A scientific evaluation to inform nutrient removal options for the Coorong

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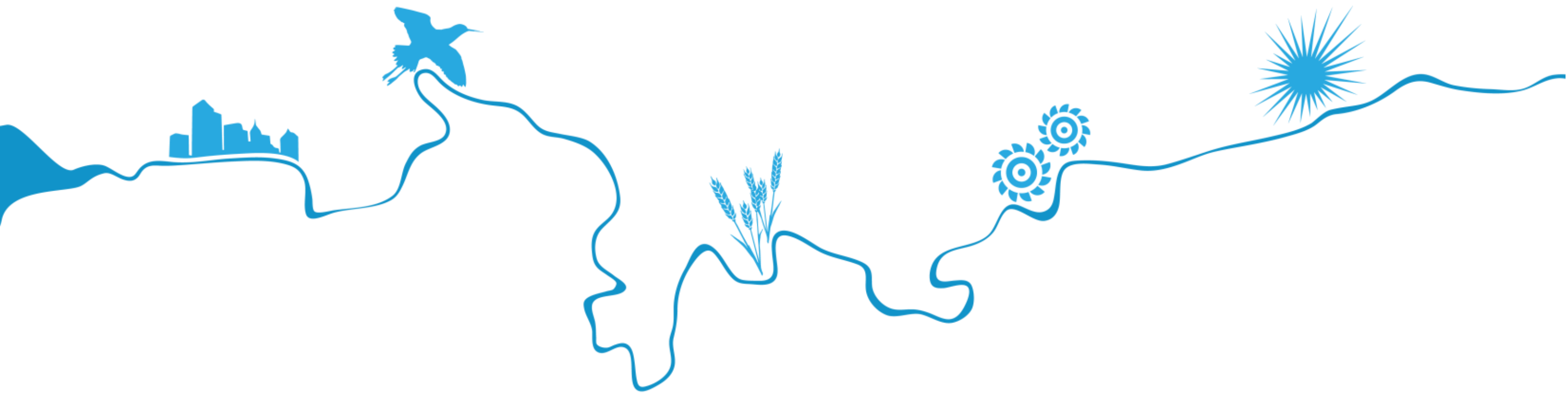

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Respect and reconciliation

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

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

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

Acknowledgments

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The Goyder Institute for Water Research is the delivery partner for research components of Healthy Coorong, Healthy Basin, providing independent research to inform future management decisions for the region.

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Executive summary

The Coorong, in particular the South Lagoon, is currently in a highly eutrophic state with high algae, organic matter and nutrient concentrations. The aim of the Healthy Coorong, Healthy Basin (HCHB) Phase One Trials and Investigations (T&I) Project Component 1 Understanding Coorong Nutrient Dynamics Activity 1.4 'Nutrient Removal Options' was to undertake a scientific assessment and evaluation of options to reduce nutrient availability and conditions that promote excessive algal growth in the Coorong. Emerging evidence from the HCHB T&I Project Component 1 undertaken between July 2020 and April 2022 was used to inform this nutrient removal options assessment along with scientific literature review and local expert opinion. The following options were considered:

- Improving lagoon flushing and connectivity (including different options to achieve this such as increased River Murray inflow, enhanced seawater exchange, improving lagoon connectivity)
- Nutrient load reductions from the Murray-Darling Basin and South-East catchments that enter into the Coorong
- Artificial oxygenation of water and sediment
- Aquatic plant (e.g. *Ruppia*) restoration
- Benthic macroinvertebrate restoration
- Macroalgal and/or filamentous algal mat harvesting
- Hostile sediment removal and capping.

A description of these nutrient removal options, their scale of application, prerequisites for success, potential issues, and likely feasibility is discussed below:

- Based on scientific evaluation, improved lagoon flushing and connectivity was determined to be the most likely option that could likely achieve HCHB Program aims related to nutrient reduction. It is considered that this option will best address the primary driver of eutrophication (i.e. excessive production and accumulation of algae, organic matter, and nutrients) in the Coorong water and sediment. Improved flushing will also reduce the persistent and extremely high salinity (hypersaline) conditions in the Coorong South Lagoon.
- Large flows from the River Murray are very important to flush the Coorong and help maintain suitable water quality. The implementation of the Basin Plan is critical to preserve and enhance these (i.e. via increased provision of water for the environment). The HCHB Coorong Infrastructure Investigations Project (CIIP) is scoping additional options that can promote increased flushing (e.g. pumping seawater in and/or out of the South Lagoon and dredging) which is in alignment with the findings from this study.
- Restoration of macroinvertebrate and aquatic plants (e.g. *Ruppia* and *Althenia* species) communities has the potential to assist with nutrient removal via these biota oxygenating sediments to an extent that enables breakdown of organic matter, nitrification-denitrification processes (nitrogen loss mechanisms) and binding of phosphorus in the sediment (via iron oxide formation). However, for restoration of macroinvertebrate and aquatic plant communities via active or passive means to be successful, existing water and sediment quality conditions need to be improved. Currently salinities in the South Lagoon are persistently and extremely hypersaline and exceed the tolerance thresholds (>60 psu) required to sustain communities of burrowing and filter feeding macroinvertebrates. Similarly, high turbidity (which limits light penetration at a particular water level) and hypersalinity (>90 psu) is a major barrier to the distribution, abundance and condition of *Ruppia* health. Maintaining an optimal salinity zone of between 35 psu (seawater salinity) and 60 psu via increased lagoon flushing would enable complementary nutrient removal and processing by *Ruppia* and macroinvertebrates. This salinity range was more common in the Coorong historically based on

contemporary and paleo limnology evidence. Lower salinities in the longer term will also enable a more diverse food web to form, enhancing broader HCHB goals such as returning fish and bird species currently absent or rarely present.

- Monosulfidic black oozes (MBOs) are the predominant sediment type throughout the South Lagoon and southern region of the North lagoon. Their build up is driven by high algal and organic matter deposition to the sediment due to a legacy of eutrophication and long water residence times. Sediment organic loads and sulfide in the MBOs also inhibit *Ruppia* growth.
- Nutrient release to the water column from existing (internal) nutrient loadings is likely to continue from the sediment, even under higher flushing scenarios, due to the legacy of nutrient accumulation over many decades. Nevertheless, increased water flushing will export total nutrients and algae, and will reduce algal-organic matter loadings to the sediment, reducing nutrient fluxes and build-up of anoxic MBOs over time. This will assist in the recovery of healthy aquatic plant communities.
- Substantial reduction in nutrient loads (i.e. nutrient concentrations in an inflow multiplied by volume of that inflow per unit time) entering the Coorong from the Murray-Darling Basin and South-East catchments could reduce nutrient concentrations and supply to algae within the Coorong. This option would be beneficial but difficult, costly and complex to implement due to the need for whole-of-catchment nutrient reduction programs over a sustained period of time, and multi-jurisdictional actions that are outside the scope of this feasibility assessment. The South-East sub-catchments would have the most opportunity to develop nutrient reduction programs due to their smaller size, South Australian location, and direct input into the Coorong South Lagoon. Reduction of both South-East and River Murray catchment nutrient loads should still be considered a long term goal, but is unlikely to be successful without hydrological restoration and increased flushing.
- Artificial oxygenation of water was deemed not to be warranted as monitoring data shows the Coorong water remains moderately to well oxygenated (>4 mg/L dissolved oxygen), presumably due to regular wind mixing. Furthermore, this option could only be applied at a localised scale due to the complex infrastructure required. Proven technology for direct sediment oxygenation does not appear to exist.
- Macroalgal harvesting and removal, and hostile sediment removal and capping, are considered potentially beneficial and applicable at localised scales (i.e. accessible and culturally acceptable shoreline areas), but are not able to address the system wide restoration objectives of the HCHB program. Macroalgal harvesting also has significant potential practical issues associated with implementation due to the need to cost-effectively and safely dispose of the saline biomass, and minimise disturbance on the aquatic plant communities the algae are commonly associated with (i.e. via physical attachment).
- Options that were discounted from detailed consideration were the use of large-scale water treatment systems, the addition of straw, whole-of-lagoon drying, and the use of chemicals/algaecides.

A combination of system scale, regional and local scale actions could help to achieve HCHB objectives of nutrient reduction. Ecological restoration (passive or active) strategies involving aquatic plants and macroinvertebrates will be important to reconsider once hydrological restoration has reduced the extreme salinity and eutrophication. The outputs from Activity 1.4 will help inform the scoping of CIIP hydrological restoration scenarios and complementary ecological restoration options. Broader ecological responses to the nutrient removal options were not considered but would be important to consider in any future detailed scoping of options. Quantitative assessment of the degree of 'nutrient removal' provided by many of the options also requires additional consideration (e.g. water-sediment-plant-macroinvertebrate mesocosm studies aligned and designed to inform proposed flushing and salinity lowering scenarios in CIIP).

Introduction

1.1 Background

The Coorong is culturally, environmentally and economically important at local, national and international scales but has experienced a long-term decline in its ecological condition due to reductions in inflows and increased rates of sedimentation. Whilst there has been recovery of some elements of the Coorong ecosystem associated with increased inflows since the end of the Millennium Drought in 2010, the South Lagoon has not recovered to the levels expected. There has been a shift of the ecosystem state from being dominated by aquatic plants (e.g. *Ruppia*) to extensive phytoplankton and filamentous algae associated with eutrophication (Mosley et al. 2020). Eutrophication can be defined as an increase in the supply of organic matter to an ecosystem (Nixon 2009, Le Moal et al. 2019), and is a major and ongoing concern in many aquatic systems worldwide (Cloern 2001, McDowell et al. 2020). The accumulation of organic matter can cause many deleterious impacts including high availability of nutrients that promote algae growth, depletion of dissolved oxygen, toxicity (e.g. from high sulfide and/or ammonia concentration, and harmful algal species) and loss of both submerged aquatic vegetation (such as seagrasses) and benthic invertebrate communities (low biodiversity) that contribute to food webs and broader ecosystem health (McGlathery et al. 2007, Nixon 2009). Internationally, efforts have been undertaken to revert eutrophic conditions in coastal ecosystems, with re-oligotrophication (lowering of nutrient levels) often taking several decades to achieve ecological regime shifts (e.g. in Mediterranean, Le Fur et al. 2019, Derolez et al. 2020).

The decline in the health of the Coorong ecosystem is likely caused by a number of complex, interacting factors, many of which are not well understood and some likely dependent on the longer-term history of the site (e.g. lack of freshwater input from River Murray during the Millennium Drought, particularly the extreme period from 2007-2010). This history and complexity inhibit the capacity to forecast the ecological response to future management scenarios and therefore the capacity of water managers to identify management interventions required to improve the health of the Coorong.

The Phase One Trials and Investigations (T&I) Project of the Healthy Coorong, Healthy Basin (HCHB) program consists of a series of integrated components that will collectively provide knowledge to inform the future management of the Coorong. *Component 1 – Understanding Coorong nutrient dynamics* forms part of the T&I Project. Through assessments of the relative importance of external and internal nutrient sources and processes within the Coorong, the research aims to provide a holistic understanding on how the nutrient load in the Coorong could be lowered to improve management. T&I Component 1 comprises four main activities as shown in Figure 1.

1.2 Aims and scope

The aim of this investigation (Activity 1.4 'Nutrient Removal Options') was to provide scientifically defensible advice to identify existing and new management interventions most likely to reduce nutrient levels in the Coorong. This final technical report presents the results of work completed during the period from July 2020 to April 2022.

The scope of this Activity consists of desktop investigations that inform the feasibility assessment and design of nutrient removal options as part of HCHB. Various nutrient removal options are assessed for their efficacy at a system (lagoon) scale, in alignment with the HCHB program objectives. However, to achieve restoration of the Coorong a combination of local and system scale restoration activities may be needed that contribute to nutrient removal.

The outputs from Activity 1.4 will inform HCHB's Coorong Infrastructure Investigations Project (CIIP) scenarios. The objective of CIIP is to investigate the feasibility of multiple long-term operational infrastructure options to improve the ecological health of the Coorong. The aim of Activity 1.4 is to help long-term management options under consideration, whilst also considering other complementary nutrient removal options that fall outside of the CIIP scope.

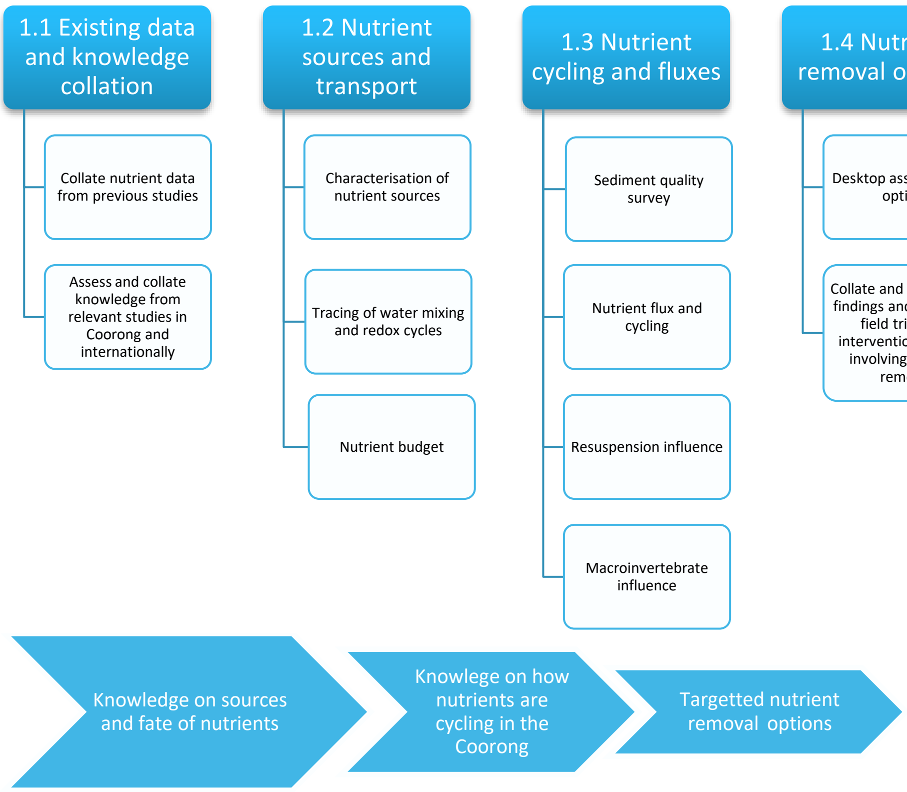

Figure 1. The main research activities and linkages in the Understanding Coorong nutrient dynamics Component of the HCHB Trials and Investigations Project.

