TP9 MD-WERP

Foraging Habitats for Colonial Nesting Waterbirds in the Murray-Darling Basin

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Summary

Over the past decade, significant research and monitoring have been conducted on waterbirds in the Murray-Darling Basin, leading to an improved understanding of their condition and environmental watering requirements. In the past, environmental water management focused mainly on extending inundation during breeding events to minimize nest abandonment and improve fledging success. However, recent research suggests that recruitment of fledged chicks into the adult breeding population is often low. While there may be multiple drivers of low recruitment, the availability of foraging habitat is one driver that managers can directly influence. This project explores the potential provision of water to increase the availability of foraging habitat during nesting and immediately after breeding events as a management strategy to improve waterbird outcomes.

Colonial-nesting, large-bodied wading species of waterbirds were chosen as initial priorities for exploration of methods, because breeding colonies of these species are important targets for environmental watering across the Murray-Darling Basin. Two functional groups relevant to foraging habitats were identified: obligate wetland-feeding large waders and non-obligate wetland-feeding large waders. Obligate species are highly dependent on surface water for feeding, while non-obligate species are less dependent and frequently forage in more terrestrial environments. All species in these groups are highly mobile, moving in response to the availability of foraging and breeding habitat. This presents challenges for managing foraging habitat in the Basin. However, key breeding sites and important individual wetlands for waterbirds are known, and foraging habitat is important pre-nesting, during nesting, and post-nesting, with some species remaining near colonies for months after fledging. The quality of foraging habitat depends on various factors, including water depth, habitat type, and productivity.

This report describes a method for identifying and prioritising foraging habitats for potential management to support waterbirds throughout their lifecycle. Steps include defining foraging distances, preferred habitat characteristics, and manageable habitats, as well as mapping locations and assessing habitat availability and fluctuations. Key findings include that obligate feeders travel much smaller distances (median of 1 km, 766 ha zone) to forage than generalist non-obligate feeders (median of 4.5km, 6361 ha zone), and there were clear inundated habitat preferences between obligate and non-obligate colonial waterbirds for foraging. The availability of foraging habitat varied significantly in space and time, with a decline in preferred shallow foraging habitat for obligate feeders at around half of all colony locations and increases at several lake system sites.

The prioritization of sites for environmental watering involves comparing long-term and current habitat availability, bird abundance, and life cycle stage. Breeding sites with active nesting birds, proportionally less available foraging habitat, and declining or highly variable habitat are prioritised, while foraging sites around these are prioritised based on their distance from the breeding site, habitat types and manageability. The goal is to support the entire waterbird lifecycle by providing sufficient foraging habitat at the right locations and times, reducing energy costs and ensuring the availability of food for chicks, juveniles, and adults. This approach aims to improve waterbird population maintenance and growth in the long term.

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1 Introduction

1.1 Context

The Murray Darling Basin (the Basin) supports a diversity and abundance of waterbirds across a broad range of habitats. This is recognised in the Basin-wide environmental watering strategy (BWS), with waterbirds being one of the four themes with objectives to improve waterbird populations and maintain waterbird diversity (MDBA 2019a).

Waterbirds in the Basin have been the subject of significant research and monitoring over the past decade (e.g. Reid et al. 2013, Kingsford et al. 2014, Bino et al. 2015, McGinness 2016, McGinness et al. 2019, Brandis et al. 2020) and our understanding of waterbird condition and requirements has improved. In the past, environmental water for waterbirds has largely been aimed at extending inundation for colonial nesting breeding events to minimise nest abandonment and improve fledging success (Bino et al. 2014, Hale et al. 2020, Wassens et al. 2021). However, population maintenance and growth also require recruitment of fledged chicks into the adult breeding population, a process that may take three to four years for some colonial-nesting species. Recent research led by CSIRO has suggested that recruitment into the adult population following fledging is often low, driven by a range of factors (McGinness et al. 2019). Of factors that can be influenced by management, the provision of water to increase availability of foraging habitat both during nesting and immediately following breeding events is likely to be one of the best 'levers' available (McGinness et al. 2019).

Waterbird outcomes across the Basin might be improved by appropriate management not only of breeding habitat, but also of foraging habitats to ensure that there are adequate food resources available for breeding and recruitment. The quality and availability of foraging habitats requires careful management of water and vegetation and consideration of drivers of change. Providing the right resources in the right locations at the right times requires knowledge about available habitat, its condition, and the movement of waterbirds across the landscape. This must all be considered in the context of climatic conditions and shared (sometimes conflicting) management objectives and capabilities.

Technology is rapidly evolving and there have been corresponding rapid improvements in environmental data availability within the Basin from on-ground monitoring programs, but especially in the field of geospatial information. This increase in spatial data availability comes not only from increasingly accessible satellite data, but also from derived outputs. Examples include Water Observations from Space (WoFs), the Wetlands Insight Tool (WIT), satellite-based river gauging, the Australian National Aquatic Ecosystem (ANAE) mapping, and a package of spatial information provided by the TERN-ANU Landscape Data Visualiser.

This increase in accessible spatial data, often at the whole of Basin scale, coupled with the outputs of recent research on waterbird movement and foraging activities, presents an opportunity to identify waterbird foraging habitats across the Basin, and to prioritise habitats for environmental watering in a given water year.

1.2 Objectives

The objectives of this project are to:

1. Define foraging habitat requirements for target waterbird groups
2. Identify remote sensing indicators of foraging habitat presence, extent and condition
3. Map foraging habitats and identify candidate environmental watering sites
4. Develop an environmental watering prioritisation method for foraging habitats.

There were an additional two objectives for this project that were unable to be achieved within the project scope and time.

"Work with projects modelling hydrology, climate change and vulnerability to predict potential change, impacts and vulnerability for foraging habitats."

It was originally planned that the outputs of the waterbird foraging habitat project could be intersected with the outputs of the MD-WERP Climate Change Vulnerability assessments to identify foraging habitat that may be most at risk under future climates. The relevant climate change vulnerability projects were still in planning and early implementation stages at the conclusion of the waterbird foraging habitat project and so there was no opportunity for integration. This may be something that may be possible into the future. In the interim we have explored changes to the extent of foraging habitat over the Landsat record (see sections 4.2.3 and 4.2.4) which probably reflects both climate change and water resource use impacts.

"Recommend SMART targets (quantitative environmental outcomes; QEOs) for foraging habitats."

Developing QEOs for the Basin-wide environmental water strategy (MDBA 2019a) was an aim of this current project. It was decided in conjunction with the Technical Advisory Group (TAG), however, that there was still too much uncertainty surrounding the extent and condition of foraging habitat and changes in this over time to inform realistic and robust targets.

1.3 How the project was developed

The waterbird foraging habitat project was guided by a Technical Advisory Group (TAG) comprised of experts in the fields of waterbirds and geo-spatial analysis, together with environmental water managers. The project team developed draft methods for discussion at online workshops with the TAG. Recommendations from the TAG were then used to refine the method that is presented in this report.

The results of mapped waterbird foraging habitat and an assessment of habitat condition over time were presented to the TAG for review. Input was sought from water managers on the utility of the foraging habitat outputs and how they could be used in improving evidence-based environmental water management. Suggestions were incorporated, where feasible, into the method documented in this report.

2 Defining foraging habitat

2.1 Target waterbirds

The project is focussed on identifying foraging habitat for colonial-nesting, large-bodied wading species of waterbirds. This is a group that is often the target of environmental water to extend inundation for breeding cycles to complete and so has been selected as the target group for this project (in consultation with MDBA).

This was further refined in a workshop with waterbird experts to two functional groups relevant to foraging habitats:

1. Obligate wetland-feeding large waders (e.g. spoonbills, herons and egrets); these are species that are highly dependent on surface water for feeding because of their diets, foraging techniques and evolutionary adaptations
2. Non-obligate wetland-feeding large waders (e.g. ibis; Figure 1); these are species that are less dependent on surface water and associated food sources for feeding and frequently forage in more terrestrial environments.

	
Royal spoonbills nesting: an example of an obligate wetland-feeding large wader	Straw-necked ibis nesting: an example of a non-obligate wetland-feeding large wader

Figure 1 Examples of species in the two functional groups forming the focus of this project. Photos: Heather McGinness, CSIRO.

2.2 Conceptual understanding of foraging habitat

The quantity and quality of waterbird foraging habitat is a key driver of waterbird abundance, populations, initiation of breeding and recruitment (Kingsford and Norman 2002, Reid et al. 2009, Brandis 2010, Arthur et al. 2012, McGinness et al. 2019). In terms of successful fledging, the area of nearby foraging habitat has been positively correlated with fledgling survival (Leslie 2001). Conversely, a reduction in foraging habitat availability limits the ability of adults to successfully raise young and for juveniles to learn adequate foraging skills (Butler 1994). In situations with reduced foraging habitat area and quality, competition within and between different species for smaller amounts of food resources can influence populations as well as the condition and survival of juveniles (McGinness 2016).

Waterbird foraging habitat quality is influenced by a range of factors that vary in space and time. The productivity of foraging habitat influences the quantity and quality of food. In many temporary or intermittent wetland systems across the Basin, there is a sharp rise in productivity when systems are initially inundated (Kingsford et al. 1999, Leigh et al. 2010, Bino et al. 2015). Activation of seed and egg banks combined with the mobilisation of minerals and nutrients from the sediments leads to a boom in prey and other food sources for foraging waterbirds (Boulton and Brock 1999). The arrival of floodwaters can also drive terrestrial prey to the surface or other accessible habitats where they can be opportunistically consumed by waterbirds (Kingsford et al. 2010).

In defining foraging habitat requirements, a number of life stages need to be considered:

- Adults building condition for breeding or recovering condition post-breeding
- Adults incubating eggs
- Adults feeding chicks
- Juveniles dispersing and learning to feed
- Sub-adults surviving to become breeding adults (recruitment).

2.2.1 Obligate wetland-feeding large waders

There are seven species in the obligate wetland-feeding large wader group: Australian white ibis (*Threskiornis molucca*), eastern great egret (*Ardea alba modesta*), intermediate egret (*Ardea intermedia*), little egret (*Egretta garzetta*), nankeen night heron (*Nycticorax caledonicus*), royal spoonbill (*Platalea regia*) and yellow-billed spoonbill (*Platalea flavipes*). Foraging habitat requirements across the members of the group are largely similar with some nuanced differences (Table 1).

The diets of this group are largely aquatic fauna (fish, crustaceans, aquatic insects), although many will opportunistically forage in terrestrial environments. As with many Australian waterbirds, the habitats that they utilise are broad ranging, reflecting temporal and spatial resource availability. So, while the inland wetlands of the Murray-Darling Basin may provide foraging habitats during periods of inundation, during prolonged dry periods most of these species can use artificial (e.g. wastewater treatment plants) and / or coastal systems (Murray et al. 2012, Wen et al. 2016).

Foraging habitats are largely open water or sparsely vegetated wetland systems in water depths ranging from a few centimetres, to around 50 cm for some species. Several pieces are visual hunters and so forage largely during daylight (egrets and herons) while others can forage using tactile techniques and so can forage day or night (e.g. spoonbills).

All species in this group nest in vegetation over water and require water to remain under nest sites as well as inundation of shallow foraging habitat nearby during the breeding season. The foraging habitat requirement across the lifecycle of obligate wetland-feeding species is illustrated in Figure 2.

