Recommended actions for restoring the ecological character of the South Lagoon of the Coorong

Justin Brookes, Paul Dalby, Sabine Dittmann, Jody O'Connor, David Paton, Rebecca Quin, Daniel Rogers, Michelle Waycott and Qifeng Ye *(alphabetical order)*

Goyder Institute for Water Research
Technical Report Series No. 18/04

www.goyderinstitute.org

Goyder Institute for Water Research Technical Report Series ISSN: 1839-2725

The Goyder Institute for Water Research is a partnership between the South Australian Government through the Department for Environment and Water, CSIRO, Flinders University, the University of Adelaide, the University of South Australia and the International Centre of Excellence in Water Resource Management. The Institute enhances the South Australian Government's capacity to develop and deliver science-based policy solutions in water management. It brings together the best scientists and researchers across Australia to provide expert and independent scientific advice to inform good government water policy and identify future threats and opportunities to water security.

The following Associate organisation contributed to this report:

Enquires should be addressed to: Goyder Institute for Water Research
Level 4, 33 King William Street
Adelaide, SA 5000
tel: 08 8236 5200
e-mail: enquiries@goyderinstitute.org

Citation

Brookes, J., Dalby, P., Dittmann, S., O'Connor, J., Paton, D., Quin, R., Rogers, D., Waycott, M., and Ye, Q. (2018). *Recommended actions for restoring the ecological character of the South Lagoon of the Coorong*. Goyder Institute for Water Research Technical Report Series No. 18/04, Adelaide, South Australia. ISSN: 1839-2725.

Disclaimer

Contents

Figures

Tables

Acknowledgments

The independent reviewers are thanked for their constructive feedback. The reviewers were Professor Peter Fairweather (Flinders University), Associate Professor Mike Geddes (The University of Adelaide), Dr Matt Gibbs (Department for Environment and Water and The University of Adelaide), Dr Klaus Joehnk (CSIRO), Dr Anupama Kumar (CSIRO), Dr Luke Mosley (University of Adelaide) and Dr Jason Nicol (SARDI).

Thank you also to Dr Kane Aldridge (Goyder Institute for Water Research) for scoping the project and supporting the Expert Panel prepare the report and Andrew Beal (DEW) and Sandy Carruthers (DEW) for establishing the management context for the project.

Executive summary

The Coorong is considered to be the most important waterbird wetland in the Murray-Darling Basin. It has been degraded to the point where it is at risk of losing the key elements which make it such an iconic wetland of local, national and international importance.

On top of a long-term decline in the condition of the site due to water extractions, the Coorong was substantially damaged during the Millennium Drought. Several characteristics of the Coorong have undergone a substantial and sustained change. Most notably this has included large reductions in the abundances and some waterbirds, particularly fairy tern and migratory shorebirds. This is associated with the prevalence of filamentous algae that is preventing aquatic plants from completing their life-cycle and interfering with the ability of waterbirds to feed on both plants and invertebrates in mudflats. The system is now in a vulnerable state and may have little capacity to absorb continued and cumulative environmental stress resulting from water extractions and changes in climate.

Managers currently have a number of 'levers' available to them to manipulate water levels and salinity. These include River Murray environmental flow provisions, barrage operations, Murray Mouth dredging and flows from the South-East of South Australia. However, managers have little capacity to confidently forecast the ecological responses due to critical knowledge gaps. There is a risk that well-intentioned management could exacerbate the vulnerability of the system and result in a permanent loss of some species. To address the immediate threats to the South Lagoon and give managers the ability to manipulate the management 'levers' available to them without causing long-term harm, a number of actions are recommended in the short term. These are in addition to **environmental water recovery and successful implementation of the Murray-Darling Basin Plan**, which have been well documented as critical for condition of the site. The additional short-term actions recommended by the Expert Panel are:

1. **Protect and increase waterbird populations by creating nurseries for aquatic plants within the South Lagoon and increasing habitat and food resources in the broader landscape**

   The South Lagoon has been a high-quality habitat for waterbirds because of the extensive mudflats and presence of abundant and accessible food sources, such as invertebrates (e.g. chironomids), fish and aquatic plants. Reduced inflows from the River Murray have led to sub-optimal water levels and water quality and the loss of food sources for waterbirds. Consequently, waterbird abundances, in particular shorebird abundances, have declined dramatically. It is hypothesised that the loss of aquatic plants and degraded water quality allowed filamentous algae to thrive, further reducing the abundance of aquatic plant and waterbird communities.

   The establishment of plant nurseries throughout the South Lagoon of the Coorong is recommended to build-up the populations and propagules that can be used to reseed larger areas of the South Lagoon. This action will bind nutrients to help reduce nutrient availability for phytoplankton and filamentous algae, provide food resources for waterbirds including shorebirds, and will assist with the repopulation of aquatic plants, particularly *Ruppia tuberosa*.

   It is also recommended that new habitat areas for waterbirds should be created and protected in adjacent areas such as the Lake Alexandrina, Lake Albert and the South-East of South Australia.

2. **Undertake trials to shift the system from algal dominated to aquatic plant dominated**

   Without a shift from algae to aquatic plants, the South Lagoon cannot support the abundance of food that makes this wetland productive for birds and fish. Furthermore, the presence of algae increases the risk that the sediments become anoxic, exacerbating the nutrient problem and increasing the build-up of sulfidic materials, which are also toxic. There is a poor understanding of how to shift the South Lagoon back to a plant dominated system, and a lack of agreement within the scientific community on the best approach. To overcome this lack of knowledge, we recommend the following short-term trials (not in priority order):

   A. *Undertake a comprehensive survey of the distribution and abundance of aquatic plants and algae across the South Lagoon.*

B. *Laboratory trials investigating the effects of nutrients (in water and sediment), salinity, turbidity and temperature on the relative performance of algae and plants and nutrient cycling.*

C. *Create physically isolated ponds along the South Lagoon and trial the effect of different salinities and water levels on the plant/algal dominance based on the outcomes of the laboratory trials.*

D. *Laboratory tests and trials within the South Lagoon to test approaches of lowering nutrient levels in the water column such as bubbling oxygen into the water and adding materials for binding nutrients.*

E. *Trial the effectiveness of mechanical removal of filamentous algae.*

F. *Investigate the effectiveness of native filter feeders and bioturbators (especially molluscs) and aquatic plants to reduce nutrients and turbidity in the Lake Alexandrina, Lake Albert, North Lagoon and Upper South-East before the water reaches the South Lagoon.*

G. *In the current 2018-19 season, manipulate flow, salinity and water levels in the South Lagoon to favour plants over algae - informed by hydrodynamic and habitat modelling.*

3. **Improve our knowledge on nutrient cycling and how to maximise nutrient turnover into productive elements such as plants, invertebrates, fish and birds and incorporate knowledge into a response strategy**

   Once the immediate knowledge gaps have been addressed, there is a medium-term challenge to shift the system to being more aquatic plant dominated and less phytoplankton and filamentous algal dominated. The shift from plants to algae is considered to be partly due to and elevated nutrient levels in the water column and sediments. There is little understanding of the relative importance of nutrient sources and sinks and the role of internal cycling. Furthermore, there is limited understanding of how nutrients pass from primary producers to waterbirds, which is required to inform the likely responses to different management actions. To address this, a coordinated program of research, planning and investigation is required, including the following:

   A. *Undertake research on the nutrient sources and sinks, nutrient transport processes, biogeochemistry and foodweb dynamics of the ecosystem.*

   B. *Develop a response strategy to restore the ecological values of the Coorong that incorporates new knowledge on nutrient cycling and foodwebs.*

   This program should also incorporate recommended action two. Importantly, this should also include the establishment of **an agreement with the Murray-Darling Basin Authority and Commonwealth Environmental Water Holder to enable the delivery of environmental flows to the site until the end of summer**.

4. **Undertake a climate change vulnerability assessment of the Coorong and implement climate adaptation activities for the region**

   To retain a high abundance of waterbirds and fish in this internationally and nationally significant refuge site, careful management will be required to address the impacts of climate change, including likely temperature increases, rainfall and river flow decline, more frequent extreme climate events (e.g. droughts) and sea-level rise. The following actions are recommended to support the ecosystem to adapt to climate change over the long-term:

   A. *Undertake a climate change vulnerability assessment of the Coorong to identify which components of the ecosystem are most vulnerable to climate change and the adaptation that is required to maintain ecological function and values of the site.*

   B. *Implement management interventions for the Coorong through the Ramsar Management Plan to ensure the ecological condition of the ecosystem is enhanced into the future.*

Although out of scope, the Expert Panel also identified that **promoting the value of the Coorong as a national treasure** that supports waterbird communities across the continent and internationally would be highly valuable. This would facilitate the support of all Australians in the protection of this valuable habitat and ensure that sufficient resources and water are provided to sustain the health of the Coorong.

To ensure that the important ecological values of the site are not lost, it is recommended that these actions begin immediately.

1 Context

The Coorong is widely regarded as a unique and important wetland that provides important ecological, cultural, social and economic values at local, national and international scales. Along with Lake Alexandrina, Lake Albert and the Murray Mouth (Figure 1), the Coorong was listed as a Ramsar wetland of International Importance in 1985. This requires the Australian and South Australian Government's to maintain the ecological character of the site. There is considerable evidence to suggest that the ecological condition of the Coorong has been steadily degrading since European settlement and that the "Millennium Drought" was a major disturbance causing a rapid decline in condition. Whilst the relatively recent increase in natural and managed inflows to the Coorong have improved the condition of some ecological values, there is evidence to suggest that other values have not recovered or have continued to decline, particularly those of the South Lagoon.

Given this, the South Australian Minister for Environment and Water and the South Australian Department for Environment and Water sought the following scientific information from the Goyder Institute for Water Research:

- Advice on the status of the ecological character of the South Lagoon of the Coorong; and
- Recommended actions for the ecological character of the South Lagoon of the Coorong.

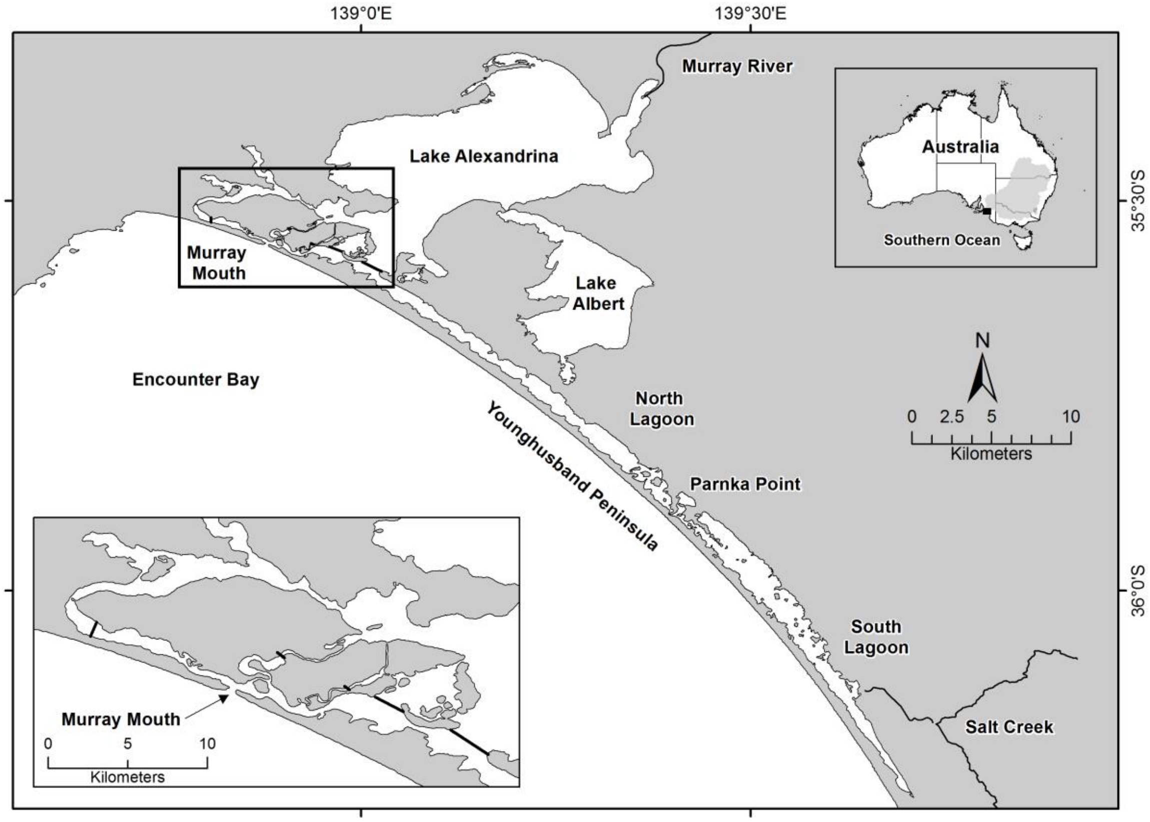


Figure 1. Map showing the Coorong, and Lakes Alexandrina and Albert Wetland, including the Murray Mouth and Coorong North and South Lagoons.

2 Approach

An Independent Expert Panel was established with expertise covering various ecological components of the South Lagoon of the Coorong: water quality, plants, algae, invertebrates, fish and waterbirds.

A facilitated workshop was held to discuss the advice and recommendations. This workshop was facilitated by the preparation of background material regarding the conceptual understanding of the South Lagoon ecosystem and its current condition (Appendix 1).

The draft report was circulated to a Peer Review Committee who also have extensive research experience with the Coorong. The members were:

- Professor Peter Fairweather (Flinders University);
- Associate Professor Mike Geddes (The University of Adelaide);
- Dr Matt Gibbs (The University of Adelaide);
- Dr Klaus Joehnk (CSIRO);
- Dr Anupama Kumar (CSIRO);
- Dr Luke Mosley (University of Adelaide); and
- Dr Jason Nicol (SARDI).

Feedback from the Peer Review Committee was sought on whether the recommended actions were scientifically defensible; whether there were any major risks to the recommended actions and any major gaps in the recommended actions. All comments were considered by the Expert Panel and a final report was prepared.

The information contained within this report represents the outcomes of the overall approach. The final recommendations are those where there was agreement amongst the Expert Panel and Peer Review Committee. David Paton was not able to actively participate following the expert panel workshop due to being on sick leave and so the final recommendations may not necessarily represent his views entirely.

Additional workshop notes regarding critical risks and key knowledge gaps identified by the Expert Panel are included in Appendix 2. Additional data used to support the views of the Expert Panel are included in Appendix 3.

3 Summary of the key issues identified by the Expert Panel

The Coorong, along with Lakes Albert and Alexandrina, is one of Australia's most important wetland areas (Phillips and Muller, 2006). The site supports a high abundance and diversity of wetland fauna, particularly waterbirds (Phillips and Muller, 2006). The Coorong is an important non-breeding habitat for global migratory shorebirds. For some shorebird species, the Coorong has historically supported up to 20% of the global non-breeding population (Paton et al., 2009). During drought periods the Coorong is the most important refuge for migratory and non-migratory waterbirds across the Murray-Darling Basin and hosted 90% of waterbirds in the Basin during the 'Millennium Drought' (Kingsford and Porter, 2008).

This abundance and diversity of life is underpinned by a high diversity of wetland habitats. In the Coorong, the typical salinity gradient (Figure 2) from the north (estuarine-marine) to the south (hypersaline) is a key component that characterises the diversity of habitats and biota across the system (Paton et al., 2009).