2 Methods

2.1 Site description

The Coorong is a shallow and narrow lagoon system, which runs north-west to south-east, parallel to the South Australian coast for ~110 km and separated from the sea by a sand barrier (Figure 2). The Coorong naturally splits about halfway along its length into the North and South Lagoons at a narrow constriction (near Parnka Point, Figure 2) that is approximately 100 m wide, and transitions from saline to hypersaline in the south. The average widths of the North and South Lagoons are 1.5 and 2.5 km respectively, and the average water depths are 1.2 and 1.4 m respectively (Gibbs et al. 2018). The Coorong has a constricted channel connection to the sea towards its north-western end, referred to as the Murray Mouth. Exchange of seawater occurs from the Murray Mouth into the main body of the Coorong North Lagoon, but the tidal flow is currently restricted. Water level variation in the Coorong is thus less driven by tides, but rather inflows from the Murray-Darling Basin and winds/storms. The River Murray enters into Lake Alexandrina and is regulated to flow, when sufficient water is available, out to the Murray Mouth-Coorong via barrage structures. The Tauwitchere Barrage is the largest and also closest barrage to the main body of the Coorong, and hence may exert the most influence on water quality under certain release conditions (Mosley et al. 2016).

The South Lagoon also receives inputs of fresh to brackish water from a network of drains from the South-East region of South Australia, discharging at Salt Creek. This discharge is generally seasonal and can be regulated via structures in Morella Basin immediately upstream from Salt Creek, and further upstream in the drainage network. Groundwater discharge zones exist along the length of the Coorong, from both perched freshwater lenses and the regional unconfined aquifer, but hydraulic gradients are relatively low (Haese et al. 2008, Barnett 2018).

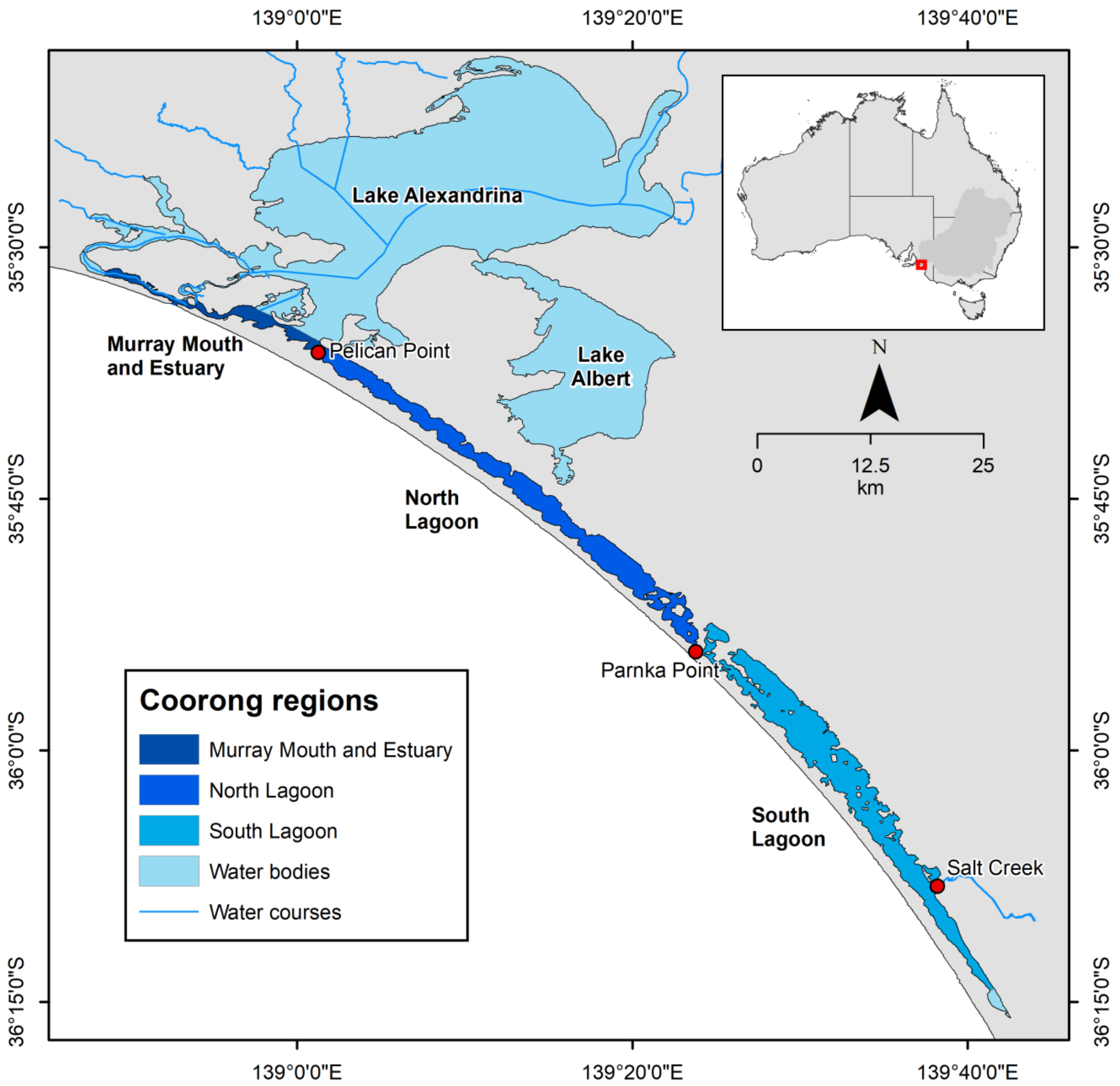

Figure 2. Map of the Coorong showing key regions.

2.2 Assessment of nutrient removal options

Information on nutrient removal options for the Coorong was researched and collated from various sources.

The activity utilised knowledge from the other investigations carried out in Component 1 that identify key sources, fluxes and cycles of nutrients. The options were also informed by discussions within the T&I Project, Department for Environment and Water (DEW), first nations, and the broader community in various forums. A global literature review was also conducted using the scientific database "Web of Science". Relevant search terms ("nutrient removal estuaries", "sediment capping and estuaries", and "artificial oxygenation and estuaries") were entered. The abstracts of the publications (scientific journal papers, technical reports and book chapters) identified in the search results were scanned and findings of relevant publications were synthesised to inform the options identified in this report.

An HCHB complementary actions workshop on 25 January 2022 helped inform this study. A Component 1 team workshop was held on 24 March 2022 to discuss the various nutrient removal options as informed by research evidence that has emerged.

Key elements considered in this assessment included the mechanism and predicted amount of nutrient removal, practicality, feasibility, scale of potential applicability of strategy to the Coorong, likelihood of adverse environmental impacts of the removal option, and likely relative costs. Quantitative assessment of nutrient removal, trialling of options, or broader assessment of ecological and cultural impacts, were not included.

A multi-criteria analysis (MCA) database was developed to score the options against the following criteria (weighted equally):

1. Scale (e.g. whole of lagoon or localised applicability)
2. Pre-requisites to success of option
3. Potential issues with option
4. Feasibility of achieving the HCHB aims

Following the scientific literature review, expert input, and incorporation from other activities of the HCHB T&I Component 1 Project and discussions with DEW, the following options are considered in more detail below.

- Improving lagoon flushing and connectivity
- Nutrient reductions from the Murray-Darling Basin and South-East catchments
- Artificial oxygenation of water and sediment
- Aquatic plant (e.g. *Ruppia*) restoration
- Benthic macroinvertebrate restoration
- Macroalgal and/or filamentous algal mat harvesting
- Hostile sediment removal and capping.

3 Results and discussion

3.1 Improving system flushing and connectivity

Hypothesis: Increased flushing of the Coorong will increase the export of nutrients out of the South Lagoon, reducing nutrient availability to algae and organic matter loading to the sediment. Improved connectivity between and within the lagoons also assists in export of nutrients and organic matter from both the North and South Lagoon, and out of the Murray Mouth.

A key driver of eutrophication in estuaries globally is reduced flushing (Bricker et al. 2007, Swaney et al. 2008, Steward and Lowe 2010, Le Moal et al. 2019) which increases the residence time and retention of nutrients, organic matter, and salt. This commonly occurs when river or seawater inflows are altered via anthropogenic influences such as water extraction, construction of regulating structures, or climate change (Nixon 2009). The Coorong is a very long (~110 km extending from the Murray Mouth south), narrow (~1-2 km wide), and shallow (~1-2 m mean depth) waterbody. Evaporation of water from the lagoon results in a considerable gradient of nutrients, organic matter, and salt concentrations from the Murray Mouth towards the southern end (Mosley et al. 2020). This results in the Coorong having reverse estuarine conditions, with salinity being lower closer to the natural opening to the ocean.

A consequence of longer water residence times is higher organic nutrient deposition to the sediments (Priestley et al. 2022) and an increase in the relative importance of various internal biogeochemical processes (e.g. nutrient flux from sediment to water), resulting in enhanced recycling of nutrients (Huang et al. 2022). Tight coupling of organic matter and nutrient cycling often exists between the water column and sediment in shallow estuaries, such as the Coorong (Heip 1995).

Consistent with international evidence, reduced flushing of the Coorong appears to be a key determinant of the degree of eutrophication. Increasing total nitrogen (TN) and phosphorus (TP) occurs in the Coorong as the salinity rises above seawater values (Figure 3) (Mosley et al. 2020). Similar patterns occur for chlorophyll *a*. This is because when salinity and nutrients are not flushed out to the ocean, they can concentrate in the lagoon as water is removed via evaporation. Hence salinity can be used as a proxy for flushing.

Reduced River Murray inflows, particularly during the Millennium Drought, have led to the system becoming extremely hypersaline (>2 times seawater, >70 practical salinity units, psu), and having very high concentrations of nitrogen and phosphorus (Figure 3) in the water column (Mosley et al. 2020). Thus, the Coorong, with its reverse estuary character, restricted geomorphology (Figure 2) and semi-arid climate, is undoubtedly a system with a propensity to retain nutrients, and it appears highly sensitive to reductions in flushing.

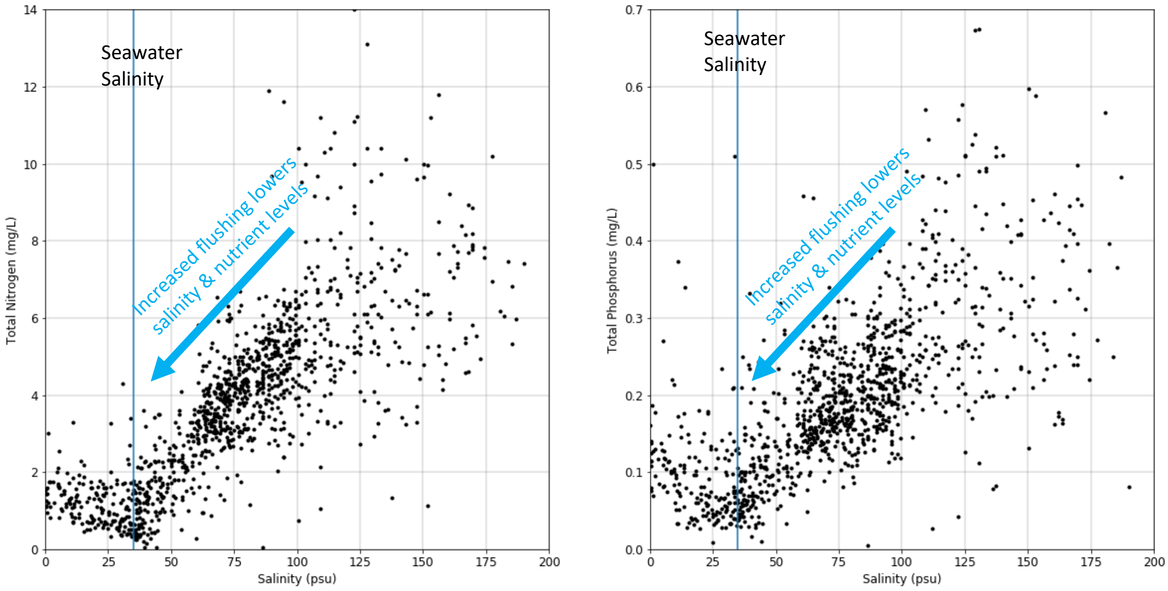

Figure 3. Relationship between total nitrogen (TN) and phosphorus (TP) and salinity in the Coorong based on historical monitoring data (adapted from Mosley et al. 2020). The blue arrows show expected effects of increased flushing.

Based on evaluation of the scientific literature, increasing system flushing (frequency and magnitude over the longer term), in particular for the South Lagoon, is likely to:

a) export nutrients, algae and organic matter.
b) reduce sediment organic carbon and nutrient loads.
c) reduce algae and total nutrient concentrations in the water column to reduce deposition of organic matter and nutrients to the sediment.
d) reduce algal-derived turbidity to enable increased light penetration for aquatic plants (seagrasses) such as *Ruppia*.
e) reduce hypersalinisation to enable re-establishment of benthic macroinvertebrates.
f) reduce formation of anoxic sulfide-rich sediments.
g) restore healthy nutrient cycling processes (e.g. nitrification-denitrification).

