substantial flows to the CLLMM region. Post-flood nutrient and microalgae measurements have been monitored with the intention of better understanding the links between hydrodynamic processes, physico-chemical conditions and higher trophic level interactions to better inform the long term management of the site.

The Long Term Plan for the Coorong, Lower Lakes and Murray Mouth Region (DEH 2010) makes adaptive management a priority. Adaptive management is an effective way to combine immediate management actions with long-term learning and flexibility that leads to review and revision of management practices. Within this framework, this report assesses the potential to make greater use of nutrient and microalgae monitoring data in the CLLMM region to strengthen the links between the physical-chemical conditions and food web dynamics. The purpose of this report is to assess whether there is potential to learn more from existing measurements, especially if they are better integrated with other knowledge sources. The assessment is informed by a review of existing data and reports, and interviews with researchers with long-standing involvement with nutrient and microalgae data in this region. Note that this report is a review of previously completed reports and did not include any further data analysis.

Available data and analyses

The focus of this review is on recent nutrient and microalgae monitoring and analysis, primarily conducted by the University of Adelaide, the Department of Environment, Water and Natural Resources (DEWNR) and the Environment Protection Authority South Australia (SA EPA). It is useful to place that work in the context of long-term monitoring in the region by DEWNR and SA EPA and the range of ecological research conducted as part of the Coorong Lower Lakes and Murray Mouth Ecology Cluster (CLLAMMecology), a CSIRO cluster initiative that helped fund a concerted research effort in the region (Brookes, Lamontagne *et al.* 2009).

LONG-TERM PHYSICO-CHEMICAL AND NUTRIENT MONITORING

Regular monitoring of physico-chemical properties and nutrients by DEWNR in the Coorong since 1998 has provided a backbone for much of the analysis and interpretation involving water quality, nutrients and microalgae. Much of this sampling period coincided with a decadal drought in the Murray Darling Basin (2000-2010) and so the representativeness of these measurements is uncertain. A key feature of the CLLMM region is high variability, and cycles of drought and flood in particular. This variability is reflected in barrage flow and salinity time series in Figure 1.

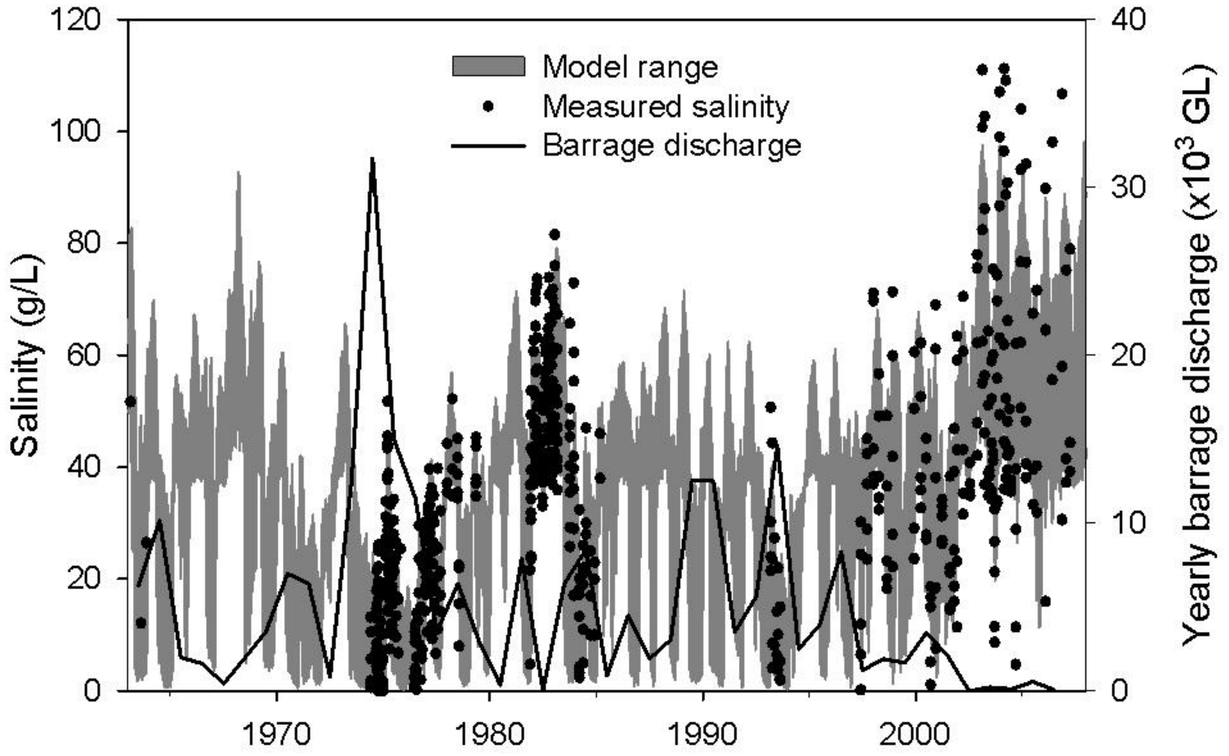

Figure 1 Observed salinity and barrage flows in the Coorong North Lagoon and modelled salinity range from hydrodynamic modelling. Image provided by Ian Webster, CSIRO.

Monitoring is a vital means of characterising this variability and informing management options that accommodates variability rather than managing for steady state conditions. Details of DEWNR monitoring sites and parameters are given in Table 1, and Figure 2 provides a diagram showing the frequency of measurements. At a minimum these data allowed key water quality parameters to be tracked over time against water quality guidelines and management targets (e.g. DEH 2010; DENR 2010).

The measurements were assessed in a recent (unpublished) internal review of the monitoring program (DENR 2010). The focus of the review was on the effectiveness of the monitoring for water quality management objectives, such as the ability to identify trends or trigger alerts. One of the recommendations from that review was the need for clear monitoring program objectives, which is echoed in this review and discussed later as an important consideration in future monitoring. The water quality monitoring was found to be adequate for the provision of long-term baseline data, for example for reporting against water quality guidelines and targets, but not appropriate for triggering alerts. More specific recommendations revolved around decisions whether to retain particular measurements in the future, given considerations such as cost and limits of readability amongst others.

Table 1 DEWNR monitoring sites in the Coorong from January 1998 to June 2010.

Sample Sites	Date Range	Eastings	Northings
Coorong Monument Road	2007 - 2010	303168	6066540
Ewe Island Barrage	2007 - 2010	316560	6062006
Coorong Sub Lagoon 1 Tauwitcherie	1998 - 2010	320979	6059330
Coorong Sub Lagoon 2 Mark Pt	1998 - 2004	326000	6055000
Coorong Sub Lagoon 3 Long Point	1998 - 2010	333756	6048257
Coorong Sub Lagoon 4 Noonameena	1998 - 2004	347000	6041000
Coorong Sub Lagoon 5 Bonneys	1998 - 2010	347969	6037304
Coorong Sub Lagoon 6 McGrath Flat North	1998 - 2004	354500	6031000
Coorong Sub Lagoon 7 Parnka Point	1998 - 2010	355258	6025752
Coorong Sub Lagoon 8	1998 - 2004	363000	6021500
Coorong Sub Lagoon 9 Stony Well	1998 - 2004	367000	6018500
Coorong Sub Lagoon 10 Nth Jacks Point	1998 - 2010	371049	6011575
Coorong Sub Lagoon 11 Sth Policemans Point	1998 - 2004	373950	6006000
Coorong Sub Lagoon 12 Sth Salt Creek	1998 - 2010	377463	6000059
Coorong Fairview Drain Keilira Regulator	1999-2005		
Coorong Morella Basin	2000-2006		
Coorong Salt Creek Footbridge	2000-2005		

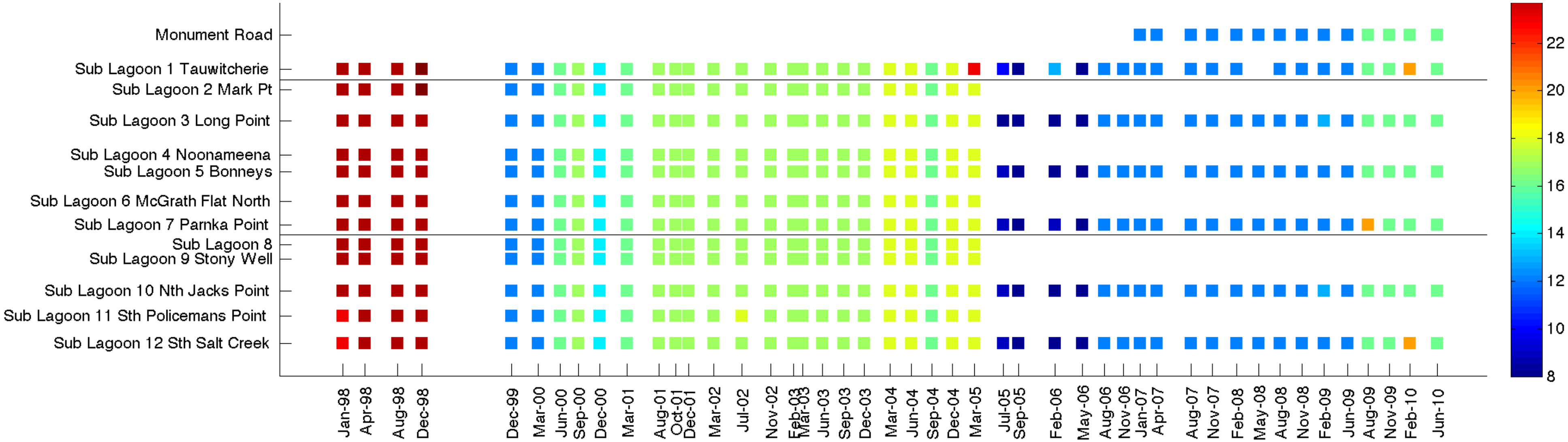

Figure 2 DEWNR Coorong monitoring intensity at each location over time from January 1998 to June 2010. Square markers indicate dates and locations of measurements, and the colours indicate the number of parameters from Table 2 measured. Locations are plotted on the vertical axis according to site latitude and horizontal lines mark the delineation between Murray Mouth region, North Lagoon and South Lagoon. Note there has also been monitoring at Ewe Island Barrage that is not included in this diagram.