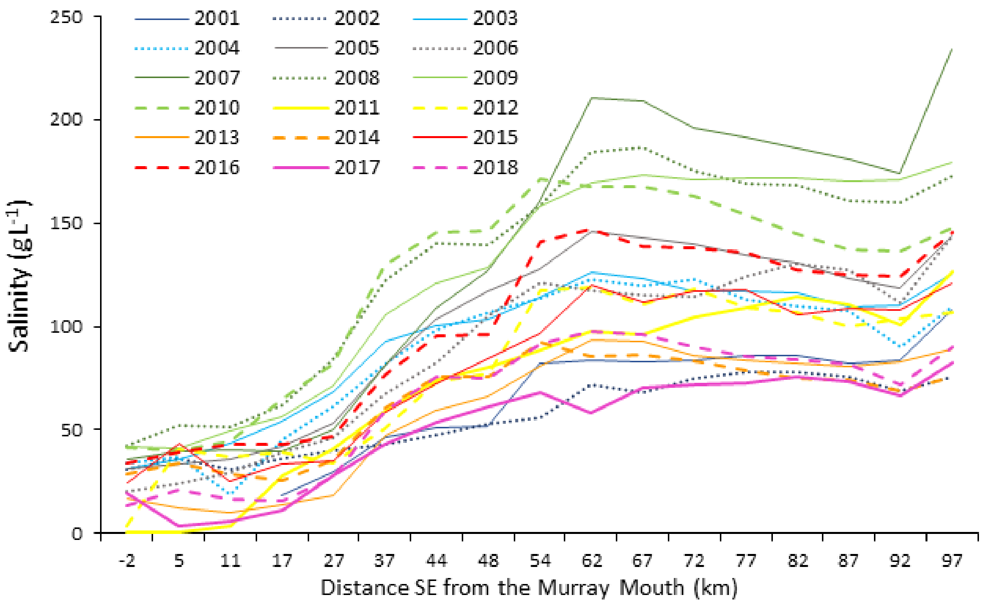


Figure 2. Salinity levels in January along the Coorong from 2001 to 2015. Position along the Coorong is defined as distance from the Murray Mouth, where negative values are north-west of the Mouth and positive values are south-east. The junction of the North and South Lagoons (Parnka Point) is at kilometre 59.

The Coorong has experienced major changes to its hydrology in the last few decades because of upstream water extractions and prolonged dry periods (e.g. Millennium Drought). These changes have resulted in long-term declines in flow, which have changed the water levels and the quality of water within the South Lagoon. Where historically aquatic plants dominated the South Lagoon, algae now dominate (Paton et al. 2018a). The shift from plants to algae is speculated to be due to a combination of a reduced flooding of the mudflats in late spring and early summer and increased nutrient availability.

Ruppia tuberosa is the dominant macrophyte in the South Lagoon, indicative of the plant's capacity to cope with a wide range of salinities (Brock, 1982). Elevated salinities (>65 g/L) in the South Lagoon would limit interference of algae on *Ruppia tuberosa* (Paton et al. 2017a) and provides ideal habitat for chironomid larvae and ostracods, which are particularly important food resources for shorebirds (Paton et al. 2018a).

The reduction in extent of aquatic plants has led to a loss of habitat and food resources, particularly for shorebirds, for which the seeds and turions of *Ruppia tuberosa* are thought to be an important source of food (Paton et al. 2015). The shift in dominance from aquatic plants to algae has reduced access to foraging habitat for waterbirds (Paton et al. 2018a). While the decline in abundance of *Ruppia tuberosa* is thought to be reasonably well understood, what is less well understood is the relationship between aquatic plants, algae, and the interacting effects of salinity, temperature, water level, and particularly nutrients. To restore key ecological components and processes of the site, a better understanding of how to shift the system towards an aquatic plant dominated state is needed. Understanding of how to maintain the invertebrate communities that have been highly abundant food resources for waterbirds, and particularly international migratory birds is also required. There is some disagreement amongst scientists about the salinity regime that should be maintained in the South Lagoon to achieve the desired outcomes. This is an indication of uncertainty in the ecological response to different salinity regimes given the current condition of the site and will be addressed through the recommended actions.

Managers of the site face novel challenges for how to manage the site in the future. There is no precedent for how to manage this site given the high levels of algae, the unique salinity regime and physical nature of the South Lagoon. The historic management regime aimed to maintain and improve key elements of the system, but now must contend with how to *restore* the system to a more desirable state (i.e. more suitable habitat for migratory shorebirds, extensive *Ruppia* beds etc.) that supports the site's amazing biodiversity into the future. This requires thinking about the *system* as a whole, including inter-relations with the Lower Lakes (Lake Alexandrina and Lake Albert), the South-East of South Australia (herein the South-East), groundwater, the Southern Ocean, rather than just managing individual elements (e.g. water level, salinity). This may require using our available management 'levers' differently (e.g. River Murray environmental flow provisions, barrage operations, Murray Mouth dredging, flows from the South-East), or using different 'levers' in the future. However, such a shift in strategy needs to be done prudently, both by understanding the risk of current and future management options and by improving our understanding to reduce this risk.

4 What is the status of the ecological character of the South Lagoon of the Coorong?

The South Lagoon of the Coorong is a permanent waterbody that is connected to the North Lagoon by a narrow channel at the northwest end near Parnka Point. Water levels vary seasonally by approximately 0.9 m, being higher in winter and lower in summer. This results in the seasonal exposure of extensive areas of mudflats and limiting water exchange between the North and South Lagoons. The site has supported an abundant and diverse waterbird community across various life stages, which was the primary criteria for the site's Ramsar listing. This is attributed to the provision of mudflat foraging habitat and isolated islands that are in proximity to fish, as well as a diversity and abundance of invertebrates in the water column and sediments.

A summary of the current condition of the South Lagoon ecosystem that was prepared by the Expert Panel is shown in Table 1. Based on this information, it is the view of the Expert Panel that the key ecological features that make this system unique and valuable are still in place, including the north-south salinity gradient, the large areas of mudflat habitat, and the species of plants, invertebrates, fish and birds. However, the concentration, abundance and distribution of many parameters and species have dramatically altered. Because of all of the pressures described in the preceding section, the system is now in a vulnerable state. It is the view of the Expert Panel that the South Lagoon now has little capacity to absorb continued and cumulative environmental stress.

Table 1. Status of the ecological character of the South Lagoon (compared to status at the time of its Ramsar listing).

Component/value	Details
Flow sources	• Inflows from the River Murray have declined, which has reduced freshening flows of water into the Coorong. This has resulted in a drop in water height across the mudflats in spring, which historically supported expansive areas of foraging habitat for waders. • South-East flows are now introducing fresher water at the high end of the salinity gradient.
Salinity	• Salinity in South Lagoon increased during the Millennium Drought, but is now beginning to recover to pre-drought levels (Figure 2). • A spatial and temporal salinity gradient exists within South Lagoon, typically increasing from north to south (Figure 2). The salinity gradient supports diverse biota because there is a diversity of habitats and food resources supported by different salinities. • The salinity gradient has been altered over the last 5 years (Figure 2) with freshwater inflows from the South-East freshening the southernmost part of the lagoon compared to levels during the Millennium Drought but are within historical ranges (Geddes and Butler, 1984).
Water quality	• High turbidity, caused by phytoplankton, particulate organic matter and suspended solids, reduces the productivity and reproduction of aquatic plants. Turbidity is high in the South Lagoon because of the high concentrations of organic material due to eutrophication. Sediments may also be remaining suspended more in the water column because the density of macrophytes is low.

	• Water column nutrients were elevated during the Millennium Drought (Appendix 3) and seem to be recovering to pre-drought levels (Appendix 3). The elevated levels may have contributed to be the cause of excessive growth of phytoplankton and filamentous algae. Whilst monitoring suggests water column levels are recovering to pre-drought levels there is limited understanding of role of sediments in providing additional sources of nutrients.
Aquatic plants	• While aquatic plants are still present, they have shown limited recovery since 2009. Algae now dominate the primary productivity of the South Lagoon, which has the potential to prevent further recovery. When water levels recede, the algae form a dense mat that excludes foraging shorebirds, and creates low-oxygen conditions in sediments, killing invertebrates and raising the risk of the build-up of sulfidic material (Appendix 3).
Waterbirds	• The abundance of some shorebird species appear to be recovering from the major reduction during the Millennium Drought. Numbers of shorebird are below, and some well below, their long-term median abundances. Some shorebird and other waterbird species (e.g. Curlew Sandpiper) have not recovered since the drought broke (Paton, Paton and Bailey, 2018b). • Shorebirds are spending 80% of their time foraging, indicative of poor resource levels (Paton et al., 2018b) with reduced numbers of chironomid larvae and *Ruppia tuberosa* seeds and turions (Paton et al. 2018b).
Fish	• There has been an increased abundance of small-mouth hardyhead (a key small-bodied prey fish species) and a general increase in fish species diversity compared to that during the Millennium Drought (Ye et al. 2015). • There is a lack of knowledge of variability in 1980s, with the majority of research data collected from 2006. Commercial fishery data suggest a greater fish species diversity and abundance in late 1980s.
Macro-invertebrates and foodwebs	• Since 2015, the South Lagoon has supported 1-6 benthic macro-invertebrate species with very few individuals only (Dittmann et al. 2017). The low diversity and abundance are due to high salinities (>64 ppt), hypoxic conditions, high sediment organic matter and low sediment chlorophyll a conditions (Dittmann et al. 2015; 2017; Appendix 3). Total abundances and diversity of macroinvertebrates are not considered the best indicator of food sources for shorebirds as not all invertebrates are available to shorebirds. • Polychaetes were recently detected near the southern end of the South Lagoon for the first time in 33 years but these are unlikely to be accessible to shorebirds due to limited tidal influence. • Greatest chironomid abundance is found in junction of the North and South Lagoons, which is correlated with higher salinities and higher abundances of bird species that feed on chironomid larvae (e.g. red-necked stint, sharp-tailed sandpiper and red-necked avocet). Chironomid abundances were much lower in 2018 than in previous years. • In January 2018, the fish community near Salt Creek switched from being dominated by surface dwelling fish (e.g. small-mouth hardyhead) to bottom-dwelling fish (e.g. congolli). Successful breeding of Fairy-terns requires their primary food source (hardyhead) to be abundant near their traditional breeding islands in the southern Coorong (Paton et al. 2018b).

5 Recommended actions for restoring the ecological character of the South Lagoon of the Coorong

To restore the ecological character of the South Lagoon of the Coorong, management is required to sequentially:

1) avoid the permanent loss of ecological values of the South Lagoon of the Coorong;
2) restore the ecological values of the South Lagoon of the Coorong; and
3) create an ecosystem that maintains the ecological values under climate change.

Central to these actions is the restoration of aquatic plants and particularly *Ruppia tuberosa*, which is considered critical to the functioning of the South Lagoon ecosystem due to its importance to waterbirds and the maintenance of water quality (e.g. turbidity, nutrients, dissolved oxygen).

Ultimately the Expert Panel agreed that the following hydrological and ecological conditions were required to achieve these outcomes:

- Manage a temporally dynamic salinity gradient from north to south in the South Lagoon without having permanent, fixed bounds around these salinities.
- Manage for high water levels in spring-early summer to ensure *Ruppia tuberosa* can complete its life cycle and provide seeds and turions as food for shorebirds.
- Reduce the abundance and distribution of filamentous algae.
- Change 'nutrient pathways' from algae back to aquatic plants.

To achieve these outcomes and address the immediate threats to South Lagoon and give managers the ability to manipulate the management 'levers' (e.g. River Murray environmental flow provisions, barrage operations, Murray Mouth dredging, flows from the South-East) available to them without causing long-term harm, the below actions are recommended by the Expert Panel in the short term. These are in addition to **environmental water recovery and successful implementation of the Murray-Darling Basin Plan**, which have been well documented as critical for condition of the site.

1. Protect and increase waterbird populations by creating nurseries for aquatic plants within the South Lagoon and increasing habitat and food resources in the broader landscape

A. Identify and maintain/restore priority sites for aquatic plants, particularly Ruppia tuberosa

The establishment of plant nurseries throughout the South Lagoon of the Coorong is recommended to build-up the populations and propagules that can be used to reseed larger areas of the South Lagoon. This action will bind nutrients to reduce nutrient availability for phytoplankton and filamentous algae, provide food resources for waders and waterbirds, and will assist with the re-population of aquatic plants, particularly *Ruppia tuberosa*. Creating and maintaining these nurseries will require active management to reduce algae (see action 2 below) and potentially herbivory. While algal removal may be an intensive process, the approach may be valuable for assisting the creation of suitable nursery areas for aquatic plants. Any translocations of aquatic plants (including propagules) should only occur if high water levels can be secured through spring and water quality maintained within preferred ranges.

This action will also allow for testing the potential for larger-scale interventions for restoration.

<u>Scientific rationale:</u>

- The decrease in abundance and distribution of aquatic plants from the South Lagoon is a reduction of food and habitat for waterbirds (Paton et al. 2017a).
- It is the experience globally that a lack of aquatic plants in wetlands leads to high nutrient availability, which then encourages algal growth (Collier et al. 2017).

- Aquatic plants utilise nutrients as they grow and so reseeding areas of the system may also help address reducing available nutrients.
- *Ruppia tuberosa* populations are currently unable to complete their life-cycles due to competition with filamentous algae (Paton et al. 2017a).

B. Protect and create new waterbird habitat areas in adjacent areas

This should explore the potential of establishing high-value habitat outside the Coorong area in Lake Alexandrina, Lake Albert and the South-East to complement habitat for waterbirds. Steps to implement this action include:

- Establishing an inventory of possible habitats in the Lower Lakes and South-East wetland systems.
- Feasibility assessments of restoring existing habitats to create better conditions for highly valued species at risk within the Coorong.
- Trials into the feasibility of managing wetlands across the surrounding region to provide complementary habitat for highly valued species at risk within the Coorong.
- Managing adjacent wetlands in a coordinated manner to maximise feeding and breeding habitat for domestic and migratory shorebirds and waterbirds.

These additional habitats need to be integrated with management of the South Lagoon to maximise the ecological outcomes across the broader landscape.

<u>Scientific rationale:</u>

- At the time of listing, the South Lagoon was a superb habitat for waterbirds because of the extensive mudflats and high abundance of food sources such as invertebrate Chironomid larvae, *Ruppia tuberosa* seeds and turions and small-mouth hardyhead fish (e.g. Rogers and Paton, 2009).
- The loss of food sources and difficulty of maintaining appropriate water levels on the mudflats due to reduced flows in the River Murray has contributed a decline in abundances of some waterbird species (Paton et al. 2017b)
- The wetlands of the South-East provide important habitats for waterbirds (e.g. Bachmann et al. 2016) and the reduction in their extent and condition may also contribute to the declining habitat and resources for waterbirds in this region.
- Climate change impacts are likely to have a significant effect on the South Lagoon (e.g. sea level rise, lower flows, warmer water temperature) (Lester et al., 2013).
- Conservation strategies recommend spreading the risk of species survival by ensuring there are multiple but connected habitats for individuals to make use of if one area of habitat experiences a strong disturbance event.

2. Undertake trials to shift the system from algal dominated to aquatic plant dominated

Without a shift from algae to aquatic plants, the South Lagoon cannot support the abundance of food that make this wetland productive for waterbirds and fish. Furthermore, the presence of algae increases the risk that the sediments become anoxic, exacerbating the nutrient problem and increasing the build-up of sulfidic materials, which are also toxic. There is a poor understanding of how to shift the South Lagoon back to a plant dominated system, and a lack of agreement within the scientific community on the best approach. To overcome this lack of knowledge, we recommend the following short-term trials (not in priority order):

A. Undertake a comprehensive survey of the distribution and abundance of aquatic plants and algae across the South Lagoon.
B. Laboratory trials investigating the effects of nutrients (in water and sediment), salinity, turbidity and temperature on the relative performance of algae and plants and nutrient cycling.
C. Create physically isolated ponds along the South Lagoon and trial the effect of different salinities and water levels on the plant/algal dominance based on the outcomes of the laboratory trials.

D. *Laboratory test and trials within the South Lagoon to test approaches of lowering nutrient levels in the water column such as bubbling oxygen into the water and adding materials for binding nutrients (e.g. zeolites - a clay mineral with high surface area that binds nutrients). This should include isolating bays in the South Lagoon with fences of shade-cloth to keep filamentous algae from accumulating.*
E. *Trial the effectiveness of mechanical removal of filamentous algae.*
F. *Investigate the effectiveness of native filter feeders and bioturbators (especially molluscs) and aquatic plants to reduce nutrients and turbidity in the Lower Lakes, North Lagoon and Upper South-East before the water reaches the South Lagoon.*
G. *In the current 2018-19 season, manipulate flow, salinity and water levels in the South Lagoon to favour plants over algae. The best strategy to do this should be informed by hydrodynamic and habitat modelling. This may include the use of environmental water to support barrage releases in summer to maintain high water levels in the South Lagoon to enable aquatic plants to complete their lifecycle. This should include monitoring the response in populations, the chemistry of the water, conditions in the sediments and impacts on fish, invertebrates and birds.*

Scientific rationale:

- See scientific rationale for action 1B.
- The presence of algae increases the risk that the sediments become anoxic exacerbating the nutrient problem and increasing the risk of build-up of sulfides which are toxic at high concentrations.
- There is a poor understanding of how to shift from algal dominated to plant dominated in this particular site, but reducing nutrient loads is highly likely to be an important step.
- Whilst preferred salinity and water levels for *Ruppia tuberosa* and filamentous algae have been identified (Appendix 1; Collier et al. 2017), there is little knowledge regarding the combined effects of salinity, water level and nutrients on the interactions between *Ruppia tuberosa* and filamentous algae.
- Without a shift of from algae to aquatic plant dominance, the South Lagoon cannot support the abundance of food that makes this wetland so productive for return to an ecological state that provides abundant food resources to birds and fish (Paton et al. 2017b).