Table 1. Habitat characteristics of species in the obligate wetland-feeding functional group (Barker and Vestjens 1990, Marchant and Higgins 1990, Jaensch 2002, Garnett et al. 2015 unless otherwise specified). Generic information used where species specific information was lacking.

Trait	Australian white ibis	Eastern great egret	Intermediate egret	Little egret	Nankeen night heron	Royal spoonbill	Yellow-billed spoonbill
Foraging							
Diet	Mostly aquatic fauna (crustaceans, fish, frogs) but also terrestrial invertebrates (e.g. locusts) and reptiles (Carrick 1959).	Aquatic fauna: notably small fish (< 12 cm), also frogs, crustaceans, insects and small birds.	Aquatic fauna: notably small fish, also frogs, crustaceans, insects.	Aquatic fauna: notably small fish (< 3 cm), also frogs, crustaceans, insects.	Aquatic fauna: notably small fish, also frogs, crustaceans, insects. Will take eggs, nestlings, mammals.	Aquatic fauna: mainly small fish and crustaceans, but also aquatic insects (Vestjens 1975, Lowe 1982).	Aquatic fauna: mainly insects, also crustaceans and small fish (Vestjens 1975).
Typical habitat	Wide range of inland and coastal wetlands. Foraging in open water or sparse vegetation.	Wide range of inland and coastal wetlands. Foraging in open water or sparse vegetation.	Mainly in freshwater wetlands coastal and inland, rarely in saline wetlands	Wide range of inland and coastal wetlands. Foraging in open water or sparse vegetation.	Wide range of inland and coastal wetlands. Foraging in open water or sparse vegetation.	Wide range of inland and coastal wetlands. Foraging over bare substrates, but also in and around vegetation.	Wide range of inland and coastal wetlands. Foraging over bare substrates, but also in and around vegetation.
Foraging method	Wading, walking, in littoral zones, using both visual and non-visual techniques.	Walking and 'stand and wait' visual hunting methods (Recher et al. 1983).	Walking, wading visual hunters.	Walking, wading visual hunters (Recher et al. 1983).	Walking and 'stand and wait' hunting mostly at night (Recher et al. 1983)	Mostly by feel, slow sweeping techniques by day or night.	Mostly by feel, slow sweeping techniques by day or night.
Typical water depth	Usually in shallow water from mudflats to 25 cm deep (Carrick 1959, Paton et al. 2011).	Shallow water most often 15 – 25 cm (Recher et al. 1983).	Shallow water, 10 – 20 cm	Shallow water 10 – 15 cm (Recher et al. 1983).	On the edge of deep water.	Shallow water from 5 to 50 cm deep (sometimes submerging entire head (Vestjens 1975, Lowe 1982).	Shallow water from 5 to 50 cm deep.

Trait	Australian white ibis	Eastern great egret	Intermediate egret	Little egret	Nankeen night heron	Royal spoonbill	Yellow-billed spoonbill
Breeding							
Nest site	At variable heights in trees, shrubs or reeds in water or on dry land, and on artificial structures.	High in a tree or tall shrub standing in water, often at a higher site than associated species.	High in a tree or tall shrub standing in water	High (eg. 3-7 m above water) in a tree or tall shrub standing in water.	In a tree or tall shrub standing in water, at variable height; often in a discrete zone.	In a tree, tall shrub or reeds/rushes standingin water (0.5-1.5 m deep), at variable height.	Usually in a tree, on a horizontal or vertical branch, a few metres above water.
Water depth	Sufficient to prevent nest site becoming dry before nestlings fledge.	Sufficient to prevent nest site becoming dry before nestlings fledge.	Sufficient to prevent nest site becoming dry before nestlings fledge.	Sufficient to prevent nest site becoming dry before nestlings fledge.	Sufficient to prevent nest site becoming dry before nestlings fledge.	Sufficient to prevent nest site becoming dry before nestlings fledge.	Sufficient to prevent nest site becoming dry before nestlings fledge.
Seasonality	Opportunistic in response to rainfall and wetland inundation (Carrick 1962, Leslie 2001).	October to December in the south; March to May in the north. May be in response to rainfall (Geering 1993).	October to March in the south; January to April in the north.	October to March in the south; January to April in the north. In response to rainfall (Geering 1993).	Mainly spring and summer but laying also in autumn and late winter.	October to March in south-eastern Australia.	Late winter to spring in the south, may be summer-autumn (or into winter) further north.
Incubation	20 – 23 days	28 days	24 – 26 days	20 – 25 days	20 – 22 days	25 days	26 – 31 days
Nestling period	48 days but still dependent on parents for feeding for several weeks.	40 - 64 days	42 – 53 days to first flight	40 days to first flight	40-50 days	28 days but still dependent on parents for feeding for some time after fledging.	Around 30 days

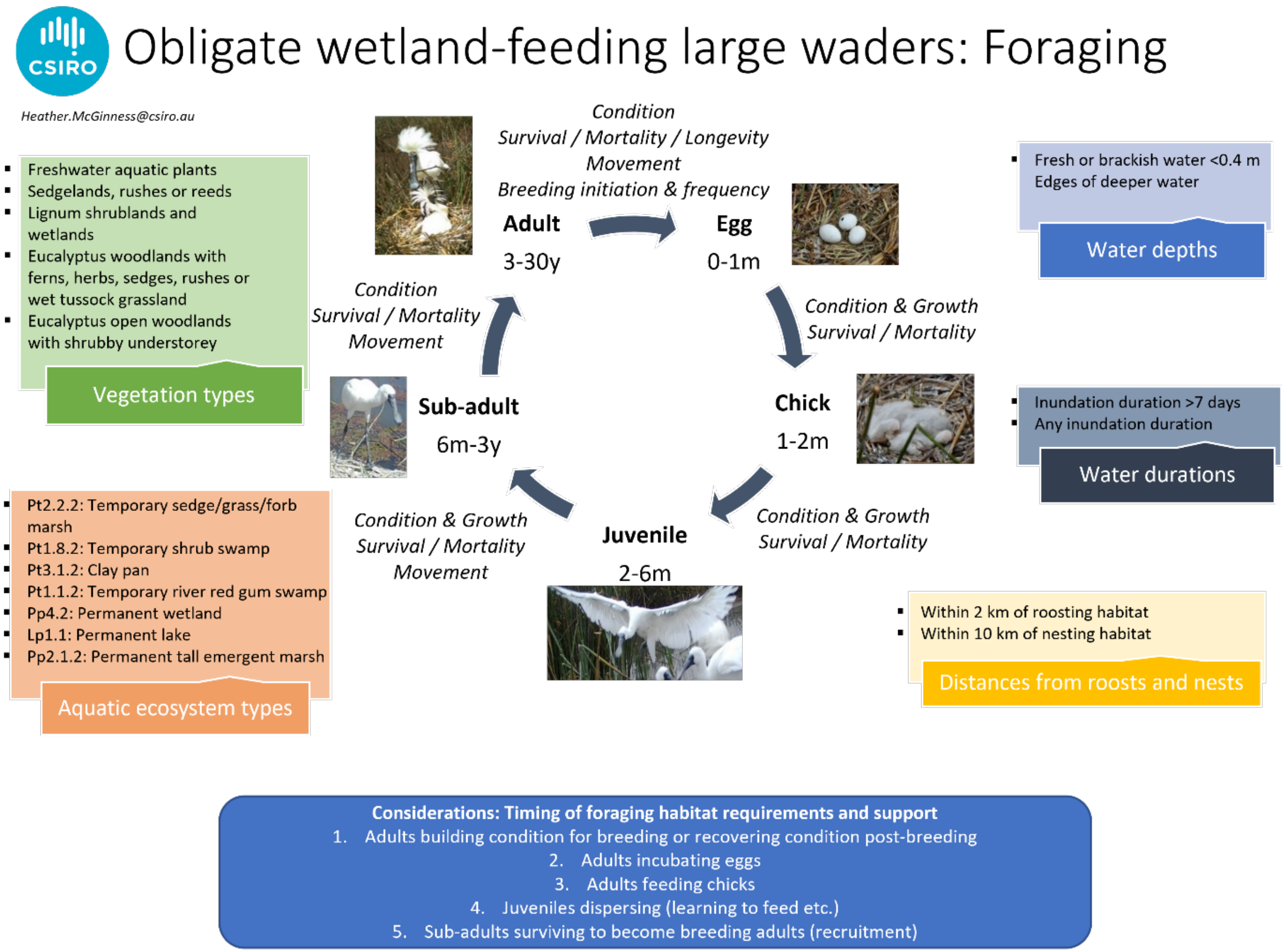

Figure 2: A conceptual model of obligate wetland-feeding waterbird foraging habitat requirements for population maintenance (example of royal spoonbills shown).

2.2.2 Non-obligate wetland-feeding large waders

There are four species in the non-obligate wetland-feeding large wader group: cattle egret (*Bubulcus ibis*), glossy ibis (*Plegadis falcinellus*), straw-necked ibis (*Threskiornis spinicollis*), and white-faced heron (*Egretta novaehollandiae*). Foraging habitat requirements of group members vary in their reliance on aquatic foraging habitats (Table 2), with some species (e.g. white-faced heron) often foraging in wetlands and other species (e.g. cattle egret) rarely using inundated habitat for foraging.

Diets of this group reflect the lower reliance on wetlands for foraging, with a higher proportion of terrestrial insects and other animals in their food intake. Similarly, water depths in foraging habitat become less important, although all members, when foraging in inundated habitats use very shallow water. The members of this group are more likely to opportunistically use non-wetland habitats such as agricultural fields, pastures and feedlots, but whether the quality of food items in all these habitats is equal is highly uncertain. There may also be risks associated with foraging in these environments such as toxins. The foraging habitat requirement across the lifecycle of obligate wetland-feeding species is illustrated in Figure 3.

Table 2. Habitat characteristics of species in the non-obligate wetland-feeding functional group (Barker and Vestjens 1990, Marchant and Higgins 1990, Jaensch 2002, Garnett et al. 2015 unless otherwise specified). Generic information used where species specific information was lacking.

Trait	Cattle egret	Glossy ibis	Straw-necked ibis	White-faced heron
Foraging				
Diet	Mostly terrestrial insects, but also frogs, lizards and small mammals.	Mostly aquatic invertebrates and insects, but also terrestrial invertebrates.	Small aquatic and terrestrial animals, notably crickets and grasshoppers (Carrick 1959).	Broad range of small animal prey items including crustaceans, fish, terrestrial insects.
Typical habitat	Although it may forage in wetlands, most often seen in pastures with long grass.	Mostly inland wetlands, preferring shallow low emergent vegetation habitat (Taylor and Taylor 2015).	Occurs in wide range of wetland and dryland habitats, commonly in artificial wetlands such as irrigated fields.	Broad range of habitats including inland wetlands, marine, rivers and terrestrial habitats (Recher et al. 1983).
Foraging method	Walking and picking insects from vegetation (Recher et al. 1983).	Walking and picking prey from around emergent vegetation (Taylor and Taylor 2015).	Probing soil or shallow water for prey.	Walking and 'stand and wait' hunting (Recher et al. 1983).
Typical water depth	Not relevant.	Damp ground to 10 cm deep water.	Dryland, damp soil, to very shallow water (Carrick 1959, Paton et al. 2011).	Damp ground to water 15 cm, but most often in shallow water.
Breeding				
Nest site	At variable heights in trees, in middle to upper branches.	Low in a tree or tall shrub standing in water.	At variable heights (but mainly low) over water in shrubs and reeds.	Trees fringing rivers and wetlands, but also commonly away from water.