Table 2 DEWNR monitoring sites in the Coorong from January 1998 to June 2010.

Biological, physical and nutrient measurements	Chemical measurements
Chlorophyll a	Sodium Adsorption Ratio - Calculation
Chlorophyll b	Sodium/Total cations ratio
Chlorophyll by Acetone Extraction	Ion balance
Ammonia as N	Carbon Dioxide - Free
Nitrate + Nitrite as N	Carbonate hardness as CaCO3
Phosphorus - Filterable Reactive as P	Magnesium Hardness as CaCO3
Phosphorus - Total	Bicarbonate
TKN as Nitrogen	Total Hardness as CaCO3
Silica - Reactive	Alkalinity as Calcium Carbonate
Nitrate + Nitrite as NO3	Langelier Index
Ammonia (NH3 unionised) as N	Chloride
Ammonium (NH4 ionised) as N	Dissolved solids by calculation
Total Dissolved Solids (by EC)	Chlorides - Total as NaCl
Conductivity	Calcium Hardness as CaCO3
pH	Noncarbonate hardness as CaCO3
Turbidity	Carbonate
	Fluoride
	Hydroxide

The monitoring program in the Coorong altered after June 2010 with changes to site locations, parameters measured and even the reporting methods. An analysis of the degree of overlap (shared sites and parameters) was not possible within this review. Similarly, monitoring of physical conditions in the Lower Lakes has intensified since 2009, building on existing event-based and regular monitoring of water level and electrical conductivity. A comprehensive collation of all monitoring in the Coorong and Lower Lakes since 2010 has been assembled by Hipsey and Busch (2012): refer to Appendix A of their report for maps of monitoring sites and tables of parameters measured. Hipsey and Busch (2012) reported they have developed a flexible analytical framework to make it easier to bring together data spreadsheets from different organisations. Such frameworks are vital precursors to any integrated modelling or assessment work, and well worth developing and maintaining.

CLLAMMECOLOGY RESEARCH CLUSTER

The Coorong Lower Lakes and Murray Mouth Ecology Cluster (CLLAMMecology) was established by CSIRO in late 2006, and enabled research collaborations across key institutions in the region, including the University of Adelaide, Flinders University, the South Australian Research and Development Institute

(SARDI) and CSIRO. The research was conducted over three years and brought together hydrodynamic, biogeochemical and ecological knowledge and enabled the development of analysis tools and products specifically built to inform management in the region. The CLLAMMecology research cluster delivered a final report in 2009 that built upon several years' monitoring and research in the Coorong and Lower Lakes, and including historical monitoring data (Brookes, Lamontagne *et al.* 2009). Aspects of the research that are particularly relevant to this review include:

1. The development of a hydrodynamic model of the Coorong, described by Webster (2010) as follows: "*The one-dimensional hydrodynamic model simulates water motions and water levels along the Coorong from the Mouth to the south end of the South Lagoon as these respond to the driving forces associated with water level variations in Encounter Bay (including tidal, weather band, and seasonal), the wind blowing over the water surface, barrage inflows, flows from the Upper Southeast Drainage area (USED), precipitation, and evaporation from the water surface.*" A more complete description of the hydrodynamic model is provided by Webster et al (2007).
2. A review of the biogeochemistry of the Coorong by Ford (2007), and this work included an unsuccessful attempt to calculate nutrient budgets using the Land Ocean Interactions in the Coastal Zone (LOICZ) method (Gordon, Boudreau *et al.* 1996) to calculate nitrogen and phosphorus budgets. The problems were addressed by using the hydrodynamic model to infer the physical exchanges (Grigg, Robson *et al.* 2009): nutrient budgets in the Coorong were constructed by combining the aforementioned DEWNR nutrient monitoring measurements with hydrodynamic model output, so creating time-varying nutrient budgets from January 1998 to November 2007 that were consistent with the hydrodynamics. Nutrient measurements were interpreted in a nutrient budget framework for the Lower Lakes (Cook, Aldridge *et al.* 2008) for the period between 1979 and 1996.
3. State and transition modelling of ecosystem response to flow provided a clear, defensible way to link knowledge of flow, water level and salinity with ecological outcomes, and to do so in a way that could explore the consequences of different future scenarios (Lester and Fairweather 2009; Lester and Fairweather 2011; Lester, Webster *et al.* 2009; Lester, Webster *et al.* 2011).
4. Other studies relevant to nutrients and micro algae included field surveys carried out by Haese et al (2009) to identify nutrients limiting primary production in the water column and nutrient sources delivered through groundwater inflows and as a result of organic matter degradation within the sediments. The study yielded useful measurements and conceptual models that aided in the interpretation of other biogeochemical work in the Coorong. Seasonal variations in primary production were measured along the north-south salinity gradient that develops in the Coorong using 14C and dissolved oxygen techniques (Nayar and Loo 2009). Their results pointed to low phytoplankton productivity at their three sites and evidence for considerable heterotrophic productivity.

Key to the nutrient budget modelling and the state and transition modelling was the development of a hydrodynamic model of the Coorong (Webster 2005; Webster 2007; Webster 2010; Webster 2011). It is increasingly common to require a 'systems' or 'integrated' view informing the stewardship of valued ecosystems, and the Coorong hydrodynamic model has been a key component enabling diverse sources of knowledge to be combined in a self-consistent, quantitative framework. A result that emerged across all these pieces of work was the importance of adequately accounting for the role of the hydrodynamics. Over the study period the Coorong functioned as an inverse estuary: evaporation exceeded the sum of rainfall and river inflows and drove an inward flow of seawater at the Murray Mouth. These dynamics affected the movement and accumulation of all material in the system, and the hydrodynamic model was needed to account for these dynamics in any interpretation of the data.

The hydrodynamic model provided the transport fluxes used to develop nutrient budgets from the 1998-2007 Coorong monitoring data (Grigg, Robson *et al.* 2009). A strong North-to-South gradient of chlorophyll *a* concentrations had been observed in the latter years of monitoring data, with highest concentrations observed in the South Lagoon (Figure 3a). In the absence of any other information, the intuitive response to these observations would be to infer that the South Lagoon is highly productive. However, the Coorong is an inverse estuary, and evapo-concentration processes dominated its hydrodynamics over the period of study. In light of this knowledge, it is to be expected that any constituent in the system would accumulate in the South Lagoon. These evapo-concentration processes need to be taken into account when making any data-derived inferences about the origin and fate – the sources and sinks – of nutrients and other constituents. The analysis derived aggregate budgets for two riverine flow conditions: 'flow' years from January 1998 to January 2002; and 'no flow' years from January 2002 to November 2007 (Figure 3c). A particular effort was devoted to sensitivity analyses in order to identify results that held across a range of assumptions. Physical fluxes due to evapo-concentration were found to be of similar magnitude to the internal fluxes. For most variables analysed (including chlorophyll *a*) the South Lagoon was a sink with evapo-concentration processes moving material from the North to the South Lagoon against the North-South concentration gradient; the movement of material is such that these concentration gradients are reinforced rather than dissipated (and so a counter-intuitive finding). Webster (2007) provides detailed descriptions of evapo-concentration, horizontal mixing and Murray Mouth exchanges.