3. Improve our knowledge on nutrient cycling and how to maximise nutrient turnover into productive elements such as plants, invertebrates, fish and birds and incorporate knowledge into a response strategy.

A. *Undertake research on the nutrient sources and sinks, nutrient transport processes, biogeochemistry and food web dynamics of the ecosystem.*

Once the immediate knowledge gaps and actions have been addressed, there is a medium-term challenge to shift the system to being more aquatic plant dominated and less phytoplankton and filamentous algal dominated. The shift from plants to algae is considered to be partly due to and elevated nutrient levels in the water column and sediments. There is little understanding of the relative importance of nutrient sources and sinks and the role of internal cycling. Furthermore, there is limited understanding of how nutrients pass from primary producers to waterbirds, which is required to inform likely responses to different management actions. To address this, a coordinated program of research, planning and investigation is required, that also incorporates the actions in recommendation two.

To inform management decisions regarding the implications of various management actions, knowledge is needed to:

- Undertake a comprehensive sediment quality survey to assess distribution of key parameters (e.g. organic carbon, nutrients, sulfides, redox potential, contaminants) at a whole of system scale.

- Understand the mass balance of nutrients flowing into and out of the Coorong with consideration of River Murray inflows, South-East Flows, Murray Mouth openness, groundwater inflows, and resuspension dynamics due to wind action and legacy nutrients in the sediments.
- Understand the internal biogeochemistry under different salinity and water level conditions, and different benthic communities.
- Understand the seasonal changes in nutrient, salinity and water levels required to sustain the critical Coorong foodweb of plants, invertebrates, fish and birds.
- Assess the potential to flush nutrients from the system using available management 'levers'.

This research should result in coupled hydrodynamic, geomorphic, ecological and biogeochemical models for the Lower Lakes, Coorong and Upper South-East.

<u>Scientific rationale:</u>

- The excessive growth of filamentous algae indicates excessive nutrient availability in the Coorong.
- It is likely that the sediments are a significant source of nutrients supporting this excessive growth but there is little research to support this. Furthermore, there is little knowledge available to support management decisions regarding the relative contributions of the River Murray, South-East flows, wind induced resuspension, groundwater and the Southern Ocean to the nutrient loads and the internal storage.
- Interactions between salinity, water levels and nutrients are the key drivers of the ecosystem (Appendix 1), but the interactive effect of these parameters is unknown and there is little specific knowledge to guide management.
- There is a build-up of organic matter and sulfide (black oozes) and anoxia in sediment due to eutrophication and a lack of bioturbation due to the extreme levels of salinity that were experienced during the drought (Dittmann et al., 2016). In the absence of oxygen, nutrients are released at higher rates from the sediment to the water where they can promote algal growth. The algae eventually die and sink and are broken down in the sediment which consumes oxygen, the cycle continues and is hard to break without active intervention.
- Depending upon the prevailing salinity, the abundance and diversity of invertebrate communities at the base of the foodweb will change. Understanding how a change in salinity may affect the food resources available for the migratory waders is a key step in determining the variable salinity gradient necessary to satisfy a range of ecological objectives. Bioturbation by larger invertebrates (e.g. worms, molluscs) can also help to oxygenate the sediment and promote the storage of nutrients and other contaminants within sediments. Understanding the influence of salinity on bioturbation is an important component of understanding nutrient fluxes from sediments.

B. Develop a response strategy to restore the ecological values of the Coorong that incorporates new knowledge on nutrient cycling and foodwebs.

The response strategy should guide the restoration, management and maintenance of the ecological character and wise use of the site. It should outline the management actions required to achieve ecological targets and avoid management triggers and limits of acceptable change. The response strategy should be implemented as part of the site's revised Ramsar Management Plan and consider the current conditions, actions recommendations above and be adaptive to consider forecasted climatic conditions (informed by recommendation 4 below). For example, it should consider:

- Operations of management 'levers' for managing appropriate salinity, nutrient and water levels, to support ecological values, including the re-population of *Ruppia tuberosa* from nursery habitats that are actively managed in bays along the South Lagoon.
- The optimal water level and salinity regime once *Ruppia tuberosa* populations are re-established with consideration to the appropriate timing and volume of South-East flows.

- Mechanisms for minimising nutrient levels in inflows from the River Murray and South-East (e.g. catchment/farm management activities, passing water through wetlands before it reaches the Coorong to enable uptake of bioavailable nutrients).
- Murray Mouth dredging regime, including the potential to increase or decrease dredging activity to increase water levels within the South Lagoon.

The response strategy should include:

- The management goals and objectives agreed for the site;
- The suite of activities underway and planned to meet these objectives (within an adaptive management framework); and
- Arrangements for the measurement and monitoring and evaluation of progress.

Importantly, this should include the establishment of **an agreement with the Murray-Darling Basin Authority and Commonwealth Environmental Water Holder to enable the delivery of environmental flows to the site until the end of summer**. Appropriate water levels and the salinity gradient in the South Lagoon of the Coorong are required to allow successful reproduction of *Ruppia tuberosa* and establish resilient populations. This is currently limited by an inability to deliver environmental flows to the region in summer.

Scientific rationale:

- See scientific rationale for recommendations 1A and 1B.

4. Undertake a climate change vulnerability assessment of the Coorong and implement climate adaptation activities for the region.

To retain a high abundance and diversity of waterbirds and fish in this internationally and nationally significant refuge site, careful management will be required to address the impacts of climate change, including likely temperature increases, rainfall and river flow decline, more frequent extreme climate events (e.g. droughts) and sea level rise. The following actions are recommended to support the ecosystem to adapt to climate change over the long-term:

A. Undertake a climate change vulnerability assessment of the Coorong to identify which components of the ecosystem are most vulnerable to climate change and the adaptation that is required to maintain ecological function and values of the site.

Scientific rationale:

- Climate change is considered a major risk to the site due to potential impacts of reduced inflow, sea level rise and increased temperatures, which are known to be important drivers of the ecosystem.
- Climate change will likely have multiple compounding impacts, but these impacts are unknown.
- Whilst some modelling of potential changes in the ecosystem state of the Coorong has been undertaken (Lester et al., 2011, 13), there remain many critical knowledge gaps with no action plan in place to manage key risks.
- Without action, adjacent waterbird habitat is likely to be reduced under climate change, increasing the importance of the Coorong as a major feeding and breeding habitat.

B. Implement management interventions for the Coorong through the Ramsar Management Plan to ensure the ecological condition of the ecosystem is enhanced into the future.

Using the evaluation of previous actions, undertake a feasibility assessment of larger scale interventions in the South Lagoon of the Coorong, including but not limited to:

- Large scale reseeding of aquatic plants, removal of filamentous algae and nutrient reduction strategies to reduce nutrient availability.

- The creation and management of additional wetland habitats for managing high-risk components of the Coorong ecosystem.
- Structures, pumps or other management ‘levers’ to regulate South Lagoon salinities and water levels so that there is foraging habitat for migratory shorebirds and so that aquatic plants remain inundated when they are reproducing.

Scientific rationale:

- See scientific rationale for actions 1A, 1B and 4.

Although out of scope, the Expert Panel also identified that **promoting the value of the Coorong as a national treasure** that supports waterbird communities across the continent and internationally would be highly valuable. This would facilitate the support of all Australians in the protection of this valuable habitat and ensure that sufficient resources and water to sustain the health of the Coorong.

To ensure that important ecological values of the site are not lost, it is recommended that these actions begin immediately.

References

Bachmann M, White J, Paton D, and Taylor B (2016). Exploring how restored flows to the wetlands of the northern Bakers Range Watercourse can benefit the Coorong Ramsar site. Nature Glenelg Trust, Wetlands and Wildlife, University of Adelaide and Department of Environment, Water and Natural Resources, Adelaide, South Australia.

Brock MA (1982). Biology of the salinity tolerant genus Ruppia L. in saline lakes in South Australia II. Population ecology and reproductive biology. *Aquatic Botany* 13:249-268.

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

Dittmann S, Baring R, Baggalley S, Cantin A, and others (2015). Drought and flood effects on macrobenthic communities in the estuary of Australia's largest river system. *Estuarine, Coastal and Shelf Science* 165:36-51.

Dittmann S, Baring R, and Ramsdale T (2016). Macroinvertebrate monitoring, analysis and synthesis for Coorong and Murray Mouth locations, Final report and response on Key Monitoring Questions. Report for the Department of Environment, Water and Natural Resources, Adelaide.

Dittmann S, Jessup-Case H, lam Gordillo O, and Barin, R (2017). Benthic macroinvertebrates survey 2016-17: Coorong and Murray Mouth Icon Site. Report for the Department of Environment, Water and Natural Resources and the Murray-Darling Basin Authority.

Geddes MC and Butler AJ (1984). Physiochemical and biological studies on the Coorong Lagoons, South Australia, and the effects of salinity on the distribution of the macrobenthos. *Transactions of the Royal Society of South Australia* 108, 51–62.

Kingsford RT and Porter JL (2008). Survey of waterbird communities of the Living Murray icon sites – November 2007. Final report to the Murray Darling Basin Commission.

Lester RE, Webster IT, Fairweather PG, and Young WJ (2011). Linking water-resource models to ecosystem-response models to guide water-resource planning – an example from the Murray-Darling Basin, Australia. *Marine & Freshwater Research* 62(3): 279-289.

Lester RE, Fairweather PG, Webster IT, and Quin RA (2013). Evaluating scenarios involving future climate and water extraction: ecosystem states in the estuary of Australia's largest river. *Ecological Applications* 23:984–998.

Paton DC, Paton FL, and Bailey CP (2015). Ecological Character Description for *Ruppia tuberosa* in the Coorong. School of Biological Sciences, University of Adelaide, South Australia.

Paton DC, Paton FL and Bailey CP (2017a). Monitoring of *Ruppia tuberosa* in the southern Coorong, summer 2016-17. University of Adelaide, Adelaide.

Paton DC, Paton FL, and Bailey CP (2017b). Condition monitoring of the Lower Lakes, Murray Mouth and Coorong Icon Site: Waterbirds in the Coorong and Lower Lakes 2018. The University of Adelaide and The Department of Environment, Water and Natural Resources.

Paton DC, Paton FL, and Bailey CP (2018a). Monitoring of *Ruppia tuberosa* in the southern Coorong, summer 2017-18. University of Adelaide, Adelaide.

Paton DC, Paton FL, and Bailey CP (2018b). Condition monitoring of the Lower Lakes, Murray Mouth and Coorong Icon Site: Waterbirds in the Coorong and Lower Lakes 2018. The University of Adelaide and The Department of Environment, Water and Natural Resources.

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

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

Rogers DJ and Paton DC (2009). Spatiotemporal Variation in the Waterbird Communities of the Coorong. CSIRO, Water for a Healthy Country National Research Flagship, Canberra.

Phillips W and Muller K (2006). Ecological Character of the Coorong, Lakes Alexandrina and Albert Wetland of International Importance. South Australian Department for Environment and Heritage, Adelaide.

Ye Q, Bucater L and Short D (2015). Fish responses to flows in the Murray Estuary and Coorong during 2013/14. SARDI Research Report Series No. 884.

Appendix 1. Conceptual description of the South Lagoon of the Coorong

BACKGROUND

Ramsar Listing of the Coorong, and Lakes Alexandrina and Albert Wetland

The Coorong, and Lakes Alexandrina and Albert wetland was designated a wetland of international importance under the Ramsar Convention in 1985. The Ramsar Convention covers all aspects of wetland conservation and wise use, and recognises wetlands as ecosystems that are extremely important for biodiversity conservation and for the wellbeing of human communities.

At the time of listing, the site was in a state of decline from the impacts of extensive water extraction from the Murray–Darling Basin since the late 1800s and the installation of barrages to separate the lakes from the estuary in the 1930s. Extracting high volumes of water for human use has reduced end of River Murray system flows.

From late 1996 to mid-2010 much of southern Australia, including the Coorong region, experienced a prolonged period of dry conditions (known as the Millennium Drought). This, combined with the early impacts of climate change, added to the site's ecological stress.

The current Ecological Character Description (ECD) published in 2006 (Phillips and Muller, 2006), indicated that the site had been undergoing ecological decline for a considerable period prior to listing, and that this ecological decline has been accelerated and exacerbated by unsustainable water extractions (in the Murray-Darling Basin). Despite these declines, the site continued to meet eight of the nine Ramsar criteria for listing at the time.

Following the completion of the 2006 ECD the South Australian Government advised the Australian Government that the site had undergone a change in ecological character. Subsequently, a notification of a change in character was made to the Ramsar Secretariat by the Australian Government as the Convention's Administrative Authority.

It was broadly assumed in 2009/10 that the site was adversely affected, severely by the Millennium Drought and preceding development in the Murray-Darling Basin. The majority of experts and community expected that the Coorong and Lakes ecology and its ecological character was permanently altered. With this in mind, an updated description of the site's ecological character was undertaken in collaboration with local scientific experts to identify the critical components, processes and services, an assessment and substantiation of changes to the character since Ramsar listing.

DISCUSSION

High-level description of the character of the South Lagoon ecosystem

The Coorong South Lagoon is a permanent waterbody that is connected to the North Lagoon by a narrow channel at the northwest end. Water levels vary seasonally by approximately 0.9 m, being higher in winter and lower in summer, resulting in the seasonal exposure of extensive areas of mudflats. The provision of mudflat foraging habitat and island breeding refuges (in proximity to fish prey) have supported an abundant and diverse waterbird community across various life stages, which was the primary justification for the site's initial Ramsar listing.

Table 1 below provides a high-level description of the historical character and current characteristics. Table 2 provides a more detailed description of the character of the South Lagoon and changes since the 1980s (where possible). Recent data and expert opinion indicate that many of the characteristics of the South Lagoon are returning to a state, or level more like those prior to the Millennium Drought (e.g. Ye et al. (2015), O'Connor (2015), Oliver et al. (2015), Paton et al. (2015a), Paton et al. (2017a and b), Table 3). However, several characteristics have undergone a sustained change, most notably changes in the submergent halophyte vegetation, Coorong foodweb, and some waterbirds, particularly fairy tern and migratory shorebirds, including curlew sandpiper (O'Connor (2015), Paton et al. (2015b), Paton et al. (2017a and b)). These changes demonstrate that some characteristics of the South Lagoon have undergone long-term decline and are not representative of levels at the time of listing.

It is uncertain how resilient the system will be to future impacts from climate change and human-induced change. Whilst the site is still recovering, some of the ecological character may not return to the state prior to the Millennium Drought.

Table 2. Description of the historical (1980s) and current characteristics of the South Lagoon.