Increased flushing of the South Lagoon will decrease salinity as hypersaline water is transported out of the system and replaced with water of lower salinity. From the total nutrient perspective this is illustrated conceptually in Figure 4 where increased flushing will decrease TN and TP levels, and decrease eutrophication as algae and other organic matter are also flushed out.

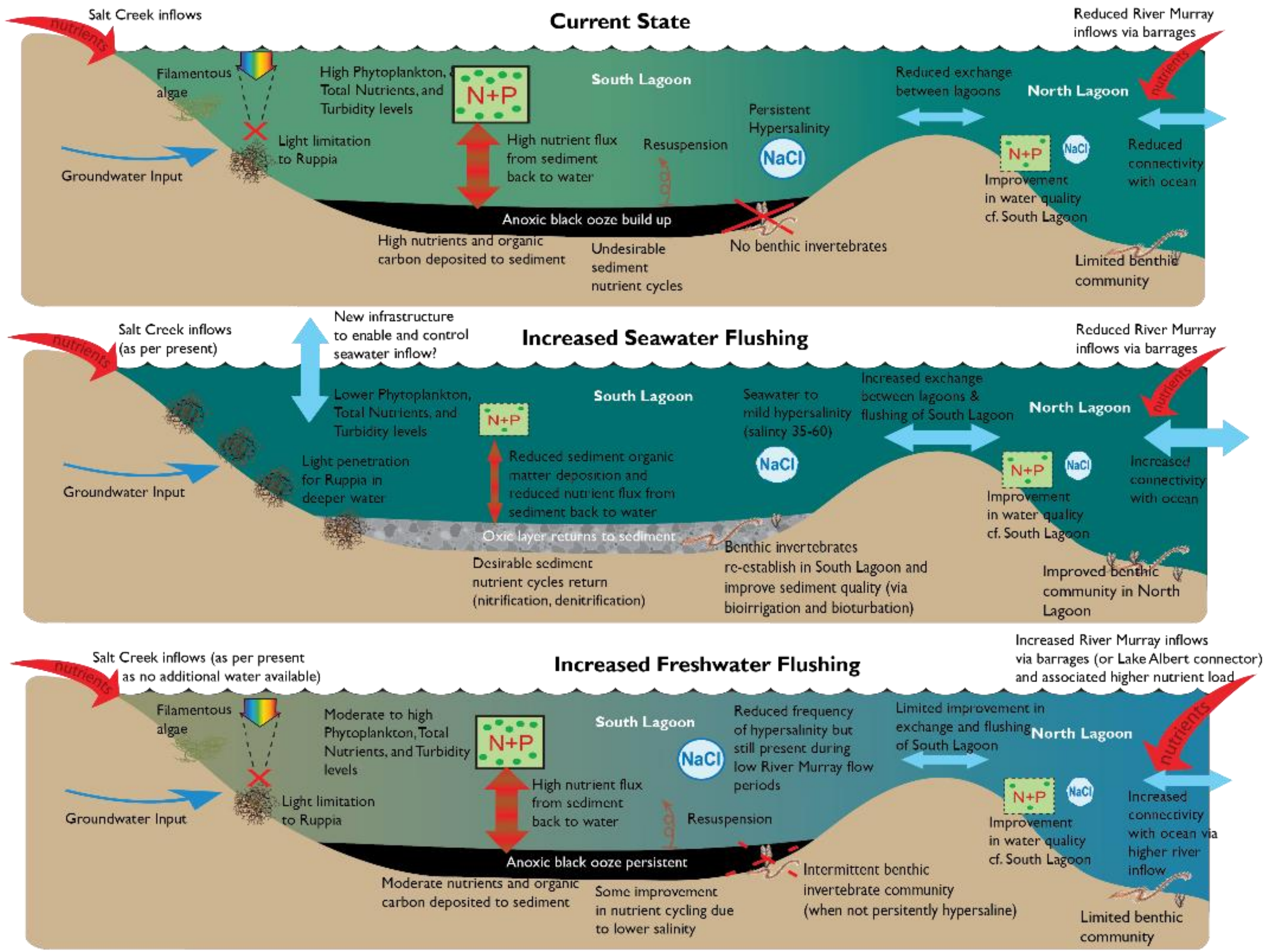

Figure 4. Conceptual model of the current water quality state in the Coorong (top), and with increased seawater (middle), and increased freshwater flushing (bottom).

Three options are available to increase flushing of the Coorong:

(1) increased freshwater inflows; and/or
(2) increased seawater inflows/connectivity (i.e. via pumping); and/or
(3) increased connectivity within and between lagoons and the Murray Mouth (i.e. via dredging).

Conceptual models for these options are shown in Figure 4 alongside a conceptual model of the current persistent hypersaline and hypereutrophic state. The increased freshwater flushing (primarily from the northern end) option (Figure 4) would not necessarily require investment in new infrastructure. However, the degree of dilution and nutrient export that could be achieved due to increased freshwater flushing via the Lower Lakes barrage releases is limited by volumes of River Murray inflows and the available water for the environment in the Murray-Darling Basin. Large River Murray flows are required to create flushing of nutrients out of the South Lagoon the Coorong, based on nutrient budget assessments for different flow periods (Priestley et al. 2022), and historical data analysis (Geddes and Butler 1984, Mosley et al. 2020).

There is potential additional surface water available from the South-East region that could be redirected to Salt Creek which flows into the southern end of the South Lagoon. However flows are seasonal and volumes are relatively small in comparison to the inputs from the River Murray-Lower Lakes barrages. Increased lagoon flushing during higher River Murray inflows appears to counteract any increase in external nutrient loads during these times (Priestley et al. 2022).

Conceptually, increased seawater flushing may be achieved through the (i) passive or active introduction of seawater to the South lagoon, or (ii) extraction (e.g. via pumping out) of hypersaline water from the South Lagoon to the ocean that would promote greater inflow of seawater through the Murray Mouth and North Lagoon. Increased seawater flushing could in theory provide a higher reliability of dilution and nutrient export compared to increased freshwater flushing, as it is not constrained by climatic factors (e.g. droughts) and availability of Murray-Darling Basin inflows. Seawater also has a much lower nutrient concentration than freshwater available through discharges from the Lower Lakes barrage or Salt Creek, so proportionally would result in lower nutrient loads entering the Coorong compared to the freshwater flushing options. Achieving increased seawater flushing of the South Lagoon would, however, require (a) new infrastructure for siphoning, channelling or pumping of seawater directly out of and/or into the South Lagoon, and/or (b) significant dredging works (scale yet to be determined) required to remove sedimentation in several locations/restrictions in the North Lagoon and between the two lagoons (e.g. the region southward from The Needles through Parnka Point to Hack Point). The infrastructure options to achieve increased flushing are being actively investigated as part of CIIP. It is noted that any such infrastructure options have social, economic and cultural implications that will be considered alongside the potential (both positive and negative) environmental impacts. If such an intervention was undertaken, the desired salinity regimes and gradients would need careful consideration in order to maintain and restore key ecosystem functions.

Increased flushing of estuaries via new connections to the ocean has proved successful in the Peel-Harvey Estuary in Western Australia (see Huang et al. 2020). An artificial channel, termed the “Dawesville Cut” was built in 1994 with the purpose of increasing flushing and reducing nutrient and algal concentrations. Nutrient and chlorophyll concentrations were markedly reduced following the Cut opening (see Figure 5). Importantly, the increasing rate of water exchange due to the Cut has made the nutrient concentrations within the estuary less sensitive to the inflow load by successfully improving the estuary flushing and decreasing water residence time and hypersalinity during the dry season (Huang et al. 2020). Even though this is a different system, it provides important information relevant to the Coorong on how improved flushing (e.g. via new piped seawatere exchange as considered by HCHB CIIP) could be used to reduce eutrophication.

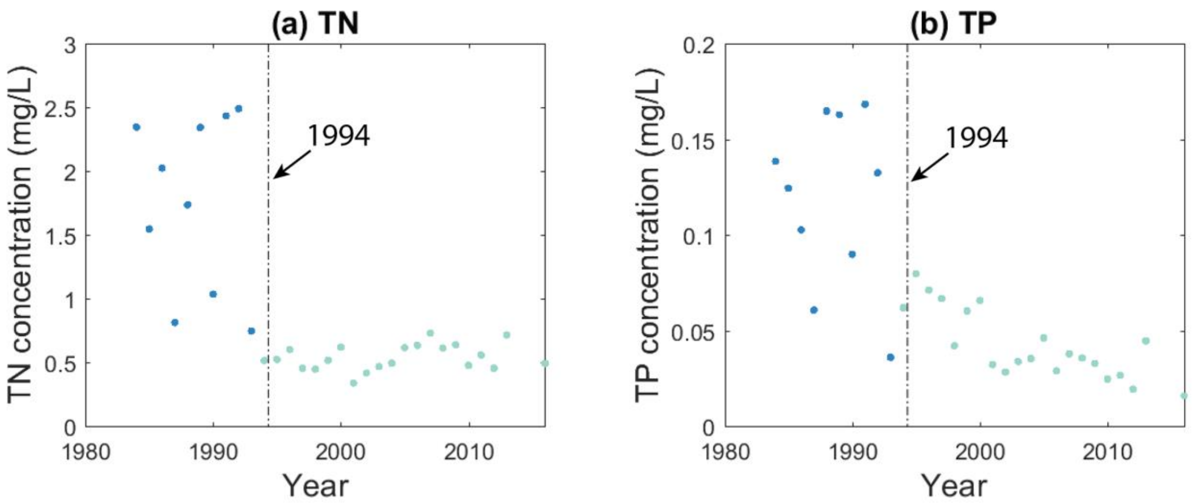

Figure 5. Changes in the mean nutrient concentration of (a) total nitrogen (TN) and (b) total phosphorus (TP) in the Peel–Harvey Estuary (based on the average of the six main monitoring stations) (from Huang et al. 2020). The vertical dashed lined indicates the timing of the "Dawesville Cut" in 1994.

It should also be noted that the increased seawater and freshwater flushing options are not mutually exclusive, i.e. they may be implemented in combination with one or more complementary management options (e.g. macroinvertebrate and aquatic plant restoration as outlined below) for improving the environmental condition of the Coorong.

3.2 Reduction in nutrient loads entering the Coorong from the Murray-Darling Basin and South-East catchment

Hypothesis: Nutrient concentrations are reduced in the inflows from the catchments that contribute to the Coorong, which reduces loadings of nutrients that are available to algae within the Coorong.

Another key driver of eutrophication identified in estuaries globally is increased external nutrient inputs (Bricker et al. 2007, Swaney et al. 2008, Steward and Lowe 2010, Le Moal et al. 2019). Elevated external nutrient loadings may occur where land use changes occur (e.g. increase in intensive agriculture or urbanisation), leading to increased point and non-point (or diffuse) source pollution loads. Point source pollution is defined as when a contaminant enters the environment from an easily identified and confined location (e.g. wastewater discharge pipe). Non-point source pollution arises from discharge of a combination of pollutants from a larger area (e.g. stormwater runoff from an agricultural or urban area).

3.2.1 Nutrient reductions in the Murray-Darling Basin catchment

Reducing nutrients from the Murray-Darling Basin inflows could reduce eutrophication in the Coorong. A reduction in external nutrient loads to very low levels would limit nutrient supply to algae in the Coorong, provided flows are maintained alongside reduced nutrient levels. Nutrient load reductions in the Murray-Darling Basin would likely have a greater impact on the North Lagoon water quality as nutrients are discharged into that region from the barrages.

Total diffuse sources of pollution are comparatively much greater on average than point sources in the Basin (Table 1). The dominant TN load is from unimproved pastures which reflects that this is the dominant land use in the Murray-Darling Basin (89% of area), while the highest TP load is from cropping areas which also have the second highest nitrogen input. Improved pasture and woodland/forestry areas also make a substantial contribution to diffuse TN and TP loads. The highest N and P loads occur from the New South Wales Border and Gwydir sub-catchments which are tributaries of the Darling River (Biswas and Mosley, 2018). While point sources such as Sewage Treatment Plants, piggeries and feedlots form a relatively small (1-2%) proportion of total Basin nutrient loads (Table 2), these may have a negative impact on water quality at a more localised scale due to their often continuous and/or direct discharge to waterways. This is particularly the case during low flow-drought periods due to a lack of dilution (Mosley 2015).

Calculated TN and TP loads to the River Murray from the major tributaries range from about 0.1 to 1 t day^{-1} and 0.01 to 0.1 t day^{-1} respectively (see Biswas and Mosley 2018). The Campaspe and Loddon rivers input substantially lower median loads than the other major tributaries due to their lower flow volumes. The Ovens, Goulburn and Wakool systems contribute the highest median TN loads, while these rivers plus the Darling contribute the highest median TP loads. The arid to semi-arid nature of most of the sub-catchments of the River Murray means delivery of diffuse source loads is intermittent, and generally correlated with moderate to large rainfall events (Biswas and Mosley 2018).

A variety of Murray-Darling Basin nutrient management tools, mainly targeting non-point sources of nutrients, would be needed for this strategy to be successful for reducing eutrophication in the Coorong. However it is currently unclear what level of nutrient reduction in inflows would be required to reduce Coorong eutrophication. A major risk with this option is that external nutrient loading alone is not necessarily an accurate predictor of eutrophication (Bricker et al. 2007, 2014, Cloern 2001, Nixon 2009), and given the Coorong is poorly flushed with high sediment nutrient concentrations, catchment nutrient management is likely to be unsuccessful without other options being implemented alongside it. Recent Coorong nutrient budgets (Priestley et al. 2022) showed an overall removal of nutrients when barrage flows were high (e.g. end of 2016), although nutrient loads are also high at this time. This reinforces the need for improved flushing as a primary management option.

Table 1. Summary of pollutant load data (diffuse and point source, total nitrogen (TN) and total phosphorus (TP)) for the Murray-Darling Basin (data obtained from the National Pollutant Inventory). The percentage that each source comprises of the total Murray-Darling Basin pollutant load is also shown. From Mosley and Biswas (2018).