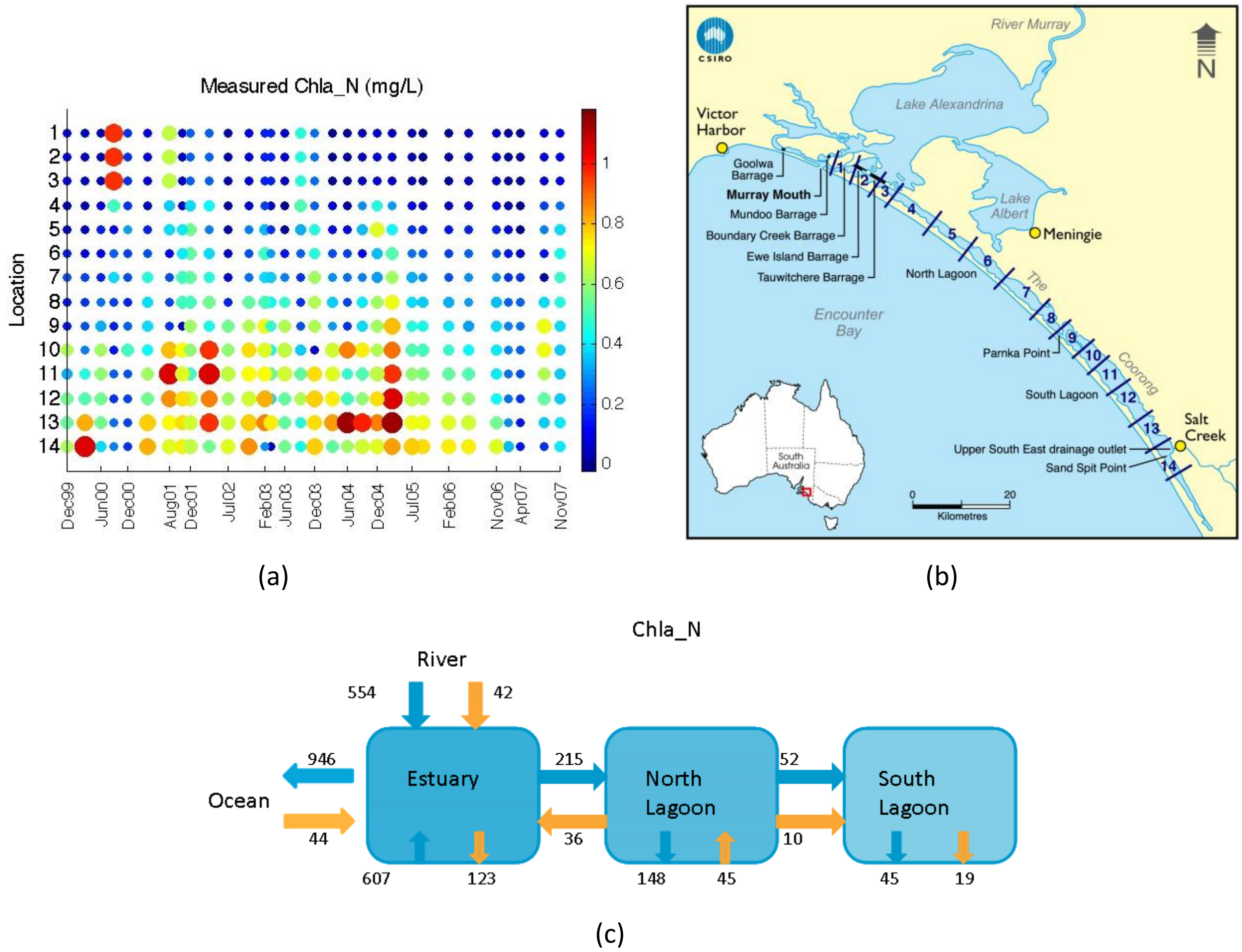

Figure 3 (a) Phytoplankton nitrogen concentration estimates derived from measured chlorophyll *a* concentrations. (b) Location numbers correspond to boxes uses in the hydrodynamic model (right hand side). (c) Estimated budget for flow (before Jan 2002, blue arrows) and no-flow (after Jan 2002, orange arrows) years. Units are tonnes per year. Arrows within each box are internal fluxes (from both water column and sediment processes). Figures from (Grigg, Robson *et al.* 2009).

An ecosystem state model was developed that coupled with the hydrodynamic model and was used to assess 20 possible future scenarios, including climate change, sea-level rise and various management options. The ecosystem state model was a data-derived model built using classification and regression tree approaches. It used the available data for physico-chemical parameters, including nutrient data, abundances of macrophytes, birds, fish and benthic macroinvertebrates, and meteorology and water quantity. It did not include microalgae data. Linking a data-derived statistical model of ecosystem states with a process-based hydrodynamic model was a powerful combination. It ensured good integration of the hydrodynamic knowledge, for which there is a relatively high level of certainty, while ensuring statistically significant inferred ecosystem states, which are derived from data with far greater uncertainties and variability. A finding from the ecosystem state and transition modelling was that the most valuable monitoring data were those measurements that were repeated in time and space across all variables of interest according to a well-considered monitoring design. The absence of repeated data meant that some measurements were of less value than they could have been had these criteria been met.

The CLLAMMecology work was conducted during drought years when there were no significant flows and much of the research tracked the decline of ecological condition (Brookes, Lamontagne *et al.* 2009). However the models developed during the study provide a powerful platform for assessing future data needs and for incorporating new monitoring and research measurements into current understanding of the system. These models are playing a role in directing ongoing research effort but this could be further enhanced by incorporating new data into the current models. This may help to improve their reliability and may also identify needs for model improvement or adaptive development.

The usefulness of the Coorong hydrodynamic model did not occur by accident and it was developed in response to a careful scoping process in which conceptual models were developed in discussions and workshops with stakeholders. The outcomes of this process are documented in Lamontagne et al. (2004) and formed the basis for the design of the CLLAMMecology program. This process identified the need for a hydrodynamic model to do the following:

1. Represent water exchange, water level and salinity in the Coorong as a function of key drivers (e.g. barrage flows, ocean water levels, Murray Mouth characteristics, Upper South-East Drainage inputs and climate);
2. Be simple enough to produce simulations over several decades because the system changes at that scale;
3. Be suitable for integrating with biogeochemical or ecological models.

In this process monitoring data played an important role in informing the system conceptualisation and the data enabled the resulting hydrodynamic model to be well calibrated.

LOWER LAKES

The risk of acid sulfate soil exposure in the Lower Lakes has been a primary motivation for research and analysis in Lower Lakes (Mosley, Barnett *et al.* 2010), and it has led to a different approach and emphasis to the CLLAMMecology research. The aspect of the research of relevance to this review is the development of a hydro-geochemical model of the Lower Lakes, calibrated using available physico-chemical monitoring data (Hipsey, Busch *et al.* 2010; Hipsey and Busch 2012). Although the model development and application has been focussed on understanding and managing acid sulphate soil risks, its value extends beyond this application. In particular, this modelling approach is a powerful way to integrate all available nutrient, water quality and microalgae monitoring in the Lower Lakes to inform system-level understanding and management. The model authors have made recommendations for how to improve the model's ability to inform on broader biogeochemical and water quality processes.

RECENT MICROALGAE MONITORING AND ANALYSIS

Reports published by Aldridge and Brookes (2011) and Aldridge and Payne (2012) document monitoring and analysis aimed at investigating the responses of water quality and microalgae communities to barrage flows from the Lower Lakes. The work was motivated by the return of barrage flows after several years of drought during which there were no flows from the Lower Lakes to the Coorong. It was anticipated that the flows would deliver increased nutrient loads to the Coorong, triggering an associated increase in primary and secondary production. It was also anticipated that there might be potential impacts of acidic water passing to the Coorong due to the inundation of acid-sulfate soils in the Lower Lakes. Specific hypotheses were addressed by Aldridge and Brookes (2011):

- Flows will have increased habitat availability for aquatic organisms due to decreased salinity and decreased hypoxia/anoxia that was caused by salinity stratification;
- Flows will have increased food availability for aquatic organisms due to (a) imported nutrients and autochthonous productivity, and (b) imported phytoplankton with high abundance of diatoms and green algae, which are preferred food sources for species such as Goolwa Cockles (Seuront and Leterme 2009).

And a further hypothesis in the follow up study by Aldridge and Payne (2012) was:

- The microalgae community will shift away from *Cyanobacteria* towards *Bacillariophyta* with continued inflows during 2011- 2012.

Table 3 Monitoring sites used by Aldridge & Brookes (2011) and Aldridge & Payne (2012). Sites C1 through to C11 were used by Aldridge & Brookes (2011). Sites used in both studies are marked with an asterisk (*) and site C12 was used by Aldridge & Payne (2012) only.

Site	Description	Longitude (°E)	Latitude (°S)
C1*	Goolwa Barrage Downstream	138.81737	35.52718
C2	Half Way	138.8511	35.54021
C3	Sugar's Beach	138.87921	35.55139
C4	Southern Ocean	138.87552	35.55749
C5*	Murray Mouth	138.88164	35.5572
C6	Hunter's Creek	138.89107	35.53571
C7	Mundoo Channel	138.89784	35.53969
C8	Boundary Creek	138.93509	35.55551
C9*	Ewe Island	138.96111	35.56748
C10	Tauwitchere	139.00363	35.58852
C11*	Mark Point	139.07573	35.63423
C12**	Parnka Point	139.396	35.90197

Measurements made at Aldridge & Brookes (2011) sites in addition to microalgae identification and abundance counts: profiles of water temperature, specific electrical conductivity, dissolved oxygen (concentration and saturation), pH, turbidity and chlorophyll a; Unfiltered water samples were analysed for total phosphorus (TP), total Kjeldahl nitrogen (TKN), chlorophyll a and phytoplankton identification and abundance. Filtered samples were analysed for ammonia (NH_4 -N), oxidised nitrogen (NO_x -N), filterable reactive phosphorus (FRP) and filterable reactive silica (FRSi).

Measurements made at Aldridge & Payne (2012) in addition to microalgae identification and abundance counts: specific electrical conductivity.

The monitoring by Aldridge and Brookes (2011) was conducted between November 2010 and May 2011 at eleven sites at approximately fortnightly (and no more than 6-weekly) intervals. The monitoring involved physico-chemical properties, nutrient concentrations and microalgae abundance and diversity. The monitoring by Aldridge and Payne (2012) was conducted between February 2012 and June 2012 at monthly intervals at a smaller subset of the sites used by Aldridge and Brookes (2011), with an extra site included at Parnka Point (where the Southern and Northern Coorong Lagoons meet). Measurements of microalgae abundance and diversity were made as in the previous study; however the only other measurements made were conductivity depth profiles. Locations are listed Table 3 and Figure 4.