Theme	Historical characteristics (1980s)	Current characteristics
Fish	• Lack of knowledge of variability in 1980s, majority of research data collected from 2006. • Commercial fishery data suggested at least 17 fish species present in the South Lagoon from mid to late 1980s • Large numbers of smallmouthed hardyhead were present in the mid-1980s (Geddes 1987)	• Smallmouthed hardyhead is the dominant species. Increased distribution, abundance and recruitment was observed post-drought compared to mid-2000s (Ye et al. 2012) • At least ten other native species also occur in the lagoon (Ye et al., 2015; L&C commercial fishery data) • Greater fish diversity observed from 2011-2014 compared to drought years (e.g. 2006-2007) (Ye et al. 2015)
Vegetation	• Submergent halophytes affected by drought in early 1980s but recovered to be 'extensive' in the mid 1980's (Geddes & Butler 1984, Geddes 1987) • Dominant species includes *R. tuberosa,* and *Lamprothamnium papulosum.* Also present were *R. megacarpa*, *and Leilaena cylindrica* (Lester et al. 2013) • Presence of hypersaline lagoon community characterised by *L. papulosum* was included on the initial Ramsar listing	• Submergent halophyte diversity has declined: now dominated by *R. tuberosa* and *Lepilaena* (Collier et al. 2017). • Recent increases in distribution & abundance of *R. tuberosa* (Paton et al., 2017a). • *R. tuberosa* is limited by inadequate seed bank and presence of filamentous green algae, which disrupts reproduction (Paton et al. 2017a)
Waterbirds	• 21 regularly supported species (O'Connor 2015) • Limited breeding data for 3 tern species and Australian pelican (O'Connor et al., 2013, Paton, 2003) • 1985 survey counted >150,000 birds (Paton and Rogers 2009) • 1980s shorebird surveys indicated consistently high numbers of individual species (O'Connor 2015)	• 21 regularly supported species (O'Connor 2015, Paton et al., 2017b) • Improvement in the size and success of breeding events for terns and Australian pelican post-drought (Paton and Paton 2016) • Post drought counts ranged from 28,000-94,000 (O'Connor 2015, Paton et al., 2015, 2016, 2017b) • Some species, particularly migratory shorebirds, have experienced significant declines since the 1980s (Paton et al. 2009) • Fairy tern & curlew sandpiper occur at ~15% and <5% of their 1980s populations respectively (DEWNR data unpublished)
Physical habitat	• Diversity of wetland types that provided mudflat habitat for shorebird foraging, island breeding refuges and fringing vegetation for roosting (Phillips and Muller 2006)	• Diversity of wetland types continues to be provided (DEWNR unpublished) • Islands continue to provide waterbird breeding habitat (Paton and Paton 2016) • Recent high flow conditions (2010-11 and 2016-17) limited available mudflat habitat for waterbird foraging (Paton and Bailey 2011, Paton et al. 2017b) • Widespread filamentous green algae was observed, eliminating habitat and access to food for shorebirds in some areas (Paton et al. 2017b)

Theme	Historical characteristics (1980s)	Current characteristics
Water quality	• Salinity varied widely from 40ppt to >100 ppt in the early 1980s (Geddes and Butler 1984) • Mean total phosphorus was 110.5 mg m^{-3} in April and 87.3 mg m^{-3} in November 1982 (Geddes and Butler 1984) • Mean chlorophyll a values 21.6 mg m^{-3} and 29.2 mg m^{-3}, with no clear patterns along the lagoon (Geddes and Butler 1984)	• Recent salinity levels (2010-2018) ranged from 55-122 ppt, with an average of 80 ppt (DEWNR Hydstra data) • Nitrogen identified as the primary limiting nutrient; and total nutrient loads tied to organic components of the whole ecosystem (Collier et al. 2017)
Macro-invertebrates	• Macroinvertebrate data limited, with records indicating dominance of halophytic diptera and salt-lake crustacean species (Geddes and Butler 1984)	• Macroinvertebrate populations remain depleted due to high salinities (>64 ppt), low to hypoxic conditions, higher organic matter and lower chlorophyll a (Dittmann et al. 2015; 2017) • Since 2015, the South Lagoon has supported 1-6 species with very few individuals only (Dittmann et al. 2017)

Table 3. Summary of the ecological character of the South Lagoon, including a description of their importance to the system (value), drivers of the character, and changes in the character and the basis of the assessment of these changes.

South Lagoon ecological character		Value Ecological, social, cultural and economic	Drivers	How has the South Lagoon been tracking?	Source of information
Fish	**Diversity**	A critical component of the system, providing a number of services and benefits, including: - Key elements in food webs, including as food source for Ngartjis (i.e. pelicans) - Important species for local recreational and commercial fisheries; - Contribute to site biodiversity; and - Cultural value to Ngarrindjeri as part of their living culture, both as food source and connection to their spiritual beliefs. Characterised by 1-10 native fish species.	Driven by: • flow regime; • connectivity; and • salinity Decreasing species richness with increasing salinity.	Not considered to have changed significantly over time, but considerable spatio-temporal variation in response to freshwater inflows and changes in salinity are evident.[1] • Lack of knowledge of variability in 1980s, majority of research data collected from 2006. • Diversity reduced in Millennium Drought with hypersaline conditions, only low numbers of smallmouthed hardyhead recorded[1]. • Post-2010 return of freshwater inflows associated with increase in fish diversity and the abundance of smallmouth hardyhead.[1] • Greater fish diversity observed between 2011-2014 than during the Millennium Drought.[1]	Ye et al. 2015
Vegetation	**Submergent halophytes**	A critical component of the system, providing a number of services and benefits, including: - Key element in foodweb; - Provision of habitat; and - Contribution to sediment retention, carbon and nutrient cycling.	Main drivers of distribution include: • water levels; and • salinity Other drivers include: • water temperature; • light limitation; • nutrient supply; and, sediment condition (anoxia).	Submergent halophyte diversity in the South Lagoon has declined since the 1980s[7,9], with *R. tuberosa* the dominant species since 1970s.[6,7] • *R. tuberosa* growth was limited and sparse in early 1980s[4], but extensive in 1984 as salinities reduced.[5] • Distribution and density of *R. tuberosa* declined between 2000 and 2010, and recorded as completely absent in 2010.[7] • Significantly increased in distribution from 2011 and 2014[3], but recovery of abundance is slow due to absence of effective seed bank.[9] 2017 data showed improved cover and abundance of *R. tuberosa*[10], and current observations suggest that a mixed *R. tuberosa* and *Lepilaena cylindrocarpa* occurs in the South Lagoon (Van Dijk & Collier pers. comms. 2017). Historical records of filamentous green algae occurring along macrophyte beds and bottom of lagoon were observed.[4] Recent presence of filamentous green algae has disrupted reproduction, affecting resilience within the system[10].	[3]Frahn & Gehrig 2015 [4]Geddes & Butler 1984 [5]Geddes 1987 [6]Lucas & Womersley 1973 [7]Nicol 2005 [8]Paton & Bailey 2011 [9]Paton et al., 2015 [10]Paton et al., 2017a

South Lagoon ecological character		Value Ecological, social, cultural and economic	Drivers	How has the South Lagoon been tracking?	Source of information
Waterbirds	**Diversity**	A critical component of the system, characterised by: - 21 regularly supported species (Table A6.1) - Diversity of species across functional groups, including shorebirds, waterfowl and piscivores. One of primary reasons for the site's Ramsar listing.	Driven by: • water levels; and • salinity Decreasing species richness with increasing salinity or extreme water levels.	All 21 regularly supported species that were present in the 1980s are still detected in current monitoring. However some are present in much lower abundances.[10,11,12] • Diversity was affected during the drought: caspian terns were undetected in 2004 as were red-necked avocet in 2009[11] • Post-drought, 2 species were absent in the Jan 2011 survey but all 21 species were present from 2012-2017[10],[11,13,14,15].	[11]O'Connor2015 [12] DEWNR (unpublished) [13]Paton et al., 2014 [14]Paton et al., 2015b [15]Paton et al. 2016
	Breeding	A critical process that also provides critical services supported by: - Islands that provide key nesting habitat for breeding waterbirds (Table A6.2); and - Annual nesting for five species, including the threatened fairy tern. The South Lagoon was identified as one of either wetlands in the MDB as critical to supporting waterbird breeding in wet years.[22] Waterbirds are Ngarrindjeri Ngartjis and their successful breeding is fundamentally connected to Ngarrindjeri wellbeing and reproduction.	Driven by: • water levels (affects connectivity of islands); and • salinity (drives food availability).	Overall, waterbird breeding continues at the site but there have been noticeable declines in the magnitude and/or success of breeding attempts for some species. • Breeding data from the 1980s and 1990s is lacking, but some successful events were recorded for fairy, caspian and crested terns, and the Australian pelican.[16, 17] • During the Millennium Drought, few breeding attempts were successful mainly due to the loss of island refuges and fish prey. Notably, breeding attempts by the Australian pelican were unsuccessful from 2003-2005[18], and for Fairy Tern from 2004-05.[18] • Recent breeding success observed for Australian pelican, fairy tern, caspian tern and crested tern.[19,20] • One quarter of the 2017 fairy tern population were young recruits from the previous breeding season[21]	[16] O'Connor et al., 2013 [17]Paton 2003 [18]Paton 2005 [19]O'Connor 2015 [20]Paton & Paton 2016 [21]Paton et al. 2017b [22]Bino et al. 2015
	Abundance	A critical component of the system that incorporates: - High total waterbird abundance (typically 25-000-90,000 birds); and - Migratory shorebirds that are present in abundances >1% of their international flyway population. One of primary reasons for the site's Ramsar listing.	Driven by: • water levels; and • salinity Abundance of most species decreases with increasing salinity and extreme high or low water levels.	There have been declines in abundance of some waterbird species both before and after Ramsar listing. • 1985 survey detected >150,000 waterbirds[24]. • ~25,000-65,000 waterbirds were detected annually from 2000-2010.[11] 85% of species that were common in 1985 had declined by 2000-2007.[23] • Extreme hypersaline conditions & availability of brine shrimp in 2009 attracted >200,000 banded stilt [24]	[23]Paton et al. 2009 [24]Paton & Rogers 2009 [25]Paton & Bailey 2014 [26]Paton et al. 2015b [27]Paton et al. 2016

South Lagoon ecological character		Value Ecological, social, cultural and economic	Drivers	How has the South Lagoon been tracking?	Source of information
				• From 2011-2015, total abundances ranged from 36,000-67,000[11, 25,26], with a relatively high count of 94,000 birds in 2016, [27] and a low count of 28,000 birds in 2017 due to high water levels[10]	
	Priority wetland and threatened spp.	Supporting priority and threatened species is a critical service that supports: - Threatened waterbird species (Table A6.3); and - Migratory shorebirds listed on international agreements (Table A6.4).	Driven by: • water levels; and • salinity Abundance of most species decreases with increasing salinity and extreme high or low water levels.	The abundances of four priority migratory shorebirds (listed on international agreements) and at least two threatened species have declined since the site was Ramsar-listed in 1985.[11,23,28] • Fairy terns have experienced substantial declines since 1985 and were not supported in the South Lagoon during the drought[29]. • Curlew sandpiper did not meet site-specific flyway contributions[12] in 2004-05, and red-necked stint also declined in the mid-2000s.[23,28] • All four priority migratory species and fairy tern have shown modest increases in abundances since 2012, although none are detected in comparable numbers to that observed in the 1980s[10,11,12,26,27] • Curlew sandpiper is now recorded in the Coorong at 9% of its long-term median abundance[21] and failed to meet site-specific flyway contributions again from 2008-14[12]. • Fairy tern abundances have improved in the past 7 years, with successful breeding events in most years since 2011, however the population is still only two-thirds of its size from the turn of the century[21]. • Numbers of 3 additional priority species have shown little improvement post-drought and remain at relatively low abundances compared to the 1980s [10,12,14,15]	[28]Paton 2010 [29]Paton & Rogers 2009
Physical habitat	**Diversity of wetland type**	The complexity of physical wetland habitat types provides a critical service by supporting: - High biodiversity values of the site; - Waterbird foraging, roosting and breeding; - Feeding grounds for fish; and - Part of Ruwe/Ruwar.	Driven by: • hydrological regime, including frequency and magnitude of inundation	Extent and diversity of wetland types in the 1980s is unknown. Baseline for the diversity of wetland types was established in 2003.[30] • South Lagoon continued to support diversity of wetland types since 2003.[31] • Characteristics of intertidal mudflats and saline lagoons experiences change during the drought.	[30]Seaman 2003 [31]Butcher & Brooks 2015

South Lagoon ecological character		Value Ecological, social, cultural and economic	Drivers	How has the South Lagoon been tracking?	Source of information
		Characterised by six major types, including intertidal mudflats and saline lagoons.[23]			
	Roosting and foraging habitat for waterbirds	Providing habitat for waterbirds to roost and forage is a critical service that includes: - Shoreline mudflats: foraging habitat for shorebirds; - Islands and fringing vegetation: roosting refuges; - Provision of critical 'summer' refuge habitat, particularly important in dry years; and - One of primary reasons for the site's Ramsar listing.	Driven by water levels and salinity.	• Availability and quality of habitat was severely affected during the Millennium Drought (i.e. very low water levels, and loss of macroinvertebrate prey throughout much of the mudflat habitat).[28] • In spring 2010 and 2016, large unregulated flow events led to very high south lagoon water levels, and mudflat habitat became inaccessible to shorebirds.[27,32] • Apart from the two years of very high water levels, the availability these mudflat habitats has improved.	[32]Paton & Bailey 2011
	Breeding habitat for waterbirds	Provides a critical service supporting: - Island breeding sites that provide refuge from predators and access to food (fish); - Shoreline nesting habitat for beach-nesting birds; - Ongoing provision of services to support annual breeding; and - One of primary reasons for the site's Ramsar listing.	Driven by water levels and salinity.	• Thousands of crested terns and Australian pelican nests and 40-100 fairy tern nests were recorded annually in the 1980s.[16] • Very low water levels during the Millennium Drought resulted in the loss of island refuges after they became connected to the mainland and accessible by terrestrial predators.[29] • Water levels have been adequate to maintain disconnect between islands and the mainland since late 2010.	
Water quality	**Salinity**	Salinity is a critical component of the system and a stressor, which can influence: - Biotic reproductive processes; and - Biotic distribution, abundance and community structure.	Driven by: • North Lagoon inflows; • North Lagoon water quality; • rainfall on the lagoon surface; • evaporation; and	Salinity data has varied significantly since the1980s[4,5], attributed predominantly to variation in barrage flows, as well as increased evaporation during the Millennium Drought. • From 1975-1977 the southern end of the South Lagoon showed fluctuations in salinity from around 40ppt-70ppt.[4] • Salinity varied widely from 40ppt to >100ppt[4] in the early 1980s, with the brief period of high flow from the Murray in 1981 having little effect on salinity in the South Lagoon.[4] • Salinity in 1982 was particularly high and representative of hypermarine conditions.[4]	[33]Mosley et al. 2017

South Lagoon ecological character		Value Ecological, social, cultural and economic	Drivers	How has the South Lagoon been tracking?	Source of information
			• inflows from the South-East via Salt Creek.	• For 1975-1985 salinity exceeded 100ppt 15% of the time (based on daily data) (DEWNR unpublished data). • Salinity (1998-2010) ranged from 74-160ppt (DEWNR Hydstra data). • Salinity (2010-2018) ranged from 55-122ppt, with an average of 80ppt (DEWNR Hydstra data). • Marginal effect of water releases from South-East on salinity during 2013-2016.[33]	
	Nutrient and nutrient cycling	Supporting component (and process) of the South Lagoon and important role in the systems' biogeochemical processes, which in turn drive patterns of primary productivity and food webs. Characterised by: - Typically acting as a sink for nutrients; - Containing significant loads of nutrients that are not yet full characterised;[29] - Nitrogen the primary limiting nutrient[28]; and - Total nutrient loads tied to organic components of the whole ecosystem.[29]	Biogeochemical processes are influenced by salinity, hydrological regime, nutrient influx, and by benthic bioturbation and evaporation.	• Primary production remained high during Millennium Drought, despite low nutrient inputs from the River Murray, suggesting high level of retention and nutrient cycling in sediment pools.[34] • Historical investigations into nutrient pools and fluxes identified the ratio of Total Nitrogen to Total Phosphorus, and ratio of Plant Nitrogen to Total Phosphorus indicated a predominantly internal source of nutrients (algae, detritus).[35] • Concentrations of DOC, DON, and DOP all increase southwards along the Coorong faster than salinity increases, indicating sources of these in the South Lagoon. • In contrast to relatively high concentrations of nutrients embodied in organic forms, the concentrations of bioavailable species are low. Recent years (2012-2016) the TN:TP ratio has been considerably higher and indicates switch to P limited based on total nutrient availability[32], and total pool of TN high in South Lagoon, but fraction of bio-available N is very low.[36] • Water releases from Salt Creek are lower in organic nitrogen than occurs in the Coorong, thus reducing the organic nitrogen and total nitrogen concentrations in the southern Coorong[36]. • The water releases contain considerably higher concentrations of dissolved inorganic nitrogen (ammonium and nitrate), but these concentrations rapidly diluted to within background concentrations within 10km of Salt Creek.[33]	[34]Deegan et al. 2010 [35]Grigg et al. 2009 [36]Collier et al. 2017
South Lagoon food web		The Coorong food web is relatively short but is a critical service to sustaining the character of the site.	Driven by: • hydrological regime; • water levels;	• Extensive *R. tuberosa* beds[5] and large numbers of small-mouthed hardyhead were present in the mid-1980s.[4] • Invertebrate data is limited at the time of listing, but there are some records of halophytic Diptera and salt-lake crustaceans.[5]	[37]Brookes et al. 2015 [38]Dittmann et al. 2015

South Lagoon ecological character		Value Ecological, social, cultural and economic	Drivers	How has the South Lagoon been tracking?	Source of information
		It is characterised by: - *R. tuberosa* as a critical habitat and food resource; - Small-mouthed hardyhead as a single key species and important prey for waterbirds; and - Macroinvertebrates as primary and secondary consumers, processors of primary production, and vital food resources for other biota.	• salinity; and • nutrient dynamics • sediment biogeochemistry	• Reduced food web complexity and productivity was observed during the Millennium Drought, and included decreased abundance of macroinvertebrates[37,38], fish[38] and *R. tuberosa*[7]. • Post-drought recruitment, abundance and distribution of small-mouthed hardyhead increased substantially.[39] • Recent persistent loss of *R. tuberosa* habitat means that primary production will be dominated by algae[40]. • Macroinvertebrate populations remain depleted due to low to hypoxic conditions, higher organic matter and lower chlorophyll a.[41] • Since 2015, the lagoon has supported 1-6 species, including *Capitella*, Amphipods, Ostracods, *Arthritica* and Chironomids[41]	[39]Ye et al. 2012 [40]Kim et al. 2013 [41]Dittmann et al. 2017

Table 4. Performance against ecological objective targets for the Lower Lakes, Coorong and Murray Mouth icon site from 2006-08 to 2016-17 (MDBA 2018). Note: objectives are not specific to the South Lagoon sub-unit of the Icon site. Met is where all ecological targets were met; partial met is where one or more ecological targets were met; not met is where no ecological targets were met; and not monitored is where the target was not monitored in that year.

