Review of the ecology, status and modelling of waterbird populations of the Coorong South Lagoon

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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.

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Executive Summary

The diverse and abundant waterbird community of the Coorong, Lakes Albert and Alexandrina Wetland has played a central role in its listing as a Wetland of International Importance under the Ramsar Convention. This report reviews the ecology and current status of the waterbirds in the Coorong and proposes a quantitative modelling approach to understand and predict the response of representative waterbird species to active management of the Coorong South Lagoon.

The Coorong is an important site for migratory shorebird species of the East Asian-Australasian flyway, many species of which are suffering population declines. The Coorong also provides important foraging and breeding habitat for non-migratory and summer/drought refuging waterbirds, including piscivores, waterfowl and large waders. The need for appropriate management of the physical and biological aspects of the Coorong, to enable it to support a diverse assemblage of waterbirds and shorebirds, presents a substantial challenge. The majority of waterbird species use the shallow edges of the Coorong lakes and lagoons for foraging and roosting, so their abundance is very sensitive to water level and shoreline habitat conditions. Lessons from the extreme conditions of the Millennium Drought, and the subsequent lag in the recovery of the system, suggest relationships between biological and physical characteristics of the Coorong South Lagoon and the ability of the system to support both non-migratory and migratory species. In particular, a pattern of rapidly declining water levels during spring and summer along with extreme salinity and/or eutrophic conditions have impacted the structure and function of Coorong food webs and influenced resource availability for waterbirds in the Coorong South Lagoon.

Although species-level responses to drought-driven conditions in the Coorong South Lagoon varied substantially, data from the annual waterbird census indicates that the Millennium drought produced more ‘losers’ than ‘winners’. It also documents an increase in the abundance of some species in the decade since the drought broke. Maintaining higher water levels for longer and salinity below about 100 g/L through the warm season, together with reduced nutrient inputs and/or increased nutrient flushing, are expected to: increase water and sediment quality; support aquatic vegetation and food webs (e.g., *Ruppia* seagrass beds, benthic invertebrates and fish); limit the negative impact of phytoplankton and filamentous macro-algae; and increase the availability of foraging habitat for shorebirds and wading birds.

To date, although Bayesian Belief Network models based on a mixture of expert opinion and empirical data have been used to predict the response of Coorong waterbirds to varying ecological conditions, quantitative models that link waterbird distribution and abundance to abiotic and biotic drivers have not been developed. An approach to formulating such models based on the annual, spatially stratified Coorong waterbird monitoring program is outlined, to allow quantitative predictions of the response of key waterbird species under different management scenarios in the Coorong South Lagoon.

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1 Introduction

1.1 Background

The diverse and abundant waterbird community of the Coorong, Lower Lakes (Alexandrina and Albert) and Murray Mouth (CLLMM) played a central role in the international recognition of the site as a Wetland of International Importance under the Ramsar Convention in 1985 (O'Connor et al. 2012). The Ramsar site (Figure 1) continues to support significant numbers of migratory and non-migratory waterbird species during their life histories, and the wetland meets all five Ramsar Criteria that can be qualified using data from birds (i.e. Criteria 2 to 6) (O'Connor et al. 2012). 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 primarily due to reductions in inflows. In particular, extraction of water for human uses in combination with the Millennium Drought (2001-2009) resulted in very low freshwater input from the Lower Lakes for an extended period (Montazeri et al. 2011, Aldridge et al. 2017), negatively impacted the ecological condition of the whole Coorong system, and produced ‘winners’ and ‘losers’ amongst the waterbird assemblage (Gosbell and Grear 2005, Ecological Associates 2010, Paton et al. 2020).

The CLLMM Ramsar site supports high bird species richness, with 307 bird species recorded with 1 km of the site (O'Connor et al. 2012); 119 of which use or are reliant on wetland habitat (Ecological Associates 2010). The site regularly supports 100,000 to 300,000 waterbirds and in some years can account for > 90 % of the waterbird abundance found across all six of the Living Murray Icon Wetland sites within the Murray-Darling Basin (Kingsford and Porter 2008, 2009). The CLLMM provides important habitat for threatened waterbird species that are formally listed under national (e.g. the Curlew Sandpiper *Calidris ferruginea*) and state legislation (e.g. the Little Tern *Sternula albifrons*, the Australian Painted snipe *Rostratula australis*); supports the key life-history stages of waterbird reproduction (15 species, particularly colonial- and beach-nesting birds) and moulting (56 species) (Paton 2010, O'Connor et al. 2012); and provides a refuge from drought for many species by supporting waterbird reproduction and/or survival when inland lakes are dry (O'Connor et al. 2012). The system also provides critical foraging habitat for migratory birds of the East-Asian Australasian flyway (EAAF) (Clemens et al. 2016) and regularly supports > 1% of the total flyway population size for 10 waterbird species (O'Connor et al. 2012). An important driver of this enormous waterbird abundance diversity is the range of wetland habitat types present within the CLLMM, including the freshwater habitats of Lakes Alexandrina and Albert, the tidal, estuarine mudflats of the Murray estuary, and the extensive hypermarine mudflats that are particularly found in the Coorong South Lagoon (Phillips and Muller 2006).

The waterbird assemblage of the Coorong, and particularly the Coorong South Lagoon, complements those found in other parts of the CLLMM (Paton et al. 2009, Rogers and Paton 2009), and contributes substantially to the overall abundance and diversity of waterbirds across the entire Ramsar site. Annual waterbird monitoring indicates that, in summer, the Coorong supports approximately twice as many waterbirds as the Lower Lakes (Paton 2010). For example, the most recent waterbird census (January, 2020) reported 176,900 waterbirds (64 species) using the Coorong, compared to 102,700 waterbirds (50 species) in the Lower Lakes (Paton et al. 2020). However, the annual census also documents substantial variation in the abundance and composition of the Coorong waterbird assemblage over time. For example, the abundance of individual species can vary by over 100-fold between successive years (Paton et al. 2020) and, by 2015, only 33 of 82 species ever recorded had been detected every year since 2000 (Paton et al. 2015). This temporal variation in waterbird abundance and diversity is presumably due to a range of factors, including wetland habitat condition along the EAAF (Clemens et al. 2016), regional climatic variation (e.g. El Niño cycles and water availability in arid Australia), and both long-term trends and inter-annual variation in local conditions within the CLLMM and the Coorong itself.

Annual condition monitoring of the Coorong waterbird assemblage has typically focused on approximately 40 species which are regularly detected in January each year (Table 1) (Paton et al. 2019, 2020). Of these, 21 are currently being considered as representative species for the Coorong South Lagoon (DEW in prep)

Figure 1. Location map of the Coorong, Lakes Alexandrina and Albert site which was designated as a Wetland of International Importance under the Ramsar Convention in 1985.

Table 1: The forty waterbird species considered in the most recent waterbird condition assessment for the Coorong. Also provided is the response-group categorisation of each species and, where applicable, the conservation status as listed under the Environmental Protection and Biodiversity Conservation (EPBC) Act (Murray–Darling Basin Authority 2017). The 21 species currently listed as representative species within the draft revised Ecological Character Description for the Coorong South Lagoon (DEW in prep) are illustrated with grey shading. *Migratory shorebird. Source: Paton et al. (2020).