Trait	Cattle egret	Glossy ibis	Straw-necked ibis	White-faced heron
	Sometimes on islands.			
Water depth	Sufficient to prevent nest site becoming dry before nestlings fledge, unless on an island.	Sufficient to prevent nest site becoming dry before nestlings fledge, eg. 30-50 cm.	Sufficient to prevent nest site becoming dry before nestlings fledge, eg. 30-50 cm.	Not applicable, due to dryland sites. Although in mixed colonies with other egrets can be over water.
Seasonality	October to January.	September to April, maybe in response to rainfall.	Mainly August-December in southern areas, in the inland recorded all months.	Laying recorded in most months including late winter, few records April-May.
Incubation	24 days	20 - 23 days	20 – 25 days	25 days
Nestling period	42 days	25 days, but dependent on parents for weeks after.	30 days, but dependent on parents for weeks after.	40-45 days

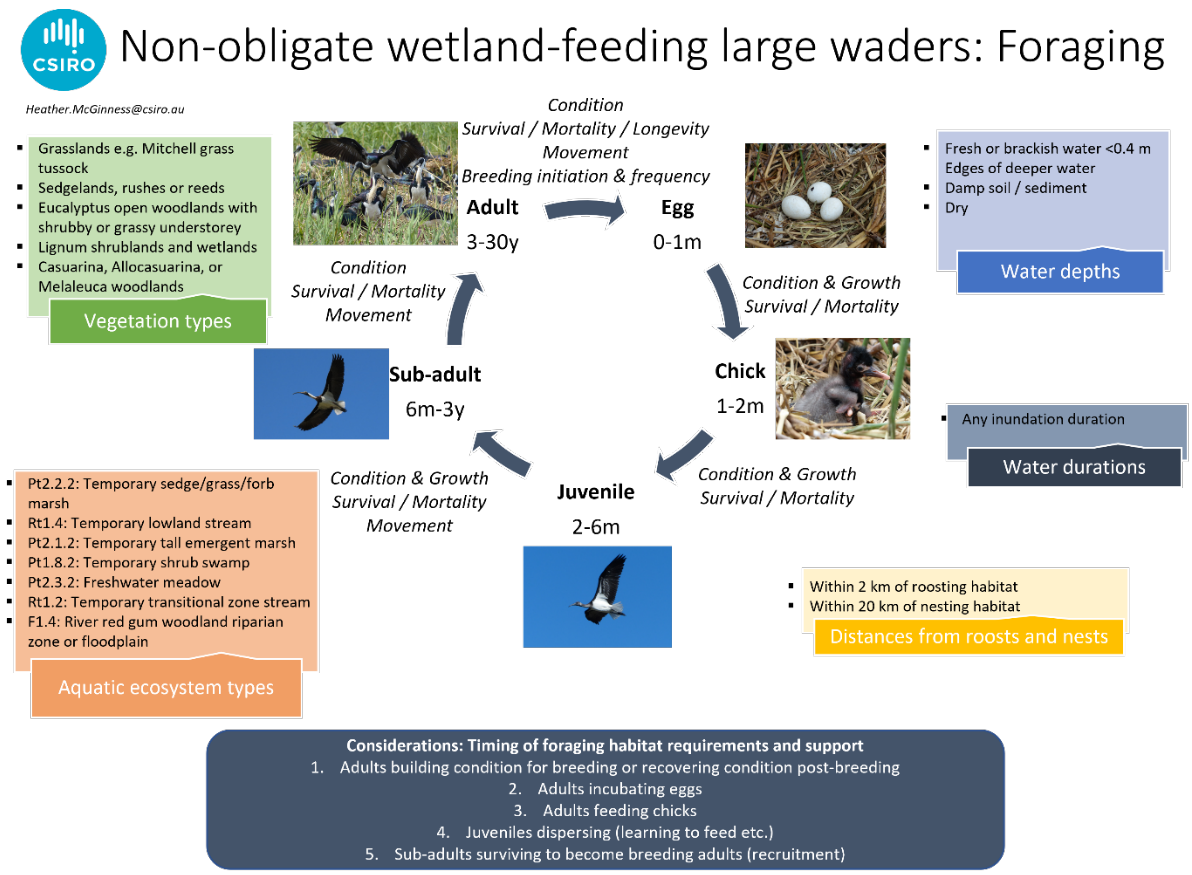

Figure 3: A conceptual model of non-obligate wetland-feeding waterbird foraging habitat requirements for population maintenance (example of straw-necked ibis shown).

Figure 4: An example of mixed terrestrial and aquatic foods eaten by non-obligate wading waterbird species – in this case, regurgitate from a straw-necked ibis in the Booligal Wetlands in the Lachlan catchment. Photo: Heather McGinness, CSIRO.

3 Quantifying foraging habitat

Most Australian waterbirds are highly mobile, moving in response to foraging and breeding habitat availability and capable of travelling long distances quickly (Roshier et al. 2002, Kingsford and Norman 2002, Wen et al. 2016). Colonial nesting wading species vary in their movement patterns, with some remaining resident for long periods, while others move nomadically, and others migrate annually. Within species individuals vary among these movement types and are known as 'partially migratory' species (e.g. straw-necked ibis). Partial migration is thought to be a population characteristic that facilitates species persistence in the face of spatial and temporal variation in resources, environmental conditions and their predictability (Buchan *et al.* 2020; Chapman *et al.* 2011; Lundberg 2013).

This opportunistic and variable movement of waterbirds across Australia to exploit available habitats presents a dilemma with respect to managing waterbird foraging habitat in the Basin. However, we know the locations of key colonial nesting waterbird breeding sites, and waterbird foraging habitat is important around breeding colonies pre-nesting (to build up reserves), during nesting and post nesting, with some species remaining near colonies to forage for many months post fledging (Geering et al. 1998, McGinness et al. 2019). Even when individuals disperse or migrate long distances soon after breeding, there are periods of time when those individuals need to feed to build body condition in the local area around the nesting colony before departing. There are also key individual wetlands in the Murray Darling Basin that are consistently important for waterbirds (Roshier et al. 2002, Dutson et al. 2009, Kingsford et al. 2014). For example, from 1983 to 2012, aerial surveys recorded 80% of waterbirds in the top 20 wetlands (Kingsford et al. 2014).

Extending environmental water management to consider foraging habitat extent and quality is a potential next step in environmental water management for waterbirds in the Basin. Quantifying waterbird foraging habitat around known colonial nesting sites is therefore the focus of this current project.

3.1 Colony locations

Breeding locations for the target waterbird species were derived using the dataset compiled for the recent vulnerability assessment of waterbirds and vegetation in the Basin (Hale et al. 2023). Waterbird records from the Basin were sourced from the following:

- Atlas of Living Australia records (https://www.ala.org.au/) which includes citizen science records (e.g. eBird as well as State based waterbird monitoring)
- MDBA aerial waterbird surveys (supplied by the MDBA)
- East Australian Aerial Waterbird Surveys (supplied by the MDBA)
- Commonwealth Environmental Water Holder waterbird monitoring (supplied by CEWH).

Records for target species were collated into a single source and records cleaned by:

- Ensuring each species was afforded a unique and consistent common name
- Removing any locations data (latitudes and longitudes) that fell outside the Basin

- Removing records that had no date fields that could be assigned to a year
- Removing records that had no location data.

Breeding records were identified and cross-checked using relevant record fields including 'Reproductive Condition', 'Taxon Remarks', 'Individual Count', and 'Sum of Nest'. Where coding systems such as eBird and NestWatch systems are used by observers, selected codes relevant to breeding were identified and used to filter the data. In MDBA records, the fields 'Sum of Count' and 'Sum of Nest' were used. Records with low confidence were excluded. For example, in identifying breeding sites using the ALA reproductive condition field, records tagged as 'none', 'F' (flying over), 'C' (courtship or copulation), 'suggestive behaviour', 'distraction display', 'breeding plumage' or 'adult' only were not included, and eBird records with moderator confidence of less than C4 (confirmed) were not included.

Aerial waterbird surveys are the only easily accessible records that provide a count of nests and / or broods. Records in databases such as the Atlas of Living Australia rarely quantify breeding abundance, however they do flag evidence of breeding at the same time as the count of individuals. In order to focus on important breeding locations and discard isolated observations of single nests from citizen science sources, records were filtered to > 100 nests or > 100 individuals of the target species with evidence of breeding. This resulted in 166 colony locations (Figure 5). Colonies were numbered and allocated an informative name that incorporated the colony number and the locality as provided by the source data sets. For ALA records from NSW listed as 'locality withheld', the name of the Basin-wide Environmental Watering Strategy waterbird areas were used (UNSW aerial waterbird survey areas; MDBA 2019b).

Breeding colonies located around Lakes Alexandrina, Albert and the Coorong were not included because the inundation mapping used to quantify shallow foraging habitat did not include these areas (refer section 3.3 below).

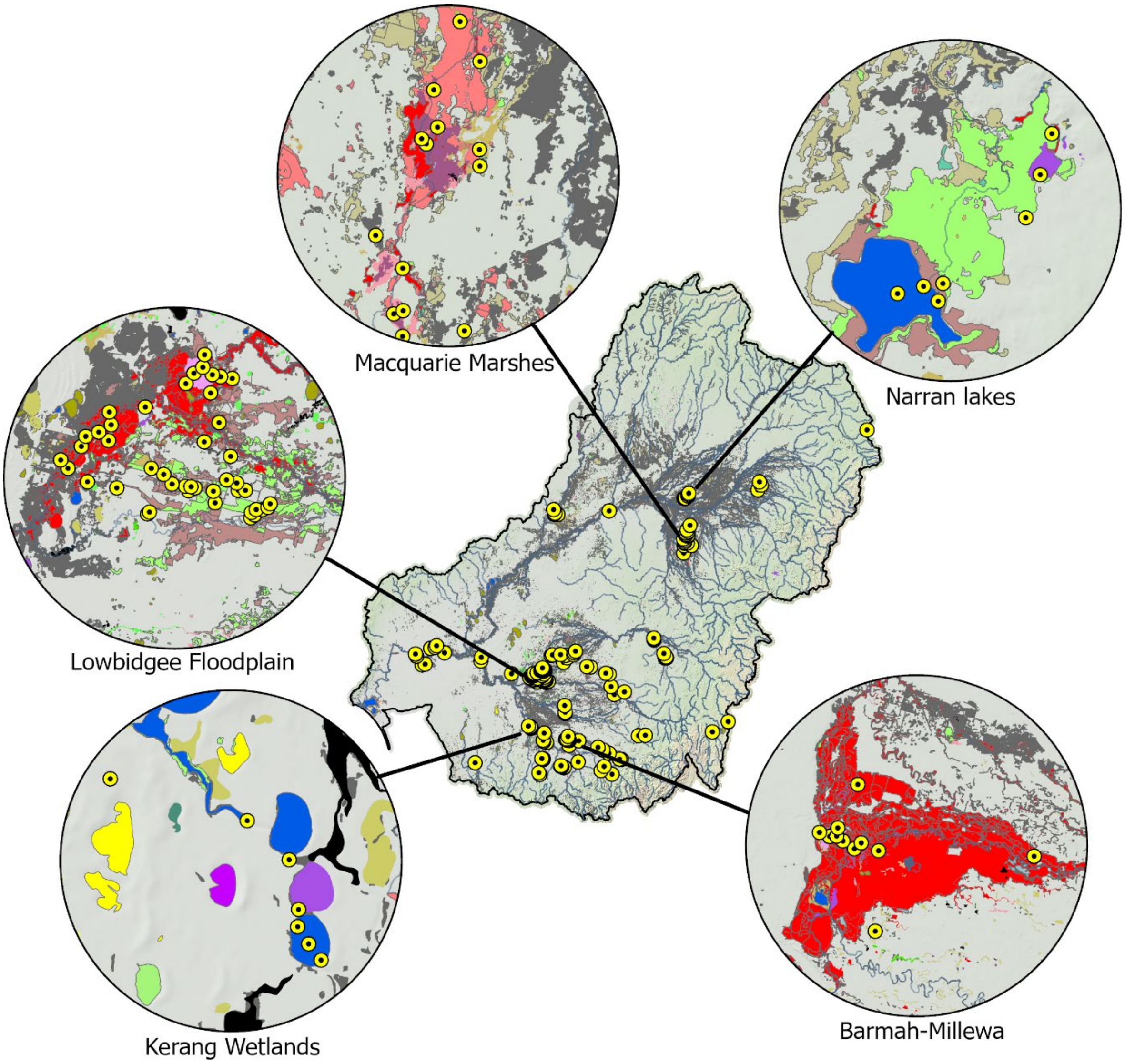

Figure 5. Locations of colonies for mapping waterbird foraging habitat.