DIFFUSE SOURCES	TN load (t yr^{-1})	TP load (t yr^{-1})	% total TN	% total TP
Unimproved pasture	69,918	3,236	46%	26%
Cropping	47,962	6,155	32%	50%
Improved pasture	16,727	1,565	11%	13%
Woodland/forest/forestry	12,254	680	8%	6%
Cotton-Murray	1,290	164	1%	1%
Urban	629	95	<1%	1%
Horticulture - perennial	586	59	<1%	<1%
Horticulture - annual	268	39	<1%	<1%
Coal Mining	0.21	0.05	<1%	<1%
subtotal - diffuse source	***149,634***	***11,992***	***99%***	***98%***
POINT SOURCES	**TN (t yr^{-1})**	**TP (t yr^{-1})**	**% total TN**	**% total TP**
Large Sewage Treatment Plants (STPs), water supply and drainage point sources	592	37	0.4%	0.3%
Sub-threshold point sources*	986	231	0.7%	1.9%
subtotal - point source	***1,578***	***268***	***1.1%***	***2.2%***
TOTAL (diffuse and point sources)	**151,212**	**12,260**	**100%**	**100%**

*Emissions below the National Pollutant Inventory threshold that arise from smaller emitters (e.g. smaller STPs, piggeries, dairies).

Furthermore, in most Murray-Darling Basin catchments, no single method of nutrient reduction (i.e. targeting only certain point sources or only certain diffuse sources) is likely to be successful, and there has been mixed success with diffuse source nutrient control (Bricker et al. 2020). A major nutrient reduction program in the Murray-Darling Basin is likely to be very costly, take a long time (decades), would require significant government, community and political support, and hence although it could be highly beneficial it would be difficult to implement. With the implementation of the Murray-Darling Basin Plan ('Basin Plan') there is a shift in focus to developing a broader suite of water quality management plans. However, the Basin Plan's activities do not currently extend into best management practice implementation to reduce pollutant loads (e.g. reducing fertiliser use and runoff). Hence the feasibility of this option is currently considered to be low.

3.2.2 Nutrient removal in South-East catchment and wetlands

Similar to the Murray-Darling Basin, the South-East catchment that drains to Salt Creek and the Coorong South Lagoon has a predominant agricultural land use dominated by cattle and sheep grazing, and cropping for hay production. Knowledge of the nutrient loads from this catchment and how they have changed over time is limited (EPA 2000, Everingham and Kawalec 2009). However, an accepted principle is that nutrient loads increase with development and intensification of agriculture, based on global analysis (McDowell et al. 2020). This is due to the widespread use of fertiliser for agricultural production and contributions from grazing animals. A whole-of-catchment nutrient reduction program would conceivably reduce external nutrient loads to the Coorong via Salt Creek. However, it is highly uncertain whether this would be sufficient to improve overall Coorong water quality in and of itself due to (a) the variable and seasonal nature of Salt Creek flows that results in limited timescales of flushing (Mosley et al. 2020), (b) the other nutrient load contributions from the River Murray that input to the South Lagoon (after passage through the North Lagoon)(Priestley et al. 2022), and (c) that existing internal nutrient loads (i.e. that flux from the sediment to the water, promoted by anoxic conditions and high concentrations of nutrients in the sediments, Huang et al. 2020) will likely persist from some time.

There is potential for nutrient removal via passage of water through South-East wetlands *en route* to the Coorong. The idea is that aquatic plants in the beds of the drain channels and wetlands will remove dissolved nutrients (requirement for photosynthesis) and total nutrients may also be potentially attenuated through plant uptake, settling and filtration processes. A recent snapshot water quality survey of Tilley Swamp by the HCHB T&I Component 1 team found on dissolved nutrient removal (relative to inflowing drain water) averaged 21% for ammonium, 57% for nitrate and nitrite, and 35% for filterable reactive phosphorus. On average the results suggest that Tilley Swamp was effective at removing total nutrients and nitrate from the inflowing drain water (Mosley et al. 2022b). There was minimal outflow from Tilley Swamp at the time of sampling however, so whether this option can be used as an effective nutrient management strategy for water *en-route* to the Coorong requires further assessment under higher inflow and outflow conditions.

3.3 Artificial oxygenation of water and sediment

Hypothesis: Dissolved oxygen in the water and sediment is enhanced by artificial oxygenation/aeration. This reduces flux of dissolved nutrients from the sediment by creating more iron oxides that can bind phosphorus and promoting nitrification-denitrification processes which can export nitrogen to the atmosphere.

Oxygenation of the water column and sediment has been suggested as an option that would assist in removing nutrients. Anoxic water and sediment conditions are known to occur in eutrophic systems and it is well established in the literature that this enhances nutrient fluxes from the sediment to the water column, in particular for P due to reduction of iron (Fe) oxide binding phases (Di Toro 2001). The sediment of the South Lagoon is currently highly anoxic. The consequences of anoxic sediment are (a) few barriers for diffusion of dissolved phosphorus (P) to the water column (i.e. iron oxides which bind P do not form under anoxic conditions); and (b) high ammonium levels as no oxygen is available to convert ammonium to nitrite and nitrate. Oxygenation of the overlying water, if hypoxic-anoxic conditions are present, could improve dissolved oxygen concentrations at the sediment-water interface, thereby increasing oxygen fluxes into the sediment (Larsen et al. 2019).

In the Coorong there was no evidence of anoxia in previous water quality monitoring data from 1998 to 2019 (Mosley and Hipsey 2019), and few periods that could be considered hypoxic (<4 mg/L dissolved oxygen). The lack of anoxia in the water column, despite highly eutrophic conditions, is presumed to be due to the shallow nature of the Coorong and regular wind-driven mixing replenishing oxygen levels in the water from the atmosphere. However, there was some uncertainty in these previous assessments as most of the measurements had been made in the daytime when photosynthesis is occurring and producing oxygen in the water. In eutrophic systems this can lead to highly oxygenated levels during the daytime, but hypoxic (low dissolved oxygen (DO)) or anoxic (zero DO) conditions overnight due to algae and microbe respiration. Figure 6 shows recent continuous DO data from the station near Woods Well in the South Lagoon. There is no evidence of hypoxia or anoxia with DO levels being maintained mostly >70% saturation relative to atmospheric oxygen levels. This is consistent with results from two loggers that were deployed (in HCHB T&I Component 1), one 0.5 m above the bottom of the water column and one 0.5 m below the water surface, in a deeper basin area near Woods Well in the South Lagoon in March 2020. This area and timing were considered a high-risk period for anoxia or hypoxia as temperatures were high and inflows from the River Murray and ocean were low at this time. Over a one-month period there was no evidence of anoxia at the top or bottom of the water column, and only one period that could be considered hypoxic in the bottom logger data.

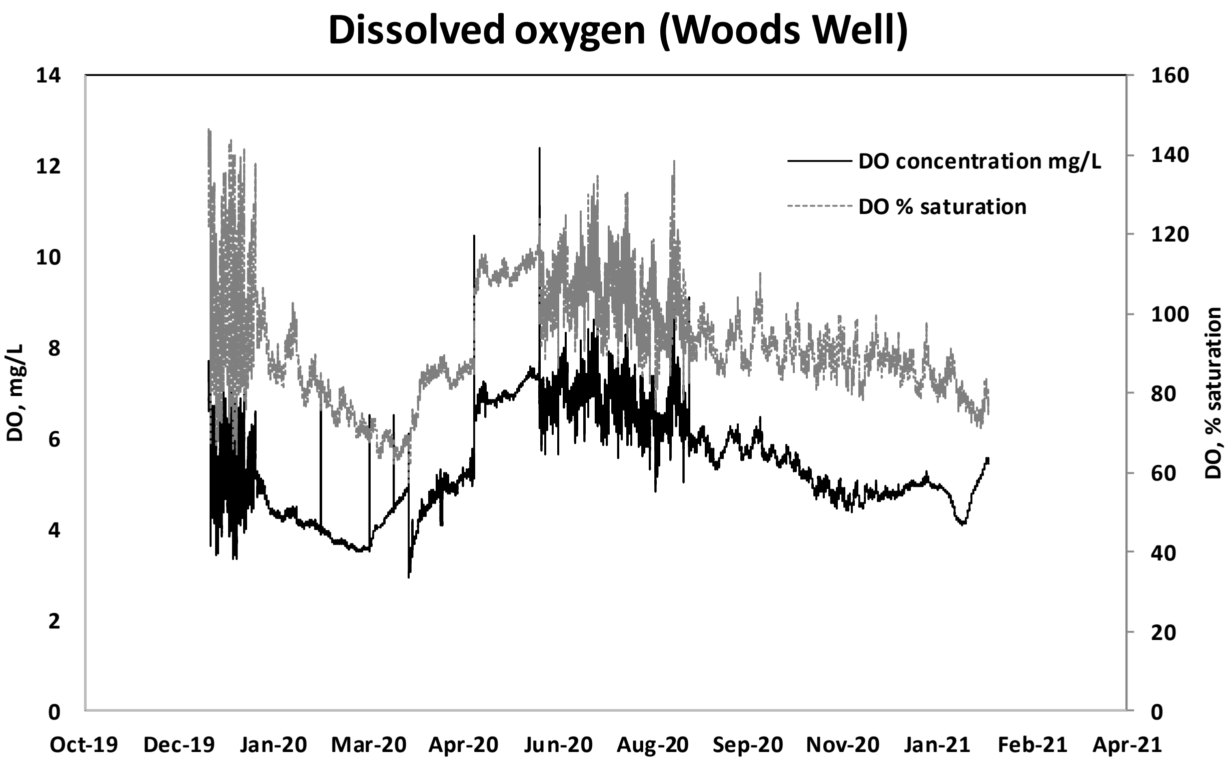

Figure 6. Continuous dissolved oxygen (DO) logging data from the DEW monitoring site (A4261209) near Woods Well from October 2019 to April 2021.

There are examples of this from the Swan River and Estuary in Western Australia where injection of pure oxygen into bottom water was shown to significantly improve DO in the water column over a distance of >10 km (Huang et al. 2018, Larsen et al. 2019). The Swan River study and other studies assessed in the literature involved oxygenating the water column which, in the case of anoxic conditions being alleviated at the sediment:water interface, can promote oxygen diffusion into the sediments. However, there were no studies found that involved direct oxygenation of anoxic sediments. Hence in the case of the Coorong, this concept would require substantial research and development, and does not address the primary driver of anoxic sediments (i.e. high algal-organic matter deposition to the sediments). Also given the scale of the Coorong (approximately 110 km from Murray Mouth to the southern end of the South Lagoon), oxygenation technology is likely only viable at the local scale (e.g. embayments) and hence does not support HCHB system-wide restoration objectives.

In summary, based on current evidence, water column and sediment oxygenation is not considered a worthwhile strategy to pursue for managing eutrophication in the Coorong.

3.4 Aquatic plant restoration

Hypothesis: Aquatic plants (e.g. *Ruppia*) are restored in the South Lagoon. These aquatic plants remove nutrients from the water and sediment for their growth, and their roots increase oxygenation of the sediment that reduces nutrient flux from the sediment to the water column.

Large ecosystem state changes have occurred in the Coorong since the 1950s, with a change in dominant species from slower growing aquatic plants such as *Ruppia* to fast growing phytoplankton and filamentous algae. While the main aquatic plant species now present, *Ruppia tuberosa* and *Althenia cylindrocarpa*, are salt tolerant, the salinity tolerances for germination of *R. tuberosa* seeds and turions have been regularly exceeded (Kim et al. 2013). *Ruppia megacarpa* appeared to have been lost from the Coorong as it had a much lower salinity tolerance than *Ruppia tuberosa* (Dick et al. 2011, Kim et al. 2013, Asanopolous and Waycott 2020). However recently *Ruppia megacarpa* has been identified as being present in Salt Creek and seeds have been found in the Coorong (Michelle Waycott, pers. comm. June 2021).

Along with extreme hypersalinity, it is also highly likely that eutrophication has also contributed to the decline in *Ruppia* condition (Collier et al. 2017, Waycott et al. 2020a and b). Nutrients are now being retained more in the system and partitioned into high turnover organic phases. The persistently high organic-derived turbidity is limiting light penetration and hence *Ruppia* habitat suitability (Waycott et al. 2020a and b). In addition, seasonal formation of filamentous algal mats shade and physically disrupt the ability of *Ruppia tuberosa* and *Althenia cylindrocarpa* to flower and set seed (Asanopolous and Waycott 2021).

Water eutrophication results in high organic loadings to the sediment that leads to anoxic surface sediment conditions and toxic sulfide build up that can also lead to loss of *Ruppia,* along with additional nutrient flux, turbidity and shading (Heijs et al. 2000, Azzoni et al. 2001). In addition, the decomposition of algal mats in areas with little water movement or detrital catchment areas results in organic sludge forming over the remnant *Ruppia* beds smothering them and adding high organic loads to sediment surface layers.

Restoration of aquatic plant habitat directly (e.g. translocation of seeds) and indirectly (i.e. by improving system conditions for survival and reproduction) is considered a potential nutrient removal option for the Coorong. However, it is unclear what the scale of this ‘nutrient removal’ benefit would be at a system level. The feasibility of system-wide aquatic plant restoration is also dependent on the need for improving and maintaining water and sediment quality given that these conditions resulted in their decline (i.e. need to reduce salinity, micro- and filamentous-algae, organic carbon, and monosulfidic black ooze (MBO) levels). Currently, water quality often exceeds salinity thresholds for *Ruppia* seeds and turions (Kim et al. 2019) and, due to high organic turbidity, light penetration is poor in the South Lagoon which means *Ruppia* is predominantly confined to the lagoon margins where it is also susceptible to exposure due to water level decline. Seagrasses such as *Ruppia* uptake nutrients from both the surface water and sediment pore water, but cycle nutrients more slowly than rapidly growing phytoplankton and filamentous algae (Waycott 2020). There is evidence that the roots of *Ruppia* oxygenate the black ooze sediment in the Coorong (Figure 7), which is a known feature of seagrasses (Borum et al. 2007). This root oxygenation likely helps maintain healthy nutrient cycling processes (nitrification-denitrification, Huang et al. 2022) and reduces nutrient fluxes from the sediment to the water (Di Toro 2011). These effects are limited to the rhizosphere (immediate zone of influence around plant roots) of aquatic plants however, and bulk sediment may remain unaffected. Further investigations on the interaction between the oxygenation of sediment by *Ruppia* roots and subsequent nutrient fluxes are occurring as part of HCHB T&I Component 1 Activity 1.3 and Component 2.