Common Name	Scientific name	Group	EPBC threat status
Australian Pelican	*Pelecanus conspicillatus*	Piscivore	-
Australian Shelduck	*Tadornis tadornoides*	Herbivorous waterfowl	-
Australian White Ibis	*Threskiornis molucca*	Large wader	-
Banded Stilt	*Cladorhynchus leucocephalus*	Large wader	-
Black-faced Cormorant	*Phalacrocorax fuscescens*	Piscivore	-
Black-winged Stilt	*Himantopus himantopus*	Large wader	-
Black Swan	*Cygnus atratus*	Herbivorous waterfowl	-
Cape Barren Goose	*Cereopsis novaehollandiae*	Herbivorous waterfowl	Vulnerable
Caspian Tern	*Hydroprogne (Sterna) caspia*	Piscivore	-
Chestnut Teal	*Anas castanea*	Herbivorous waterfowl	-
Common Greenshank	*Tringa nebularia*	Shorebird*	-
Crested Tern	*Sterna bergii*	Piscivore	-
Curlew Sandpiper	*Calidris ferruginea*	Shorebird*	Critically endangered
Eastern Curlew	*Numenius madagascariensis*	Shorebird*	Critically endangered
Eurasian Coot	*Fulica atra*	Herbivorous waterfowl	-
Fairy Tern	*Sterna nereis nereis*	Piscivore	Vulnerable
Great Cormorant	*Phalacrocorax carbo*	Piscivore	-
Great Crested Grebe	*Podiceps cristatus*	Piscivore	-
Great Egret	*Ardea modesta*	Large wader	-
Grey Teal	*Anas gracilis*	Herbivorous waterfowl	-
Hoary-headed Grebe	*Poliocephalus poliocephalus*	Piscivore	-
Hooded Plover	*Thinornis rubricollis*	Shorebird	Vulnerable
Little Black Cormorant	*Phalacrocorax sulcirostris*	Piscivore	-
Little Egret	*Egretta garzetta*	Large wader	-
Little Pied Cormorant	*Microcarbo melanoleucos*	Piscivore	-
Masked Lapwing	*Vanellus miles*	Shorebird	-
Musk Duck	*Biziura lobata*	Herbivorous waterfowl	-
Pacific Black Duck	*Anas superciliosa*	Herbivorous waterfowl	-
Pacific Golden Plover	*Pluvialis fulva*	Shorebird*	-
Pied Cormorant	*Phalacrocorax varius*	Piscivore	-
Pied Oystercatcher	*Haematopus longirostris*	Shorebird	-
Red-capped Plover	*Charadrius ruficapillus*	Shorebird	-
Red-necked Avocet	*Recurvirostra novaehollandiae*	Shorebird	-
Red-necked Stint	*Calidris ruficollis*	Shorebird*	-
Royal Spoonbill	*Royal Spoonbill*	Large wader	-
Sharp-tailed Sandpiper	*Calidris acuminata*	Shorebird*	-
Silver Gull	*Chroicocephalus novaehollandiae*	Shorebird	-
Straw-necked Ibis	*Threskiornis spinicollis*	Large wader	-
Whiskered Tern	*Chlidonias hybrida*	Piscivore	-
White-faced Heron	*Ardea novaehollandiae*	Large wader	

within the draft revised Ecological Character Description for the Coorong South Lagoon (DEW in prep). The current review focuses on the aforementioned 40 species (Table 1) that includes migratory and non-migratory shorebird species (e.g. red-necked stint *Calidris ruficollis*, curlew sandpiper, red-capped plover *Charadrius ruficapillus*) and non-migratory large-bodied waders (e.g. banded stilt *Cladorhynchus leucocephalus*, black-winged stilt *Himantopus himantopus*, red-necked avocet *Recurvirostra novaehollandiae*, white-faced heron *Ardea novaehollandiae*), which can be found in internationally significant numbers in the Coorong South Lagoon, particularly during periods of continental drought. The Coorong South Lagoon also provides important habitat for piscivorous species (e.g. Australian pelican *Pelecanus conspicillatus*, crested tern *Sterna bergii*, fairy tern *Sterna nereis nereis*, great egret *Ardea modesta*) and waterfowl (e.g. Australian shelduck *Tadornis tadornoides,* black swan *Cygnus atratus*, Cape Barren goose *Cereopsis novaehollandiae*, chestnut teal *Anas castanea*, grey teal *Anas gracilis*, and musk duck *Biziura lobata*).

A key feature of the Coorong is a salinity gradient which impacts most biological components of the system, from primary producers to invertebrate and vertebrate fauna (Ye et al. 2020). In general, salinity increases from north to south, albeit substantial variation in salinity over a range of temporal scales is also driven by rates of inflow from freshwater and marine systems (Reeves et al. 2015). While the Coorong North Lagoon is an estuarine system that experiences substantial tidal flushing provided the Murray Mouth remains open, the Coorong South Lagoon receives freshwater inflow from the South-East drainage systems (via Salt Creek) and over the barrages from the Lower Lakes. After examining diatoms preserved within sediment-core samples from the Coorong, Fluin et al. (2009) concluded that the pre-European system was dominated by diatoms associated with marine and estuarine environments, that the incursion of marine waters from the North Lagoon into the Coorong South Lagoon was limited, and that inflow of relatively fresh water from the South East region helped control salinity in the Coorong South Lagoon. The diatom flora of the post-European period also suggested a widespread increase in salinity, which is corroborated by the chemistry of sedimentary organic matter across the Coorong (Krull et al. 2008), the loss of the seagrass *Ruppia macrocarpa* from the North Lagoon, and the shift of the salinity-tolerant *Ruppia tuberosa* further into the North Lagoon (Nicol 2005).

Before significant extraction of water from the Murray-Darling Basin for human use and the diversion of surface-water flows from the South East, on average the waters of the Coorong South Lagoon were probably clearer, less saline and lower in nutrients than they are today (Aldridge et al. 2017). Further, water levels in the Coorong South Lagoon likely remained higher throughout the spring and early summer, which would have supported the critical reproductive period of *Ruppia tuberosa* (Paton et al. 2015). These systemic changes due to contemporary human activities were exacerbated by the Millennium Drought, during which the water declined below -0.6 m AHD and salinity regularly exceed 150 g/L near Salt Creek in the Coorong South Lagoon. Drought-breaking rains from mid-2010 (associated with the onset of La Niña conditions) led to a period of increased freshwater inflow. However, many physical and biological aspects of the Coorong South Lagoon lagged in their recovery to the pre-drought state, and there is some concern that the drought has triggered a shift to an alternate stable state. In particular, whereas historically aquatic plants (particularly *Ruppia tuberosa*) were prominent in the Coorong South Lagoon, filamentous algae have dominated since the Millennium Drought (Paton et al. 2018). This shift is possibly due to a combination of reduced flooding of the mudflats in late spring and early summer and increased nutrient availability (Brookes et al. 2018).

There is strong evidence that populations of many Coorong waterbird species were in decline by the early 2000s (Gosbell and Grear 2005), and these declines were exacerbated by the drought in many cases (Paton et al. 2009, Ecological Associates 2010, Paton 2010). Today, the Coorong South Lagoon is still considered eutrophic (Mosley et al. 2020), and the poor water and sediment quality have impacted aquatic plants (Paton et al. 2018, Waycott et al. 2020), invertebrates and fish assemblages, with ensuing negative impacts on habitat quality for waterbirds (Ye et al. 2020). These changes to the ecosystem, and subsequent inability to restore conditions that will enable recovery to previous levels of abundance and diversity, are likely caused by a number of complex interacting factors which are not well understood (Brookes et al. 2018). This is limiting 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. Nevertheless, the management of the Coorong waterbird assemblage necessarily entails the management of water levels, and also prevailing salinities and nutrient inputs, in order to maintain the foraging and breeding habitats that sustain these bird populations, particularly within the Coorong South Lagoon which is less impacted by tidal flushing. The management of key processes and drivers of habitat quality/availability requires detailed knowledge of the direct and indirect impacts of these abiotic drivers on the distribution and abundance of waterbird species.

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 4 – Maintaining viable waterbird populations* forms part of the T&I Project. It aims to develop measures of habitat quality for key waterbird species in the Coorong, to develop ecological response models for key waterbird species within the Coorong as well as priority wetlands in the surrounding landscape; and to use telemetry and historical datasets to understand the movement of waterbirds between the Coorong and surrounding wetlands.

1.2 Aims

The overarching aim of *Activity 4.1 – Habitat suitability models for key waterbird species* is to develop an understanding of how key waterbird species will respond to future management scenarios within the Coorong South Lagoon. This will be achieved through the compilation of existing knowledge, models and data; the development of new models for key waterbird species using existing knowledge and targeted data collection to fill model data gaps where there are critical uncertainty implications; and running of models to assess the responses of key waterbird species to various management scenarios for different operational decisions and management interventions being considered.