	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17
Maintain or improve *Ruppia tuberosa* colonisation and reproduction	Not monitored	Not monitored	Not monitored	Not monitored	Not met	Not met	Partial	Partial	Partial	Not met	Partial
Maintain or improve waterbird populations in the Lower Lakes, Coorong and Murray Mouth	Not met	Not met	Not met	Not met	Not met	Met	Met	Met	Met	Not met	Not met
Maintain abundant, self-sustaining populations of small-mouthed hardyhead in the North Lagoon and South Lagoon of the Coorong	Not monitored	Not monitored	Not met	Not met	Not met	Met	Met	Not met	Not met	Not met	Met
Restore resilient populations of black bream and greenback flounder in the Coorong	Not monitored	Not monitored	Not met	Not met	Not met	Partial	Not met	Not met	Not met	Not met	Not met
Maintain or improve mudflat invertebrate communities that are of high condition relative to southern Australian estuarine mudflat ecosystems	Partial	Not Met	Not met	Not met	Not met	Not met	Partial	Partial	Partial	Partial	Met
Maintain or improve habitable sediment conditions in mudflats	Not met	Not met	Not met	Not met	Met	Met	Met	Met	Met	Met	Met
Support aquatic habitat by establishing and maintaining variable salinity regimes in the Murray Mouth Estuary, North Lagoon, and South Lagoon	Data yet to be extracted from reports	Met	Met	Met	Met	Partial	Partial				

CONCEPTUAL DIAGRAM OF THE ECOLOGICAL CHARACTER OF THE COORONG SOUTH LAGOON

The South Lagoon comprises the main lagoon, ephemeral lagoons towards the most southern area of the Coorong and also a series of spring fed freshwater wetlands at the base of the dunes. Water levels are variably fluctuating up to 0.9 m annually. Salinity in the South Lagoon is influenced by inflows from the North Lagoon, rainfall on the Lagoon surface, evaporation, and historical inflows of fresh water from groundwater via soaks, and inflows from the South-East of South Australia via Salt Creek. Variable freshwater inflow via Salt Creek can cause intermittent localised freshening of the hypersaline conditions. The South Lagoon is on average 2.5 km wide and 1.4 m deep at 0 m water level AHD (Webster 2005).

Figure 1 is a representative conceptual diagram of the South Lagoon ecosystem, as developed in 2015 (DEWNR unpublished), showing the key characteristics, drivers, and threats of the system. Figure 2 shows changes in function of the South Lagoon ecosystem. There has been significant knowledge developed related to the salinity tolerances of biota of the South Lagoon (Table 3 and Figure 3).

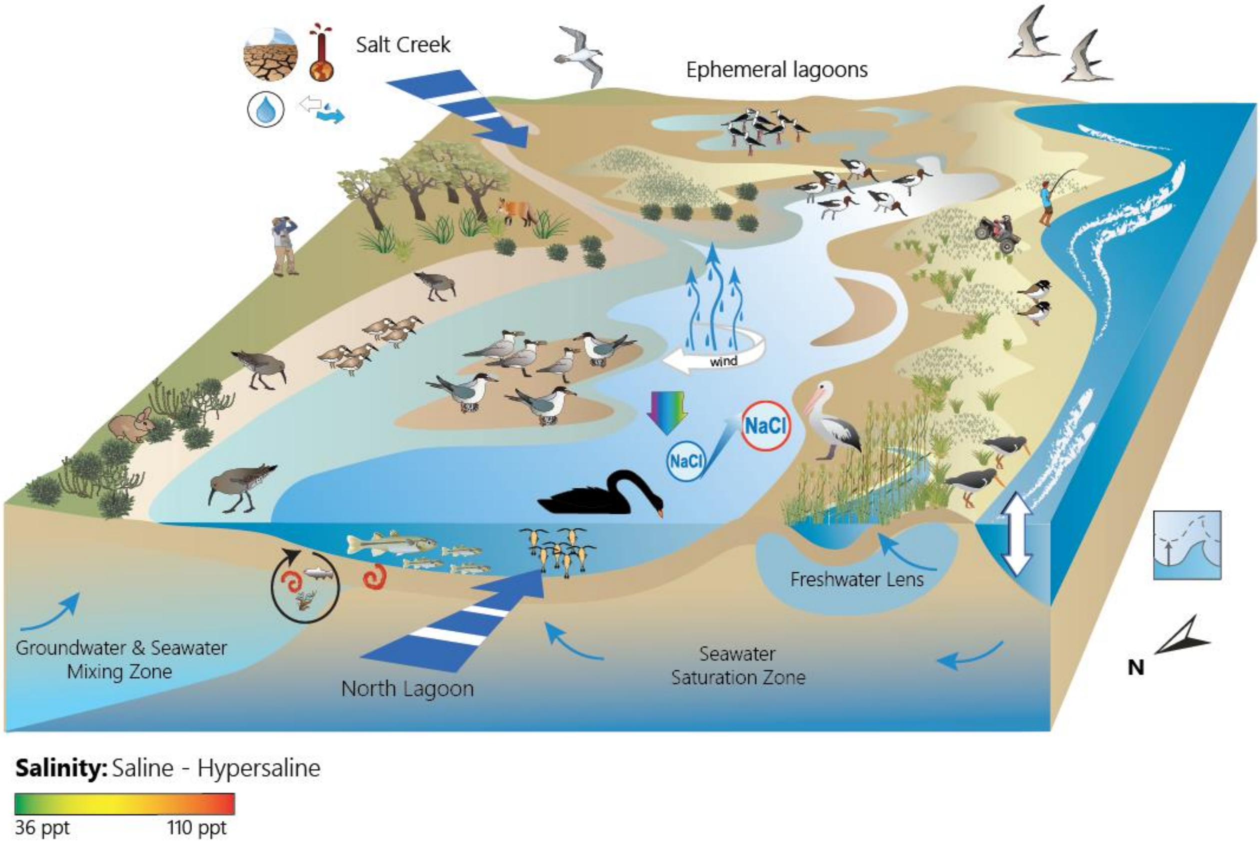
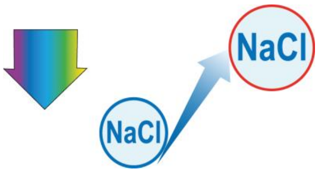


Figure 3. Conceptual diagram representing the Coorong South Lagoon. Not to scale and not all features are included; the diagram is representative only (DEWNR unpublished).

Key to symbols used in conceptual model for the South Lagoon (Figure A1-1 above)

Water level variation in the Coorong (North and South Lagoons) is a key determinant of habitat suitability and availability, as well as an important driver of water exchange and salinity. Local conditions (winds and tides) strongly influence hydrological interaction with freshwater inflows via the USED Scheme. There are variable flows between the South Lagoon and ephemeral lagoons.

Groundwater interactions and flow are complex and similar to the other saline sub-units. Wind action maintains mixing of the surface waters, with evaporation increased by wind. Groundwater discharge zones are associated with springs.



Salinity is controlled by a variable flows from the North Lagoon and Salt Creek. Evaporation is high and hypersaline conditions occur in most of the South Lagoon. A significant salinity gradient exists in the Coorong, with lower salinity in the North Lagoon increasing to hypersaline in the most distal parts of the South Lagoon. The South Lagoon typically acts as a sink for nutrients, even in high flow years, as evaporation from the shallow basins in the south draw water and suspended material from the North Lagoon. Nutrient dynamics remain a knowledge gap.

Primary production is high, with the dominant submergent macrophyte being *Ruppia tuberosa*. Fringing emergent and submergent vegetation are associated with the freshwater springs at the base of the dunes.

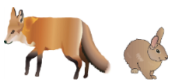
Secondary production is detrital based and reliant on a simplified food web compared to the freshwater sub-units. Invertebrate composition is substantially different, with polychaetes, crustaceans and chironomids playing important roles in the food web.

Species of conservation significance in this sub-unit are the same as the Murray Mouth and Estuary and includes hooded plover (*Thinornis rubricollis*), fairy tern (*Sternula nereis nereis*), Eastern curlew (*Numenius madagascariensis*), and curlew sandpiper (*Calidris ferruginea*). Fairy terns breed in the South Lagoon. The endangered ecological saltmarsh community also occurs in this sub-unit as well.

Characteristic fish species encountered include small mouthed hardyhead (*Atherinosoma microstoma*). Often the only fish species present in the South Lagoon, small mouthed hardyhead are an important trophic element in the Coorong food web.

The Coorong is iconic for the abundant waterbirds supported, notably for supporting migratory species. Variation in inundation result in the exposure of mud flats and intertidal marshes along the shoreline, providing important habitat for a large number of waterbirds. The South Lagoon supports key breeding locations for Australian pelicans and fairy terns. The beach area of this sub-unit supports large numbers of migratory shorebirds and beach-nesting birds.

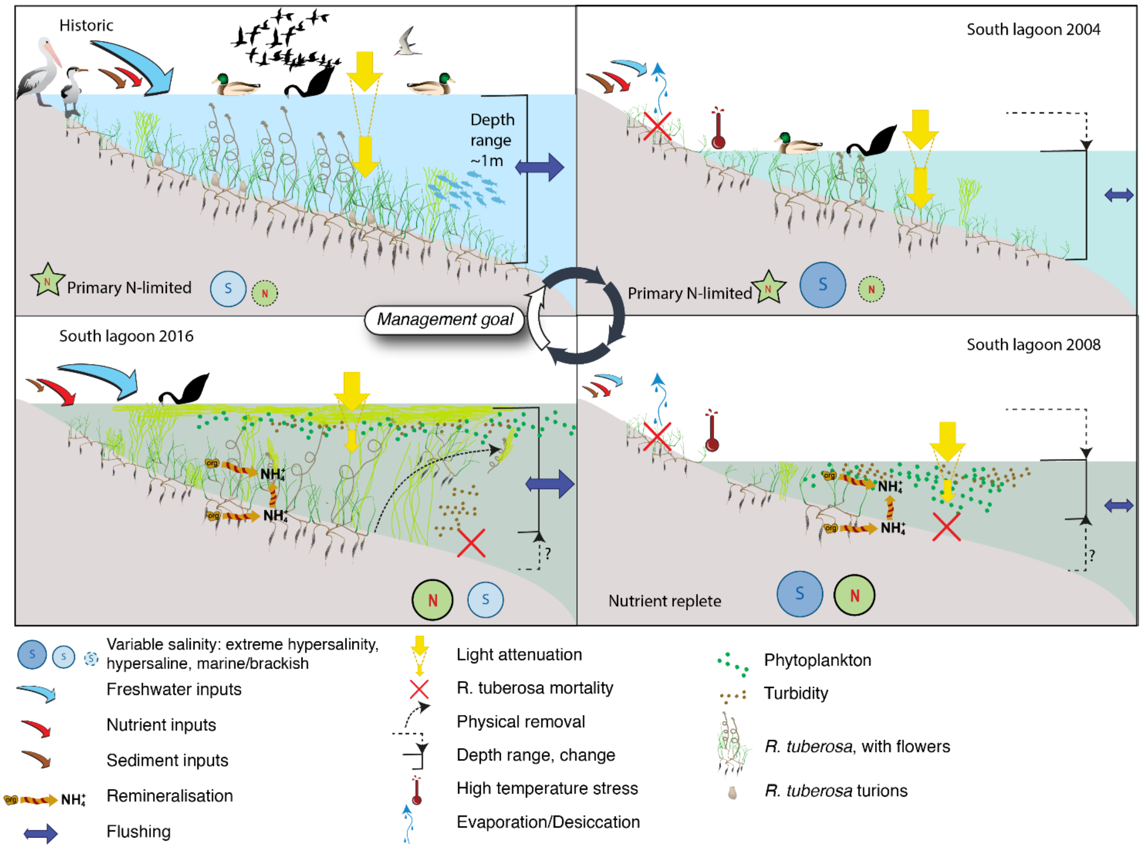
Climatic conditions and climate change impacts are the same as occurs across the other saline sub-units.