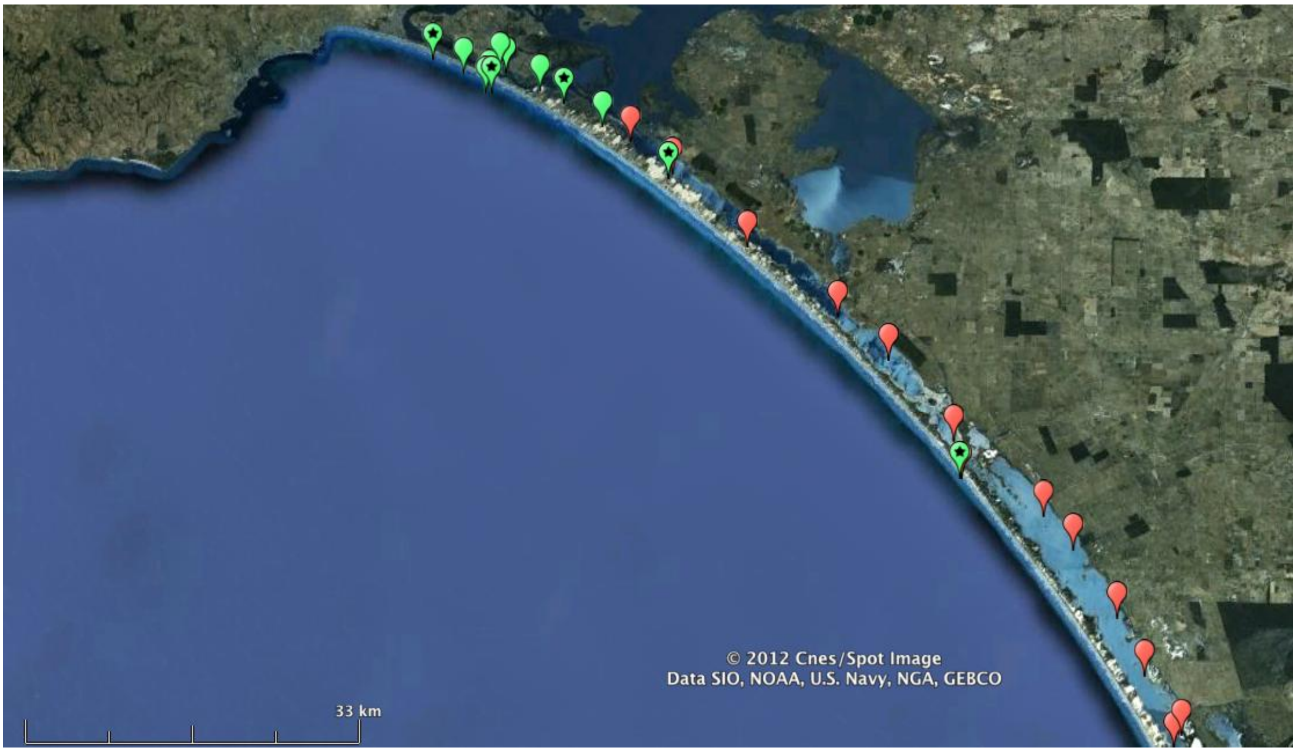

Figure 4 Coorong monitoring sites. Green markers are the locations for microalgae monitoring by Aldridge & Brookes (2011) and Aldridge & Payne (2012). Red markers are the locations for nutrient monitoring by DEWNR between 1998 and 2010 (Table 1). Refer to Hipsey and Busch (2012) for most recent maps and summary of all sites and quantities measured in the Coorong and Lower Lakes.

Aside from descriptions of time series and profiles of the various constituents and physico-chemical parameters, the main analysis method brought to bear on the interpretation of the data was the use of nonmetric multidimensional scaling (NMS) ordination. In this case the analysis yielded plots, in either two or three dimensions, in which each point represented a site's microalgae community for a particular date based on cell counts. These points were located in graph space according to the similarity of the sets of cell counts between sites and dates: the closer together the points the more similar the community composition. Furthermore, the method allowed an analysis of the relationship to a second set of physico-chemical properties at the same sites and dates, providing statistical evidence for possible driving influences on patterns in cell counts.

Note that this analysis approach places an emphasis on microalgae counts and their spatial-temporal patterns and statistical correlations with salinity and other physico-chemical properties. There are useful qualitative findings from the work, and these include:

- Clear shifts in microalgal community composition over time, with inferred implications for higher trophic levels (e.g. based on knowledge of species food preferences).
- The NMS ordination analysis shows that within-trip results are more similar than within-site results (i.e. measurements are clustered by trip rather than by site in the NMS ordination), suggesting that capturing higher frequency temporal dynamics may be more informative than denser spatial sampling. The exception is for site C12 (Parnka Point) – a site included only in Aldridge and Payne (2012)– where the NMS analysis shows the community was quite distinct from the other sites and remained so over the duration of the study. This site is much further south than the other sites, and so this result shows that covering a greater spatial extent is informative.

- The NMS ordination analysis also derives statistically significant relationships between some physico-chemical conditions and microalgal responses, which can be used to prioritise further analyses and hypothesis testing.
- Calculations of stoichiometric ratios to inform what nutrients are limiting microalgae growth at particular sites and locations.
- Evidence for salinity stratification and associated hypoxic conditions.

There is much background process knowledge that is drawn upon in the interpretation of the results. For example:

- The potential for unwanted reinforcing feedback loops such as: increased nutrient availability fuelling increased microalgal biomass, which reduces light availability for submerged plant growth, which in turn creates conditions for more sediment suspension, which then exacerbates light-limiting conditions and so allowing the ongoing dominance of microalgal populations rather than submerged vegetation. The existence of such feedback loops as proposed in the report creates conditions that are problematic to reverse once established.
- The observed high abundance of *Chlorella* at Parnka Point was expected to reduce the amount of light available to support the growth of *Ruppia tuberosa*.
- It was proposed that the switch in microalgae community at high salinities at the southern-most site (Parnka Point) might be due to reduced predation, increased competition, elevated nutrient levels or a combination of the three.
- The potential influence of interactions between stratification, dissolved oxygen and nutrient limitation were referred to in Aldridge and Brookes (2011), and related to implications for habitat availability, sediment nutrient release, ammonia accumulation due to prevented nitrification, and microalgae productivity (citing Nayar and Loo (2009)).
- Explanations of trends in concentrations of nitrate, ammonia and total organic nitrogen were developed in terms of processes such as coupled nitrification/denitrification and uptake of nutrients into microalgae biomass.
- There were no dissolved organic carbon measurements, however its potential role and influence on dissolved oxygen and pH was inferred.

So while the interpretation of data in these reports draws on relevant process knowledge, the data were not collected with an aim to make quantitative estimates of these processes. In other words, the monitoring and analysis approach was not intended to infer the state of autotrophy or heterotrophy, nor to estimate microalgae growth rates, material fluxes, ecological interactions such as competition or grazing rates (other than qualitative descriptions) nor quantitative constraints set by hydrodynamic transport processes (other than in a qualitative way by referring to the potential influence of salinity stratification). The next section reviews the potential to extend interpretation of existing physico-chemical, nutrient and microalgae data in this direction.

Opportunities to infer more from existing data

This review is to assess whether there is the potential to better use existing nutrient and microalgae measurements to understand system functioning, and whether this information could be used for making useful inferences about higher trophic level responses. The response to this question has been primarily informed by interviews with key researchers experienced in using these data and familiar with the CLLMM system. Their responses fell into two categories: (1) general, overarching considerations; (2) specific, tangible opportunities.

OVERARCHING CONSIDERATIONS

The relationship between flow and ecological response is not easily characterised and understood for the CLLMM site. It is made particularly difficult by several interrelated factors, including:

- Long chains of cause and effect. For example, barrage flows influence water levels, salinity, material inputs and residence times, which in turn shape the nature of primary production and habitat availability, so shaping the higher trophic level responses, which in turn affect material fluxes and primary production. There are multiple, interconnected ways in which these factors influence one another.
- Highly variable system, both in time and space.
- Substantial time lags, path dependence, feedback loops and other nonlinear processes. For example, the state of the system can be locked in due to events or conditions in the past (e.g. drought, flood, loss of particular species).

These aspects of system behaviour are not easily characterised through statistical analysis alone, and attempts to do so often preclude the incorporation of relevant process knowledge. However, the variability and uncertainties in responses mean that any process-based approaches should incorporate statistical methods to ensure that findings are well supported by data and statistically significant. Such approaches also offer valuable insights into the usefulness of the data.

It is neither common nor easy to combine process-based and statistical methods. Neglecting statistical approaches can mean that too much is being inferred from limited data (e.g. estimating process rates in a way that is indefensible from a statistical perspective). Neglecting process-based knowledge is a lost opportunity to include constraints on possible interpretations of the data (e.g. requiring basic consistency with principles such as conservation of mass).

Knowledge of conservation of mass, time lags and cumulative impacts are crucial. For example, in the Coorong, barrage flows, water level and salinity are not simply related and useful, predictive relationships are not easily discoverable through statistical processes alone. Yet these interactions are well encapsulated in the hydrodynamic modelling work for the Coorong. Similarly, barrage flows and microalgae will interact in even more complex and multiple ways. Where there is knowledge of these processes, such as rates or fluxes associated with biogeochemical interactions, it brings more lines of evidence to narrow the range of possible interpretations of system response. Higher trophic level responses are influenced by more system linkages with time lags and potential for system futures to be locked in by historical conditions or events (e.g. population response is typically shaped by important pre-conditions, such as the viability of seed-banks or recruitment processes).

Models play an important role as diagnostic tools. Nutrient budgets are useful because they provide insights into fluxes, sources and sinks. When managing a system for water quality targets, for example, knowledge of key sources and sinks is useful for targeting action most effectively. A nutrient budget is a bare minimum for inferring more from nutrient data, and in a highly variable system like the CLLMM site it is essential to calculate time-varying budgets rather than create static budgets (which may represent an average that is rarely actually experienced in a system that is ranging across extremes). Such budgets are also helpful for generating or testing hypotheses. For example, nutrient budget calculations reported in Grigg et al (2009) suggested that high chlorophyll *a* concentrations were consistent with passive transport in the absence of predation (so echoing similar hypothesis by Aldridge and Payne (2012) that high microalgae abundance may be due to reduced predation). More generally, the results certainly indicated that the role of hydrodynamic transport in microalgae distributions should not be ignored.

Reanalysing these budgets in light of new developments, especially with respect to the hydrodynamic model, and incorporating more recent data where possible would help consolidate the status and usefulness of the nutrient budgets. The monitoring data would seem to provide a strong base for this analysis but further detailed investigation of the data quality is required to confirm this. This review did not have the resources to investigate or analyse data sets but simply to overview them.

Reports to date have readily acknowledged the role of non-linear processes and system feedbacks such as the unwanted feedback loop reinforcing algal dominance described in the previous section. In general, process-based modelling frameworks are better able to represent and even predict such outcomes than statistical inference methods. The hydrodynamic-biogeochemical modelling conducted in the Lower Lakes (Hipsey, Busch *et al.* 2010; Hipsey and Busch 2012) represents the most comprehensive process-based approach in the CLLMM region. The model has been used to investigate acid sulphate soil risk, and a more careful review and assessment would be required to evaluate its readiness for wider application.