The aim of *Sub-Activity 4.1.1 – Review of current knowledge of waterbird ecology in the Coorong* is to review existing knowledge regarding the ecology of the waterbirds that use the Coorong and the current status of these waterbird populations, and to summarise existing and proposed approaches to modelling the response of waterbird populations to biotic and abiotic drivers. This final report is a contractual deliverable for the T&I project, and meets the reporting requirements specified outlined in the Component 4 Project Plan. It presents the results of work completed during the period from October to November, 2020.

2 Methods

2.1 Conceptual review

In general, the ecology of waterbirds in the CLLMM, and for the purposes of this paper the Coorong South Lagoon (which is defined to extend no further south than Salt Creek), are driven primarily by the availability of food resources. The availability of food is, in turn, determined by:

- the abundance, distribution and/or density of prey species; and
- the ability of waterbirds to efficiently access these prey.

The foraging behaviours and diets of waterbird species that use the Coorong are incredibly diverse (Brookes et al. 2009a, Paton 2010, Ye et al. 2020), and waterbirds are able to forage in wetlands and adjacent terrestrial, marine or freshwater habitats, which makes dietary assessments difficult (Ye et al. 2020). Further, both the role that the Coorong South Lagoon plays in population demography, and the nature of the food resources, varies among the diverse species that regularly use the system. For example, the Coorong South Lagoon is an important non-breeding habitat for global migratory shorebirds, which primarily use the site to forage rapidly to store energy (as fat) to fuel their migration to breeding habitats in the Arctic, whereas other waterbirds use the Coorong South Lagoon and surrounding habitats for foraging and breeding.

In order to describe the functional response of waterbird communities to changes to the Coorong South Lagoon ecosystem, this review categorises those waterbirds that regularly use the system into four response groups, based primarily on their foraging behaviour and preferred prey species: shorebirds, piscivorous waterbirds, large wading waterbirds and herbivorous waterfowl. This follows O'Connor et al. (2013a), but excludes the fifth group (cryptic waterbirds), as these are not generally found in the Coorong South Lagoon (outside of the freshwater reed-beds, primarily in Salt Creek).

2.2 Data analyses

To conduct a preliminary analysis of trends in waterbird abundance in the Coorong South Lagoon, abundance counts from the annual census co-ordinated by The University of Adelaide (Paton et al. 2020) were divided into 6 zones, by aggregating the species-level counts across 5-km stretches of the estuary. Linear mixed-effect models with a trend term were then fitted to the data for each species, which incorporated a random intercept for each zone, and assumed a negative-binomially distributed error distribution (to allow for extra-Poisson variance in the count data when necessary). Two independent analyses were conducted for each species, using data for the pre- and post-drought periods (2000-2010 & 2011-2020). Abundance counts in the Coorong South Lagoon were too low to allow trends to be estimated using this method for 6 species (Australian white ibis, Cape Barren goose, eastern curlew, Pacific golden plover, royal spoonbill, and straw-necked ibis.

3 Results

The management of the Coorong's waterbird population necessarily entails the management of water levels, salinities and nutrient levels, in order to maintain the foraging and breeding habitats that sustain these bird populations. This is particularly the case in the South Lagoon, which is less impacted by tidal flushing and more impacted by absolute water level and wind driven water mounding and seiching. The majority of waterbirds that inhabit the Coorong use the productive, shallow (< 30 cm deep) margins of the lagoons which support benthic aquatic vegetation that requires sufficient light penetration to flourish (Paton et al. 2015, Ye et al. 2019). Provided water levels are not too high, there are extensive areas of gently sloping shoreline suitable for foraging by wading birds, with extensive mudflats being particularly important for migratory and endemic waders (Paton et al. 2015). In contrast to the Lower Lakes, periods of high salinity in the Coorong largely prevent the establishment of reeds and thereby maintains the mudflat habitats, and also favour *Ruppia tuberosa* over filamentous macroalgae (Paton et al. 2018). Nonetheless, maintaining suitable shoreline foraging habitats for a range of species under variable flow scenarios presents a significant challenge.

A key feature of the Coorong is a salinity gradient: salinity increases southwards and there is a corresponding reduction in the diversity of aquatic invertebrates and fish, although not necessarily an accompanying decrease in overall productivity (Paton 2010, Ye et al. 2019, Ye et al. 2020). In the Coorong South Lagoon, key dietary fauna for waterbirds include benthic infauna, the chironomid *Tantarsus barbitatarsisiii*, the brine shrimp *Parartemia* zeitziana, and the small-mouthed hardyhead *Antherinosoma microstoma*. The diversity of benthic vegetation also declines with increasing salinity, and was negatively impacted during the Millennium Drought, with some species disappearing completely (Paton et al. 2015). The salinity-tolerant *Ruppia tuberosa* is the key sediment-stabilising primary producer within the Coorong South Lagoon and has lagged in its recovery since the Millennium Drought (Paton et al. 2018, Waycott et al. 2020), although unpublished observations from 2020 indicate some recovery of *Ruppia tuberosa* beds and significant flower production.

As waterbird distribution and abundance is primarily driven by bottom-up ecological processes (food availability), the current and desired states of the waterbird community in the Coorong South Lagoon can at least partly be described by direct and indirect features of foraging habitat quality, that are, in turn, driven by hydro-ecological processes and aquatic trophic dynamics (O'Connor et al. 2013a). The aquatic trophic dynamics include measures of food availability, foraging performance, and the distribution and abundance of waterbird species. However, waterbird communities also respond to environmental change beyond the Coorong South Lagoon, including wetland habitat condition along the East-Asian Australasian flyway (EAAF) and regional climatic variation (e.g. El Niño cycles and water availability in arid Australia) which will affect some of these local responses (Kingsford and Norman 2002, Kingsford et al. 2010, O'Connor et al. 2013a, Clemens et al. 2016).

3.1 Ecology of waterbirds of the Coorong

The following presents an overview of the ecology of four waterbird response groups upon which the subsequent discussion is based:

(1) Shorebirds. Small-bodied migratory and non-migratory shorebirds with generalist diets, that forage on epibenthic and near-surface infauna, such as ostrocods, chironomid larvae, polychaetes and amphipods, as well as the seeds and turions of aquatic macrophytes (Rogers and Paton 2009). Most species tend to be tactile (rather than visual) foragers, although the red-capped plover is one exception to this rule. These species prefer to forage in either very shallow water (often < 5cm), or on saturated mudflats above the waterline (Collazo et al. 2002). The species in this group are generally associated with fine-sediment mudflats (Rose and Nol 2010), and are typically sensitive to water-level regime (Collazo et al. 2002). Species in this group may be impacted indirectly by physicochemical changes to the aquatic environment, through changes in the distribution and abundance of prey species, and changes in the distribution of water level regimes Collazo et al. (2002), (Duijns et al. 2015). Most are migratory species (Table 1) with high energy requirements to support northward migration. Common species include the curlew sandpiper *Calidris ferruginea*, red-necked stint, sharp-tailed sandpiper *Calidris acuminata*, and red-capped plover.

(2) Piscivorous Waterbirds. This group of species commonly rely on fish as their primary food source. For some species (e.g. crested tern, which are primarily oceanic foragers) local fish populations within the Coorong South Lagoon comprise just a small part of their overall diet. However, some species almost exclusively forage on fish within the Coorong South Lagoon, particularly during certain life history stages (e.g. during breeding, or early nestling stages) (Paton and Rogers 2009). Most species tend to be visual foragers, but utilise a range of harvesting strategies (e.g. aerial diving species such as terns, versus pursuit diving species such as cormorants). Species include Australian fairy tern, Australian pelican, crested tern, hoary-headed grebe *Poliocephalus poliocephalus*, and cormorant *Phalacrocorax* species.

(3) Large Wading Waterbirds. This group of species is primarily composed of Australian endemics, are often widespread, and can respond to habitat availability at continental scales (Pedler et al. 2018). Their common feature is that they employ a wading foraging strategy, feeding on pelagic or epibenthic aquatic organisms (Marchant and Higgins 1990). While some are visual foragers, many are tactile (Marchant and Higgins 1990). This group are relatively generalist with respect to animal species on which they prey, but are typically limited to foraging at water depths of 5-25 cm, depending on species (O'Connor et al. 2013a). Species include the banded stilt, red-necked avocet, and Australian white ibis *Threskiornis Molucca*, the great egret, and the white-faced heron *Egretta novaehollandiae*.