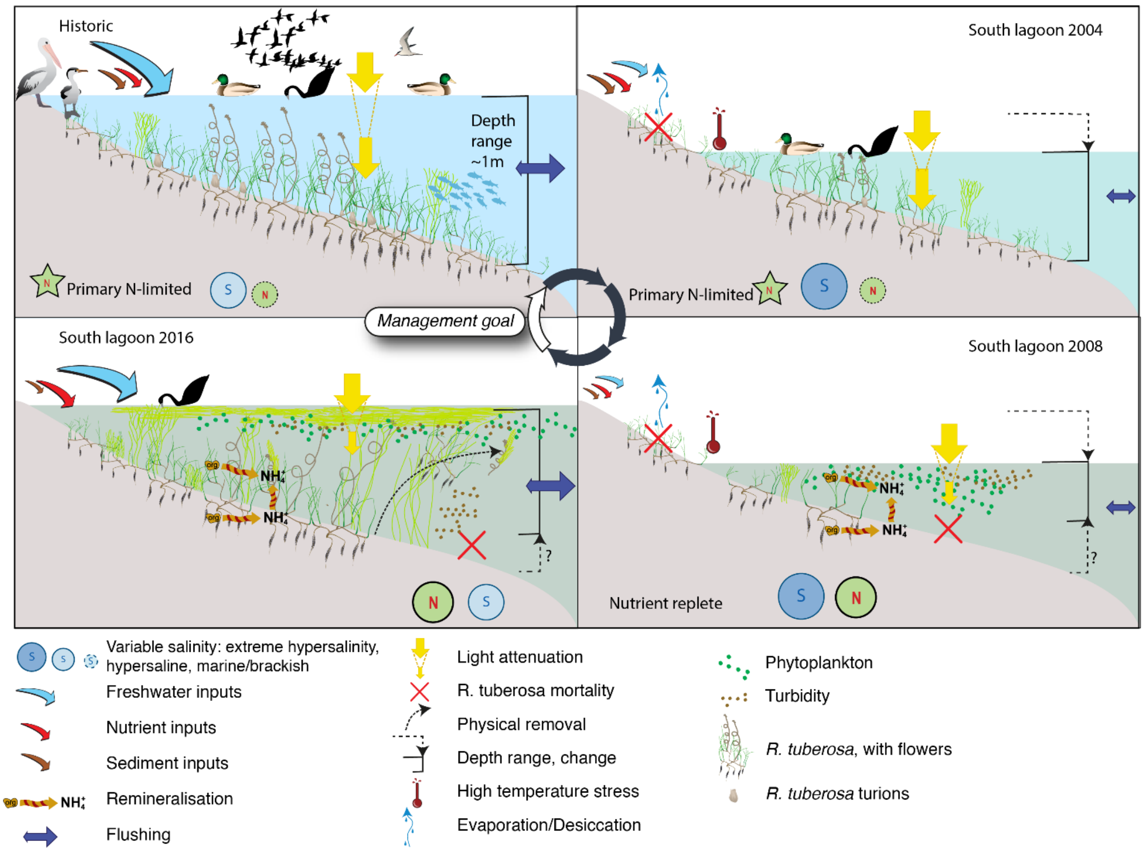


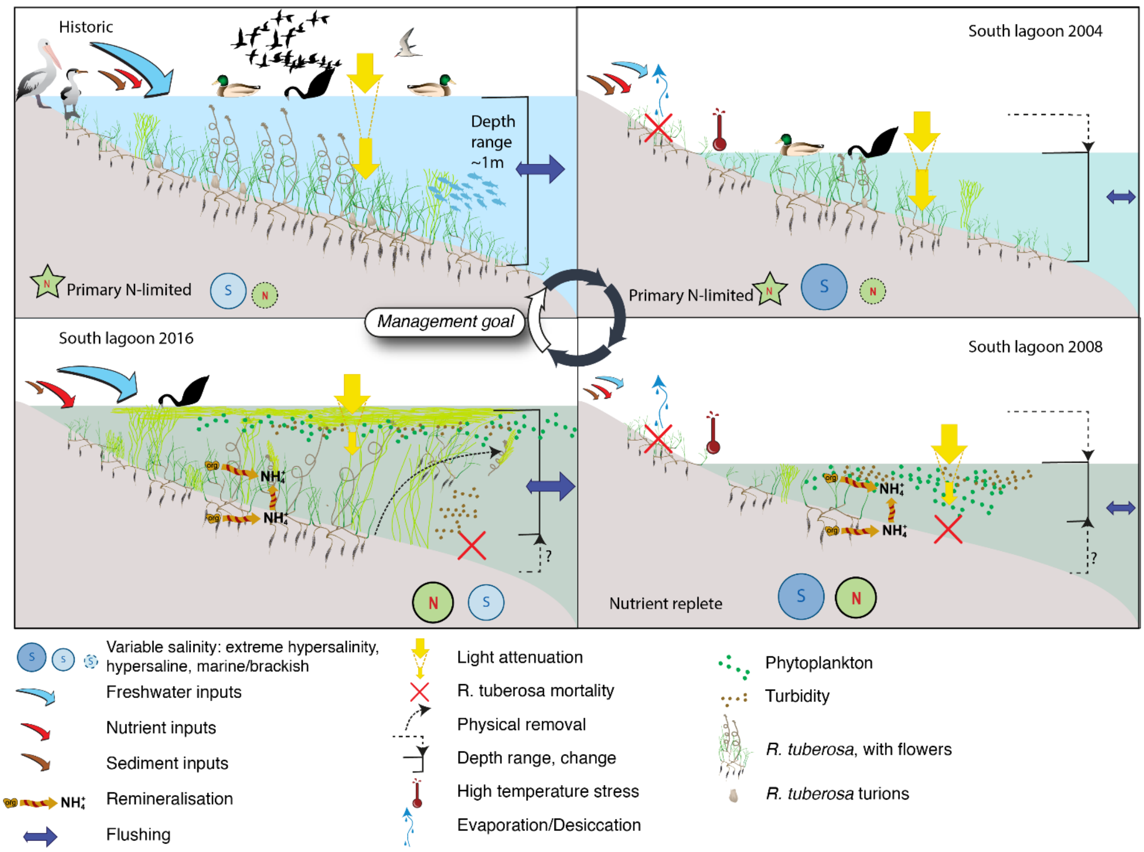
Invasive species and problematic native species affecting this sub-unit include foxes, rabbits, weeds, and kangaroos.

Recreational use is mainly focused on the beach and dunes, with fishing, and collection of pipis common activities. Some recreational activities act as threats to the beach dwelling shorebirds (disturbance of nesting sites).

Places within this sub-unit have particular significance for the Ngarrindjeri but is seen as part of the whole Yarluwar-Ruwe.


Historic
Depth range ~1m
Primary N-limited
South lagoon 2004
Primary N-limited
Management goal
South lagoon 2016
South lagoon 2008
Nutrient replete
Variable salinity: extreme hypersalinity, hypersaline, marine/brackish
Freshwater inputs
Nutrient inputs
Sediment inputs
Remineralisation
Flushing
Light attenuation
R. tuberosa mortality
Physical removal
Depth range, change
High temperature stress
Evaporation/Desiccation
Phytoplankton
Turbidity
R. tuberosa, with flowers
R. tuberosa turions


Historic
Depth range ~1m
Primary N-limited
South lagoon 2004
Primary N-limited
Management goal
South lagoon 2016
South lagoon 2008
Nutrient replete
Variable salinity: extreme hypersalinity, hypersaline, marine/brackish
Freshwater inputs
Nutrient inputs
Sediment inputs
Remineralisation
Flushing
Light attenuation
R. tuberosa mortality
Physical removal
Depth range, change
High temperature stress
Evaporation/Desiccation
Phytoplankton
Turbidity
R. tuberosa, with flowers
R. tuberosa turions



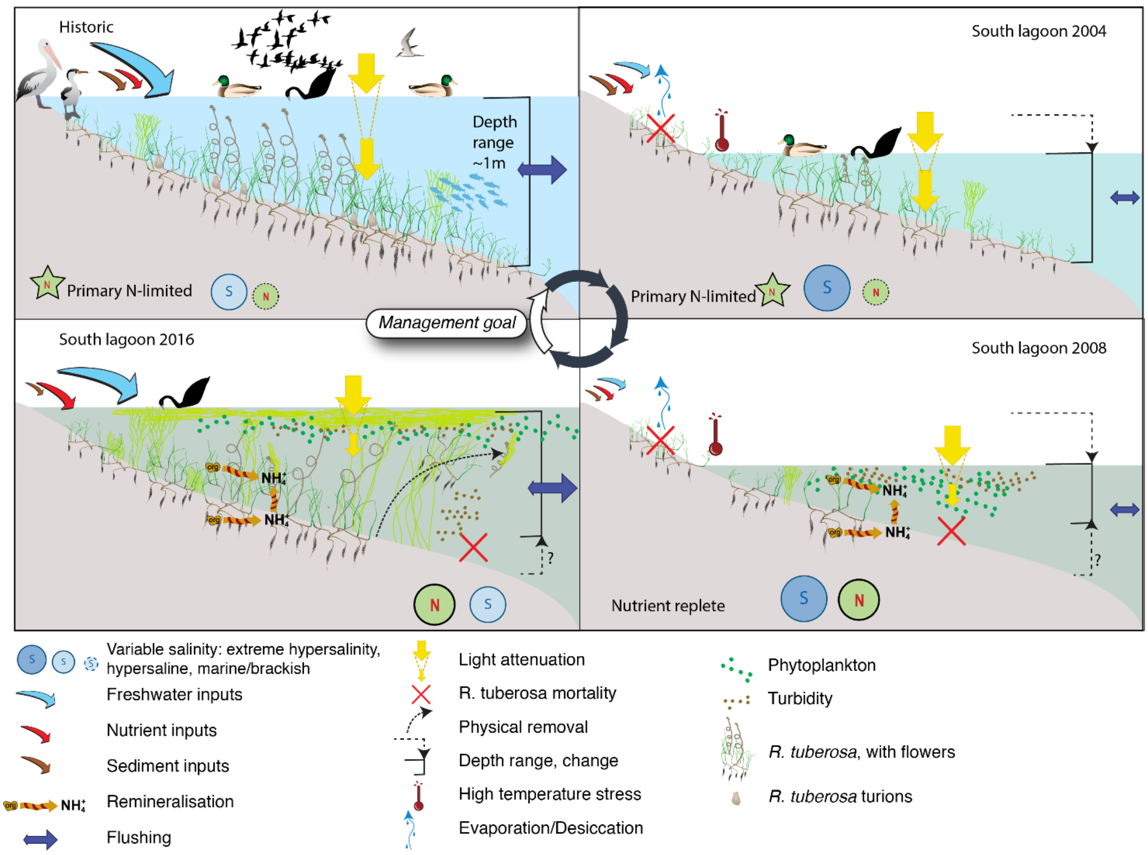


Figure 4. Conceptual summary of changes in the South Lagoon, with a specific focus on *R. tuberosa*, filamentous green algae and water quality (Collier et al. 2017).

Table 5. Summary of salinity tolerances for biota in the South Lagoon.

Component	Optimal	Suboptimal	Unsuitable	Reference
Small-mouthed hardyhead	Up to 108 g/L	100-130g/L	N/A	McNeil et al. (2013)
Brine shrimp (*Parartemia zietziana*)	Tolerance 27-353 g/L	N/A	N/A	Timms (2014)
Chironomids (*Tanytarsus barbitarsus*)	Up to 125g/L	Other locations: up to 177g/L	N/A	Dittmann et al. (2006)
Filamentous green algae	10-40g/L	<10 g/L & 40-80 g/L	Suffer high mortality >80 g/L	Collier et al. (2017)

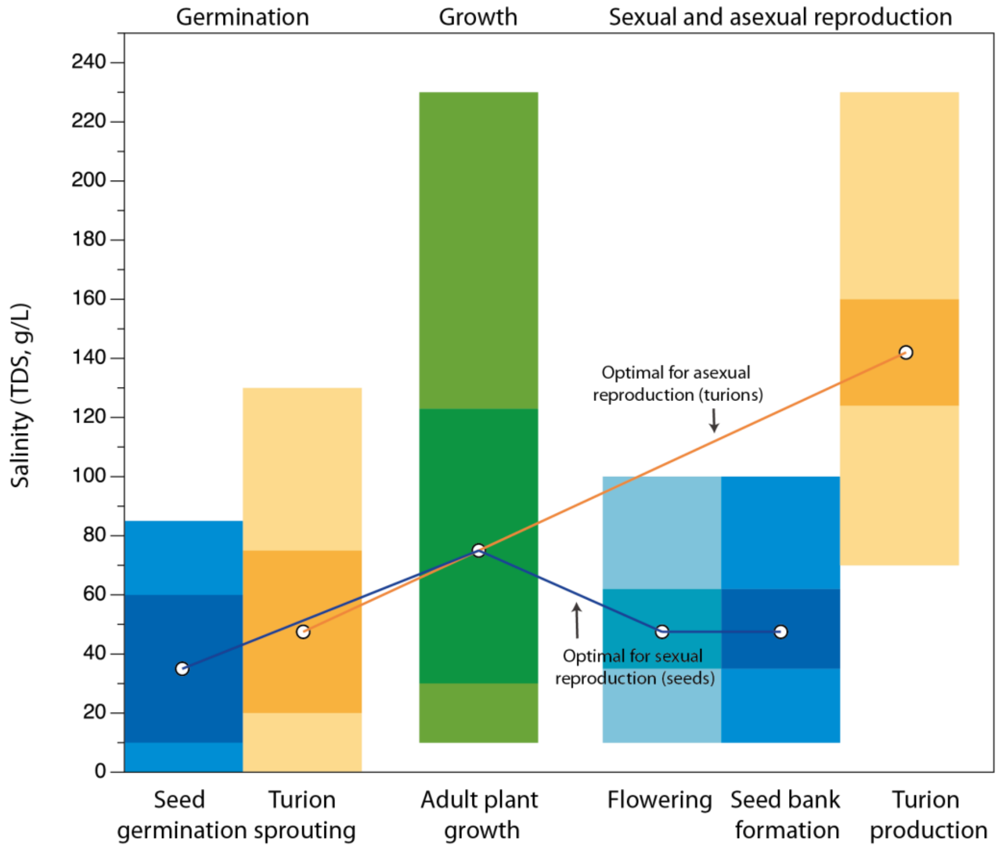


Figure 5. Summary of optimal salinity for different stages of the *R. tuberosa* life cycle. This is separated into optimal conditions for sexual reproduction (flowers and seed germination in blue), or by turion formation (in orange). Darker shades indicate the optimal salinity while lighter shades indicate sub-optimal conditions. Unsuitable conditions are not indicated on this figure. From Collier et al. (2017).

Appendix 2. Expert Panel workshop notes

Table 6. Most significant risks to ecological values identified by the Expert Panel. This is a collation that emerged from the workshop held by the authors and is not a prioritised list of risks.

Risk	Details
Nutrient levels (compound risks)	High nutrient loads and lack of export favour algal growth and cause additional ecosystem disturbance including inhibition of the ability of birds to forage on mudflats, reducing oxygenation of sediments and interruption of reproduction by *Ruppia tuberosa*. It is noted that the total nutrient concentrations in the Salt Creek inflows are much lower than in the South Lagoon and that total nutrient and chlorophyll levels reduce in the South Lagoon during Morella Basin release events. Nutrient loads or dynamics within the system, which limits management options, is not fully understand
Maintaining low salinities	It has been observed that lower salinities (<80ppt) in spring/summer favours algal growth and disrupts *R. tuberosa* reproduction. See also Appendix 1.
Maintaining high salinities	High salinities (>60 ppt) will prevent establishment of diverse and abundant macroinvertebrate and fish communities
Inability to effectively manipulate water levels in South Lagoon	Failure to provide adequate water levels in spring/summer can result in failure for *R. tuberosa* to flower/set seed. Extremely high-water levels can also exclude waterbirds from breeding or foraging habitats. Water level management needs to occur in conjunction with providing salinity and nutrient levels that favour growth of *R. tuberosa* over algae and to maintain foraging habitat for birds.
Further disturbance (multiple potential causes)	Lack of resilience within the system makes it prone to further changes. *R. tuberosa* and some bird species in particular are considered 'on the brink'. Fish production and species diversity have been much reduced compared to 1985-1990.
Current issues with South Lagoon cannot be 'fixed'	In this case, we need to consider how we can provide favourable conditions in adjacent habitat to maintain ecological values within the broader landscape.
Improving individual components of the system without restoring ecosystems	Need to consider management actions that will result in ecosystem-level improvements.
Describing complex and unachievable water management requirements	The more complex a management option is, the harder it will be to deliver.
Taking action and not measuring outcomes	Need integrated measurements/monitoring to ensure that we understand the consequences of management actions and adopt adaptive management approach.
Lose bird species	Food and habitat are not adequately provided due to filamentous algal domination and/or hypersalinity.

Table 7. Knowledge gaps identified by the Expert Panel. This is a collation that emerged from the workshop held by the authors and is not a prioritised list of knowledge gaps.

<table>
<tr><th>Knowledge gap</th><th>Details of knowledge gap</th></tr>
<tr><td>Salinity gradient</td><td>

Describe a spatially and temporally dynamic salinity gradient for the South Lagoon.
Understand the habitat preferences of different species assemblages, including salinity thresholds dependence on a spatial north-south salinity gradient
Model the suitable habitats across the entire Coorong system.
</td></tr>
<tr><td>Integrated water management (salinity, water levels, nutrients)</td><td>

Interactive effects of water level, salinity, nutrients on the ecosystem
Actual exchange of water/nutrients between the South Lagoon and other water sources
Strategies to provide conditions that promote restoration of submerged macrophytes
Limit filamentous algae and phytoplankton growth

Reduce nutrient levels (the method and consequences of doing so are additional knowledge gaps)
Limit additional nutrient influx where practical
Salinities in spring/summer

Warmer water temperatures promote algal growth
Coincides with R. tuberosa flowering

Provide adequate water levels

High enough to cover R. tuberosa plants,
Avoid extremes that result in poor conditions for waterbirds, e.g.:

Connection of breeding islands to mainland (accessible to terrestrial predators)
Inundation of breeding islands
Mudflat inaccessible for foraging shorebirds and high enough to cover Ruppia tuberosa in late spring and early summer when it is reproducing

Management of South-East flows

Assess benefits and trade-off from spatial and temporal changes to SE Water availability
Explore options of:

Changing volume and timing of releases to South Lagoon (preferably stop freshwater releases in spring/early summer), or
Ceasing SE flows into the South Lagoon for a few years with the intent of testing for impacts on algae and R. tuberosa.

At a regional scale, where do we deliver water for different environmental outcomes (i.e. providing habitat for waterbirds)? Could store water in Morella and Tilley Swamp, divert to ocean and/or target other wetlands?

</td></tr>
<tr><td>Nutrients</td><td>

We have a poor spatiotemporal understanding of nutrient availability in system (both macro and micro nutrients).

Availability of micronutrients (i.e. iron) may assist ion algal uptake of macronutrients (i.e. nitrogen)
Exchange of nutrients between lagoons.
How would a restored macrophyte community affect nutrient availability?

What are the management options for the removal/management of excess nutrients

Requires an understanding of nutrient levels that promote an aquatic plant dominated system
Requires risk assessment for various options of chemical or physical options for

We have a poor understanding of nutrient fluxes, capability/potential for de-nitrification within the system.