The work most closely integrating a balance of statistical and process-based methods is the state and transition modelling by Lester and colleagues (Lester and Fairweather 2009; Lester and Fairweather 2011; Lester, Webster *et al.* 2009; Lester, Webster *et al.* 2011). The inclusion of nutrient and microalgae data into this framework has been problematic in the past, and yet given the important mediating role nutrients and primary production play in linking hydrodynamics to higher trophic level responses it is anticipated that the potential benefits in attempting this development make it a worthwhile exercise.

In some cases critical knowledge gaps were identified that limit the potential to learn more from existing data. These suggest the potential for small, targeted measurement programs to address specific knowledge gaps. This is discussed in the later section on future monitoring opportunities, but clear identification of these gaps require detailed attempts at modelling with the available data to demonstrate the need and these modelling efforts should continue in order to provide a framework for data collection.

SPECIFIC OPPORTUNITIES

The following specific opportunities do not represent an exhaustive search for possibilities: they are conservative recommendations based on expanding upon existing methods that have already been applied in this region.

Ruppia response

All interviewed researchers indicated further opportunities to make better links to existing data and knowledge about *Ruppia* dynamics. *Ruppia* is well-recognised as a crucial component of the ecosystem, especially as it links so much of interest: it competes for nutrients and so is both dependent upon and influences nutrient fluxes; it is a component of primary production in the system, so contributing to whether the system is autotrophic or heterotrophic; and it provides food and habitat for valued species, so is a link between supporting processes such as nutrient cycling and higher trophic levels.

Ruppia propagules were identified as crucial because an absence of a viable stock of *Ruppia* propagules is a problem regardless of nutrient and salinity conditions. This means that any inference about *Ruppia* response needs to account for these requirements and ensure a good understanding and representation of requisite conditions. The dependence on the time course of previous conditions (e.g. for build up of viable propagules) is also critical, particularly for identifying any potential system hysteresis.

Water level is a key driver of *Ruppia* dynamics (Rogers and Paton 2009). There is the opportunity to link existing knowledge of *Ruppia* physical requirements to the existing hydrodynamic model and generate habitat suitability maps. Furthermore, it would be possible to include knowledge of time lags, although further investigation is needed to assess whether adequate data exists to quantify the time lags. For example, once *Ruppia* has died in a particular location, a return to suitable conditions will see *Ruppia* re-established only after a time delay, given available propagule banks.

The recent improvements to the hydrodynamic model open up opportunities to improve previous modelling attempts and to extend the modelling to other biota. Using the available information and the types of “state transition” approaches used previously effort should be made to investigate the suitability of the monitoring data on microalgae, invertebrates and other biota for assessing their physical requirements and generating habitat suitability maps. Such an approach would be possible for microalgae, invertebrates and other species using knowledge of viable salinity ranges, for example. Researchers with expertise in these areas could work in conjunction with the hydrodynamic and state-transition modellers to quickly assess the suitability of the available data for developing such modelling constructs.

Nutrient budgets

Previous estimations of nutrient budgets in the Coorong were reliant on a hydrodynamic model configured to match the spatial locations of nutrient monitoring sites (Grigg, Robson *et al.* 2009). The improved hydrodynamic model for the Coorong is at a 1km resolution, so allowing the flexibility to generate hydrodynamic information that is configured to link with measurements from diverse monitoring locations. Previous nutrient budgets were constructed only for the drought period. The hydrodynamic model has been updated and covers the period until present. It would be instructive to calculate post-flood nutrient budgets although there are important caveats here. Previous analysis shows the importance of having barrage flow and ocean concentrations when calculating system budgets and major improvements might depend on the availability of these measurements.

The budget calculated for the Lower Lakes was limited to the period between 1979 and 1996 and the authors judged there were insufficient data to calculate a more recent budget using the same approaches. However, the hydro-geochemical model for the Lower Lakes provides a more rigorous framework for integrating Lower Lakes monitoring data and calculating budgets (Hipsey, Busch *et al.* 2010; Hipsey and Busch 2012) but the current status of these analyses are unknown.

State and transition modelling

Previous ecosystem state and transition modelling has proved to be insightful from a research point of view, as well as useful from a management application perspective. Previous ecosystem state-and-transition modelling could be extended in the Coorong to include more recent data and improvements to the hydrodynamic model. A step wise process using experts in particular areas in conjunction with the modellers could assess potential benefits of doing so. If the data are indeed unsuitable then the process would at least have identified data needs more clearly. Prospects for a state and transition modelling approach in the Lower Lakes are less certain.

Future monitoring considerations

When given the opportunity to identify future monitoring improvements, it is hard not to be drawn into outlining ideal situations that may not be realistic given resource constraints. Rather than make unrealistic recommendations, this section is structured to highlight the different kinds of considerations raised by interviewed researchers. These are:

- Observations about the existing monitoring and analysis;
- The identification of critical knowledge gaps that would help us learn more from existing data;
- Data housing and availability
- General principles for improved future monitoring

OBSERVATIONS ABOUT EXISTING MONITORING AND ANALYSIS

All interviewed researchers observed that existing monitoring and analysis has been fragmented, sometimes required at short notice and conducted as isolated experiments rather than as part of a system-wide coordinated effort. This is particularly relevant for more recent monitoring and analysis. Even where such frameworks have existed (clear monitoring design criteria set and agreed to by all parties involved), there are cases where protocols were not followed and data could not be used for intended end purposes as a result.

Quarterly nutrient data are not frequent enough to learn adequately about nutrient and microalgal dynamics. Inferring nutrient dynamics requires monthly or more frequent monitoring. The range of relevant time scales when developing an integrated picture is challenging as the existing monitoring data point to high variability across sampling dates, and currently there are insufficient high-frequency data to inform optimal monitoring requirements. Regular monitoring augmented by event driven monitoring could dramatically improve understanding.

Greater spatial coverage will make a major difference particularly to capture what is happening at system boundaries. For example, the recent NMS analysis of Aldridge and Payne (2012), showed that the Parnka Point site was markedly different from other more northern sites that were more closely clustered together in the NMS ordination. Extending the spatial coverage needs to be balanced against information required on specific sites, and should be considered in relation to the modelling framework and statutory requirements. Parnka Point is an important location as measurements have shown it marks a substantial transition point between conditions in the North and South Lagoons. Measurements to date make clear that conditions in the South Lagoon are profoundly different to the North Lagoon and spatial coverage to include the South Lagoon is important.

Many of the measurements are below limits of detection, which presents a particular challenge. If a nutrient is limiting the system then the chances of detecting its bioavailable inorganic form are low and only light-limitation will see the detection of such constituents. Although it appears to be a waste of analysis costs to have below-detection results key constituents have been chosen based on experience and knowledge of key influences and in this sense below-detection readings may provide useful information. The integration of data and the development of system understanding through the process of modelling improve our knowledge and can help ensure that the parameters selected for measurements are the most appropriate for the system under consideration

IMPORTANT UNKNOWNS PREVENTING MORE INSIGHTS FROM EXISTING DATA

The following points were identified as current unknowns that would aid interpretation and analysis of existing data. Addressing the following unknowns adequately would mostly require new measurements.

Monitoring data in the Coorong has been primarily based on shoreline samples. The representativeness of shore concentration measurements was identified as a key unknown. Are shoreline measurements in the Coorong representative of centreline concentration measurements? Shore sampling risks detecting local effects only. When estimating a nutrient budget, for example, if shore concentrations are not representative of the budget volume in question then there will be errors in the system-wide sources and sinks inferred in the budget. Note that Cook et al (2008) also mention that there are issues with representativeness of shoreline data in the Lower Lakes.

The connectivity between the two lagoons in the Coorong is also a key unknown, and a small, targeted measurement program would go a long way to address this gap. A month of measuring water levels and the flow between the two Lagoons at Parnka Point would allow the construction of relationships between water level and flow. If the measurements could be made at two different times in the year it would allow the relationships to capture low and high water level conditions. This knowledge is crucial for informing material fluxes of nutrients and microalgae between the two lagoons. Cook et al (2008) similarly identified hydrodynamic fluxes as a critical knowledge requirement for interpreting nutrient data in the Lower Lakes, and modelling work since then has improved understanding of Lower Lake hydrodynamics (Hipsey, Busch *et al.* 2010; Hipsey and Busch 2012).

Previous nutrient budget calculations in the Coorong were severely impacted by the absence of good estimates of nutrient loads entering the system. More reliable quantification of barrage, Murray Mouth and other inputs to the Coorong (e.g. from creeks, drains and groundwater) would improve confidence in calculated budgets. This issue was addressed in Grigg et al (2009) by conducting multiple budget calculations over a range of possible input conditions, allowing the estimation of budget uncertainties resulting from this missing information. Groundwater inputs were not included in this analysis and groundwater influences remain unknown. There is no compelling evidence that groundwater is a major component of the water or nutrient budget, however the lack of knowledge around groundwater is significant and would require a directed study to address adequately.

Better identified trophic links would help interpret microalgae data in particular. What species of microalgae are being consumed by whom (e.g. Aldridge and Brookes (2011) and Aldridge and Payne (2012) refer to the preferences of Goolwa Cockles identified by Seuront and Leterme (2009)). Such knowledge would inform appropriate management targets around favoured microalgae species, and would drive more investigations into the physico-chemical conditions needed for particular microalgae species. Simultaneous monitoring of different trophic levels (e.g. zooplankton and *Ruppia*) would provide further valuable data to underpin food web relationships.

It is widely understood that the system is highly variable both temporally and spatially. Little is known about the high frequency biogeochemical variability and the deployment of more automated, continuous monitoring stations would provide information on temporal variability and rapid responses to events such as flow changes or storm surges. Such continuous high-frequency monitoring exists for water level and salinity, for example[1], and there are opportunities for similar approaches for biogeochemical and bio-optical measurements. High frequency time series are also particularly useful for the calibration of hydrodynamic and biogeochemical modelling, particularly if these capture significant events.