3.2 Foraging distances

The distance that colonial nesting waterbirds travel from nest locations to forage has been the focus of recent research by CSIRO using satellite tracking (McGinness et al. in prep.; McGinness et al. 2019; funded by CEWH as part of their Monitoring, Evaluation and Research program). This research has calculated summary statistics describing foraging movement distances during distinct nest stages for representative species from each of the current project's target foraging functional groups (Royal Spoonbill (obligate wetland-feeders) and Straw-necked Ibis (non-obligate wetland-feeders); Table 3 and Table 4).

For the purposes of mapping waterbird foraging habitat around colony locations, three distances were considered based on the median, 75th percentile and maximum distance travelled. Flight distances associated with the immobile chick phase were selected as the most appropriate because this phase is the most vulnerable and requires foraging habitat and food to support both growing chicks and adults, and it is also the phase for which the most robust data were available for calculation of statistics. Updated statistics will become available over time as the CEWH waterbird movement monitoring project progresses and further tracking is undertaken, allowing reanalysis to reduce uncertainty. This will be particularly important for the obligate wetland feeders, which at the time of this current project were based on relatively small sample sizes.

Table 3. Summary statistics of foraging distance in kilometres by nesting stage for royal spoonbill, representing the obligate wetland feeder group. Shading indicates the distances used to map foraging habitat.

Stage	Minimum	25th %	Median	Mean	75th %	Maximum	No. of events
Whole nesting event	0.19	0.71	1.03	1.34	1.50	6.95	22
Nest establishment	0.19	0.63	1.06	1.06	1.50	1.93	2
Incubation	0.36	0.73	1.05	1.11	1.44	1.82	17
Immobile chicks	0.58	0.79	1.00	2.85	3.98	6.95	3
Mobile chicks	NA	NA	NA	NA	NA	NA	0

Table 4. Summary statistics of foraging distance in kilometres by nesting stage for straw-necked ibis, representing the non-obligate wetland feeder group. Shading indicates the distances used to map foraging habitat.

Stage	Minimum	25th %	Median	Mean	75th %	Maximum	No. of events
Whole nesting event	0.03	0.04	2.56	7.20	7.43	87.39	1059
Nest establishment	0.03	0.04	0.04	0.27	0.05	7.79	64
Incubation	0.03	0.05	4.03	10.60	17.35	87.39	275
Immobile chicks	0.03	0.08	4.49	10.51	22.26	55.19	132
Mobile chicks	0.03	0.05	2.69	5.63	6.70	66.95	588

Based on these initial statistics, the obligate wetland-feeders travel much smaller distances to forage that the more generalist non-obligate wetland-feeding group. The median foraging distance for obligate wetland-feeders was just one kilometre, with the maximum around 7 kilometres. By comparison, the median foraging distance for non-obligate wetland-feeders was 4.5 km and the maximum more than 55 km. This difference is illustrated visually at two colony locations in the Murrumbidgee (Figure 6).

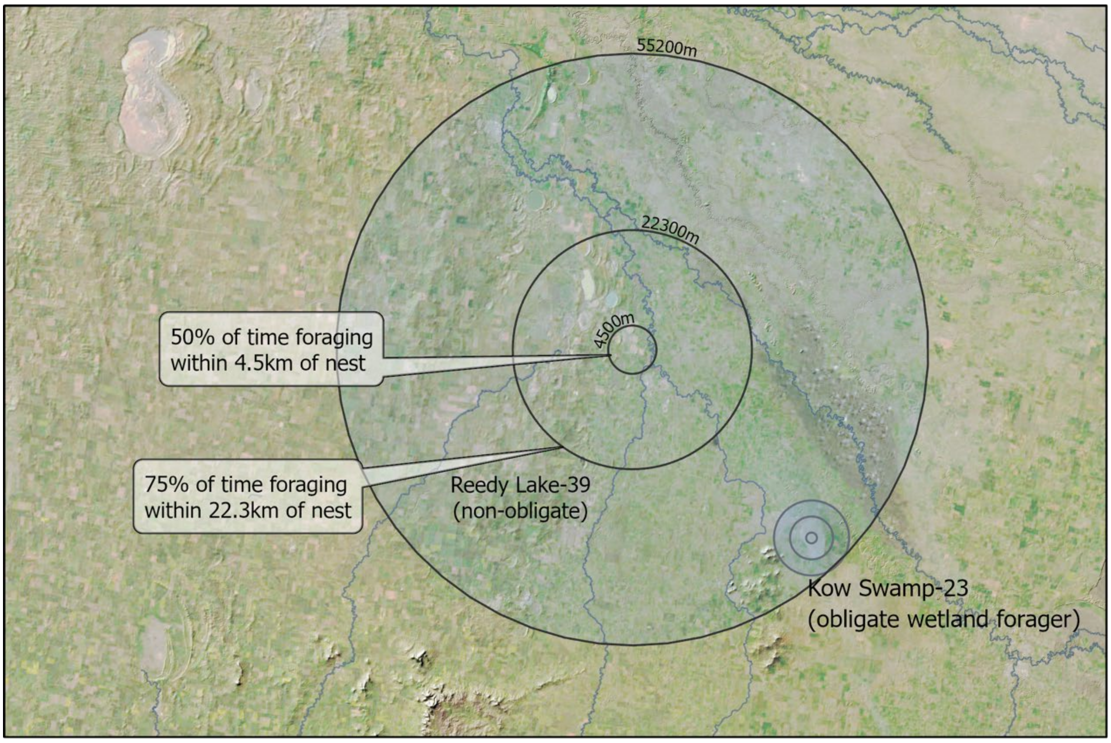

Figure 6. A comparison of median, 75th percentile and maximum foraging distances for the two functional groups, with obligate wetland feeders at Kow Swamp and non-obligate wetland feeders at Reedy Lake.

Areas of foraging habitat within each foraging distance zone were calculated based on the area within each zone, excluding the zones contained within (concentric doughnuts). For obligate wetland figures there are a maximum of 766 hectares within the inner zone, extending to over 12,000 hectares at the maximum foraging distance (Figure 7). Areas within the foraging zones of non-obligate wetland-feeders are much larger, from around 5000 hectares in the inner zone to over 2 million hectares in the outer zone (Figure 8).

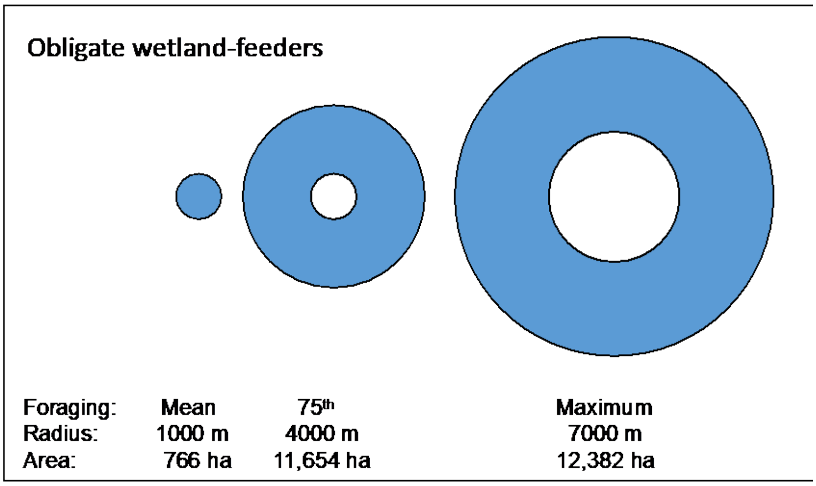

Figure 7. Size of the foraging zones for obligated wetland-feeders.

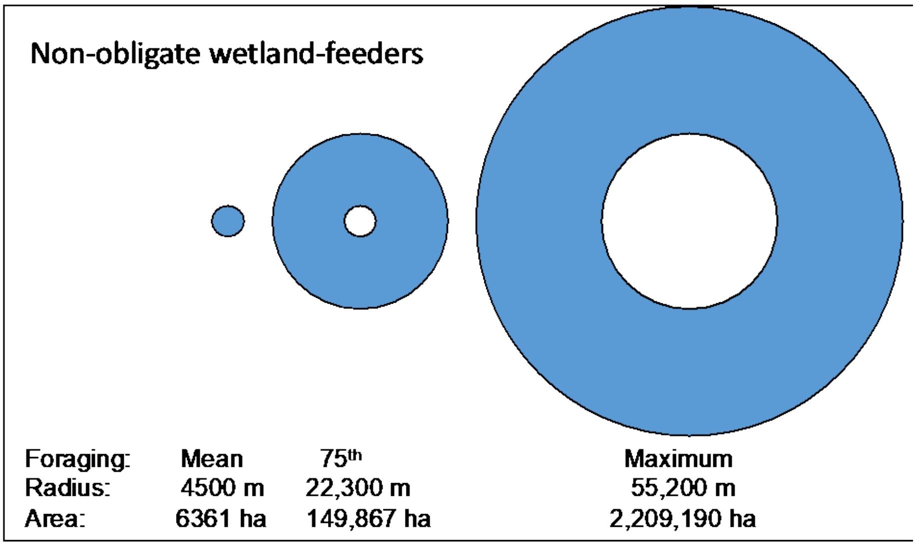

Figure 8. Size of the foraging zones for obligate wetland-feeders.

3.3 Mapping foraging habitat

The concentric circular foraging zones were subdivided into Australian National Aquatic Ecosystem (ANAE) types using ANAE classification of the Basin (Brooks 2021). This enables the area of different ANAE ecosystem types, and the inundation of different ecosystem types within the foraging areas to be quantified.

All target species utilise shallow water foraging habitats (see Table 1 and Table 2) and extent of shallow water inundation within the foraging zones of the two function groups was used as the indicator of foraging habitat. The CSIRO Two-monthly Maximum Flood Water Depth Spatial Timeseries for the Murray–Darling Basin (Teng et al. 2023) provides water depth across the Basin (excluding the Coorong, Lower Lakes and Murray Mouth) every two months from January 1988 to December 2022 (Figure 9).