Current nutrient model doesn't allow for internal flux.
Inputs and outputs of nutrients under different flow conditions.
How do nutrients actually get out of system?

We have a poor understanding of how nitrogen and phosphorus availability limits growth of algae.

Can we flush out total nutrients with a planned flow event, including pulse events?

</td></tr>
</table>

<table>
<tr><th>Knowledge gap</th><th>Details of knowledge gap</th></tr>
<tr><td></td><td>What other measures would be required (i.e. removal of nutrients from sediment) Add materials that bind to/trap nutrients?
Impact of restoring macrophytes community?
Remediation of sedimentary conditions by increased macroinvertebrate bioturbation
Is there a nutrient sink in the middle of lagoon?
What role does groundwater, South-East, River Murray, ocean and evapoconcentration play in the nutrient dynamics of the South Lagoon?</td></tr>
<tr><td>Food web</td><td>We have a very limited understanding of how the food web functions and interacts:
We don’t know how different forms of primary production make their way into the food web
What are the food resources available for migratory shorebirds under different salinity regimes</td></tr>
<tr><td>Removal of algae</td><td>Options for short-term removal of filamentous algae (in conjunction with long-term control measures via integrated water management- see above)
Physical removal of filamentous algae at key sites/experimental sites to encourage successful reproduction of R. tuberosa.
Potential options include: removable rope lines that algae attach to, sweep algae away from top of R. tuberosa beds, and/or rake algal mats from shorelines
Chemical removal, for example:
Low dose hydrogen peroxide can inactivate cyanobacteria before affects other biota. Has no by-product but may affect phytoplankton. Copper-based algicides not recommended.
Products to reduce sediment:nutrient fluxes.
What is the source population? Or will there always be propagules that we need to manage (e.g. via management of salinity and nutrients)</td></tr>
<tr><td>Interactions between planktonic, microbial, macrobenthic and algal communities</td><td>Currently unable to predict interactive algal, macrobenthic and phytoplankton responses to varying conditions.
We cannot rely on how the system operated 30 years ago as a basis for managing the system today
What effect would the control/removal of algae have on the macrophyte and macroinvertebrate community?
Limited understanding of the complex set of microbial, macrobenthic, microphytobenthic and phytoplankton interactions that are variable along salinity and exposure gradient. Impact on nutrient availability?</td></tr>
<tr><td>Fish</td><td>Lack of historic information, but species richness and biomass may have been higher in the 1980s as indicated by commercial fishery catches. Productivity in general is assumed to have been higher historically.
Lack of seasonal information about the distribution and abundance of fish in the North and South Lagoons of the Coorong and the dynamic pattern of movement.
What roles do the North and South Lagoons play in supporting smallmouthed hardyhead reproduction; and understand their distribution and movement, and environmental drivers in order to maintain abundance of this key prey species in this region.
What role does the South Lagoon play in the ecology of key commercial/recreational fish species in context the broad-scale population dynamics and the influence processes within and beyond the Coorong?
How have changes in R. tuberosa changed fish (smallmouthed hardyhead and other key species) population dynamics?
Understand the functional role of fish in the food web.</td></tr>
<tr><td>Pest management</td><td>Integrated pest management, especially for terrestrial predators of birds (i.e. foxes).
What benefits would building terrestrial predator-proof fences give at a regional scale? This may be less important for birds such as terns and pelicans as long as island nesting sites remain disconnected from the mainland (within proximity of adequate fish prey).</td></tr>
</table>

Knowledge gap	Details of knowledge gap
Climate change	• Our management of the system currently doesn't account for the future impacts of climate change, either with respect to sea level rise or temperature and rainfall • Climate change will also impact on the broader landscape of wetland habitats for waterbirds • Initially we should undertake a climate vulnerability assessment for the site, collating existing information on critical factors including (but not exclusive to) projected water availability (including seasonality of flow), impacts on infrastructure (including operations), and local environmental conditions (e.g. evaporation, temperature) • This will help inform an adaptive pathway for the site, where we can identify at what stage we need to consider changing our management strategy based on changed conditions.
Complementary measures	• Assess feasibility of providing supplementary habitat (including food resources) at a region-scale • Engage farmers to create wetlands or provide food crops to support South Lagoon species? ○ Communication/education about roles in protecting wetlands • Education and reduction of nutrient usage in source catchments (Murray and South-East) • Identify the extent and distribution of actual and potential wetland habitats, and map these (conceptually) to the habitat types associated with bird species most at risk of loss in the South Lagoon. This is so we can understand the extent to which short-term loss of habitat in the South Lagoon can be offset by regional wetland restoration. • Some system models around how we think these wetlands work, to identify intervention points for restoration

Appendix 3. Relevant monitoring data

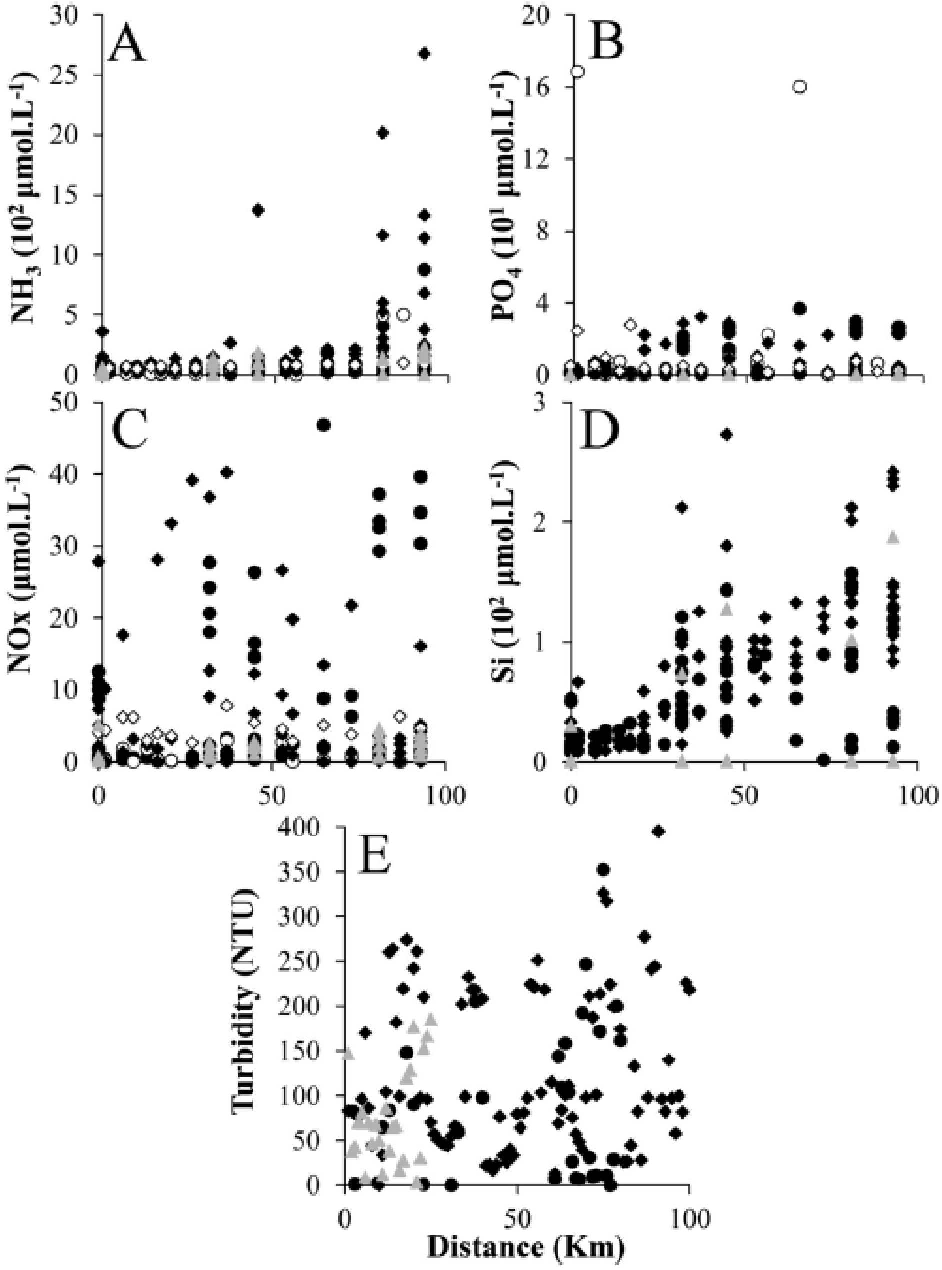


Figure 6. Fluctuations of nutrients (A-D) and turbidity along the Coorong during the Millennium Drought. Dates shown are February 2007 (open circles), May 2009 (open diamonds), August – December 2011 (grey triangles), August – December 2012 (black diamonds) and February-August 2013 (black circles). From Mosley et al. (2017).

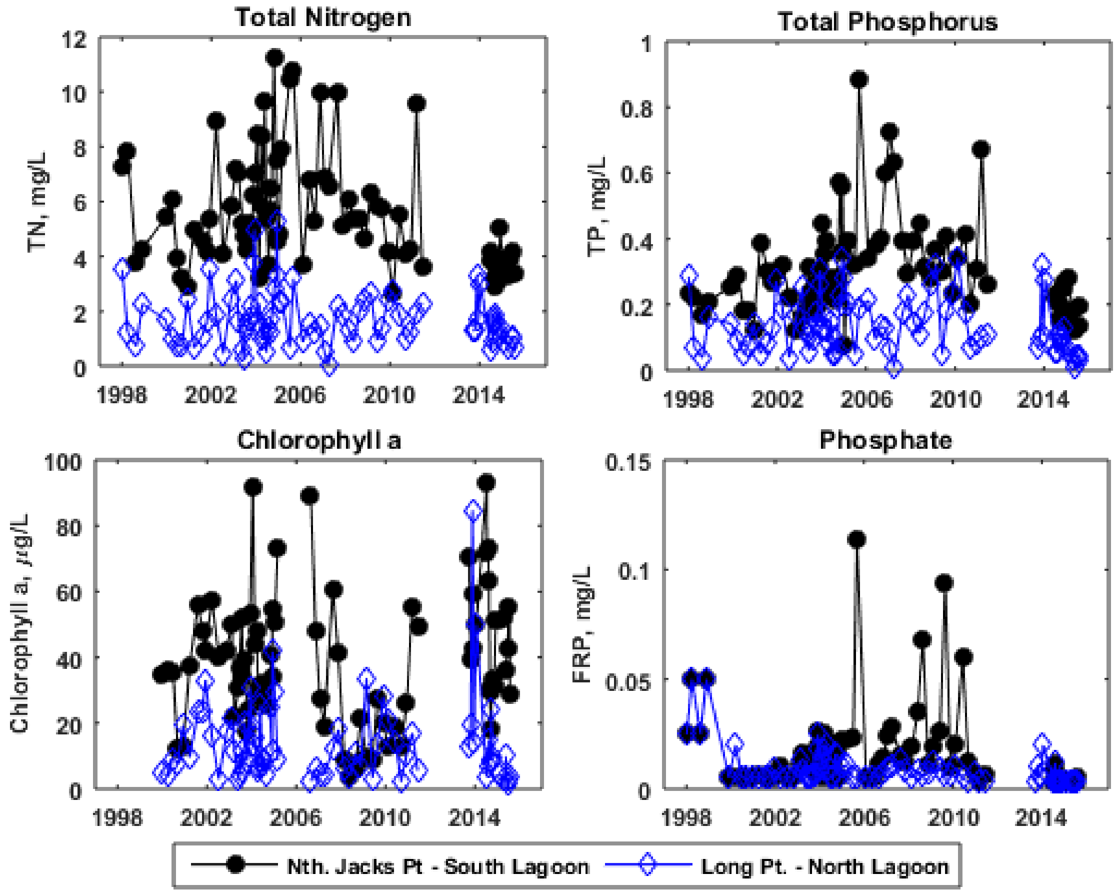


Figure 7. Nitrogen and phosphorus levels in the North and South Lagoon showing the long-term variability, and elevation of both in the southern lagoon in particular during the Millennium Drought. From Mosley et al. (2017).

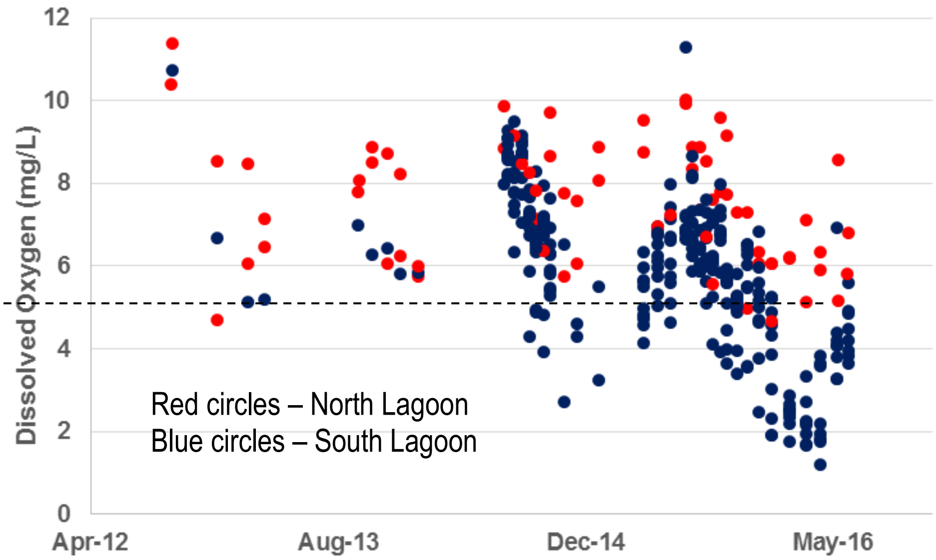


Figure 8. Daytime dissolved oxygen levels in the Northern and South Lagoon water from 2012 to 2016. Note: night time dissolved oxygen levels could be substantially lower. From Mosley et al. (2017).

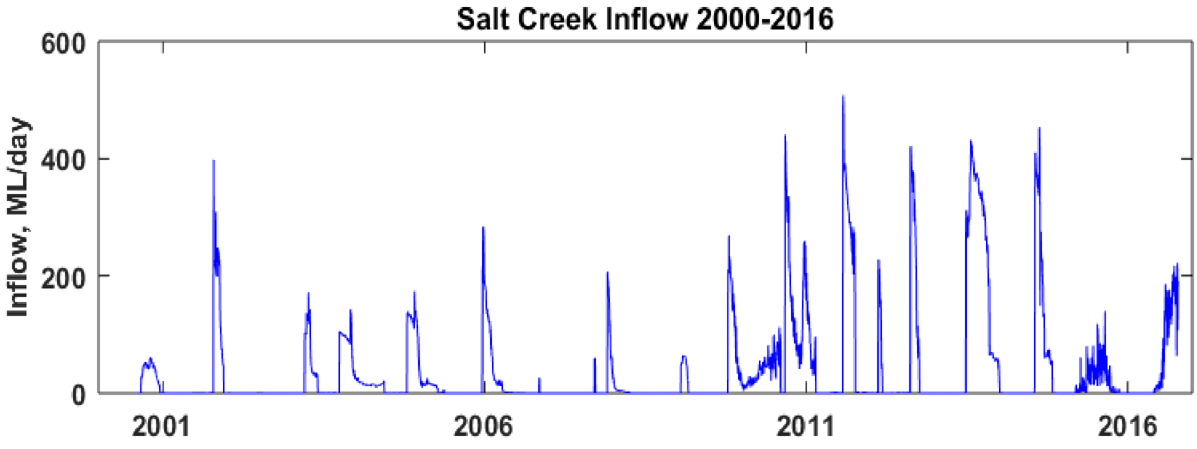


Figure 9. Inflows from Salt Creek from 2001 to 2016. From Mosley and Geddes (2018).