The use of floating aquatic plant beds or offsite algal extractors were not considered as viable nutrient removal options as the literature that was assessed contained no examples of system-scale success using these options for estuaries or systems the scale of the South Lagoon.

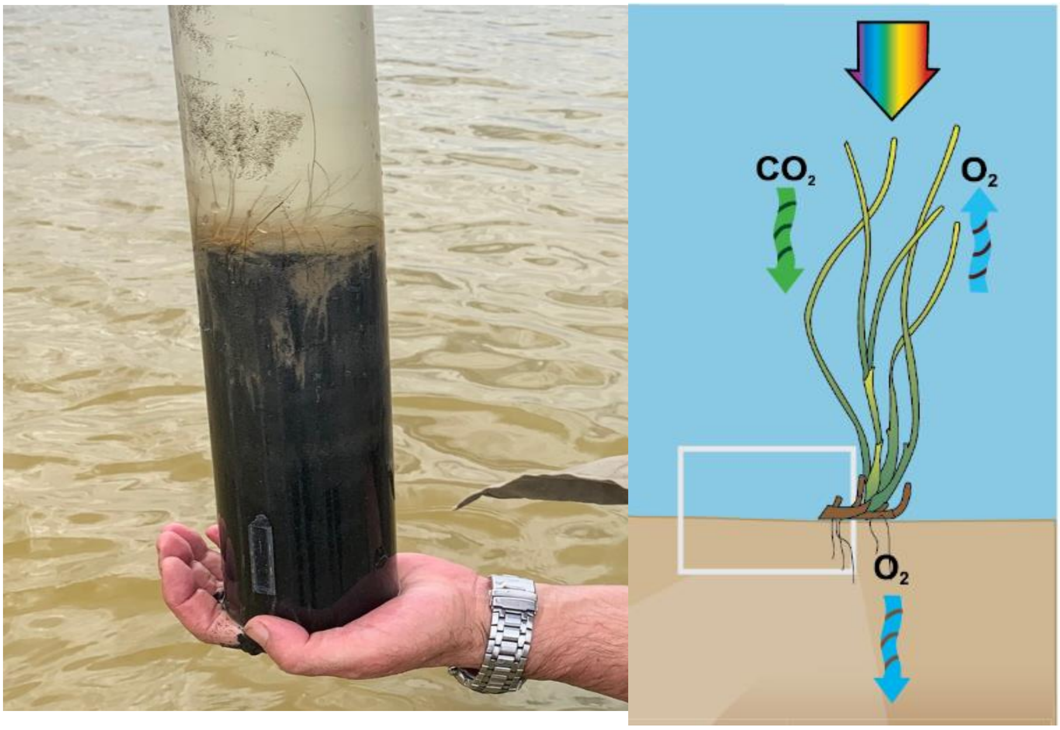

Figure 7. Apparent influence of aquatic plants (*Ruppia*) on sediment quality. The apparent influence of oxygen in the zone of root influence (rhizosphere) is visible by the lighter brown colouration adjacent the plant roots. The conceptual model to the right illustrates how this process can occur via photosynthesis in rooted aquatic plants.

3.5 Benthic macroinvertebrate restoration

Hypothesis: Macroinvertebrate communities are restored in the South Lagoon, and this contributes to removing nutrients from the water via filter feeding and increased oxygenation of the sediment via bioturbation that reduces nutrient loads.

Increasing hypersalinisation in the South Lagoon and southern region of the North Lagoon has resulted in the almost complete loss of benthic macroinvertebrate communities (Dittmann et al. 2015, Tweedley et al. 2019) (see recent data in Figure 8). Fossil and archaeological evidence indicates that the South Lagoon was not hypersaline and was widely inhabited by macroinvertebrates prior to European settlement (Disspain et al. 2011, Reeves et al. 2015). The absence of benthic macrofauna from the South Lagoon has been recorded since the first macroinvertebrate investigations in the Coorong (Geddes and Butler 1984) and thus has persisted for several decades. The loss of macroinvertebrates is likely due to the salinity tolerances (<60-65 psu) of key species being persistently exceeded (Dittmann et al. 2015, Remailli et al. 2018, Lam-Gordillo et al. 2022a), although other impacts due to poor sediment quality may now be present. Loss of these benthic macroinvertebrates and their ecological functions in the South Lagoon is highly likely to have contributed to increased retention and recycling of nutrients in the system as outlined in detail below.

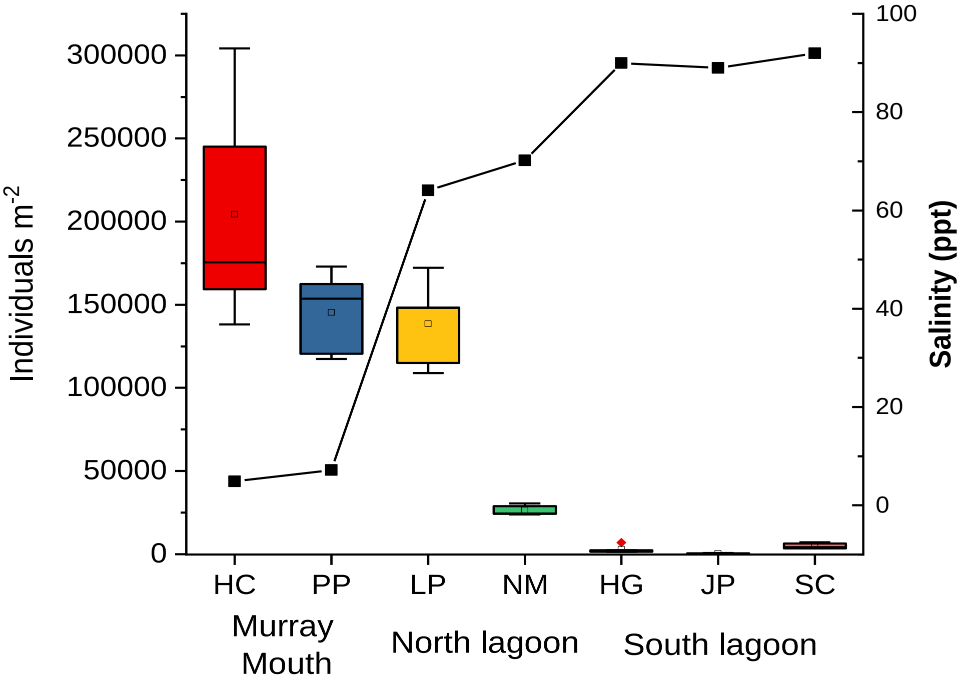

Figure 8. Macroinvertebrate abundance (individuals per m^2) versus salinity in the Coorong (Souce: Lam-Gordillo et al. 2022a). HC: Hunters Creek; PP: Pelican Point; LP: Long Point; NM: Noonameena; HG: Hells Gate; JP: Jack Point; SC: Salt Creek. The red dot at HG is considered an outlier.

Burrowing and bioturbating invertebrates oxygenate the sediment by reworking the sediment and dispersing organic matter, promoting the oxidation of sulfide (i.e. less anoxic black ooze), the formation of iron oxides (which sequester phosphate), and also stimulate rates of coupled nitrification-denitrification promoting nitrogen loss as gaseous end-products (Welsh 2000, Stief 2013). Therefore, macroinvertebrates act as ecosystem engineers, altering the sedimentary environment which affects bacterial populations and changes microbially-driven nutrient cycling.

In the Coorong, functioning macroinvertebrate communities are still present in the Murray Mouth region and northern North Lagoon where salinities are below 60 psu (Dittmann et al. 2015, Lam-Gordillo et al. 2022a). However, the polychaete sibling species *Capitella capitata*, which is an indicator for polluted and eutrophic sediment conditions (Cardosreo et al. 2007), has been dominating the benthic community in the North Lagoon since 2004 (Dittmann et al. 2018). Burrowers present at salinities between 40-60 psu are *Capitella* (1-10 cm, depth in sediment), some *Arthritica semen* (the micro-bivalves; 0-5 cm), and chironomids on the sediment surface (0-2 cm) (Lam-Gordillo et al. 2020). In the particular case of Noonameena (located between the North and South Lagoons), the polychaete *Australonereis ehlersi* (a large bioturbator that burrows 20 cm deep) has been infrequently recorded with low abundance.

The depth of these *Australonereis* burrows corresponds to the apparent oxic zone in the sediment (see

Figure 9). In contrast, much of the South Lagoon sediment has an oxic zone <0.1 cm (see

Figure 9), and loss of burrowing/bioturbating activity by macroinvertebrates due to persistent hypersalinity is highly likely to be a contributor to this (Lam-Gordillo et al. 2022a). Overall, the loss of these benthic macroinvertebrates and their ecosystem functioning is also likely to have contributed to the increasing eutrophication by favouring nutrient recycling over nutrient elimination/sequestration processes, and thus maintaining the current hyper-eutrophic state. This theory is supported by there being much more nitrate in sediments of the North Lagoon where invertebrates were present, which is indicative of more oxygenated sediment conditions, whereas ammonium is the more dominant species of nitrogen under anoxic conditions where macroinvertebrates were not present (Lam-Gordillo et al. 2022a). A conceptual model of how benthic invertebrate functional traits and sediment quality vary along the Coorong is shown in Figure 10.

Figure 9. (top) a typical anoxic black ooze sediment in the Coorong South Lagoon with no macroinvertebrates, and (bottom) burrows of benthic macroinvertebrates (Pelican Point - left) and absent of these organisms (Jack Point - right) influencing the oxygenation of the sediment.

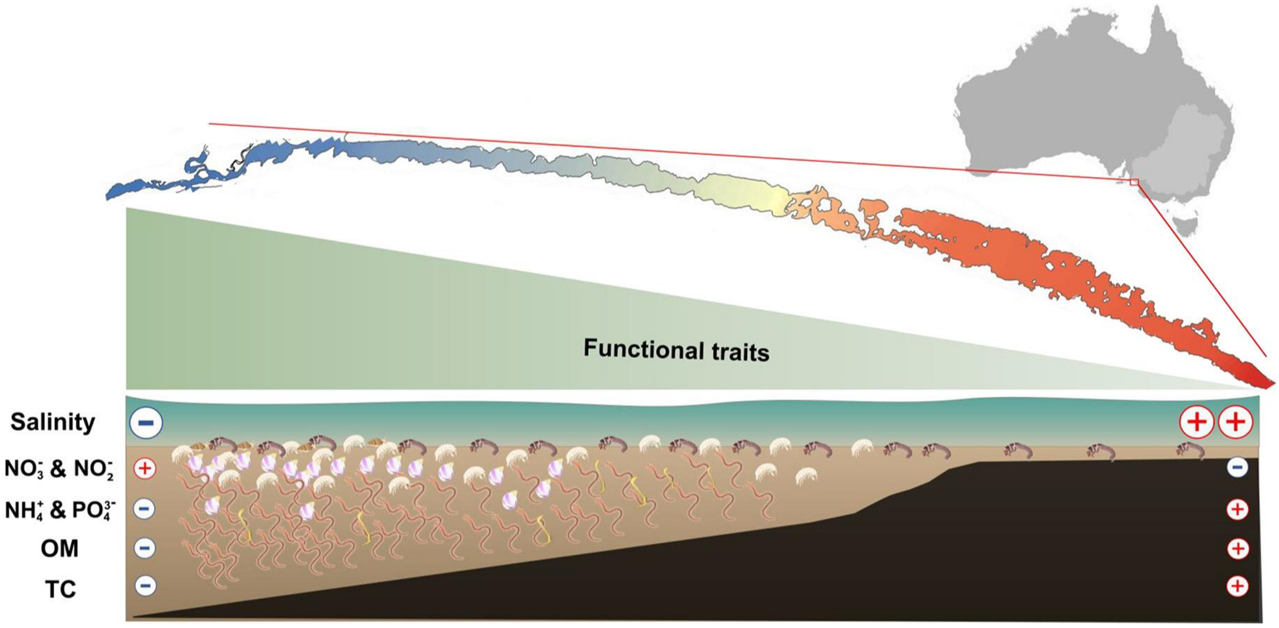

Figure 10. Conceptual model of how benthic invertebrate functional traits and sediment chemistry vary along the Coorong (Lam-Gordillo et al. 2022a). Shown is nitrate (NO_3^-) and nitrite (NO_2^-), ammonium (NH_4^+) and phosphate (PO_4^{3-}), organic matter (OM), and total carbon (TC).

As macroinvertebrates can affect nutrient fluxes from sediments enriched with organic matter, their bioturbation can be used as a bioremediation method for contaminated and eutrophic marine sediments (Kinoshita et al. 2008, Lacoste et al. 2019, Vadillo Gonzalez et al. 2019).