Ideally, inundation of < 60 cm would be selected to represent foraging habitat for these large wading bird species. Discussions with the CSIRO team, however, indicated that the accuracy of the model was likely in the order of ± 60 cm. As a consequence, one metre was selected as the depth to represent the extent of shallow water foraging habitat. The two-monthly inundation rasters were collated into a multi-dimensional mosaic in ESRI ArcGIS Pro v3. Shallow water was isolated by inserting a raster function to re-map pixel values >1m deep to 'No Data'. The remaining area of shallow water was quantified in each foraging zone, for each date, using multidimensional zonal statistics. The output is the extent of shallow water inundation in two monthly timesteps around the 166 breeding colony locations (e.g. Figure 10, to Figure 11).

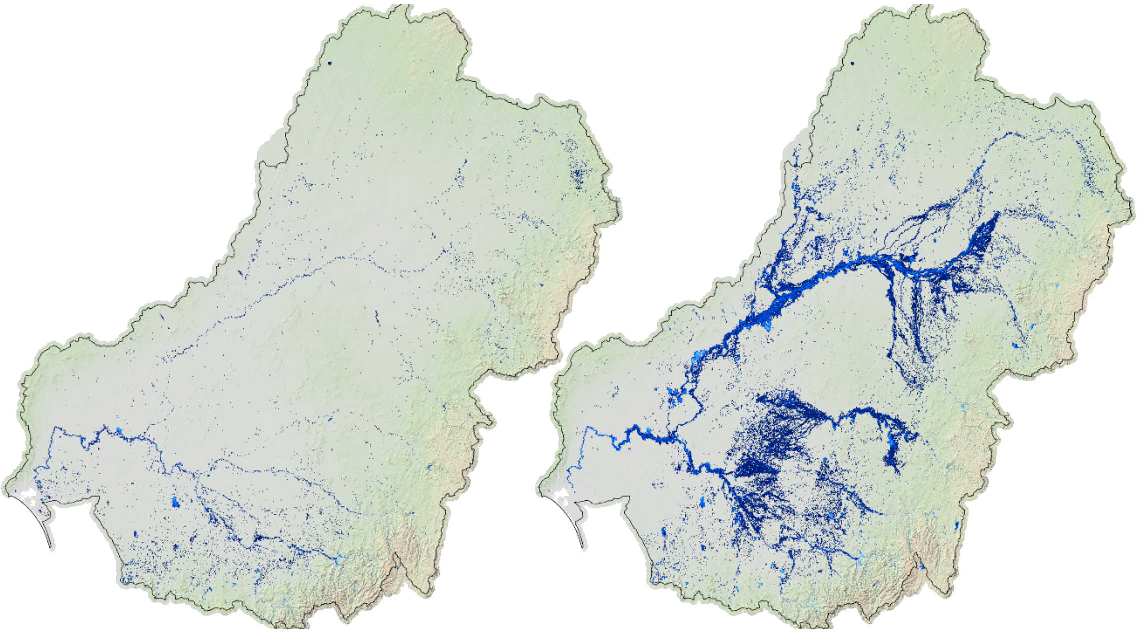

Figure 9. CSIRO fwdet two-montly inundation after a dry period (August-September 2019) and a wet period (September-November 2022)

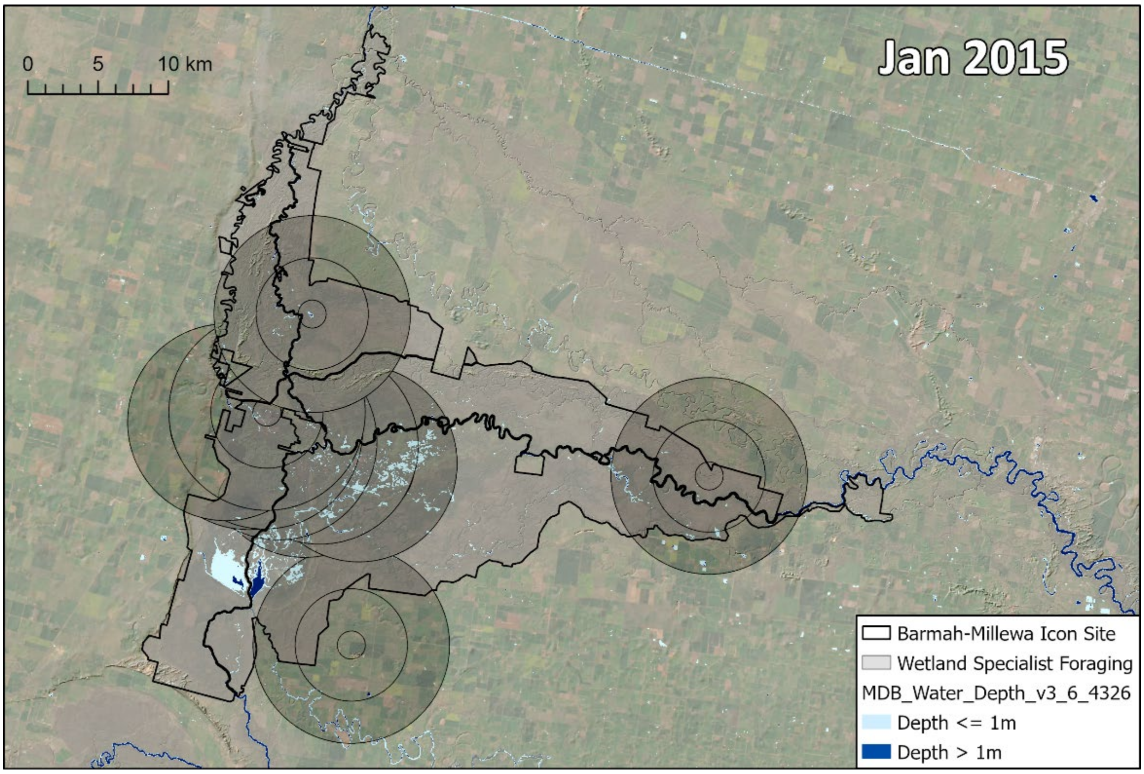

Figure 10. Waterbird Foraging habitat (depth < 1m) in Barmah-Millewa Forest in January 2015.

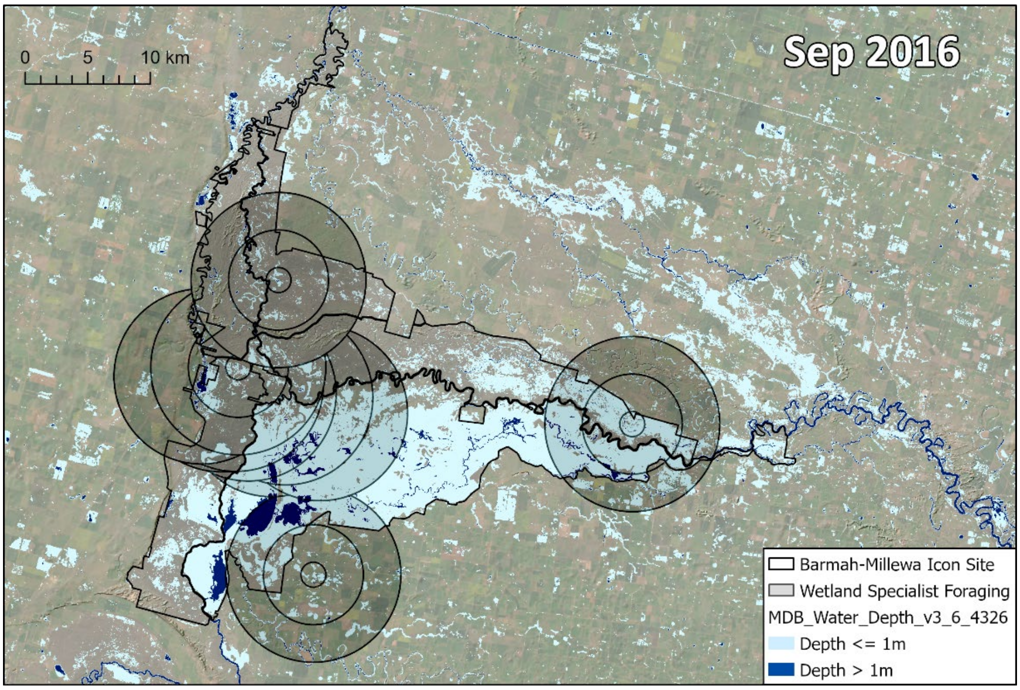

Figure 11. Waterbird Foraging habitat (depth < 1m) in Barmah-Millewa Forest in September 2016.

3.3.1 Obligate wetland-feeding functional group

The availability of foraging habitat is highly variable in space and time. For the obligate wetland-feeding group, the median shallow water extent ranged from over 80 hectares in the mid-Murray sites of Gunbower Island and Boals Deadwood to less than three hectares at 20 colony locations spread out across the Basin (Figure 12). When the maximum extent of shallow water habitat is considered (1988 to 2022), then more northern sites such as Narran Lakes, Macquarie Marshes as well as sites in the Murrumbidgee (including the Lowbidgee) offer the greatest extent, with 20 sites near the entire foraging area of the 1000 meter radius circle of 314 hectares (Figure 13). There were 12 sites where the maximum extent of shallow water habitat within 1000 metres of the colony was < 15 hectares. This included several deep lake sites, where shallow water foraging habitat close to colonies is limited.

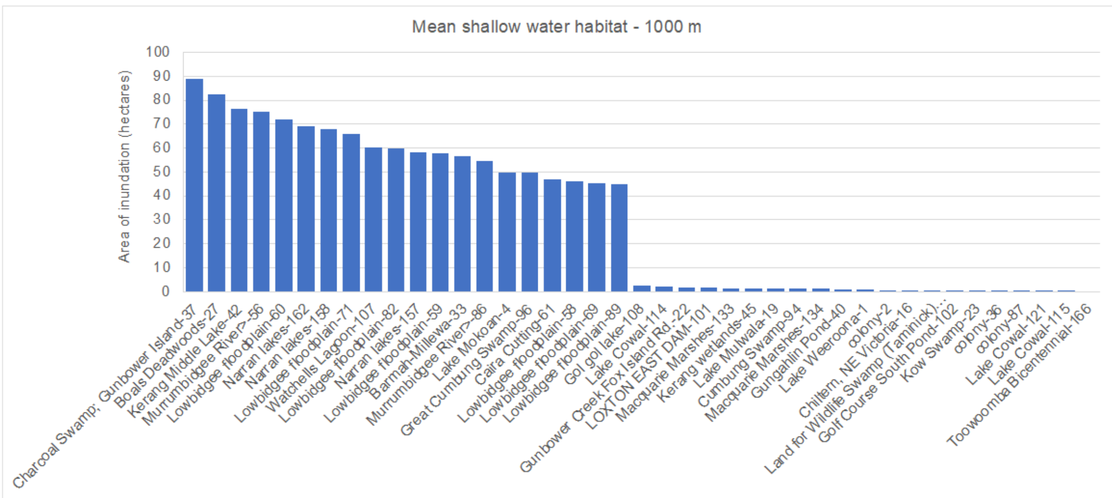

Figure 12. Mean shallow water habitat in the median foraging distance for obligate wetland-feeders at the top 20 and bottom 20 colonies.