Data housing and availability

Current data housing and access arrangements have allowed good availability of physico-chemical data and associated metadata. If they are to be better integrated with other data sources, however, comparable levels of access are necessary but these are not always possible. Intellectual property issues have hampered some attempts at integrated analysis in the past. Efforts that see good provider agreements and shared data housing arrangements are encouraged.

There is a growing requirement to house data in common, widely accessible data portals (e.g. SA Waterconnect site, CSIRO data portal) and this is an important trend. There are ongoing national developments in this area, for example:

- the Bureau of Meteorology has expanded its strategic scope to include providing a broader set of 'environmental intelligence' (BOM 2010);
- National Plan for Environmental Information (NPEI)[2] to improve access to knowledge of Australian ecosystems;
- The Atlas of Living Australia (ALA)[3] and the Terrestrial Ecosystem Research Network (TERN)[4] are funded by the National Collaborative Research Infrastructure Strategy (NCRIS)[5];
- The eWater Toolkit[6] includes a repository of ecological response models;
- Australian River Assessment System (AUSRIVAS)[7], the Australian Soil Resource Information System (ASRIS)[8], and the State of the Environment reporting[9];
- legacy data and assessments no longer maintained, such as the National Land and Water Resources Audit[10] and associated Australian Natural Resources Atlas[11];
- the prospect for availability of data from ecogenomic methods for ecosystem assessment (Chariton, Court et al. 2010; Hardy, Adams et al. 2011; Hardy, Krull et al. 2010).

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[1] http://www.waterconnect.sa.gov.au/RMWD/Pages/default.aspx
[2] http://www.environment.gov.au/npei/index.html
[3] http://www.ala.org.au/
[4] http://www.tern.org.au/
[5] http://www.innovation.gov.au/Science/ResearchInfrastructure/Pages/NCRIS.aspx
[6] http://www.ewater.com.au/products/ewater-toolkit/
[7] http://ausrivas.canberra.edu.au/
[8] http://www.asris.csiro.au/
[9] http://www.environment.gov.au/soe/index.html
[10] http://www.environment.gov.au/land/nlwra/index.html
[11] http://www.anra.gov.au/

GENERAL PRINCIPLES TO IMPROVE FUTURE MONITORING

Clear monitoring objectives or questions

All researchers interviewed stressed the importance of clarity around monitoring objectives. Identified purposes and objectives included:

- To track progress against defined management targets.
- To provide data for model calibration and/or verification, including deriving empirical relationships used in models. Examples include the estimation of microalgae growth rates, material fluxes, and ecological interactions such as competition or grazing rates.
- To inform risk assessments e.g. identifying new risks or monitoring the system to assess system status against risk assessment criteria.
- Make system-level assessments:
    - identify quantitative constraints set by hydrodynamic transport processes (including salinity stratification).
    - infer the state of autotrophy or heterotrophy
- Ground-truthing for interpreting remote sensing data.
- Filling identified knowledge gaps.
- Testing hypotheses or addressing well-posed questions e.g. what nutrients are limiting primary production?

The form of the data constrains what analyses are possible, and so limits the questions that can actually be answered. For example, recent nutrient and microalgal data were amenable to NMS ordination analysis conducted by Aldridge and Bookes (2011) and Aldridge and Payne (2012), but it is less clear how such data can be integrated into nutrient budgets or ecosystem state and transition modelling.

Long-term regular monitoring complemented by smaller, targeted field campaigns

For a long-term and integrated picture, piecemeal approaches to monitoring (short notice, restricted temporal and geographical extent, projects of narrow scope disconnected from each other) are less informative than coordinated long-term monitoring at designated sites with good regional coverage. Regular monitoring (e.g. monthly) complemented by more flexible additional monitoring in response to events or specific research questions (so accommodating the unexpected and uncertainties around funding or other influences) is a workable strategy. Such an approach is also useful for calibrating and validating models. The value of short term, restricted monitoring projects which are sometimes necessary due to various constraints, can be greatly enhanced if there is an underpinning modelling framework and measurements are made in a manner that ensures that they can be combined within the models.

In making future monitoring decisions, for the purposes of enabling analysis of long-term datasets, measuring data in ways that are consistent with what has come before (e.g. The Living Murray monitoring) should be a high priority. If measurement changes are needed, allowing a good overlap period would help allow impacts of changes in monitoring to be discerned.

Where long-term ecological monitoring has been possible the benefits are profound, and recent reviews by David Lindenmayer and Gene Likens have provided a good overview relevant to Australian systems with references to extensive literature on long-term ecological monitoring (Lindenmayer and Likens 2009; Lindenmayer and Likens 2010).

Other considerations and opportunities

Effective monitoring for integration ideally requires an inclusive process that involves all relevant parties and ensures a shared and consistent approach. The irregular, piecemeal and fragmented nature of funding and measurement opportunities makes it harder to ensure a shared, consistent, and long-term approach to monitoring.

Future research directions could include:

- Use of alkalinity, pH and dissolved oxygen to calculate pCO_2 and state of system autotrophy or heterotrophy. Currently this is not possible, but other locations (e.g. Moreton Bay) have become net autotrophic after floods and this is important for inferring biogeochemical function.
- High frequency CDOM measurements as a useful surrogate for DOC would help with interpreting remote sensing data and estimating the dissolved carbon budget. CDOM fluorescence informs chlorophyll and particle size.
- In general there is potential for automatic stations to learn more about variability. These would be deployed with the aim to learn more from short-term data (e.g. DOC, chlorophyll a and turbidity). For some applications 100 data points /day for a month might be more helpful (and cheaper) than 10 points in a year.
- There are promising remote sensing possibilities, especially given the higher temporal resolution and potential to track the spatial distribution of species such as *Ruppia* (and could allow rate of change of *Ruppia* to be a criterion informing management decisions). It is anticipated there would be particular difficulties due to the optical properties in the Coorong (and so would be more of a research effort rather than routine monitoring option at this stage).
- The state and transition modelling acknowledges the potential for there to be system thresholds – transitions to dramatically different states – however the statistical methods employed can only detect states that exist in the data and not infer unsampled states. Only the inclusion of process knowledge can help infer possible future ecosystem states that have not been observed previously. This is a particularly challenging research and management question, and is beyond the scope of this report to pursue further. Addressing these issues requires methods that pay particular attention to non-linearity and questions of system resilience (Folke, Carpenter *et al.* 2010; Scheffer, Carpenter *et al.* 2001; Walker and Salt 2012).

Discussion

Experience around the world points to major challenges and barriers to ensuring high quality, long-term ecosystem monitoring (see Lindenmayer and Likens (2010) for a good, recent review of ecological monitoring). Furthermore, even the most comprehensive monitoring programs only yield valuable outcomes for management if there is also investment in the analysis and interpretation of the monitoring data. Reports that provide little further analysis beyond reporting the raw monitoring data offer little in the way of system-wide insights useful for management. A finding of this review is that the most valuable, whole-of-system results have come from the investment in integrated frameworks for combining data and knowledge from multiple sources.

Past efforts at building such integrated frameworks in the Coorong– state and transition models, calibrated hydrodynamic models and system-wide nutrient budgets – were made possible because of a large, dedicated program (the CLLAMMecology research cluster). Similarly, a dedicated Acid Sulfate Soils Research Program has enabled the development of a hydro-geochemical model of the Lower Lakes. These modelling efforts relied upon existing monitoring programs to provide high-quality, frequent monitoring data. These programs of work have yielded not only valuable insights about the system itself, but about the technical requirements for such efforts at integration to be successful and a set of tools for doing so. It is harder for such outcomes to be derived from smaller, disconnected pieces of research. All researchers interviewed for this review emphasised the challenges of operating in an environment in which short, disconnected projects are the primary vehicle for making progress. Any forward planning for future monitoring and analysis needs to accommodate this reality rather than expect ideal conditions for long-term ecological monitoring and research.

All interviewed researchers stressed the importance of having clear monitoring objectives, and they each identified several objectives that spanned filling site-specific, immediate knowledge gaps through to providing whole-of-system, long-term system understanding. Many of these objectives can be met in the current operating environment: targeted, discrete field campaigns are amendable to variable and opportunistic funding structures (e.g. Table 4). The more challenging objectives of long-term, system-wide integration require a deliberate, coordinated strategy if they are to be achieved in this operating environment. Such a strategy needs to enable (a) ongoing, long-term, repeated measurements; and (b) an integrating framework for analysing and interpreting these measurements.

Table 4 Examples of monitoring objectives suited to targeted, discrete field campaigns

Example objectives amenable to targeted, discrete field campaigns
Ascertain whether shoreline measurements are representative of centreline measurements in the Coorong
Quantify the rates of exchange between North and South lagoons in the Coorong
Assess microalgae palatability to different prey species
Use high-frequency measurements to infer ideal sampling frequency
Make ground-truthing measurements for interpreting remote sensing data

The development of integrating frameworks is time-consuming and requires much coordination between different knowledge providers. The hydrodynamic modelling is an example of an integrating framework that once developed, has become a fundamental piece of research infrastructure. It provides ongoing benefit, so long as it is maintained and updated. Similarly, the state and transition modelling is an existing framework that can be updated and extended with new data and, together with the hydrodynamic modelling it, provides a demonstrated means for bringing together knowledge of the system hydrodynamics, salinity dynamics and ecological response.

These frameworks developed during the CLLAMMecology work can be extended to include more recent data: the hydrodynamic model has already been updated accordingly, for example. It is not clear if efforts to extend all aspects of that previous work would be successful, however, as there have been substantial changes to the monitoring in the time since the CLLAMMecology research cluster. The judgment of researchers interviewed for this review is that there is untapped potential to integrate more recent data into existing frameworks. There is the risk, however, that such efforts will be hampered by limitations inherent in the data. Experience to date is that the existing nutrient and microalgae monitoring data has been difficult to incorporate in this framework (Lester, pers. comm), yet nutrients and primary production are crucial mediators linking physical context to ecological response and so their incorporation into such frameworks is highly desirable. It remains an open question whether any attempt to make more use of existing nutrient and microalgae measurements in this way will be successful, especially as previous efforts have struggled, however it is recommended that the effort is made.