An *in situ* experiment in the Coorong as part of Component 1, revealed that colonisation of macrobenthic fauna was enabled by the translocation of sediment from a hypersaline site (Policeman Point) to a lower salinity site (Long Point) (Lam-Gordillo et al. 2022b). This was likely promoted by the sandy sediments readily facilitating the exchange and dilution of porewater with surface water, reaching favourable salinity levels (psu <60) where many macrobenthic organisms can survive (Dittmann et al. 2015, Remaili et al. 2018, Lam-Gordillo et al. 2022a). This experiment also showed that restoration of the bioturbation functions of benthic macrofauna, and in particular the polychaete *Simplisetia aequisetis*, modified the sediment biogeochemistry, promoting a healthier state (i.e. lower sulfide, ammonium and organic carbon concentrations) within a few weeks (following creation of suitable salinity conditions) (see summary in Figure 11). It has been suggested that biodiffuser and bioirrigator organisms, in combination with several feeding modes, promote microbial activities which are ultimately responsible for nutrient cycling and organic matter mineralisation (Welsh 2003, Braeckman et al. 2014, Bon et al. 2021). For example, organisms such as *S. aequisetis* and amphipods that build and inhabit burrows, are proposed to influence organic matter degradation rates by increasing oxygen transfer to the sediment by irrigating their burrows with the overlying water (Kristensen 2000, Welsh 2003, Volkenborn et al. 2012).

The translocation experiments carried out in the Coorong demonstrated that enhancing the distribution and/or potential re-introduction of macrobenthic fauna communities and therefore their functions should improve sediment conditions by reducing concentrations of ammonium and sulfide, and promoting oxic conditions in the sediment. Macrobenthic fauna activities could thus provide a complementary ecological restoration option for improving lagoons such as the Coorong with anoxic-eutrophic-hypersaline conditions. Reducing salinity in the South Lagoon of the Coorong sufficiently (e.g. 35-60 psu range), in combination with other mitigation and restoration activities, could allow recolonisation of the sediment by macrobenthic fauna, which in turn would improve sediment conditions and ecosystem functioning. However, larger scale mesocosm experiments across multiple locations (including hypersaline locations) would be beneficial to illustrate the potential pros and cons of interventions to reduce the salinity in the South Lagoon, and the response of macrobenthic fauna.

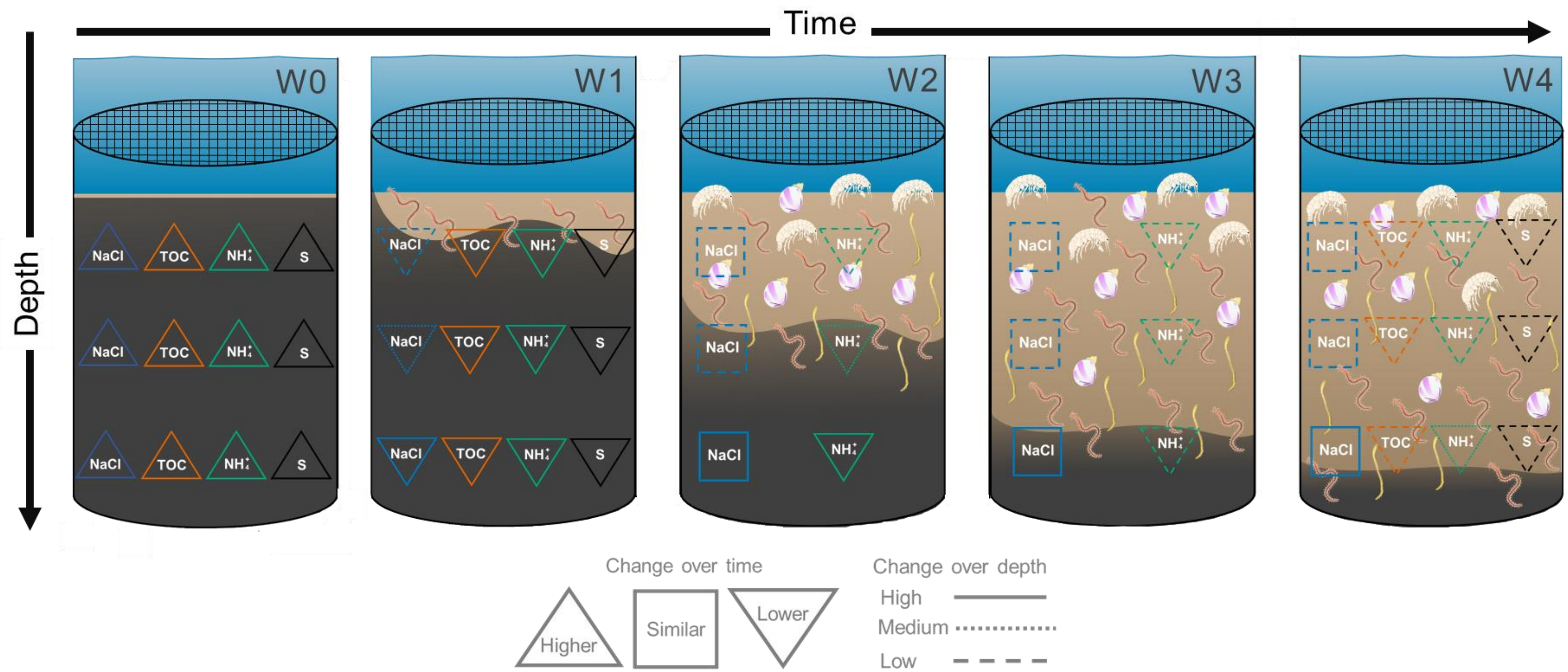

Figure 11. Conceptual model of how sediment chemistry (salinity, NaCl; total organic carbon, TOC; ammonium, NH_4^+; and sulfide, S) changed following macroinvertebrate recolonisation and burrowing when 'hostile' sediments were translocated from the South Lagoon to the North Lagoon of the Coorong. Source Lam-Gordillo et al. (2022b).

The scale of nutrient reduction in the water column that could be achieved by this option is currently unclear. Given the macroinvertebrate community in the South Lagoon has been in very poor condition for a prolonged time (>15 years, Dittmann et al. 2015), improving water quality to enable restoration and survival of the natural benthic community is a critical first step to this option. Salinity reduction can be achieved through increased freshwater or seawater flushing as described above in Section 3.1. In the eutrophic Peel-Harvey Estuary, an artificial connection between the estuary and the marine environment to facilitate such flushing resulted in a decrease of macroinvertebrate densities and deteriorating benthic conditions (Wildsmith et al. 2009). There is likely to be a lower risk of this occurring in the South Lagoon due to the current low diversity and abundance of macroinvertebrates (Figure 8), however, further assessment is required, particularly in relation to any associated changes to the North Lagoon.

Filter feeders also remove organic nutrients from the water column and have been mentioned as a potential restoration activity. Internationally, ''bioextraction'' of nutrients through the harvest of enhanced biological production, including the aquaculture of suspension-feeding shellfish, has been proposed as a nutrient management strategy (Bricker et al. 2014, 2020). Yet, nutrient removal from harvesting farmed suspension-feeders may not be effective, especially as farming of filter-feeding bivalves can also stimulate blooms of filamentous macro-algae, which impact on a lagoon ecosystem (Naldi et al. 2020). It is also important to note that shellfish reefs to our knowledge have not been part of the ecological character of the Coorong, and hence there may also be biosecurity issues with introducing these species from outside of the Coorong. The presence of toxin producing phytoplankton (e.g. cyanobacteria, dinoflagellates (including *Alexandrium minutum*) (Wiltshire et al. 2010, Leterme et al. 2018), which can bioaccumulate in suspension-feeding bivalves, likely restrict opportunity for bioextraction through shellfish aquaculture in the Coorong. Large natural "reefs" of the filter feeding tubeworm *Ficopomatus enigmaticus* occur throughout the North Lagoon and Murray Estuary (Dittmann et al. 2018) and have the potential to improve water quality and reduce suspended particle loads (Bruschetti 2019). However, when these reefs are covered with filamentous algae, their filtration activity is likely to be limited.

3.6 Macroalgal harvesting

Hypothesis: Macroalgae (e.g. filamentous green algae) is harvested from the Coorong water body or the shorelines where it has washed up or is growing. The algal material, and associated nutrients, is removed from the system which reduces overall nutrient stocks.

Harvesting is used to manage macroalgal accumulations in many eutrophic estuaries throughout the world (Runca et al. 1996, Lavery et al. 1999). Whilst removing algae also removes nutrients from the system, it primary aim is usually cosmetic, removing algal material washed up on shorelines before it decomposes and releases odours. These type of aesthetic issues have been present at times in the Coorong (see Figure 12). A variety of methods such as loaders, suction devices and floating harvesters have been used elsewhere. Small scale trials in the water body using manual, on foot, algal removal methods were undertaken in the South Lagoon (Waycott et al. 2020) resulting in successful removal of filamentous algal mats where sufficient water covered the areas of the algal biomass. However, Waycott et al. (2020) describe two factors that limited any potential benefits gained from the algal removal activity:

1. The filamentous algal mats occur over a large area coincident to the *Ruppia* beds. This results in any action taken to remove filamentous algal biomass damaging *Ruppia* plants.
2. The scale of algal removal manually is inadequate to sufficiently influence total nutrient loads, for example an area of approximately 0.25 ha was cleared and aerial drone surveys one week later showed more algal mat had formed over the area in that time.

The scale or benefits (e.g. annual removal of nutrients in biomass compared to standing stocks) is yet to be determined.

When machinery is involved, macroalgal harvesting may also impact benthic fauna and other organisms living on the water margins. However, Lavery et al. (1999) concluded that at regularly harvested sites the disturbance caused by machinery is temporary (in the order of days to weeks). The potential impact of harvesting based on the prevailing conditions in the Coorong would need to be evaluated.

Disposal of the algal material would be required and due to the likelihood of this material from the Coorong being highly saline, reuse in compost or agriculture operations may be very problematic (e.g. may require burial rather than beneficial reuse).

Figure 12. Photo of algae deposited on the shoreline of the Coorong North Lagoon near Rob's Point (left), and a algal mat smothering a *Ruppia* bed near Parnka Point (right).

It should also be noted that macroalgal harvesting does not address the root causes of eutrophication, at least in the short term, as when conditions are conducive new algae will grow to take the available space. The ability to remove sufficient nutrients to make an ecosystem state shift via this mechanism is not likely to be feasible due to (a) practical considerations of being able to harvest the macro-algae, and (b) the fact that the micro-algae pool has a large nutrient stock and this is a key loop that needs to be broken to improve water quality and light penetration for aquatic plants such as *Ruppia*. Continual macroalgal harvesting would be required if nutrient availability remains high, so in the absence of other strategies it is likely to only have localised and aesthetic benefit.

3.7 Hostile sediment removal and capping

Hypothesis: The existing anoxic, sulfide and nutrient-rich sediment is removed or capped with low nutrient sediment or artificial capping materials. The intent is that this may reduce fluxes of nutrients from the sediment to the water by altering conditions (e.g. nutrient binding sites, diffusion gradients) near the sediment:water interface.

Based on sediment quality surveys undertaken as part of other HCHB T&I Component 1 activities there are very large areas of highly-anoxic (reducing) sediments that contain high concentrations of sulfide-rich black oozes in the Coorong (Huang et al. 2022). As noted above, the accumulation of organic matter (i.e. eutrophication) is likely a key driver of formation of these oozes as this provides the energy supply for sulfate reducing bacteria that form these materials. High salinity (e.g. >60 psu) is also known to contribute to the extent of the highly sulfidic sediments, as the high salinity impacts the benthic invertebrate communities that introduce oxygenated water into deeper sediments (i.e. via bioturbation; Lam-Gordillo et al. 2022a,b) and also the bacteria-mediated processes that can process organic matter and nutrients (Wang et al. 2019).

Dredging to remove anoxic sediments (i.e. black ooze) and/or capping with clean, low nutrient sand to cover these sediments could be potentially effective to improve habitat in localised areas, although this is still to be demonstrated from an effectiveness and feasibility perspective in the Coorong, or indeed elsewhere in any estuarine-lagoon of similar scale. Localised intervention is consistent with national guidance in this area

(Sullivan et al. 2018, Simpson et al. 2018). Creating wetting and drying cycles in localised areas, or other strategies to promote sediment oxygenation could also help to break down the monosulfidic black oozes (MBOs) which are only stable under anoxic conditions (Sullivan et al. 2018 and see below for more details on MBO management).

An example of localised black ooze management via dredging for a small (1 ha) wetland in Western Australia is documented in the National Guidelines for the dredging of acid sulfate soil sediments and associated dredge spoil management (Simpson et al. 2018). Briefly, this wetland received high organic and nutrient loading from influent drainage. Combined with available sulfate and iron (chemical precursors) and highly anoxic conditions (i.e. typically <1 mm oxic layer observed on sediment), this caused the development of sulfide-rich sediments, which have in turn led to the decline in aquatic plant coverage across the wetland. To remedy this issue, the sulfide-rich sediments were removed from the wetland using a micro-dredge and geotextile desludging tubes (Figure 13). Following the initial dredge, the micro-dredge was returned to the wetland to remove the remaining sediment which had been moved by earth moving plant into more accessible deeper ponds in the wetland. The movement of this sediment was facilitated by the planned spreading of sand on the wetland base. The longer term nutrient removal outcomes were not reported. However it is clear this type of option is only applicable on a very localised scale and hence has very low feasibility of meeting the system-scale improvements demanded by the HCHB program aims.

Figure 13. Micro-dredge in operation (left) and desludging tubes (right) (from Simpson et al. 2018 – case study in national guidance for dredging of acid sulfate soils document).

Various advanced sediment capping materials have also been trialled to reduce contaminant fluxes from sediments. Capping materials aim to physically isolate contaminated sediments, provide a binding substrate for nutrients released from the sediment, and to create a less hostile environment for plants and animals. Phoslock^{TM} is a lanthanum (La) modified bentonite clay capping material developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) designed to remove dissolved P (i.e. phosphate). It achieves this by the reaction of P with La, leading to the formation of a single insoluble form of lanthanum phosphate (Ding et al. 2012). One major issue is that leaching of La can occur, leading to potentially toxic levels of this metal accumulating in the water (Ding et al. 2012). This is likely to be particularly problematic in a shallow and poorly flushed system like the South Lagoon with high ecological value. Phoslock^{TM} has also been shown to have limited utility in oxygenated water (i.e. like the Coorong) and release ammonium (Keller et al. 2021), which would enhance algal growth in the Coorong. For these reasons use of this modified capping material is not recommended for the Coorong under current conditions.