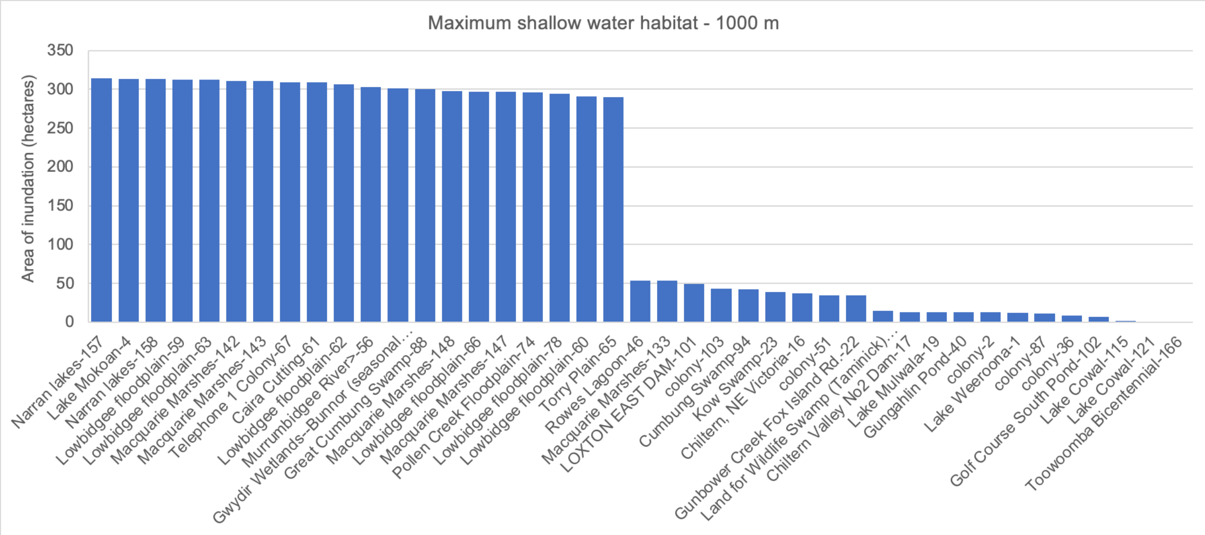

Figure 13. Maximum shallow water habitat in the median foraging distance for obligate wetland-feeders at the top 20 and bottom 20 colonies.

This pattern of similar sites offering the largest mean versus maximum extent of shallow water is relatively consistent across the three foraging distances (Figure 12, Figure 14 and Figure 16). Five colony locations were in the top 20 for mean shallow water habitat at the median (1000 metres), 75th percentile (4000 metres) and maximum (7000 metres) foraging distance for obligate wetland-feeders: Boals Deadwood-27; Lowbidgee floodplain 58 and 59 and Narran Lakes 157 and 158. Eight different sites were in the top 20 colonies for maximum shallow water extent for the three foraging distances for obligate wetland-feeders: Caira Cutting-61; Lowbidgee Floodplain-63 and 66; Macquarie Marshes 142, 143 and 148; Pollen Creek-74, Telephone 1 colony-67 and Tory Plains-65 (Figure 13, Figure 15 and Figure 17).

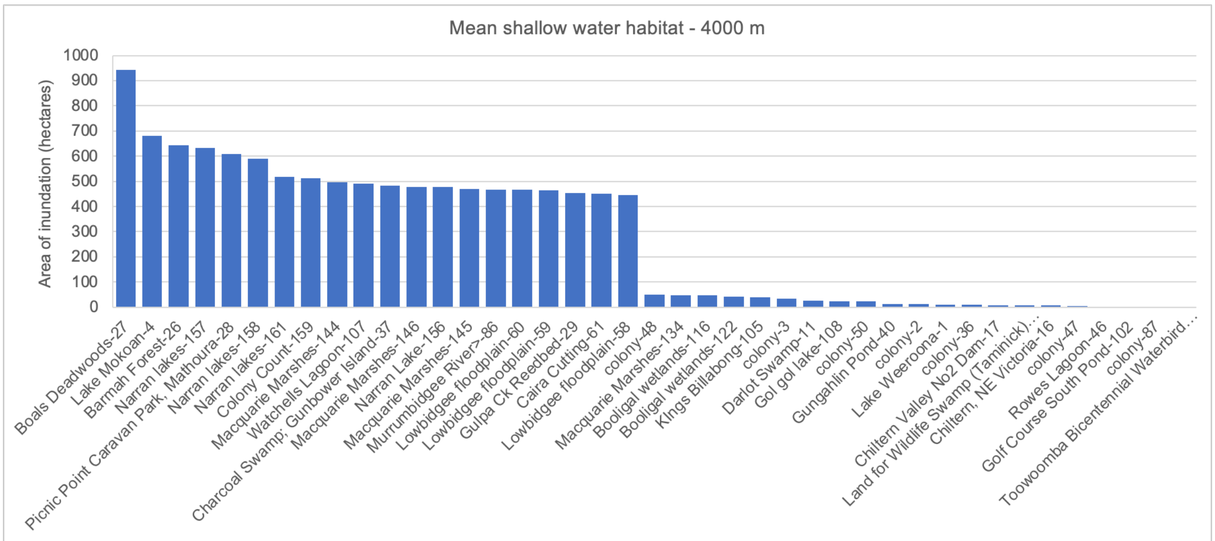

Figure 14. Mean shallow water habitat in the 75th percentile foraging distance for obligate wetland-feeders at the top 20 and bottom 20 colonies.

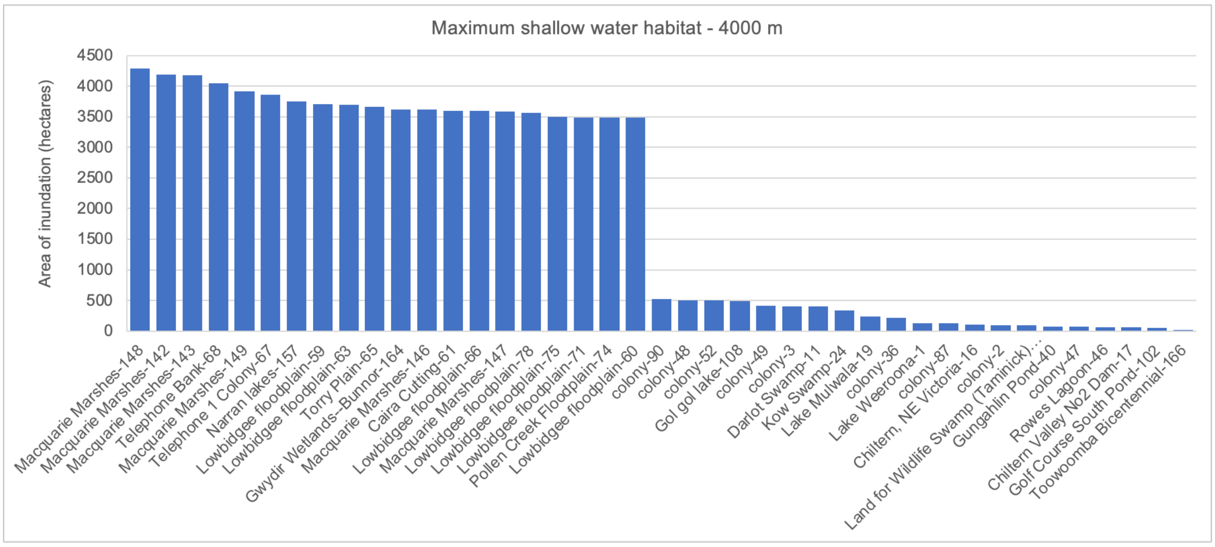

Figure 15. Maximum shallow water habitat in the 75th percentile foraging distance for obligate wetland-feeders at the top 20 and bottom 20 colonies.

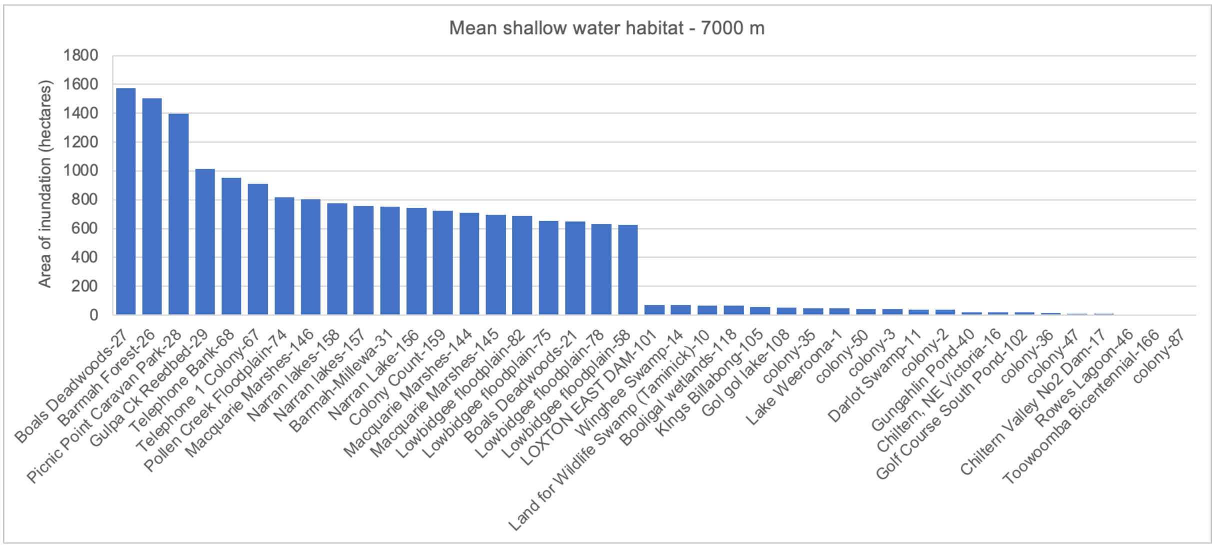

Figure 16. Mean shallow water habitat in the maximum foraging distance for obligate wetland-feeders at the top 20 and bottom 20 colonies.

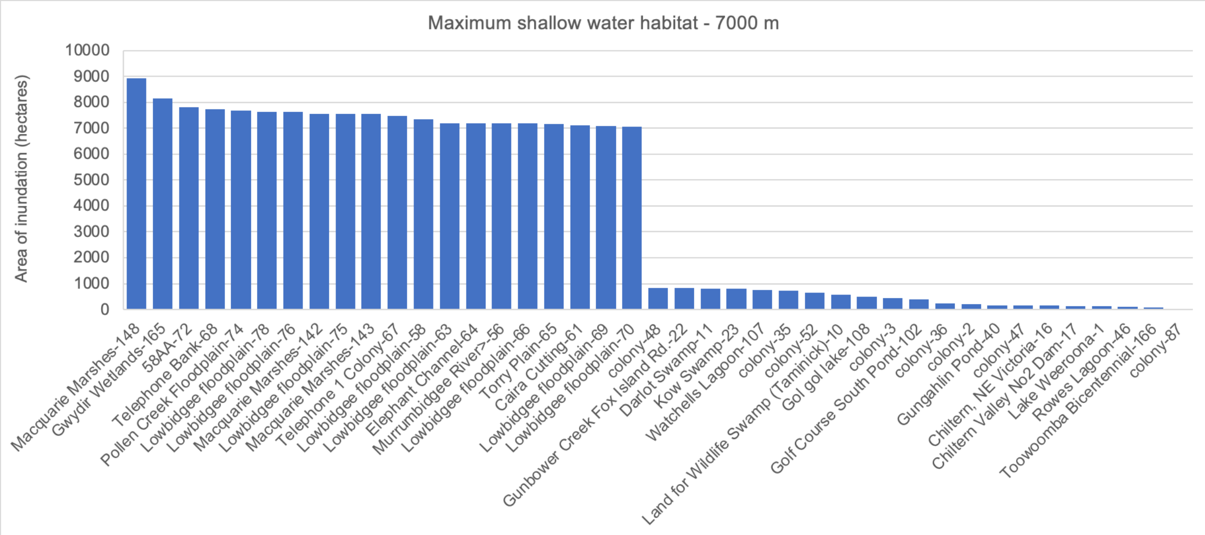

Figure 17. Maximum shallow water habitat in the maximum foraging distance for obligate wetland-feeders at the top 20 and bottom 20 colonies.