(4) Herbivorous Waterfowl. This group of species are exclusively members of the Family Anatidae (ducks, geese and swans). All species also depend on vegetative material as an important part of their diet, and in some cases, they can be essentially obligate herbivores (Marchant and Higgins 1990). Species include the black swan *Cygnus atratus*, Cape Barren goose, chestnut teal, Australian shelduck, and grey teal *Anas gracilis*.

3.2 Current status of waterbird assemblages in the Coorong

The first waterbird surveys for the Coorong were conducted in the 1980s and early 1990's, and then an annual, spatially stratified, waterbird monitoring program commenced in 2000 (Gosbell and Grear 2005, Paton 2010). The latter surveys are conducted in summer (January and February) when the abundance of waterbirds using the Coorong wetlands is generally at its greatest. Gosbell and Grear (2005) compared these two data sources and found that the abundance of many waterbird species declined between the 1980s and the early 2000s (and although population declines may also have occurred prior to the 1980s, data deficiencies preclude this conclusion). For example, the combined abundance of wading species peaked at 250,000 in the early 1980s but was as low as 50,000 in 2001 (Gosbell and Grear 2005). Further changes in the abundance and distribution of some waterbird species were observed by 2010, particularly in the Coorong South Lagoon (Paton et al. 2009, Paton 2010). These changes were likely driven by the extreme conditions that developed during the Millennium Drought, when water levels dropped below sea level in the Lower Lakes, the Coorong received negligible freshwater input from the River Murray (via the barrages), and salinities in the Coorong South Lagoon increased dramatically (Paton et al. 2015). Nevertheless, the Coorong remained habitable for waterbirds throughout the drought period.

Since 2009, evaluation of the status of waterbird populations in the Coorong has been guided by waterbird-related ecological targets first specified within the CLLMM Icon Site Monitoring Plan (Maunsell 2009) and subsequently updated in Paton et al. (2017a). These targets form the basis for reporting and evaluation for The Living Murray (TLM) program, and South Australia's Long-term Watering Plan. For 40 waterbird species that are regularly observed in the annual Coorong waterbird (Table 1), these targets are currently:

- to exceed the long-term (2000-2015) median abundance in 2 out of every 3 years;
- to exceed the 75% threshold for the long-term area of occupation (AOO) and extent of occurrence (EOO); and
- that all species should spend less than 70% of their time foraging.

The latter target reflects an assumption that the time a bird allocates to foraging is inversely proportional to the availability of resources, and is therefore an indirect measure of habitat quality. Additional targets related to waterbird breeding activity, migratory and threatened species will likely be included in updated management plans for the site (DEW in prep b). Each year, new data obtained from the annual monitoring TLM program have been used to assess the status of waterbird distribution and abundance against these targets, as well as to investigate the recovery of waterbird populations since the Millennium Drought.

The most recent assessment (Paton et al. 2019) concluded that, similar to 2018 and 2019, these targets were not met for all 40 target species in 2020. Of 64 species observed in the Coorong, and excluding the time-spent-foraging requirement, 21 species failed to meet at least one of three remaining targets, of which shorebirds were disproportionately represented amongst this group. Ten of thirteen shorebird species failed to reach their long-term median abundances in 2020, and five of these species failed to exceed this median for the last three years. Around 72,000 waterbirds (38 species) were using the Coorong South Lagoon in January-February 2020. Over half of these were waterfowl, dominated by grey teal, Australian shelduck, chestnut teal, and black swan, potentially suggesting strong grazing pressure exerted on *Ruppia tuberosa*. However, it should be noted that *R. tuberosa* monitoring indicated grazing was moderate in January 2017 and 2018, with an overall average of approximately 50% of shoots being grazed at the sampled sites, compared to around 80% of shoots grazed in the preceding years (Paton et al. 2018).

Preliminary trend analyses for the Coorong South Lagoon documented 'winners' and 'losers' amongst the waterbird assemblage during the Millennium Drought, along with a recovery in abundance following 2011 for some species. Of 23 significant trends detected for the pre-drought period, 70% (16 species) were declining trends which were estimated for 6 shorebirds, 6 piscivores, 1 large wader, and 3 herbivorous waterfowl. Only 10 significant trends were detected for the post-drought period, of which 60% (6 species) were declining trends. The abundance of some species clearly declined in the Coorong South Lagoon during the drought and has again increased over the last decade (e.g. black swan, grey teal, white-faced heron, great crested grebe), while the abundance of others increased during the drought and have since declined (e.g. banded stilt, black-winged stilt, great cormorant). Substantial discontinuities were apparent for some species; for example, the abundance of banded stilts increased during the drought, possibly due to the increased abundance of the brine shrimp *Parartemia zeitziana* (Rogers and Paton 2009, Geddes et al. 2016), but has been low thereafter. Residual analysis indicated that fit of the (log-)linear trend models was poor in some cases (e.g. crested tern, common greenshank, sharp-tailed sandpiper), suggesting that non-linear trend terms, spatial and/or temporal autocorrelated error structures and biophysical predictor variables should be explored in future modelling exercises. This will be a core element of *Activity 4.1 – Habitat suitability models for key waterbird species*.

Table 2: Trends in the abundance of waterbirds in the Coorong South Lagoon. Trends [and 95 % confidence intervals] are from generalised linear models fitted to data from two periods – pre-drought (2000-2010) and post-drought (2011-2020). Significant trends ($p < 0.05$) are highlighted with bold type. Trends could not be estimated for six species due to very few positive counts in the Coorong South Lagoon.

Common name	Pre-drought (2000-2010)	Post-drought (2011-2020)
Australian Pelican	**-0.155 [-0.267, -0.043]**	0.006 [-0.082, 0.094]
Australian Shelduck	0.065 [-0.025, 0.154]	0.033 [-0.096, 0.161]
Australian White Ibis	-	-
Banded Stilt	**0.438 [0.248, 0.628]**	**-0.426 [-0.668, -0.183]**
Black-faced Cormorant	**0.276 [0.008, 0.545]**	-0.108 [-0.353, 0.137]
Black-winged Stilt	**0.296 [0.119, 0.473]**	0.013 [-0.222, 0.248]
Black Swan	**-0.408 [-0.542, -0.275]**	**0.414 [0.298, 0.53]**
Cape Barren Goose	-	-
Caspian Tern	-0.12 [-0.266, 0.026]	-0.027 [-0.149, 0.095]
Chestnut Teal	**-0.235 [-0.33, -0.141]**	-0.006 [-0.118, 0.106]
Common Greenshank	**-0.213 [-0.297, -0.129]**	0.003 [-0.064, 0.07]
Crested Tern	-0.078 [-0.193, 0.037]	0.039 [-0.079, 0.158]
Curlew Sandpiper	**-0.418 [-0.614, -0.221]**	0.085 [-0.154, 0.325]
Eastern Curlew	-	-
Eurasian Coot	-0.14 [-0.359, 0.078]	-0.005 [-0.406, 0.397]
Fairy Tern	**-0.46 [-0.6, -0.32]**	0.094 [-0.07, 0.258]
Great Cormorant	**0.46 [0.122, 0.797]**	**-0.594 [-0.915, -0.274]**
Great Crested Grebe	**-0.348 [-0.596, -0.1]**	**0.251 [0.098, 0.405]**
Great Egret	**-0.995 [-1.509, -0.481]**	**-0.346 [-0.675, -0.016]**
Grey Teal	**-0.362 [-0.457, -0.266]**	**0.258 [0.125, 0.39]**
Hoary-headed Grebe	-0.046 [-0.18, 0.088]	0.138 [-0.023, 0.299]
Hooded Plover	**-0.239 [-0.379, -0.098]**	-0.117 [-0.26, 0.025]
Little Black Cormorant	**-1.143 [-1.65, -0.635]**	-0.025 [-0.196, 0.146]
Little Egret	-0.189 [-0.575, 0.196]	0.178 [-0.039, 0.396]
Little Pied Cormorant	0.176 [-0.073, 0.424]	-0.447 [-0.945, 0.052]
Masked Lapwing	0.003 [-0.04, 0.046]	**-0.057 [-0.101, -0.012]**
Musk Duck	**0.268 [0.074, 0.463]**	0.006 [-0.169, 0.18]
Pacific Black Duck	-0.072 [-0.352, 0.207]	0.008 [-0.273, 0.29]
Pacific Golden Plover	-	-
Pied Cormorant	**-0.764 [-1.246, -0.282]**	**-0.171 [-0.324, -0.019]**
Pied Oystercatcher	0.037 [-0.031, 0.106]	**-0.108 [-0.2, -0.015]**
Red-capped Plover	**-0.137 [-0.215, -0.06]**	0.01 [-0.115, 0.135]
Red-necked Avocet	-0.076 [-0.228, 0.075]	0.071 [-0.02, 0.161]
Red-necked Stint	**-0.243 [-0.36, -0.127]**	-0.079 [-0.21, 0.053]
Royal Spoonbill	-	-
Sharp-tailed Sandpiper	**0.166 [0.034, 0.299]**	-0.011 [-0.181, 0.16]
Silver Gull	**0.073 [0.005, 0.14]**	-0.104 [-0.218, 0.011]
Straw-necked Ibis	-	-
Whiskered Tern	**-0.133 [-0.252, -0.014]**	0.062 [-0.09, 0.214]
White-faced Heron	**-0.18 [-0.249, -0.11]**	**0.096 [0.025, 0.166]**