Lin et al. (2011) investigated, through a series of laboratory batch and sediment incubation experiments, the efficiency and mechanism of eutrophic lake sediment capping with calcite/zeolite (alumino-silicate mineral) mixtures to prevent phosphorus (P) and ammonium (NH_4^+) release from eutrophic lake sediments under anaerobic conditions. For this experiment, natural calcite and various zeolites (natural, sodium chloride (NaCl) pre-treated and calcium chloride ($CaCl_2$) pre-treated zeolites) were applied to the sediment. Calcite was efficient for the removal of phosphate in aqueous solution and the zeolite was an efficient adsorbent for the removal of NH_4^+ from aqueous solution. Sediment incubation experiments showed that the P and NH_4^+

fluxes from the anaerobic sediments were significantly reduced using the mixture of calcite and natural zeolite, while higher calcite dosage was found to be favourable for the prevention of P release which could be beneficial to reduce its availability to algae.

Simpson et al. (2002) studied the effects of tides, bioturbating organisms and periods of anoxia on metal fluxes from contaminated harbour sediments in a shallow tidal estuarine bay, together with capping technology options for the containment of metal contaminants. In the absence of capping, experiments in microcosms showed that simulated tidal processes increased zinc fluxes five-fold. Fluxes were also greater in the presence of sediment-dwelling organisms. If organisms were removed, and recolonising organisms later added, their bioturbation activities initially lowered zinc fluxes, but fluxes gradually reached steady state at the higher levels seen previously. Clean sediment (5 mm) was the most effective capping material in reducing zinc fluxes. Zeolite/sand mixtures (10 mm) also greatly reduced these fluxes, but significant breakthrough of zinc occurred after two weeks. Sand (20 mm) was not effective. The presence of organisms disturbed capping materials and increased zinc fluxes. Simpson et al. (2002) found installed capping materials should have depths of >30 cm to minimise organisms burrowing through to contaminated sediments beneath. This could create issues in the Coorong where there are shallow margins of suitable depth water for aquatic plants, with thick capping materials (>30cm) likely to alter current habitat suitability. The metal levels in the Coorong sediment are low (Huang et al. 2022), and there are unlikely to be issues with any ecological restoration options altering these fluxes.

Sediment removal and/or capping techniques were assessed as having very low feasibility to achieve HCHB aims of achieving significant lowering of nutrient availability in the Coorong at a system scale. They may be applicable and practical at a localised scale (i.e. shoreline areas with machinery access), but are unproven in large lagoon-estuarine systems such as the Coorong, would be very costly, and have a risk of creating unanticipated impacts. The removal of 'hostile sediments' (high in organic matter, sulfide and nutrients) in some locations may accelerate improvements to water quality provided it is accompanied by maintenance of lower salinities (e.g. with seawater flushing interventions, deepening of sections of the Coorong may improve water flows and provide an opportunity to remove some of hostile sediments). However, the disturbance of black oozes can also create water quality impacts (e.g. deoxygenation) which would require careful monitoring and assessment (Simpson et al. 2018).

3.8 Options not analysed in detail

Several other options were considered and eliminated from detailed consideration, including:

Water treatment systems – wastewater and other water treatment systems are available to remove nutrients from water. Typically, this is via a combination of biological (e.g. bioreactors), physical (e.g. filtration), and in some cases chemical treatment technologies. However, there is no evidence of these systems being successful at the scale of anything approaching the volumes of hypersaline, organic and algal-rich water that would need to be treated in the Coorong. They have mainly been designed for algal removal from domestic wastewater and treating algal bloom issues in small ponds. Wu et al. (2020) did a literature review of phosphate (limiting nutrient in the Coorong, Mosley et al. 2020) removal technology. However, in terms of practical application of the technology, they stated 'the presence of dissolved organic phosphorus challenges the phosphate sorption system in meeting the ultralow total phosphorus removal threshold (e.g. 0.01 mg P/L), as most sorbents target phosphate removal, and their sorption performance for dissolved organic phosphorus is unknown'. They also discuss issues with dissolved calcium (Ca) and magnesium (Mg) interfering with technology. Given in the Coorong (a) organic P is high, (b) dissolved phosphate is low, and (c) there is high dissolved Ca and Mg, the technology is highly unlikely to be successful and there is no evidence of it operating at the scale required. The volume of the Coorong is greater than 200 GL (at water levels >0 m AHD), so there would be very large and ongoing water treatment requirements which would be very costly (i.e. likely hundreds of millions of dollars based on scaling up costs of municipal wastewater treatment plants).

Straw/organic material addition – Addition of refractory organic matter (e.g. barley straw, rotting wood) has been used in ponds, canals and reservoirs to control algal blooms. Barley straw has been identified as an effective method in a variety of aquatic systems in the United Kingdom (Everall and Lees 1997, Harriman et al. 1997) and the Nile River (El-Monem et al. 2012). It has been postulated that phenols and octanoic acid released during the breakdown of barley straw inhibits algal growth, but there is also evidence that rotting barley straw increased bacterial decomposition thereby reducing nutrient concentrations (El-Monem et al. 2012). However, it is important to note that for the case of the Coorong, straw addition is adding nutrients and organic matter to the system. This could stimulate more anaerobic bacteria activity in the South Lagoon sediment, and currently there is an oversupply of organic matter at present fuelling anoxic bacteria activity, in particular sulfate reducing bacteria that form the MBOs and methanogens (Huang et al. 2022). There would also be potential negative effects on *Ruppia* or other aquatic plant species due to phytotoxicity and/or mechanical disturbance. The ability to implement this option at scale practically and cost-effectively is also unclear.

Drying of the South Lagoon – drying down the South Lagoon to expose sediment to oxygen would be a high-risk strategy both in terms of its likely effectiveness and likelihood of unintended consequences. Nutrients are not removed from drying down a system; potentially they can be immobilised while that state is maintained (e.g. phosphorus binding to Fe oxides), but could then be released when the system is wet (e.g. P release when Fe oxides undergo reduction). So it may not 'remove nutrients' or treat the cause of the problem. It is highly questionable that the South Lagoon could actually be dried effectively as much of the lagoon bed is lower than sea level, and it would go ultra hypersaline in the process of trying. Given the Coorong is a Ramsar site with important aquatic and terrestrial ecological values, drying would be extremely likely to harm these values (e.g. all fish and invertebrates would die, loss of wading bird habitat, potential loss of *Ruppia* seed bank). However, drying of small areas on the margins, or removing and drying MBOs in these areas, could potentially be beneficial prior to implementing complementary restoration options. However it remains to be demonstrated that this would be (a) practically achievable, (b) has the intended benefit in regard to nutrient reduction upon drying and rewetting, and (c) does not have any adverse ecological and cultural impacts.

Chemical/algaecide dosing – Algaecides/chemicals are commonly used in water reservoirs to control algal blooms, often copper sulfate ($CuSO_4$) as copper is very toxic to algae. Algaecides are not commonly used in marine systems, and when used in freshwater systems often have toxic side effects on other parts of the ecosystem (e.g. invertebrates, fish) (Nor 1987). Given the Coorong is a Ramsar site with important ecological values, the use of algaecides is not a viable option and was discounted from further analysis. Similar toxic metal side effects are observed with the sediment capping material Phoslock^{TM}, as mentioned above (Ding et al. 2012).

3.9 Monosulfidic Black Ooze (MBO) management

While the primary aim of this report is to provide information on 'nutrient removal options' it is also considered useful to document complementary ways in which the high amount of monosulfidic black oozes (MBOs) in the Coorong can be reduced to transition the system to a desired healthier state. These oozes form under anoxic conditions in wet sediment that are suitable for sulfate reducing bacteria activity which also requires organic matter. According to the national guidelines (Sullivan et al. 2018), the accumulation of MBOs in waterways can be minimised by following one or more of four potential management strategies:

1) Maintain erosive flow rates (floodgate control, channel design).
2) Minimise organic matter accumulation.
3) Maintain regular wetting and drying cycles (in managed waterways and wetlands).
4) Minimise and limit the sources and inputs of sulfate.

Strategies 1 'maintain erosive flow rates' and 2 'minimise organic matter accumulation' are the main options that have the highest chance of success at a system level in the Coorong as outlined below:

Maintaining erosive flow rates

Improved inflows and flushing of the lagoon would be beneficial to create conditions where MBOs are exported to the coastal ocean. The HCHB CIIP is investigating various long-term operational infrastructure to improve dilution, export, flushing and/or connectivity throughout the system.

Minimising organic matter accumulation in the sediment

Large quantities of MBOs can form in the Coorong because the Southern Coorong has persisted in a hyper-eutrophic state. Lack of flushing has led to very high organic carbon and nutrient accumulation in the water column (Mosley et al. 2020), which has led to ongoing and excessive deposition of organic matter to the sediments (Priestley et al. 2022). This coupled with very high salinity impairing breakdown of this material, has created highly anoxic conditions and provided the 'fuel' for sulfate reducing bacteria to produce MBOs. Short- and long-term goals for the Coorong should be to reduce the amount of organic matter being deposited to sediments and reduce the current load. Increasing flushing of the system and inter-lagoon connectivity is a potentially feasible option to achieve this as is being explored in HCHB CIIP. The restoration of macroinvertebrates is also conducive to breakdown of organic matter in the sediment (Lam-Gordillo et al. 2022a,b).

Maintaining regular wetting and drying cycles

Regular wetting and drying cycles can in some locations be applied to get atmospheric oxygen into the sediment, oxidizing the MBOs. However, this strategy is not readily achievable at a system scale in the Coorong as the lagoon is connected to the sea and has an elevation below sea level, and drying could create severe ecological harm (e.g. due to drying, acidification, extreme hypersalinity) in this Ramsar-listed wetland. However, some consideration could be given to this strategy for smaller areas on the margins.

However as noted above there are ecosystem restoration strategies that could reduce MBOs in the Coorong via promoting oxygen transport into the sediment. Restoration of aquatic plants and the recolonisation of sediments by macroinvertebrates creates oxygen-rich zones in the sediment. Most burrowing and filter feeding macroinvertebrates require salinities below 60 psu (approximately 1.7 times that of seawater salinity), which is often exceeded in the southern Coorong at present (Lam-Gordillo et al. 2022a). *Ruppia* roots also oxygenate the sediment, but currently aquatic plant condition and distribution is impacted by persistently high salinity (>70 psu) and poor water quality that reduces light penetration.

Minimisation of sources of sulfate

Minimisation of sources of sulfate is not relevant in a seawater and evapo-concentration influenced system such as the Coorong, i.e. there is always plenty of sulfate present. Nevertheless, enhancing freshwater inputs could help reduce MBOs in the lower salinity and well-flushed areas nearer the inflows (e.g. as per Figure 3).

In summary, improving Coorong flushing will promote the reduction of MBO levels in surface sediments via maintaining erosive flow rates, reducing algal-organic matter deposition to the sediment, and promoting oxygenation of the sediment via ecological restoration.

3.10 Integration and ranking of options

A summary of the options to remove nutrients from the Coorong, their scale of application, prerequisites for success, potential issues and likely feasibility of achieving the full HCHB program aims is shown in Table 2.

Based on the scientific evaluation undertaken, improved lagoon flushing and connectivity is likely the most feasible option for achieving HCHB program aims of nutrient reduction. This option would address the primary driver of eutrophication in the Coorong water and sediment, i.e. accumulation of nutrients and organic matter. The seawater flushing options (e.g. pump out from the South Lagoon) appear more pragmatic than the freshwater flushing options as they do not rely on additional freshwater being provided from the Murray-Darling Basin. Seawater also has low turbidity and nutrient levels relative to River Murray and Salt Creek inflows. Nevertheless, large flows from the River Murray are also critical to flush the system and the reduction of these has likely created a legacy and build-up of nutrients and organic matter in the water and sediment in the Coorong. As such the provision of environmental water through the Murray-Darling Basin Plan is important to preserve and enhance periodic flushing events.

Table 2. Summary of options to achieve nutrient removal in the Coorong South Lagoon including their scale of application, prerequisites, potential issues and likely feasibility of achieving the Healthy Coorong Healthy Basin (HCHB) program aims relating to nutrient reduction. The multi-criteria analysis (MCA) score is also shown.