There are several colony locations that consistently offer very small amounts of foraging habitat around colony locations in terms of both mean and maximum extents. This includes several artificial wetlands and several water storages / lakes including: Chiltern-16, Golf Lakes South Ponds-102; Gungahlin Pond-40, Lake Weeroona-1 and Toowoomba Bicentennial Waterbird Habitat-166.

The differences between sites that have larger mean foraging habitat extents versus maximum extent is illustrated by looking at two sites, Boals Deadwood (colony 27; Figure 18) and Macquarie Marshes (colony 148; Figure 19). Boals Deadwood is within Barmah Forest, a system that is frequently inundated and since the mid 2000s has received regular environmental water. As a consequence, the area of shallow habitat is relatively seasonal. By contrast, colony 148 in the Macquarie Marshes, is inundated less frequently, but the large periodic floods provide a large extent of shallowly inundated habitat suitable for waterbird foraging. This is consistent with what is known about these two sites from detailed studies (Hale and Butcher 2011, Office of Environment and Heritage 2012, Wen et al. 2013, MDBA 2018).

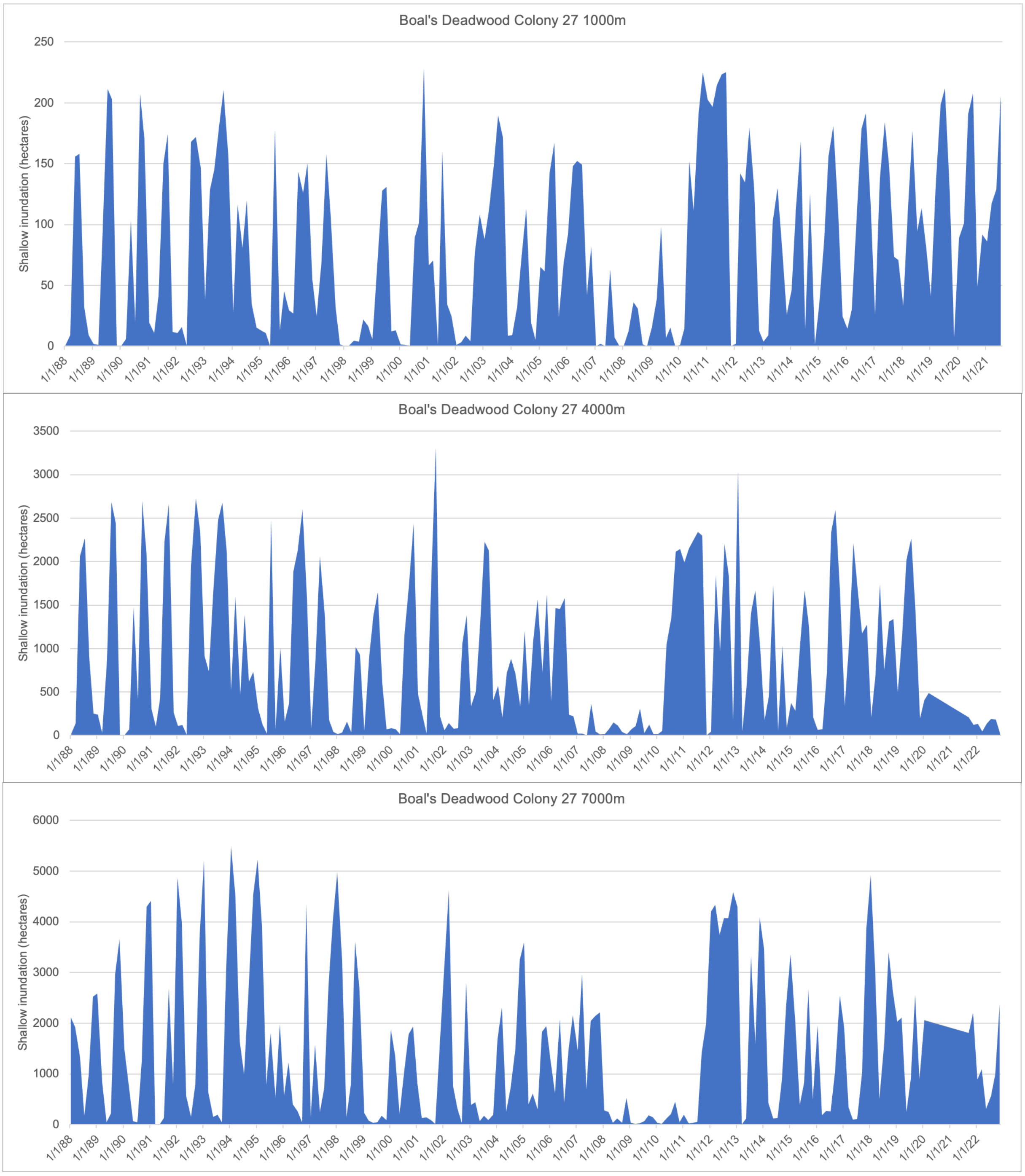

Figure 18. Waterbird foraging habitat extent at Boals Deadwood (colony 27) at the three foraging distances for the obligate wetland-feeding group from 1988 to 2022.

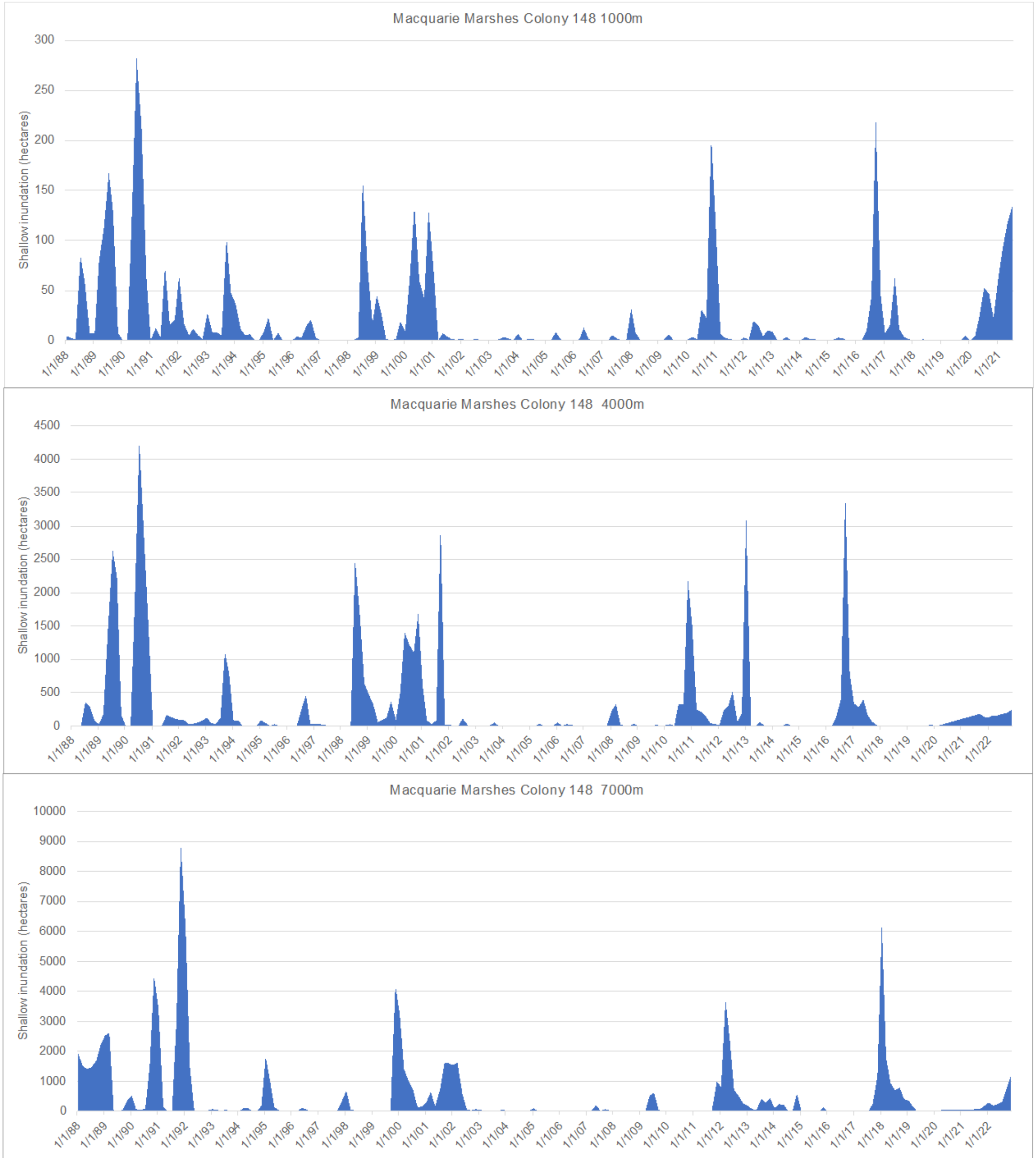

Figure 19. Waterbird foraging habitat extent at Macquarie Marshes (colony 148) at the three foraging distances for the obligate wetland-feeding group from 1988 to 2022.

3.3.2 Non-obligate wetland-feeding functional group

The availability of foraging habitat for the non-obligate wetland-feeding group is also highly variable temporally and spatially, but many of the wetlands with the largest and smallest extents of shallow water habitat remain the same as for the obligate wetland feeding group. Boals Deadwood and several other sites on the mid-Murray have high average habitat extents close to colony locations with 10 to 20% of the inner foraging zone suitable for foraging on average (Figure 20, Figure 22 and Figure 23).

In terms of maximum extent of foraging habitat, the Macquarie Marshes, Lowbidgee, Gwydir and Murrumbidgee sites are capable of providing large areas of suitable foraging habitat with respect to water depth close to colony locations (Figure 21, Figure 22 and Figure 23). At Macquarie Marshes colony 148, over 90% of the inner foraging zone was inundated with shallow water in spring 1990.

Colonies at the Gwydir wetlands have extensive areas of shallow foraging habitat along the floodplain and wetlands fringing the Barwon and Boomi River that are within the outer foraging zone presenting a trade-off with extensive foraging area with higher energetic costs to fly there (Figure 24, Figure 25, Figure 28).