Therefore, a wise strategy for the Coorong into the future could be as follows. First, conduct any further efforts in interpreting existing nutrient and microalgae data by developing improved integrating frameworks that can (a) address difficulties experienced in previous attempts and (b) incorporate other relevant process knowledge such as knowledge of *Ruppia* habitat requirements and propagule stocks. In this way, if the data yield few new insights, the investment has produced a framework that will be useful for enabling system-wide inferences from future nutrient and microalgae measurements. Furthermore, creating that framework would clarify the technical requirements for more effective nutrient and microalgae monitoring into the future.

Similarly, the development of a hydro-biogeochemical modelling capability in the Lower Lakes has allowed the integration of many sources of monitoring data to make whole-of-system inferences, albeit with a focus on the risk of acid-sulfate soil exposure. Such modelling provides valuable underpinning infrastructure for interpreting microalgae and higher trophic-level species.

It is a healthy sign that in the CLLMM region different approaches for integrating knowledge have evolved, driven by different research questions. In particular, it is interesting to see that process-based hydro-geochemical modelling has been the emphasis in the Lower Lakes, while more statistical approaches have been developed in the Coorong. Maintaining both capabilities is a useful asset. Statistical approaches have significant limitations, especially when it comes to understanding the time-evolution of the system in conditions that have not been observed previously.

Lindenmayer and Likens (2010) summarise their review of best practice in ecological modelling by identifying the following core requirements: (1) good questions; (2) a conceptual model of the ecosystem; (3) strong partnerships between scientists, policy-makers and managers; and (4) frequent use of data collected. All these attributes have been a strong part of previous monitoring and analysis in the CLLMM region, particularly while the CLLAMMecology program was in place. The researchers interviewed for this review similarly place a high priority on 'good questions', and in general, question-driven research was seen as the best way to ensure an effective adaptive-monitoring capacity. Where Lindenmayer and Likens (2010) emphasise the need for a conceptual model, existing work in the CLLMM region has ensured that not only are there good conceptual models for the system, but these have been developed further into useful integrating modelling frameworks, thus addressing one of the most difficult challenges identified by Lindenmayer and Likens (2010): the means to integrate knowledge from multiple sources. Viewed in this light, the existing ecological monitoring in the CLLMM region already meets core criteria for effective long-term ecological monitoring. The main challenges identified in this review are the difficulties in including nutrient and microalgae data in the existing integrating frameworks, and the challenges associated with reduced monitoring and use of monitoring data since the end of the CLLAMMecology research effort. The recommendations from researchers interviewed as part of this review leads to a view that priorities for ongoing monitoring should involve question-driven research and an adaptive-monitoring strategy (Lindenmayer and Likens 2009), placing a strong emphasis on ongoing learning from the data.

Conclusion

In conclusion, reviewing past research in the CLLMM region points to the value of making conceptual models of the system explicit, thus providing an integrating framework and means to test hypotheses and address management questions. This review suggests the following general strategy into the future:

1. Maintain a set of clear, well evaluated monitoring objectives and review these objectives regularly in light of monitoring results as part of the adaptive management of the region. Ensure that these objectives are well communicated.
2. Identify those monitoring objectives that are amenable to opportunistic funding arrangements, and commission field campaigns to address these as and when funding allows.
3. Ensure any investments in interpretation of monitoring data place a high priority on maintaining and building upon the existing capacity for system-wide integrated assessment, including:
    a. Integration frameworks and tools, e.g. hydrodynamic modelling, state and transition modelling, budget frameworks, GIS tools, risk assessment frameworks, system resilience assessments.
    b. Coordinating between multiple knowledge providers.
    c. Improving the effectiveness of and access to data repositories.

4. Monitoring site locations and parameters into the future:
    a. As much as practicable, maintain consistency with sites and parameters monitored in the past: regular, repeated measurements over a long time are more readily incorporated into long-term, integrated assessments.
    b. When locations or parameters are changed, ensure a period of overlap so the effects of the changes can be discerned.
    c. Where possible, measure concentrations and exchange rates at input locations (ocean, barrages, drains and creeks), particularly during flow events, as these are key determinants of biogeochemical budgets.
    d. When selecting site locations, a greater spatial extent is more informative than dense spatial coverage of a more limited extent.
    e. Ongoing review of monitoring in light of new data and insights as part of the adaptive management for the region.

Specific steps consistent with this strategy include:

1. Maintain and extend existing frameworks for integration of multiple knowledge sources to make whole-of-system assessments. These are valuable research infrastructure and allow the most value to be derived from monitoring data. Such frameworks include: hydrodynamic modelling in the Coorong, nutrient budgets in the Coorong, state and transition modelling in the Coorong and hydro-biogeochemical modelling in the Lower Lakes. This could be done in two steps:
    a. Bring experts on particular biota and model developers together for a short assessment project (e.g. 10 days' work) to determine further benefits that can be derived from existing data sets and their incorporation into existing model frameworks. The intended outcomes would be (a) a set of key questions and objectives that could be addressed using existing data and updated or extended models; and (b) a work plan for updating or extending the models with existing data (e.g. ways of addressing difficulties experienced in previous attempts, and to incorporate knowledge such as habitat requirements).
    b. Implement the plan. If updating and extending to include more existing data yield few new insights, the investment has at least strengthened the capacity to make full use of existing data, and will clarify the technical requirements for more effective future work.
2. Link existing knowledge of *Ruppia* physical requirements to the existing hydrodynamic model and generate habitat suitability maps.
3. Calculate post-flood nutrient budgets using the updated hydrodynamic model.
4. Undertake a small field program aimed at testing whether shoreline measurements are representative of centreline concentration measurements.
5. Make continuous measurements of water level in the North and South Lagoon simultaneously with flow at Parnka Point to better inform the relationship between water level and flow between the two Lagoons.

Appendix A Interview notes

The following points are notes taken from interviews with researchers from University of Adelaide, Flinders University and CSIRO who have been involved in hydrodynamic modelling, nutrient and microalgae fieldwork and analysis, and ecosystem state and transition modelling in the Coorong and Lower Lakes. The interviews revolved around the following topics:

- Analysis and interpretation opportunities with current nutrient and microalgae data, particularly when integrating across knowledge and data sources and for making links to higher trophic levels.
- Considerations to improve future monitoring.

Each interviewee received a copy of the notes summarising their interview and made minor revisions to ensure their responses were well captured. There was considerable overlap in responses between the different interviewees: the dot points from all the interviews have been collated and grouped according to topics covered (retaining duplicate points made by different interviewees).

Analysis and interpretation opportunities for existing data

Important unknowns when interpreting existing data

- Some important unknowns that would help us learn more from the data:
    - Are shore concentration measurements representative of centreline concentration measurements?
    - The relationship between water levels and flow between the two lagoons.
- Important questions of the representativeness of data, eg. shore versus centreline measurements.
- Budget calculations can be distorted by measurement artefacts. For example, shore sampling risks detecting local effects only (e.g. if shore concentrations are not representative of the budget volume in question then there will be errors in the system-wide sources and sinks inferred). If there are significant groundwater and regional rainfall runoff inputs directly to the system then this too is a complicating factor (which can be addressed to some extent by taking vertical profiles).
- The material flux between the two lagoons is a key weakness in our understanding at the moment, and current and salinity measurements along with continuous flow measurements for a period of a month would give an independent means of inferring the mass balance.
- Better quantification of barrage and other inputs are needed. Good estimates of loads entering the system are a high priority.

Benefits of combining process-based and statistical methods

- Possible statistical analysis methods are determined by the nature of the data.
- If the objective is to seek empirical/data-driven relationships between flows and phytoplankton then is there an assumption that the relationship will be a simple one? There is no assurance that (a) such empirical relationships exist; and (b) such relationships would be useful if extrapolating to infer future system responses. Understanding causal mechanisms are important and allow us to infer more from measurements. For example, interpreting nutrient measurements in a budget framework provides valuable insights.
- We can't expect to infer ecological outcomes from hydrodynamic knowledge alone. Manipulating flows to the Coorong manipulates the nutrient dynamics and primary production, and these are important mediating steps in shaping the ecological outcomes. Equally, a statistical interpretation

linking ecological response directly to flow/water-level data misses the opportunity to include available knowledge of nutrient and primary production processes.

- Inferences from the data can be strengthened by bringing in knowledge about underlying causes of observed changes. For example, population response is typically shaped by important pre-conditions, such as viability of seed-banks or recruitment processes. Knowledge of these pre-conditions and the time-lags inherent in these processes allows for more powerful data interpretation (including making assessments of ecosystem health and resilience).

Ways to integrate existing diverse knowledge and data sources

- Getting the nutrient budget right is a bare minimum for making better interpretation of nutrient data. A budget is not static, and the higher temporal resolution of the budget the better. Nutrient budgets were constructed only for drought period. It would be instructive to re-do nutrient budgets given post-flood nutrient data. Previous analysis shows the importance of having barrage flow and ocean concentrations when calculating system budgets. Budgets require much better quantification of input loads. Irrespective of future program this should be an immediate priority. Budgets are useful because they provide insights to fluxes, sources and sinks. If seeking to manage nutrient conditions, knowledge of key sources and sinks is particularly helpful as action can be better targeted as a result. A budget is a useful integrating device, converting point observations into system behaviour.
- *Ruppia* habitat:
    - *Ruppia* is a key species to focus on as it serves several roles in the system: it provides food and habitat, it is a component of primary production and it competes for light and nutrients.
    - *Ruppia* responds to salinity and water level variations and these in turn are related to barrage flows, however the relationship is not simple. Barrage flows, water level and salinity are not simply related and our knowledge of their interactions is best encapsulated in physical (hydrodynamic) models. Similarly, barrage flows and phytoplankton interact in multiple ways. Even considering nutrient response alone there are time lags.
    - There is the opportunity to link knowledge of *Ruppia* physical requirements to the existing hydrodynamic model and generate habitat suitability maps. Further more, it would be possible to include knowledge of time lags (e.g. once *Ruppia* has died in a particular location, a return to suitable conditions will see *Ruppia* re-established only after a time delay). Such an approach could also be possible for phytoplankton, invertebrates and other species (using knowledge of salinity ranges, for example).
    - *Ruppia* germination issues. An absence of viable stock of *Ruppia* propagules is a problem regardless of nutrient and salinity conditions, so any inference about *Ruppia* response needs to account for these requirements and ensure a good characterisation of requisite conditions, the dependence on the time course of previous conditions (e.g. for build up of viable propagules) and potential hysteresis.
- An understanding of ecosystem functioning or biotic connections is instructive for inferring higher trophic level implications. For example, when the South Lagoon switched from fish to brine shrimp the bird life also shifted.
- Data-sets for various ecological components should be analysed together to identify major patterns and identify major drivers of the ecological response. This could be used to identify important research questions. e.g identifying linkages between water quality and organisms, identifying linkages between lower trophic and higher trophic organisms.