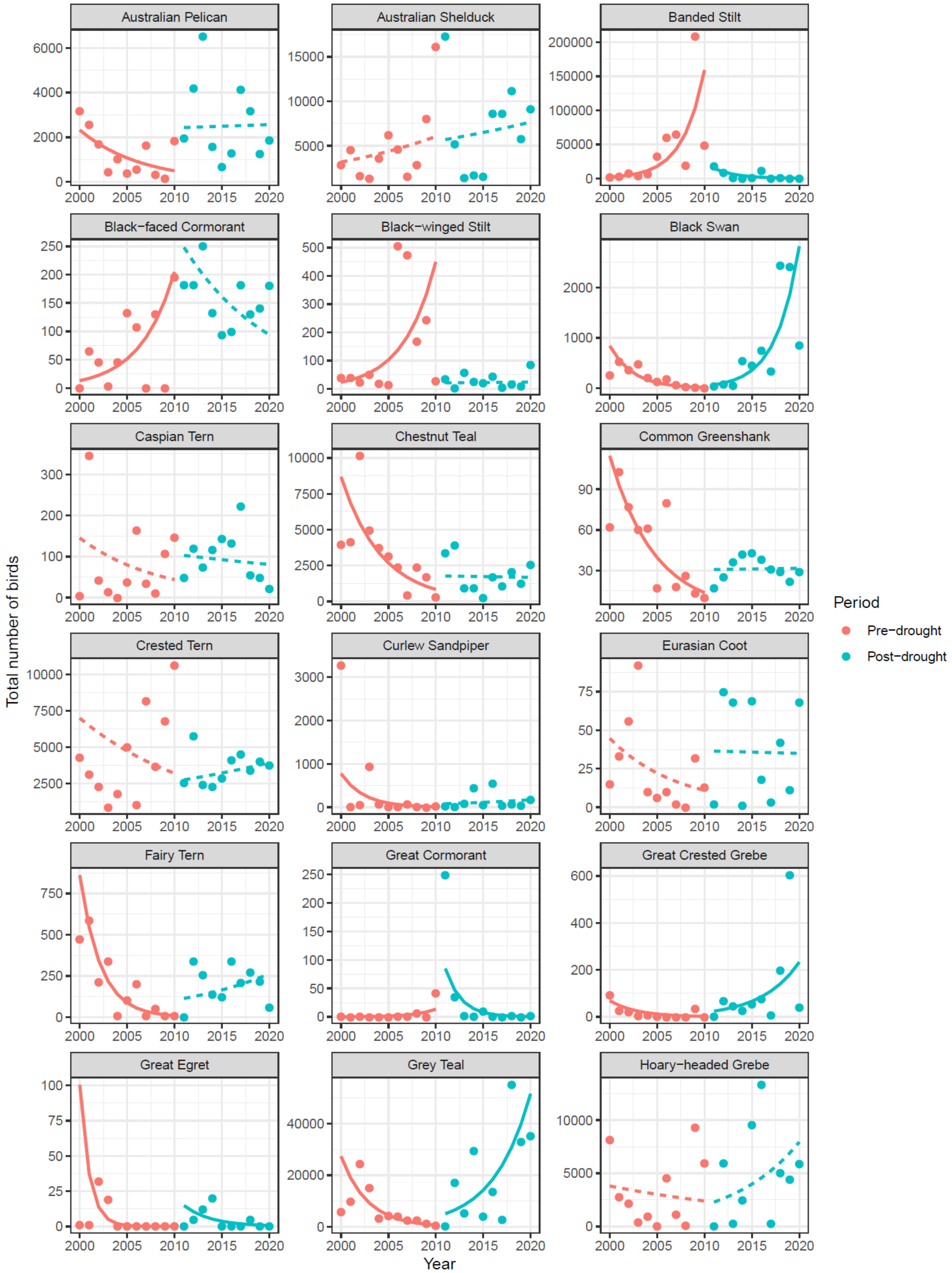

Figure 2. Illustration of trends fitted to abundance time-series for waterbirds in the Coorong South Lagoon, over the pre- and post-drought periods. Points represent the total number of individual birds counted at each annual census, and lines illustrate the fitted trends (solid line – significant ($p < 0.05$); dashed line – non-significant trend).