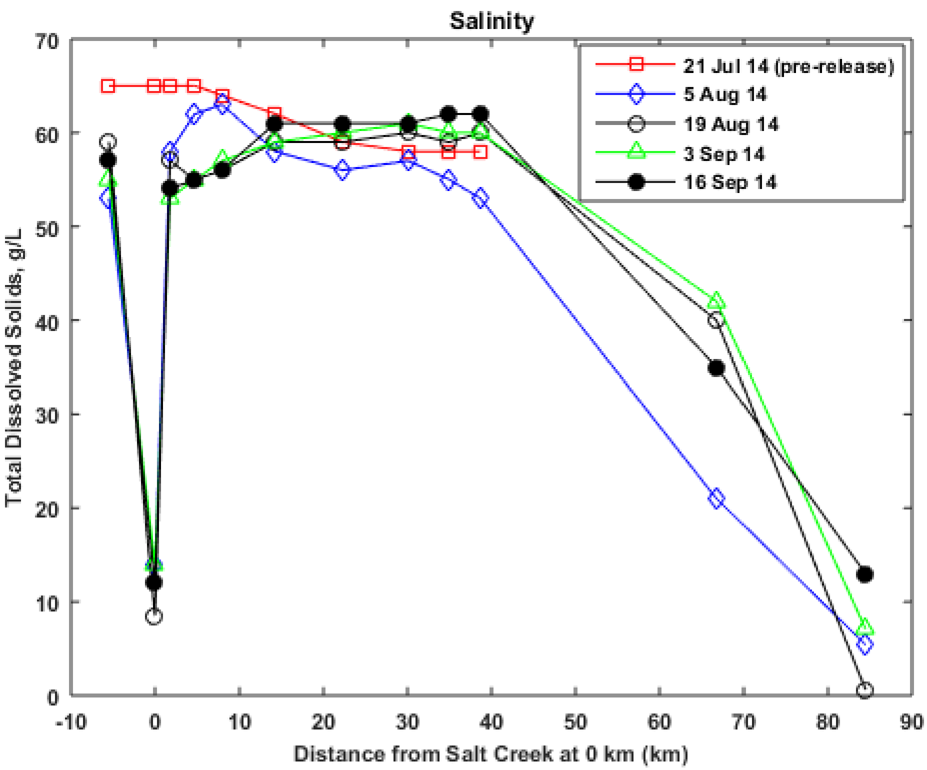


Figure 10. Salinity (as total dissolved solids) during the release from Salt Creek in 2014. From Mosley et al. (2017).

Table 8. Abundance, Area of Occupation (AOO) and Extent of Occurrence (EOO) for waterbirds counted in the Coorong in January 2018. The median abundances and target values for AOO and EOO are given for the 40 species of waterbirds regularly counted in the Coorong that are used to determine the whole of icon site score (WOISS), along with the contribution that each of these species made to the 2018 WOISS. Abundances that fall below the long-term median are indicated by red text, as are the AOOs and EOOs when these fall below the target value of 75% of the long-term average AOO and EOO. The WOISS scores for individual species were determined by assigning a value of-1 if two of the three counts over the last 3 years fell below the long-term median abundance, and -2 if all three counts fell below the median. An additional -1 was added to the individual species score if the AOO or EOO fell below the target value for these variables, and -2 if both targets for these variables were not met. From Paton et al. (2018a).

Species	Abundance				AOO		EOO		WOISS
	2016	2017	2018	Median	2018	Target	2018	Target	
Black Swan	3834	1838	5741	1633	105	45	103	72	0
Australian Shelduck	13779	12751	17916	8426	156	96	104	74	0
Pink-eared Duck	523	0	205		3		43		
Australasian Shoveler	611	84	1842		32		98		
Grey Teal	33426	15519	83602	11846	212	93	103	76	0
Chestnut Teal	4690	2863	7362	7216	117	82	103	72	-1
Pacific Black Duck	378	265	630	223	30	14	99	47	0
Hardhead	1026	4	1173		14		22		
Freckled Duck	18	0	6		2		2		
Blue-billed Duck	0	0	138		7		10		
Musk Duck	142	0	110	171	19	14	78	62	-2
Cape Barren Goose	181	265	408	97	7	5	18	16	0
Hoary-headed Grebe	14072	288	5118	4218	65	50	103	70	0
Great Crested Grebe	209	50	360	199	48	26	92	53	0
Little Pied Cormorant	190	3	581	258	62	26	52	39	-1
Great Cormorant	1696	3893	1185	1287	56	30	98	47	0
Little Black Cormorant	723	566	3562	1253	75	26	97	49	-1
Pied Cormorant	765	309	695	271	75	34	86	49	0
Black-faced Cormorant	151	265	236	130	20	5	72	50	0
Australian Pelican	4302	6041	4684	3410	200	100	104	75	0
Fairy Tern	410	361	357	337	28	26	92	57	0
Little Tern	4	2	5		3		85		
Gull-billed Tern	13	0	22		11		91		
Caspian Tern	603	1507	680	598	83	52	99	63	0
Whiskered Tern	10638	459	9064	5360	200	120	103	73	0
Common Tern	20	20	5		2		27		

Species	Abundance				AOO		EOO		WOISS
	2016	2017	2018	Median	2018	Target	2018	Target	
Crested Tern	4610	6325	3851	3897	86	50	98	70	0
Great Egret	66	4	58	36	34	20	100	40	0
White-faced Heron	156	222	251	156	105	45	104	75	0
Little Egret	40	6	32	7	16	4	100	35	0
Australian White Ibis	813	349	491	300	39	22	41	27	0
Straw-necked Ibis	10	50	6	25	3	2	14	15	-2
Royal Spoonbill	49	41	48	22	14	5	97	24	0
White-bellied Sea-eagle	0	2	2		2		20		
Pacific Gull	4	9	5		4		41		
Silver Gull	11370	13128	6648	8274	211	151	104	78	0
Purple Swamphen	0	0	1		1		1		
Australian Spotted Crake	1	0	0						
Eurasian Coot	1020	3	3145	62	9	5	99	14	0
Black-tailed Native Hen	0	0	6		2		59		
Pied Oystercatcher	158	110	111	158	30	31	94	68	-2
Sooty Oystercatcher	10	4	1		1		1		
Black-winged Stilt	589	46	368	417	46	31	71	62	-1
Red-necked Avocet	4507	1335	3291	3007	78	49	104	63	0
Banded Stilt	13301	136	820	15092	22	46	92	64	-3
Pacific Golden Plover	0	25	11	36	2	3	2	18	-4
Red-capped Plover	2695	153	1261	1234	69	58	101	74	0
Hooded Plover	7	8	4	8	3	4	45	38	-2
Red-kneed Dotterel	10	0	70		8		31		
Black-fronted Dotterel	0	0	1		1		1		
Masked Lapwing	460	452	517	466	119	73	104	77	-1
Banded Lapwing	26	7	0						
Black-tailed Godwit	25	30	42		2		1		
Bar-tailed Godwit	44	29	14		2		3		
Far Eastern Curlew	8	8	6	13	3	3	11	6	-2
Whimbrel	1	0	0						
Common Greenshank	443	333	238	430	93	66	101	75	-1
Common Sandpiper	1	1	0						

Species	Abundance				AOO		EOO		WOISS
	2016	2017	2018	Median	2018	Target	2018	Target	
Great Knot	0	0	4		2		8		
Red Knot	22	35	1		1		1		
Sanderling	41	0	4		3		9		
Red-necked Stint	27498	5667	11696	26286	97	88	103	77	-1
Sharp-tailed Sandpiper	23366	129	7910	13179	112	91	99	71	-1
Curlew Sandpiper	1248	208	968	2252	24	26	91	61	-3
WOISS (total)									**-28**

Appendices references

Bino G, Kingsford RT and Porter J (2015). Prioritizing wetlands for waterbirds in a boom and bust system: waterbird refugia and breeding in the Murray–Darling Basin. PloS one 10(7), e0132682.

Brookes JD, Aldridge KT, Bice CM, Deegan B, Ferguson GJ, Paton DC, Sheaves M, Ye Q and Zampatti BP (2015). Fish productivity in the Lower Lakes and Coorong, Australia, during severe drought. *Transactions of the Royal Society of South Australia* 139, 189–215.

Butcher R and Brooks S (2015). Coorong, and Lakes Alexandrina and Albert ECD Update: Critical Service Assessment and Supporting Components Description. Water's Edge Consulting, Melbourne, VIC.

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

Deegan BM, Lamontagne S, Aldridge K and Brookes JD (2010). Trophodynamics of the Coorong. Spatial variability in food web structure along a hypersaline coastal lagoon. CSIRO, Water for a Healthy Country National Research Flagship.

Dittmann S, Baring R and Ramsdale T (2015). Benthic Macroinvertebrate Response Monitoring in the Coorong and Murray Mouth, February 2015. Report for the Department of Environment, Water and Natural Resources, Adelaide.

Dittmann S, Cantin A, Noble W, and Pocklington J (2006). Macrobenthic survey 2004 in the Murray Mouth, Coorong and Lower Lakes Ramsar site, with an evaluation of food availability for shorebirds and possible indicator functions of benthic species. Department for Environment and Heritage, Adelaide.

Dittmann S, Jessup-Case H, lam Gordillo O and Baring R (2017). Benthic macroinvertebrates survey 2016-17: Coorong and Murray Mouth Icon Site. Report for the Department of Environment, Water and Natural Resources and the Murray-Darling Basin Authority.

Geddes MC (1987). Changes in salinity and in the distribution of macrophytes, macrobenthos, and fish in the Coorong lagoons, South Australia, following a period of River Murray flow. *Transactions of the Royal Society of South Australia* 111: 173–181.

Geddes MC and Butler AJ (1984). Physicochemical and biological studies of the Coorong lagoons, South Australia and the effect of salinity on the distribution of the macrobenthos. *Transactions of the Royal Society of South Australia* 108: 51–62.

Grigg NJ, Robson BJ and Webster IT (2009). Nutrient Budgets and Biogeochemical Modelling of the Coorong. CSIRO, Water for a Healthy Country Research Flagship, Canberra.

Kim DH, Aldridge KT, Brookes JD and Ganf GG (2013). The effect of salinity on the germination of *Ruppia tuberosa* and *Ruppia megacarpa* and implications for the Coorong: A coastal lagoon of southern Australia. *Aquatic Botany* 111: 81–88. doi: 10.1016/j.aquabot.2013.06.008.

Leblanc M, Tweed S, Van Dijk A and Timbal B (2012). A review of historic and future hydrological changes in the Murray-Darling Basin. *Global and Planetary Change* 80-81:226-246.

Lester RE, Fairweather PG, Webster IT and Quin, RA (2013). Evaluating scenarios involving future climate and water extraction: ecosystem states in the estuary of Australia's largest river. *Ecological Applications* 23:984–998.

Lucas WJ and Womersley HBS (1973). Preliminary studies on the growth of *Ruppia spiralis* (and *Lamprothamnium papulosum*) in relations to some environmental factors and their development of starch storage organs. Report to Department of Fisheries and Fauna Conservation. 18 pp.

McNeil DG, Westergaard S, Cheshire KJM, Noell CJ and Ye Q (2013). Effects of hyper-saline conditions upon six estuarine fish species from the Coorong and Murray Mouth. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2009/000014-4. SARDI Research Report Series No. 700. 26pp.

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

Murray-Darling Basin Authority (MDBA) (2018). Icon site condition: The Living Murray. Canberra, ACT.

Nicol J (2005). The ecology of *Ruppia* spp. in South Australia, with reference to the Coorong. A literature review. South Australian Research and Development Institute (Aquatic Sciences), SARDI Aquatic Sciences Publication No. RD 04/0247-2 SARDI Research Report Series No. 88, Adelaide.

O'Connor JA (2015). An assessment of Ramsar criteria and limits of acceptable change for waterbirds in the Coorong and Lakes Alexandrina and Albert wetland, DEWNR Technical report 2015/58, Government of South Australia, through the Department of Environment, Water and Natural Resources, Adelaide.

O'Connor J, Rogers D and Pisanu P (2013). Cryptic and colonial-nesting waterbirds in the Coorong, Lower Lakes and Murray Mouth: distribution, abundance and habitat associations. DEWNR Technical report 2013/19.

Oliver R, Mosley L, and Lorenz Z (2015). Utilizing the Coorong, Lower Lakes and Murray Mouth water quality and microalgae monitoring data to evaluate indicators for the Ecological Character Description. CSIRO Land and Water Flagship, Australia.

Paton DC (2003). Conserving the Coorong. Report to the South Australian Department for Water, Land and Biodiversity Conservation.

Paton DC (2005). Monitoring of biotic system in the Coorong region 2004-2005. Report for Earthwatch Australia and SA DEH. September 2005.

Paton DC (2010). At the end of the river: the Coorong and Lower Lakes. ATF Press, Hindmarsh, South Australia.

Paton DC and Bailey CP (2011). Condition monitoring of the Lower Lakes, Coorong and Murray Mouth Icon Site: Waterbirds using the Lower Lakes in 2011. University of Adelaide, Adelaide.

Paton DC and Bailey CP (2014). Condition Monitoring of the Lower Lakes, Coorong and Murray Mouth Icon July 2013. University of Adelaide, Adelaide.

Paton FL and Paton DC (2016). Colonial breeding birds in the Coorong during summer 2015-16, Report for the Department of Environment, Water and Natural Resources, University of Adelaide, Adelaide.

Paton DC and Rogers DJ (2009). Ecology of breeding Fairy Terns *Sternula nereis* in the Coorong. Final report for the Wildlife Conservation Fund.

Paton DC Bailey CP and Paton FL (2015a). Ecological Character Description for waterbirds of the Coorong and Lower Lakes. University of Adelaide, South Australia.

Paton DC Bailey CP and Paton FL (2015b). Condition monitoring of the Coorong, Lower Lakes and Murray Mouth Icon Site: Waterbirds in the Coorong 2015. University of Adelaide, South Australia.

Paton DC, Paton FL and Bailey CP (2016). Monitoring of *Ruppia tuberosa* in the southern Coorong, summer 2015-16. The University of Adelaide, Adelaide.

Paton DC, Paton FL and Bailey CP (2017a). Monitoring of *Ruppia tuberosa* in the southern Coorong, summer 2016-17. The University of Adelaide, Adelaide.

Paton DC, Paton FL and Bailey CP (2017b). Condition monitoring of the Lower Lakes, Murray Mouth and Coorong Icon Site: Waterbirds in the Coorong and Lower Lakes 2018. The University of Adelaide and The Department of Environment, Water and Natural Resources.

Paton DC, Paton FL and Bailey CP (2018a). Monitoring of *Ruppia tuberosa* in the southern Coorong, summer 2017-18. The University of Adelaide, Adelaide.

Paton DC, Paton FL and Bailey CP (2018b). Condition monitoring of the Lower Lakes, Murray Mouth and Coorong Icon Site: Waterbirds in the Coorong and Lower Lakes 2018. The University of Adelaide and The Department of Environment, Water and Natural Resources.

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

Phillips B. and Muller K (2006). Ecological character of the Coorong, Lakes Alexandrina and Albert Wetland of International Importance. Department for Environment and Heritage, Adelaide.

Seaman RL (2003). Coorong and Lower Lakes habitat-mapping program. Conservation Programs, Department for Environment and Heritage, South Australia.

Timms B (2014). A review of the biology of Australian halophilic anostracans (Branchiopoda: Anostraca). *Journal of Biological Research* 21(1): 21.

Webster IT (2005). An Overview of the Hydrodynamics of the Coorong and Murray Mouth. Technical Report No. #/2005. CSIRO, Water for a Healthy Country National Research Flagship.

Ye Q, Bucater L, Short DA and Livore J (2012). Fish response to barrage releases in 2011/12, and recovery following the recent drought in the Coorong. South Australian Research and Development Institute (Aquatic Sciences), Adelaide, SARDI Research Report Series No. 665, SARDI Publication No. F2011/000471-2.

Ye Q, Bucater L and Short D (2015). Coorong fish condition monitoring 2008–2014: Black bream (*Acanthopagrus butcheri*), greenback flounder (*Rhombosolea tapirina*) and smallmouthed hardyhead (*Atherinosoma microstoma*) populations. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2011/000471-4. SARDI Research Report Series No. 836. 105pp.

Ye, Q, Bucater, LB, Short DA and Earl J (2012). Coorong fish condition monitoring 2008-2012: The black bream (*Acanthopagrus butcheri*), greenback flounder (*Rhombosolea tapirina*) and smallmouthed hardyhead (*Atherinosoma microstoma*) populations. SARDI Research Report Series No. 649.

Ye Q, Bucater L and Short D (2015). Fish responses to flows in the Murray Estuary and Coorong during 2013/14. SARDI Research Report Series No. 884.

The Goyder Institute for Water Research is a partnership between the South Australian Government through the Department for Environment and Water, CSIRO, Flinders University, the University of Adelaide, the University of South Australia, and the International Centre of Excellence in Water Resource Management.