- Despite limitations, there are opportunities to learn more from the existing data. Previous ecosystem state-and-transition modelling could be repeated with more recent data.
- Opportunities for better integrating existing knowledge from different sources – e.g. repeating budget work in light of recent post-flood measurements, biogeochemical/benthic chamber work, isotopic work, gut analyses for higher trophic level response. For example:
  - The Budget results could be brought into comparison with the benthic chamber measurements. Do they agree? For example, if the budget says there is a source of DIN does the benthic chamber also show a flux from the sediments?
  - How do the gut analyses compare with the isotopic signatures of predator and prey?
- Hypothesis testing is an effective way of gleaning more from data. Given a range of hypotheses, which is most consistent with the data?

Features of the hydrodynamic model

- The one-dimensional hydrodynamic model is now at a 1km resolution. This has increased the flexibility for generating hydrodynamic information that is configured to link with measurements from diverse monitoring locations.
- The existing two-dimensional hydrodynamic model for the Coorong is time-consuming to run and so presents challenges for calibration and validation. The 1D model readily allows multiple runs and can be run within an optimisation framework.

Observations about existing monitoring

- In general, the most valuable monitoring data for modelling work have been those measurements that are repeated in time and space (and across all variables of interest) according to well-considered monitoring design. A lack of such consistency makes interpretation difficult, particularly if the intention is to integrate multiple sources of data to gain a better system understanding. The absence of repeated data has meant that some existing measurements are of less value than they could be.
- Quarterly nutrient data is not frequent enough given the rates of change associated with nutrient dynamics and algal response in particular. The range of relevant time scales when developing an integrated picture is challenging, and currently there are insufficient high-frequency data to inform optimal monitoring requirements. It is possible that event-driven monitoring may be more effective than regular (e.g. weekly) monitoring.
- Previous modelling work has been able to link water level and salinity to higher trophic level response thanks to sufficient water level and salinity measurements. It was not possible to include many of the microalgae measurements, for example, as the data were not in a form that was compatible with the modelling framework used. Similarly, nutrient data were too infrequent to infer their influence on ecological response.
- Effective monitoring for integration ideally requires an inclusive process that involves all relevant parties and ensures a shared, consistent approach. The irregular, piecemeal and fragmented nature of funding and measurement opportunities makes it harder to ensure a shared, consistent, long-term approach to monitoring.
- Even where clear monitoring design criteria have been set and agreed to, there are cases where the protocols were not followed and data could not be used as a result.

Data housing and access

- Existing processes within DEWNR, MDBA and EPA for storing and accessing datasets are sufficient, although had some experience of project data sets not being stored sufficiently.

- Data sharing arrangements are important, particularly when it comes to pooling data from multiple sources. Intellectual property issues have hampered some attempts at integrated analysis. Efforts that see good provider agreements and shared data housing arrangements are welcome.

Considerations to improve future monitoring

Monitoring objectives

- Need to have clear objectives. What questions are being asked and how does the monitoring help address those questions? Barrage flows affect the system in many ways, including changing salinity, water level and nutrient dynamics, and these have different and interacting impacts on the biota. When managing the system it is important to understand the contributions of each of these factors. Data are useful for distinguishing between a multitude of hypotheses and conceptualisations of how the ecosystem is being impacted by flow timing and volumes.
- Monitoring is most effective when designed in response to specific questions and objectives, or to track measurements against targets. Scientists' working hypotheses may not be well-aligned with management or monitoring objectives, so it's important to be clear about these objectives. Monitoring objectives can be used:
    - To track progress against defined management targets.
    - To provide data for model calibration and/or verification.
    - To inform risk assessments (e.g. identifying new risks or monitoring the system to system status against risk assessment criteria).
- Useful insights come from asking intelligent questions that are informed by research findings and monitoring data.
    - e.g. research informing what phytoplankton are being consumed by whom would be helpful for setting targets for desirable phytoplankton species, and setting up monitoring to track progress against the targets.
    - e.g. what are the important ecological links and the predetermining physico-chemical factors enabling those links?
    - e.g. what are important knowledge gaps?
- Monitoring needs to be designed to be consistent with purpose and to take into account problems associated with what is measured. For example, many of the measurements are below limits of detection. If nutrient-limited then chances of detecting any dissolved inorganic nutrients are low and only light-limitation will see the detection of nutrients.
- An important purpose of monitoring is to inform system-level understanding of dynamics and responses to events. This is usually made possible via mathematical frameworks, and these frameworks make the most of observations when measurements meet particular requirements. Measurements that are inconsistent with these requirements often need to be discarded, representing a lost opportunity.
- It is important to be clear about the data requirements for adequately addressing a question. Often there simply are not sufficient measurements to be able to answer the question with any confidence.

Future monitoring: benefits of long-term, regular monitoring complemented by smaller, targeted field campaigns

- For a long-term, integrated picture, piecemeal approaches to monitoring (short notice, restricted temporal and geographical extent, projects of narrow scope disconnected from each other) are less informative than coordinated long-term monitoring at designated sites with good regional coverage. Regular (e.g. quarterly) monitoring with additional monitoring in response to events is a workable strategy. Such an approach is also useful for calibrating and validating models.

- Data should be compared between years (regular long-term data sets) can be very powerful in identify trends and patterns.
- Small, targeted measurement programs would do a lot to address critical unknowns. For example, a month of measuring water levels and flow between the two lagoons would allow the construction of relationships between water level and flow. If the measurements could be made at two different times in the year it would allow the relationships to capture low and high water level conditions.
- There is no doubt that long term over-arching monitoring programs are vital (e.g. Chesapeake Bay).
- Ideal situation: an over-arching, consistent program of measurement that is complemented by a more flexible, targeted program of measurements designed to address specific questions.
- Existing monitoring efforts are at a level where any reduction in measurements results in significant loss of knowledge about the system.
- Inferring nutrient dynamics requires at least monthly monitoring and to infer seasonal variability a higher frequency is needed.
- Monitoring should be integrated better with other ecological monitoring (e.g. ruppia, zooplankton).
- In making future monitoring decisions, keep measuring data in ways that are consistent with what has come before (e.g. TLM monitoring) should be a high priority. If measurement changes are needed, at least ensure a good overlap period so that impacts of the changes can be discerned.
- It is advisable to have routine monitoring that provides a solid base of regular, repeated measurements in time and space, complemented by targeted experiments that aim to address specific questions and hypotheses.

Other opportunities

- Remote sensing possibilities, especially given the higher temporal resolution and potential to track the spatial distribution of *Ruppia* (and so allows rate of change of *Ruppia* to be a criterion informing management decisions). Points to another role for the monitoring – ground truthing for remote sensing work. Anticipate particular difficulties due to the optical properties in the Coorong (and so would be more of a research effort at this stage).
- Potential for automatic stations to learn more about variability. These would be designed to get more short term data, e.g. DOC and its variations as a tracer of water movement, Chl a can be detected, and high frequency turbidity measurements are also possible. 100 data points /day for a month might be more helpful than 10 points in a year. It could be much cheaper also.
- Future research directions:
    - measurements of alkalinity, pH and DO to calculate pCO_2 and autotrophy/heterotrophy. Currently not able to do this. Moreton Bay example – rapidly became net autotrophic after flows and this is important for inferring biogeochemical function. If always heterotrophic then it means the system is running down. It is a key indicator of ecosystem performance/carbon balance/metabolism.
    - DOC/CDOM. CDOM a useful surrogate for DOC, can be measured at high frequency and helps with both remote sensing and dissolved carbon budget. CDOM fluorescence informs chlorophyll and particle size.

Appendix B Task brief

Proposal: Review of reports on the microalgae and nutrient conditions within the Coorong and Lower Lakes.

Client: DEWNR SA.

Task Outline:

1. Read and review reports provided by DEWNR on the microalgae and nutrient conditions within the Coorong and Lower Lakes.
2. Comment on the analyses and conclusions of the various reports and gauge their contribution to the development of an integrated understanding of the interactions between microalgae and nutrient conditions and implications for higher order ecological and site management of the Coorong and Lower Lakes.
3. Set these reports in the context of other key studies of the microalgae and nutrient conditions within the Coorong and Lower Lakes.
4. Develop a view based on the DEWNR reports, other key studies, and through interviews with key authors of the reports and studies as to whether the historical data provides opportunities for further analyses that will lead to greater understanding of the interactions between microalgae and nutrient conditions within the Coorong and Lower Lakes.
5. Provide a conceptual description of additional analyses that could be undertaken to better understand the interactions between nutrients and broader groups of micro-organisms including zooplankton, or with key organisms such as Ruppia, or with ecological processes such as primary production.
6. Based on these considerations and following discussions with key authors of previous research, suggest whether changes are needed regarding the monitoring locations, parameters and frequency of sampling to improve the data set available for analysis.

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