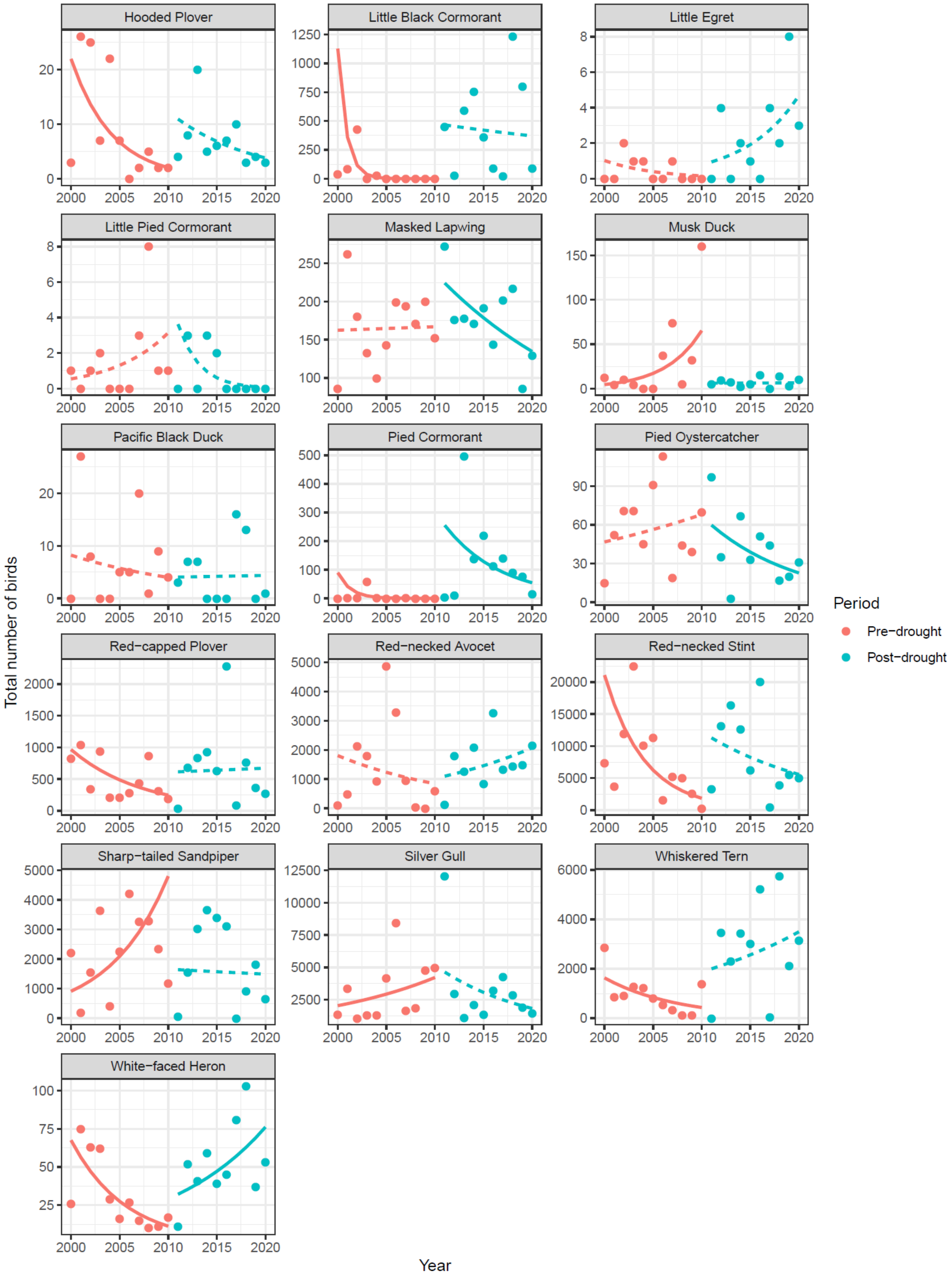

Figure 2 (continued)

The ability to assess the current state of waterbird communities in the Coorong today relies heavily on knowledge of ecological and physicochemical baselines prior to substantial anthropogenic impacts in the CLLMM system. The following consideration of the current state of the Coorong South Lagoon waterbird community relies on the following observations and assumptions:

- While warm-season salinity in recent years has been lower than that experienced during the Millennium Drought (Aldridge et al. 2017), there is a risk of undesirably high salinities that will physiologically exclude key macroinvertebrates (Dittmann et al. 2015, Remaili et al. 2018) and fish (Ye et al. 2013, Hossain et al. 2016) from areas of the Coorong South Lagoon;
- Water levels fall earlier in the warm season and remain low for longer than in pre-European times, which is suboptimal for the maintenance and restoration of aquatic macrophyte populations. In particular, *R. tuberosa* has been slow to recover in the Coorong South Lagoon since the Millennium Drought and can fail to reproduce via seeds and turions if subjected to prolonged exposure to the air, when water levels in the southern Coorong drop too early in the year and expose the young plants (Paton 2010). *R. tuberosa beds* that establish in winter are centred around the 0.0 to 0.2 m AHD contour (Paton et al. 2018). *R. tuberosa* needs an appropriate water coverage (0.3-0.9 m) to prosper, and there is concern that plants germinating in winter will be exposed to desiccation once water levels drop below about 0.3 m AHD (Paton et al. 2018).
- The contribution of phytoplankton, filamentous macro-algae, and photosynthetic bacteria to primary production is more substantial than historically (Brookes et al. 2018, Mosley et al. 2020), and while *R. tuberosa* beds are present, their more restricted extent and biomass mean that their important role in sediment stabilisation has reduced;
- Dissolved nutrients are rapidly assimilated by phytoplankton and filamentous macroalgae and turbidity is high which leads to low light conditions (Mosley et al. 2020). In addition, mudflat habitats are degraded through the development of monosulfidic black oozes and algal mats, which risks acidification events when mudflats are exposed and subject to rainfall events (Fitzpatrick et al. 2009).

This set of conditions has the following implications for the waterbird community of the Coorong South Lagoon:

(1) Shorebirds. Where mudflats remain suitable (i.e., monosulfidic black oozes and algal mats are absent), the salinity regime appears to still support abundant epibenthic fauna (Brookes et al. 2009b). However, there has been an increase in the extent of unsuitable mudflats in the Coorong South Lagoon, either through areas of mudflat that have become anoxic (and therefore supporting no epibenthic macroinvertebrates), or through shorebirds losing access to mudflats after they become covered by algal mats (in many cases both of these processes co-occur). As a result, the total extent of suitable habitat for shorebirds has been reduced. The implications of this on shorebird populations needs to be further explored, particularly given the inherently uneven distribution of shorebird habitat in the Coorong South Lagoon, and the uneven distribution of these impacts. In general, while some migratory shorebirds have shown modest increases in abundances since 2012, none are detected in comparable numbers to that observed in the 1980s (Nicol 2016, Paton et al. 2017b, 2019). For example, on average over the last three years the curlew sandpiper has been recorded in the Coorong at 39% of its long-term median abundance (Paton et al. 2020), and this target has not been met since 2015 for this species.

(2) Piscivorous Waterbirds. While small-bodied fish remain present in the Coorong South Lagoon, their average abundance and density is relatively low compared to long term historic abundance (Ye et al. 2019). Furthermore, the currently high turbidity of the water is likely to mean that foraging performance for many waterbird species is compromised (particularly for those piscivorous waterbirds that are visual predators). The reduction in foraging performance has likely contributed to a reduction in breeding outputs and recruitment for two important piscivores, the fairy tern and Australian pelican (Paton et al. 2019), both of which breed on islands in the Coorong South Lagoon, and forage predominantly in the Coorong. While there is some evidence that fairy tern abundances in the Coorong South Lagoon have improved post-drought (Figure 2), with some successful breeding in most years since 2011 (Paton and Paton 2020), the abundance of this species is typically less than or equal to around 50% that recorded at the turn of the century. Other non-breeding piscivores have also been affected; for example hoary-headed grebe (which will vacate the Coorong when inland waterbodies become widely available) are, on average across the whole CLLMM, lower in abundance during the current post-flood period than in any other period since 2000 (Paton et al. 2019). However, a weakly positive (but non-significant) trend was estimated for this species in the Coorong South Lagoon for the post-drought period.

(3) Large Wading Waterbirds. Reflecting the diverse ecological requirements of this group, the current state of the Coorong South Lagoon has resulted in a diversity of responses. For example, the abundance of banded stilt increased dramatically during the Millennium Drought, coincident with an increased availability of brine shrimp *Parartemia zietzianna* (Rogers and Paton 2009), but has been low thereafter. In contrast, trend estimates for little egret were negative and positive for the pre- and post-drought periods, respectively (albeit abundance counts are low for this species and these trends were not statistically significant).

(4) Herbivorous Waterfowl. Based on long-term patterns in the distribution, extent and abundance of aquatic macrophytes, we might expect that the abundance of specialist herbivorous waterfowl, such as black swan, pacific black duck and grey teal, might be low compared with historical abundance. However, and as noted above, recent data suggest that some species are currently in relatively high abundance in the Coorong South Lagoon, although chestnut teal are currently at historic low abundance (Paton et al. 2019, 2020). It is possible that a paucity of off-Coorong habitat availability has led to an increase in local abundance for continental nomadic species, including ducks and swans, and as for other wading species such as banded stilt and red-necked avocet (Clemens et al. 2016).

3.3 Desired state of waterbird assemblages in the Coorong

Under a future "desirable" state for the Coorong South Lagoon, based on the understanding presented above, it is assumed for the purposes of this review that the following conditions are required:

- Increased extent, density and biomass of *R. tuberosa* and other aquatic macrophytes, such that aquatic macrophytes are the dominant primary producers;
- Significant reduction in turbidity (increase in water clarity), as phytoplankton reduce in density and become the less dominant primary producers;
- Significant reduction in the extent of monosulfidic black oozes and algal mats on fringing ephemeral/seasonally exposed mudflats; and
- Hydrological conditions (water level regime, salinity regime and nutrient import-export) that support the persistence of functional *R. tuberosa* beds, maintenance of aquatic macrophytes as dominant primary producers, and abundant aquatic, epibenthic and infaunal food resources for waterbirds (e.g. high abundance of small-bodied fish, high biomass of aquatic macrophytes, and high abundance of epibenthic and infaunal macroinvertebrates).