Option	Whole of lagoon or localised scale applicability?	Pre-requisites	Potential issues with option	Likely feasibility of option achieving HCHB aims relating to nutrient reduction	MCA Score (out of 12)
Improving lagoon flushing by coastal seawater exchange into the South Lagoon or increased River Murray or South-East drainage inflow and improved connectivity (via dredging).	Whole of lagoon.	New infrastructure works for seawater option. However, it would be beneficial to be undertaken at an optimum time to reduce water column and sediment nutrient loads and so optimising the timing of any pumping is important (i.e. when nutrient and algal concentrations are highest).	• Low availability of additional freshwater from River Murray or catchments to the South-East. • New infrastructure required for use of seawater has complex and costly engineering requirements. • Disposal of dredge spoil. • Flow of hypersaline, nutrient rich water into North Lagoon with pumping in seawater option. • Could mobilise nutrients in the short term as bacteria more readily mineralise organic matter under oxic conditions.	High for using coastal seawater as a source of flushing water. This is presently the preferred option, based on this scientific assessment (not considering engineering or socio-economic aspects).	11
Reduction in nutrient loads entering the Coorong from the Murray-Darling Basin and South-East catchment.	Whole of lagoon.	None.	• Catchment nutrient management programs are difficult to implement in the Murray-Darling Basin, although would be beneficial to longer term outcomes of maintaining the healthy condition of the system. • Large internal nutrient load from sediment continues despite a reduction in nutrients in the water column.	Low.	7
Artificial oxygenation of water and sediment.	Localised.	None.	• Complex aeration infrastructure required at multiple locations. • Technology not proven for direct sediment oxygenation.	Low.	5
Aquatic plant (*Ruppia*) restoration (passive or active).	Whole of lagoon, in particular on lagoon margins	Improving and maintaining water quality (i.e. salinity,	• High risk of failure at present due to current poor sediment and water quality conditions.	Low (without pre-requisites addressed), Moderate (with pre-requisites addressed).	7

Option	Whole of lagoon or localised scale applicability?	Pre-requisites	Potential issues with option	Likely feasibility of option achieving HCHB aims relating to nutrient reduction	MCA Score (out of 12)
	unless light availability can be improved in deep water.	turbidity) and reduction in sediment nutrient, sulfide and organic matter loads to allow system-wide aquatic plant restoration.	• Shoreline access required • Source populations required for translocation.	Restoration effects may be patchy initially.	
Benthic macroinvertebrate restoration.	Whole of lagoon.	Improving water quality (i.e. salinity <60 practical salinity units, psu (~ <77,000 µS/cm Electrical Conductivity)) to allow more diverse macroinvertebrate community in South Lagoon.	• High risk of failure at present due to predominant hypersaline conditions (salinity > 60 psu) in the South Lagoon. • Passive restoration will take time for populations to establish. • Source populations required for translocation.	Low (without pre-requisites addressed), Moderate (with pre-requisites addressed). Restoration effects may be patchy initially.	5
Macroalgal and/or filamentous algal mat harvesting.	Localised.	None.	• Disturbance of waterbirds, sediment and invertebrates on shorelines. • Algal biomass co-exists and attaches to *Ruppia* beds, and therefore, *Ruppia* beds are expected to be impacted in the removal of algal biomass. • Difficulty of disposing of saline algal biomass (too salty for fertiliser).	Low at system scale, Moderate at localised scale. Could be of benefit in localised area to maintaining shoreline habitat to waterbirds for summer foraging.	7
Hostile sediment removal and capping.	Localised.	None.	• Ecosystem disturbance by machinery. • Smothering of any existing biota. • Reducing depth in applied areas which may have implication on aquatic plants • Potential toxicity (e.g. Lanthanum in Phoslock^{TM}).	Low. Clean sand capping could potentially be of benefit in a localised area (e.g. if there were barriers to survival of aquatic plants due to anoxic black ooze and it could be demonstrated there were no ecological risks).	6

Substantial reduction in nutrient loads (i.e. nutrient concentrations in an inflow multiplied by volume of that inflow per unit time) entering the Coorong from the Murray-Darling Basin and South-East catchments, could potentially reduce nutrient concentrations and supply to algae in the Coorong. However, this option would be difficult and complex to achieve due to the need to implement whole of catchment nutrient reduction programs over a sustained period of time. The South-East catchment would have the greatest opportunity to develop nutrient reduction programs due to its smaller size, being within one jurisdiction, and direct input into the Coorong South Lagoon. Irrespective of the impact on improving the current state of the Coorong, catchment management of nutrient loads should be considered in any future management options for the system. Internal nutrient loadings will continue from the sediment for some time, even under higher flushing and lower nutrient load scenarios. Nevertheless, over time increased water flushing will reduce algal-organic matter loadings to the sediment (i.e. via exporting this material), nutrient fluxes, and the build-up of anoxic black oozes. In doing so it is expected to promote what are considered 'healthier' or more desirable nutrient cycling processes.

Artificial oxygenation of water (and enhanced diffusion of oxygen into anoxic sediment) was deemed not to be warranted, as the Coorong water is moderately to well oxygenated, presumably due to regular wind mixing. Also, this option could only be applied at a localised scale due to the complex and costly infrastructure required. There does not appear to be existing technology for direct oxygenation of estuarine sediment *in situ*.

Macroalgal and/or filamentous algal mat harvesting and hostile sediment removal and capping could potentially be beneficial at localised scales, but do not address the primary drivers of eutrophication. Furthermore, there are significant potential practical issues associated with their implementation due to the need to cost-effectively and safely dispose of these materials, and minimise disturbance on the aquatic plant communities they are strongly associated with.

Restoration of macroinvertebrate and aquatic plant (e.g. *Ruppia* and *Althenia*) communities have the potential to assist with nutrient removal through oxygenating sediments and enabling greater nitrification-denitrification and binding of phosphorus (i.e. via iron oxide formation). However, a major pre-requisite of success of these strategies is re-establishment of improved abiotic habitat conditions (i.e. water and sediment quality via improved system flushing and connectivity) (Nienhuis et al. 2002). The current salinity in the South Lagoon (>60 psu) is persistently too high for re-establishing and sustaining diverse communities of burrowing and filter feeding macroinvertebrates (Lam-Gordillo et al. 2022a,b). Similarly, organic matter turbidity (which limits light penetration), and to a lesser degree salinity, is a current barrier to optimum *Ruppia* condition and distribution. The high sulfide concentration in the sediment and build-up of thick MBOs is also likely a current barrier to ecological restoration (toxic to *Ruppia* shoots and macroinvertebrates). The extent of anoxic black ooze sediments may not become lower without simultaneous lowering of salinity and eutrophication (inter-connected abiotic and biotic processes). Sediment algal-organic loads also inhibit *Ruppia* growth, and reducing these loads will assist in the recovery of healthy aquatic plant communities.

This suggests these localised and regional ecosystem restoration options are complementary to other options that improve water quality at system scale (i.e. improve lagoon flushing and connectivity) that are required to be implemented first. Increased flushing and maintaining an optimal salinity zone between 35-60 psu would likely result in much lower total nutrient levels, whilst also enabling additional nutrient removal and processing by *Ruppia* and macroinvertebrates that can persist at these salinities (see Figure 14). The 35-60 psu salinity range was not uncommon in the Coorong historically based on contemporary (Geddes and Butler 1984) and paleo limnology (Dick et al. 2011, Haynes et al. 2018) evidence. Lower salinities in the longer term, in conjunction with more mesotrophic conditions, would also likely enable a more diverse ecological community to form (Geddes and Butler 1984), enhancing broader HCHB goals and Ramsar site ecological character.

The above options were ranked against the MCA criteria in Table 2which gave results (and scores out of 12) in the following order (most to least favourable): *improving lagoon flushing* (11) > *reduction in nutrient loads* (7) = *aquatic plant restoration* (7) = *macroalgal and/or filamentous algal mat harvesting* (7) > *hostile sediment removal and capping* (6) > *artificial oxygenation of water and sediment* (5) = *benthic macroinvertebrate* *restoration* (5). It should be noted however that the lower score for benthic invertebrate restoration is reflective of the current high salinity conditions that prevents this options being viable at present. As noted above, strong consideration should be given to implementation of a combination of options that could contribute to maximum 'nutrient reduction'. Quantitative assessment of many of these options is still required. Mesocosm studies would be beneficial to test some of the integrated responses between ecological components (e.g. aquatic plants and macroinvertebrates), water quality, and sediment quality. Once these assessments have been completed the MCA analysis should be revisited.

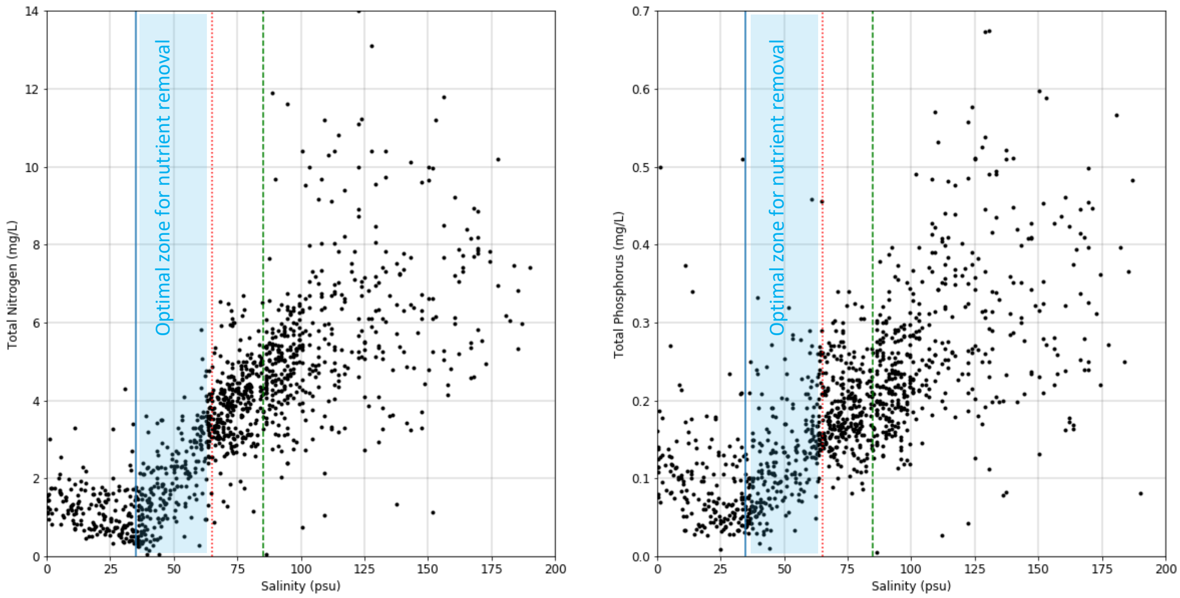

Figure 14. Relationship between total Nitrogen (TN) and phosphorus (TP) and salinity in the Coorong (adapted from Mosley et al. 2020). The approximate salinity thresholds for macroinvertebrates of ~60 psu (Dittmann et al. 2018) is shown as the red vertical line and for *Ruppia* germination of ~90 psu (Kim et al. 2013) as the green vertical line. The blue vertical line indicates seawater salinity of 35 psu.

4 Summary

In summary, based on the scientific evaluation undertaken, a combination of system scale, regional and local scale actions could help to achieve HCHB aims of nutrient reduction. It was found that the nutrient removal option with the highest likelihood of success based on scientific evaluation conducted in this report is improving lagoon flushing and connectivity. Once system-wide water quality is improved, regional macroinvertebrates and aquatic plant restoration options are complementary and could assist in further reducing nutrient levels. Localised management options involving macroalgal harvesting, aeration and/or sediment capping are considered to have a very low likelihood of successfully influencing whole of Coorong nutrient levels but could be used at smaller scales if feasibility and lack of negative environmental impact can be demonstrated. Internal organic matter and nutrient loads to and from the sediment will reduce over time but the rate of depletion of these loads is yet to be determined and there are several interacting processes to be considered.

List of shortened forms and glossary

Anoxic	Lacking in oxygen
Benthic	Of, relating to, or occurring at the bottom of a body of water
Biodiffuser	Benthic organisms that transport sediment particles randomly over short distances as they move through sediments.
Bioirrigator	The process of benthic organisms flushing their burrows with overlying water
Bioturbation	The disturbance of sediment by living organisms
Bioextraction	Removal of nutrients from an aquatic ecosystem through the harvest of enhanced biological production
Chlorophyll *a*	Photosynthetic pigment in green algae and plants
CIIP	Coorong Infrastructure Investigations Project
Denitrification	The microbial process in which nitrates and nitrites are reduced or removed from soil, water, or air by their conversion into nitrogenous gases
DEW	Department for Environment and Water
Eutrophication	Elevated supply of organic matter and nutrients
HCHB	Healthy Coorong, Healthy Basin
MBO	Monosulfidic Black Ooze, black gel-like materials that are enriched in sulfides
psu	Practical Salinity Units. A unit of salinity commonly used in marine settings. Equations can be used to convert between electrical conductivity measurements and salinity in psu.
Re-oligotrophic	Return to low supply of organic matter and nutrients
T&I	Trials and Investigations project
Zeolite	Microporous, aluminosilicate minerals commonly used as commercial adsorbents

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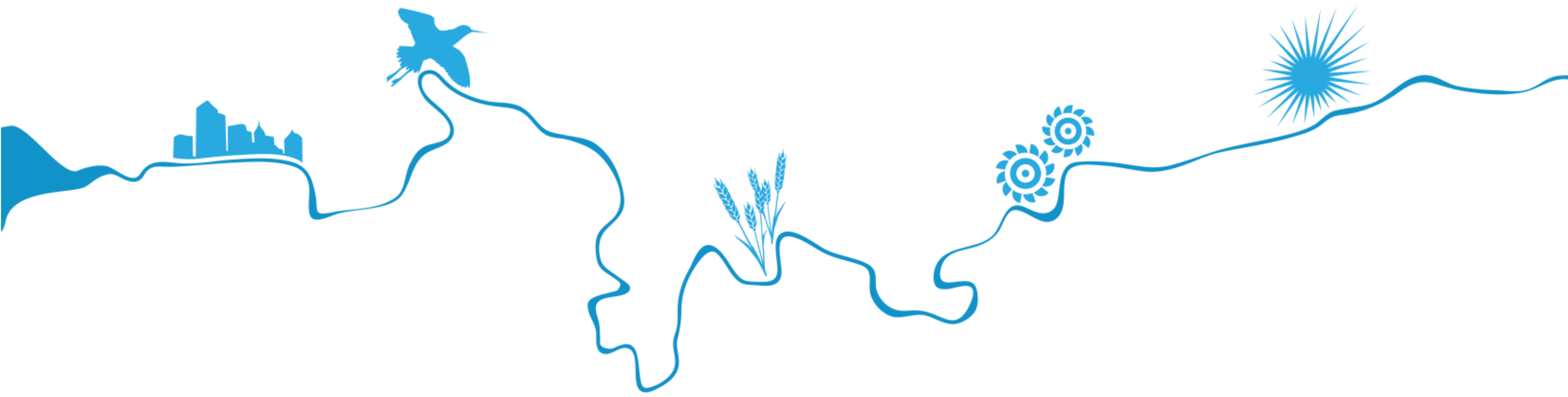

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