It is acknowledged that, as seen over the Millennium Drought and the decade since (Figure 2), active management of the Coorong system is likely to produce 'winners' and 'losers' amongst the assemblage of waterbird species. Nevertheless, if the conditions listed above are met, we expect the following general patterns in waterbird abundance, diversity and habitat availability to prevail within the Coorong South Lagoon:

(1) Shorebirds. An increase in the extent of suitable foraging habitat, with an increase in the area of oxygenated surface sediments (top 2 cm) and sediments free from algal mats. This should have direct (through an increase in the area of mudflat habitat accessible to shorebirds) and indirect benefits (through an increase in the extent, density and diversity of suitable prey species of macroinvertebrate, as well as an increase in the extent and density of vegetative food items, such as *R. tuberosa* turions and seeds). This increase in foraging habitat extent would be expected to be expressed in an increase in the abundance of migratory shorebirds (assuming the maintenance of habitat throughout the flyway), an increase in the extent of occurrence of, and area occupied by, shorebird species, and an improvement in foraging performance (rate of energy intake).

(2) Piscivorous Waterbirds. Both a potential improvement in salinity regime (avoiding salinity levels in summer that are physiologically undesirable for key prey fish species), and an improvement in water clarity, are likely to result in improved foraging performance for key species. For those species that both breed in and rely to some extent on foraging within the Coorong South Lagoon (e.g., fairy tern and Australian pelican), this improvement in foraging performance leading into and during the breeding season could lead to improved recruitment. However, species like fairy terns may show little population response if nest predation by avian and terrestrial predators is too strong, or if pelagic productivity (and fish abundance) is the most important driver of their population dynamics.

(3) Large Wading Waterbirds. The response of large wading waterbirds to these changes in ecological state will vary, reflecting the varied ecological requirements of group members. Wading species that prey primarily on fish (e.g. great egret, white-faced heron) may respond in a similar way to other piscivorous species (see above), while tactile foragers that rely more strongly on aquatic macroinvertebrates and zooplankton (e.g. red-necked avocet) may not respond strongly compared with the current state.

(4) Herbivorous Waterfowl. Given the strong dependency of some herbivorous waterfowl on aquatic macrophytes, we expect that these species will respond strongly and positively to the predicted increase in extent, density and biomass of these aquatic plants under desirable conditions. This will be particularly the case for those species, such as Black Swan, that depend more heavily on aquatic vegetation in their diet, compared with other waterfowl that also feed on aquatic fauna.

Overall, we would expect an increase in the abundance, AOO and EOO of many waterbird species in the Coorong South Lagoon in response to the predicted shift to a more desirable ecological state of the aquatic ecosystem. This would maintain and improve the status of the Coorong as an internationally important waterbird habitat, and contribute to the global conservation of threatened waterbird species (including global migratory shorebirds).

3.4 Habitat suitability and population response models

As detailed above, variation in habitat suitability (as quantified by the availability of food resources or a related proxy) is likely to be a key driver of spatiotemporal variation in the abundance of waterbird species in the Coorong South Lagoon, although external drivers operating at a range of scales will also play a role. Further, variation in local conditions within the Coorong could play an important role in the population (or subpopulation) dynamics of those waterbird species that rely heavily on the Coorong for one or more life-history stages. Under these assumptions, future management of the Coorong is likely to focus on the provision of suitable habitat for waterbirds, with some authors suggesting more focus on water levels than salinity (Paton et al. 2015).

To date, few attempts have been made to model the response of the waterbird assemblage or individual species to abiotic or biotic drivers in the Coorong. In the most relevant study to date, Bayesian Belief Network (BBN) models were constructed for 10 species of the Coorong South Lagoon (O'Connor et al. 2013a). Based upon expert elicitation and some empirical data, these models identified key ecological thresholds and suitable ranges for a number of abiotic and biotic variables (e.g., water depth salinity, sediment size, macroalgal cover, prey abundance) and could be used to forecast impacts of changing conditions on species-specific habitat suitability at the site. Given these models incorporated expert knowledge of species' responses to extreme ecological conditions (e.g. the 2001-2009 drought), it was considered that they were likely to forecast realistic waterbird responses for a broad range of ecological conditions. However, the output variables of the BBN models (e.g., fledgling success, adult survival, rate of energy intake) were not directly relatable to the primary time-series data collected on waterbirds (i.e., spatially stratified waterbird counts), and the predictive capacity of these models was never tested. An alternative approach is to fit quantitative waterbird response models to data from the annual waterbird monitoring program, and to evaluate their ability to predict hold-out data (and additional data as it becomes available over time). By testing models with data, our capacity to understand and predict the abundance response of different species to natural and managed environmental variation can be statistically assessed. Further, these models will allow spatially explicit predictions of abundance to be generated for target species under different management scenarios.

A key goal of *Activity 4.1 – Habitat suitability models for key waterbird species* is to develop quantitative response models that capture how the distribution and abundance of key waterbird species changes in response to variation in local conditions within the Coorong (and potentially external factors influencing flyway populations), and to predict the response of these species under future management scenarios. For the purposes of these investigations, model development will focus on a subset of species that are dependent on the Coorong South Lagoon, have undergone demonstrable declines in the Coorong South Lagoon since the year 2000, and that represent, ecologically, a broader group of species (such that the overall list of key water bird species adequately represents the ecology of the entire waterbird assemblage). The following list of key waterbird species was identified by the South Australian Department for Environment and Water:

- Australian Pelican (*Pelecanus conspicillatus*)
- Black Swan (*Cygnus atratus*)
- Common Greenshank (*Tringa nebularia*)
- Chestnut Teal (*Anas castanea*)
- Curlew Sandpiper (*Calidris ferruginea*)
- Fairy Tern (*Sterna nereis nereis*)
- Red-capped Plover (*Charadrius ruficapillus*)
- Red-necked Stint (*Calidris ruficollis*)
- Red-necked Avocet (*Recurvirostra novaehollandiae*)
- Sharp-tailed Sandpiper (*Calidris acuminata*)

The most basic habitat suitability (i.e. species distribution) models investigate and predict the spatial distribution of target organisms, and thereby permit a model-based assessment of spatially targeted management strategies (Guisan et al. 2013). Importantly, however, these methods also allow modelling and prediction of spatiotemporal dynamics (Elith et al. 2011). For example, habitat suitability models have been used to understand the likely response of organisms to future climate change (Cordellier and Pfenninger 2009), predict the former distribution of invasive taxa to infer range expansion (Platts et al. 2019), and assess the influence of seasonally dynamic environmental conditions on realised distributions (Gschweng et al. 2012).

The modelling approach proposed for key waterbird species of the Coorong South Lagoon combines the key elements of classical habitat suitability models (i.e., spatial estimation of the probability of species' presence) and ecological response models (i.e., that estimate the relationship between species' abundance and other variables). The annual monitoring data is spatially explicit, with the shoreline of each lake divided into 1 km × 1 km grid cells, and all waterbirds enumerated within each cell. Using these data, generalised linear mixed-effects models for each key waterbird species will be developed that simultaneously model the probability of species' presence (at the level of each grid cell) and abundance, as a function of spatially and temporally variable covariates (e.g., water depth, salinity, benthic habitat characteristics, fringing vegetation characteristics, filamentous algal mats, invertebrate counts from sediment cores). This can be achieved using "hurdle" models, which model species' occurrence and then abundance conditional on occurrence, and will allow prediction of waterbird AOO, EOO and abundance under different future management strategies. However, the model development process will also consider any new targets and thresholds included in the updated Ecological Character Description and Ramsar Management Plan documents as they become available. In collaboration with experts, a candidate set of models with different sets of predictor variables will be developed, and models with good predictive skill will be identified by out-of-sample validation (i.e., evaluating the ability of different models to predict hold-out data that was not used for model-fitting).

Modelling will be based upon the annual abundance monitoring which has been conducted since the year 2000. The data set spans approximately one medium term (20 year) dry-wet cycle, with the Millennium Drought (2001-2009) and associated poor flows and rising salinities towards the end of that period, followed by a decade of higher freshwater input. As such, over this primary monitoring period the Coorong has experienced extremes in physical, hydrological and chemical conditions (Paton et al. 2015), so models will capture waterbird responses to a broad range of conditions. One caveat is that some predictor variables will exhibit strong temporal correlation through the drought period (e.g., water level, salinity, phytoplankton concentration, prevalence of algal mats); however, many waterbirds continued to use the Coorong South Lagoon during the drought and the spatial resolution of the waterbird monitoring data will permit fine-scale investigation of the drivers of their distribution and abundance throughout Coorong South Lagoon. Further, the distribution and abundance of waterbirds in the Coorong is likely affected by processes operating at a range of scales, including habitat availability and quality locally (within Coorong itself and throughout the broader CLLMM), regionally throughout southern-eastern wetlands and water availability in the arid interior (Paton et al. 2015), and in other areas along (Hansen et al. 2016) the flyway. To acknowledge this, the impact of external factors (e.g., wetland quality across the SAA flyway, average rainfall across south-eastern Australia) can be potentially tested as part of the model selection procedure (Clemens et al. 2016).

4 Discussion

The last 40 years of Coorong-based research indicates a general decline in the ability of the system to support a diverse and abundant waterbird assemblage. This pattern of decline was punctuated by the Millennium Drought during which the Coorong South Lagoon was characterised by low water levels in spring and high salinities, which in turn impacted waterbirds directly (by altering the distribution of suitable foraging areas) and indirectly (by producing unfavourable conditions for dietary mainstays such as fish, invertebrates and *Ruppia tuberosa*). Significant freshwater input in spring 2010 inundated mudflats on the Coorong to such an extent that wading waterbirds could not use them, but also promoted the recovery of other elements of the system over the ensuing years (Paton et al. 2015, Aldridge et al. 2017, Ye et al. 2019, Waycott et al. 2020, Ye et al. 2020). However, significant concerns remain about the ability of the Coorong to support shorebird populations, with five shorebird species failing to exceed their long-term median abundance every year between 2018 and 2020 (Paton et al. 2020).

Off-site impacts, including the degradation of breeding and foraging habitat at international sites along the EAAF (particularly within East Asia's Yellow Sea region), are impacting the flyway population sizes of migratory shorebird species that use the Coorong (Bamford et al. 2008). However, there is also strong evidence that migratory shorebirds are declining faster in the Coorong than in most other Australian wetlands (Gosbell and Grear 2005, Bamford et al. 2008), which suggests local conditions within the site are typically sub-optimal for many species. There is an ongoing need to understand the specifics of shorebird habitat and foraging preferences within the Coorong itself, and also within the context of the broader CLLMM system and beyond. The models developed through Activity 4.1 will therefore be informed by results from *Activity 4.2 - Measures of habitat quality for key waterbird species*, and extended beyond the Coorong within *Activity 4.3 - Key waterbird species response models for priority landscape wetlands*.

Proposed active management options for maintaining viable populations of migratory and non-migratory waterbirds within the Coorong South Lagoon are: (1) to maintain salinities below 60 g/L during winter and always below 100 g/L (Lester et al. 2009), thereby preventing loss of species important to the food chain which occurs at extreme salinities (Ye et al. 2019, Ye et al. 2020), while noting the bottom threshold is not agreed amongst scientists and salinities that are too low will favour macroalgae over *R. tuberosa* seagrass beds; (2) to reduce nutrient loads that encourages the development of algal mats (Waycott et al. 2020); and (3) to maintain intermediate water levels for longer at the beginning of the warm season, to support the reproduction of *R. tuberosa* whilst also providing ample shallow foraging habitat along the lagoon margins (Paton et al. 2018, Ye et al. 2020). Extraction of water from the Murray-Darling Basin for human uses may lead to reduced freshwater inputs into the Coorong during the warm season. This promotes the influx of saline marine water and sands into the Coorong while the Murray Mouth remains open, risks closure of the mouth due to reduced flushing and loss of the tidal prism (most notably in the North Lagoon), and can result in water levels in the Coorong South Lagoon that are too low to support the reproduction of *R. tuberosa* beds over summer. Therefore, to achieve targets like those listed above, the Murray-Darling Basin Plan allows for environmental water returns, and engineering solutions (e.g. the South East Flows Project) are also operational or proposed to maintain higher water levels within the Coorong South Lagoon during spring and summer.

Further management interventions may be required to improve the condition of the waterbird assemblage of the Coorong. Regardless of the management options considered, however, quantitative modelling is required to investigate the response of waterbird species to abiotic and biotic drivers, and to predict the distribution and abundance of waterbirds under different management strategies. The modelling approach proposed will focus on a core set of key waterbird species that are representative of different response groups, and spatially explicit model predictions for each species will link directly to revised management targets for the system. To achieve this, there is a clear need to collect all possible ancillary information, including data on nesting and foraging habitat extent, condition and connectivity where available (Paton et al. 2015), to link through models to the abundance of waterbirds reported from the surveys. Much of the relevant biophysical data will be provided in the form of high-resolution hindcasts from hydrological models for the Coorong, which are being developed and validated as part of other HCHB project components. Substantial data compilation and assessment, along with collation of advice from experts on the target species, will also need to be undertaken before the candidate model sets are developed and validated for each species. It is also worth noting that no modelling is proposed for cryptic species (rails, crakes, snipe and bittern) that use fringing vegetation around the freshwater wetlands of the Lower Lakes and reed-dwelling passerines (warblers, grassbirds, cisticola) which are not easily detected by the annual monitoring program (Paton et al. 2015) and require dedicated surveys (O'Connor et al. 2013b).

A final caveat is that, like the majority of historical research on the Coorong waterbird assemblage, the proposed modelling will focus on the response of waterbirds to changes in their abiotic and biotic environment. However, waterbirds are also likely to play a significant role in driving the ecology of the Coorong South Lagoon (and Coorong, Lower Lakes and Murray Mouth more broadly). For example, waterfowl (e.g. black swan) can impact the standing crop and population ecology of *R. tuberosa* (and other aquatic macrophytes) (Bortolus et al. 1998, Kim et al. 2013). The harvesting of nutrients and energy (in the form of food species) by waterbirds also has the potential to be a significant driver of nutrient dynamics (Post et al. 1998, Hahn et al. 2007). Local and global changes in waterbird populations may therefore have a significant impact in the aquatic ecology of the Coorong. These "top-down" contributions will not be explicitly considered in the models but some of these aspects could be included in other ways. For example, threshold waterfowl densities for sustainable grazing of aquatic vegetation could be estimated independently, and model predictions for different management interventions could then be assessed against these thresholds.

List of shortened forms and glossary

AHD	Australian Height Datum, the official reference surface for vertical mapping, which passes through mean sea level
AOO	Area of Occupation
BBN	Bayesian Belief Network; a graphical model of the probabilistic relationships between inputs variable/states and specific output variables/states interest (e.g., the annual survival probabilities of individuals, or the population size of a species)
CLLMM	Coorong, Lower Lakes and Murray Mouth
EOO	Extent of Occurrence
EAAF	East-Asian Australasian Flyway
Epibenthic	Refers to organisms that live on or just above the wetland floor
Generalised linear mixed effects model	A statistical model for which the linear predictor includes both fixed and random effects and a non-Gaussian error distribution is assumed.
Large wading waterbirds	These species employ a wading foraging strategy and feed on pelagic or epibenthic aquatic organisms.
Herbivorous waterfowl	The species are exclusively members of the Family Anatidae; they primarily feed on the leaves, flowers, and seeds of aquatic vegetation, and typically have webbed feet and a flattened bill for crushing their plant- or algae-based foods.
HCHB	Health Coorong, Healthy Basin
Infauna	Animals living within the sediments of aquatic ecosystems
Macrophyte	An aquatic plant large enough to be seen by the naked eye
Millennium Drought	An Australian drought extending from 2001 to 2009 that impacted most of southern Australia, including the Murray-Darling Basin region.
Piscivorous waterbirds	These species are solely or primarily fish-eating, and have specialised bills and/or talons for catching underwater prey.
Shorebirds	These species forage on intertidal areas and/or the margins of wetlands, and typically they do not swim. Australia is home to **non-migratory** shorebirds which remain in Australia year-round, and also provides habitat for **migratory** shorebirds of the EAAF, which inhabit the northern hemisphere in the austral winter and migrate to the southern hemisphere for the austral summer.
T&I	Trials and Investigations project
Tidal prism	The volume of water in an estuary or inlet between mean high tide and mean low tide
TLM	The Living Murray
Turion	Asexual reproductive buds of aquatic plants

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