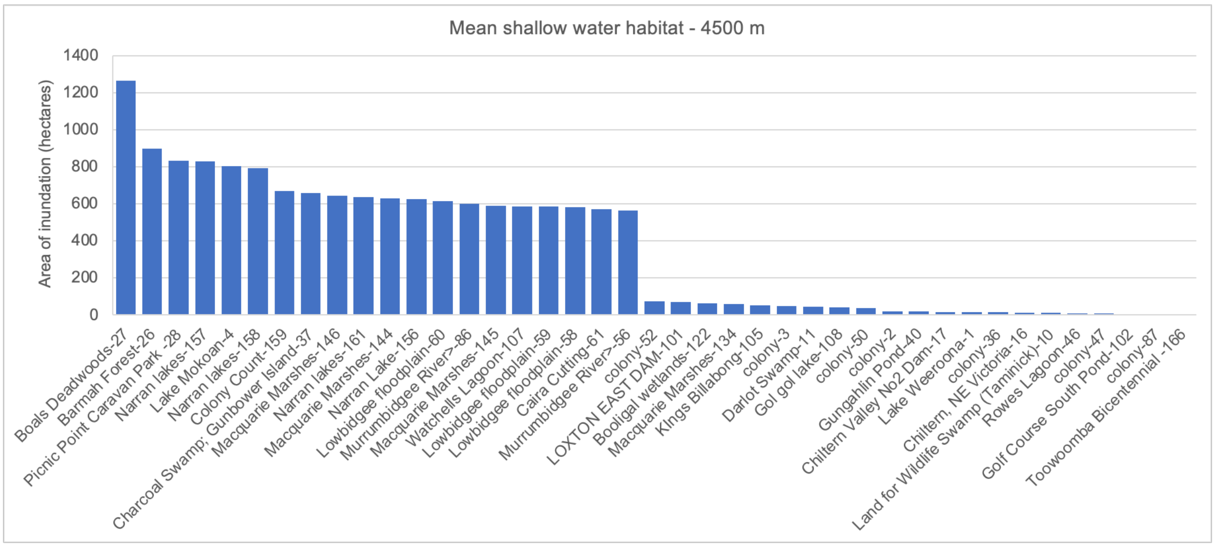

Figure 20. Mean shallow water habitat in the median foraging distance for non-obligate wetland-feeders at the top 20 and bottom 20 colonies.

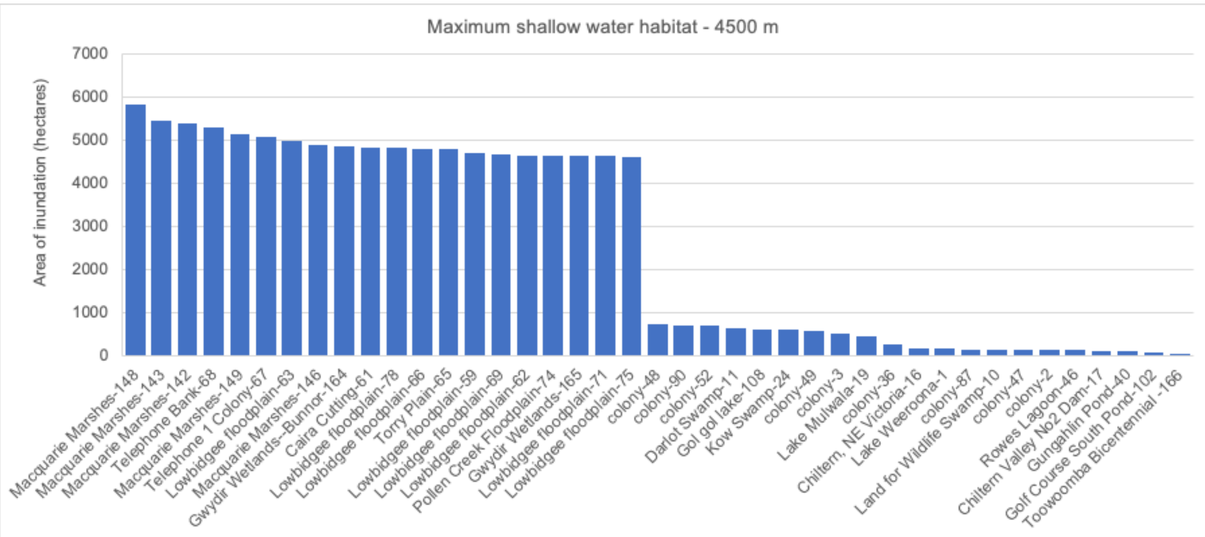

Figure 21. Maximum shallow water habitat in the median foraging distance for non-obligate wetland-feeders at the top 20 and bottom 20 colonies.

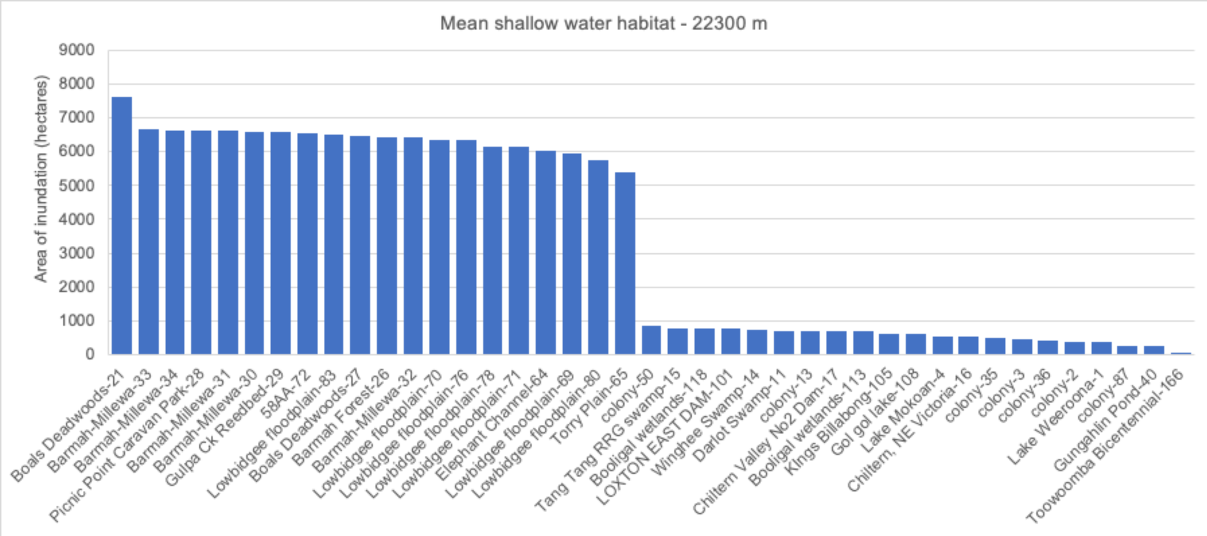

Figure 22. Mean shallow water habitat in the 75th percentile foraging distance for non-obligate wetland-feeders at the top 20 and bottom 20 colonies.

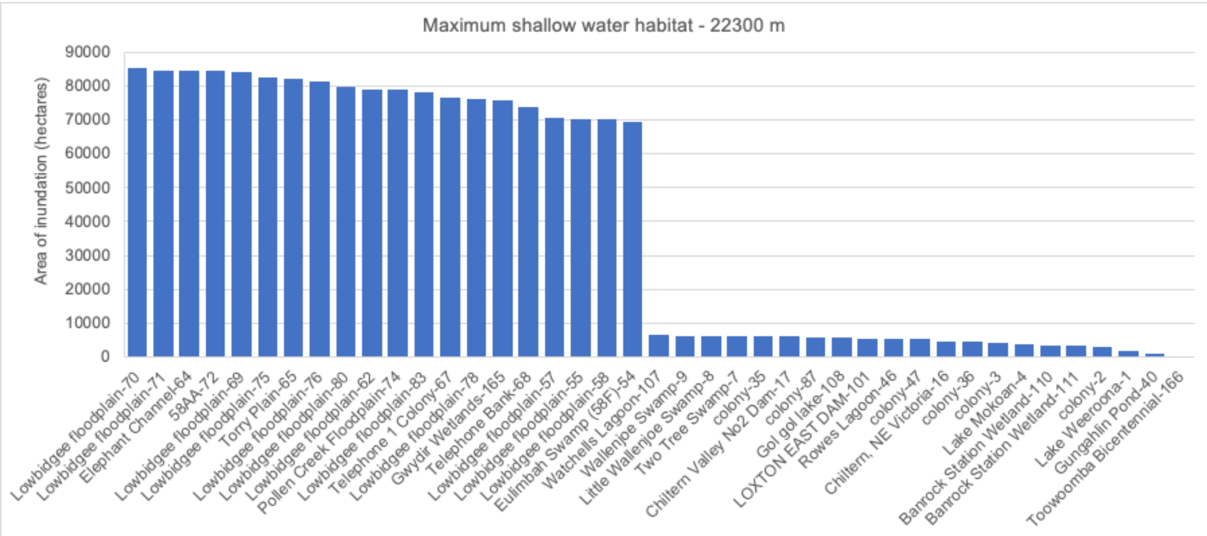

Figure 23. Maximum shallow water habitat in the 75th percentile foraging distance for non-obligate wetland-feeders at the top 20 and bottom 20 colonies.

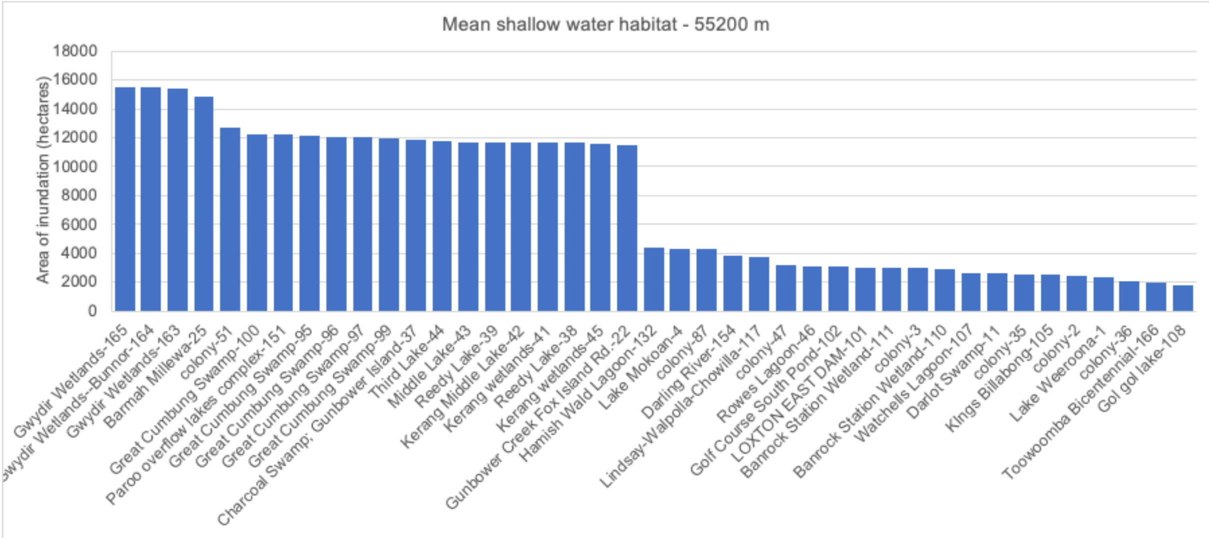

Figure 24. Mean shallow water habitat in the maximum foraging distance for non-obligate wetland-feeders at the top 20 and bottom 20 colonies.

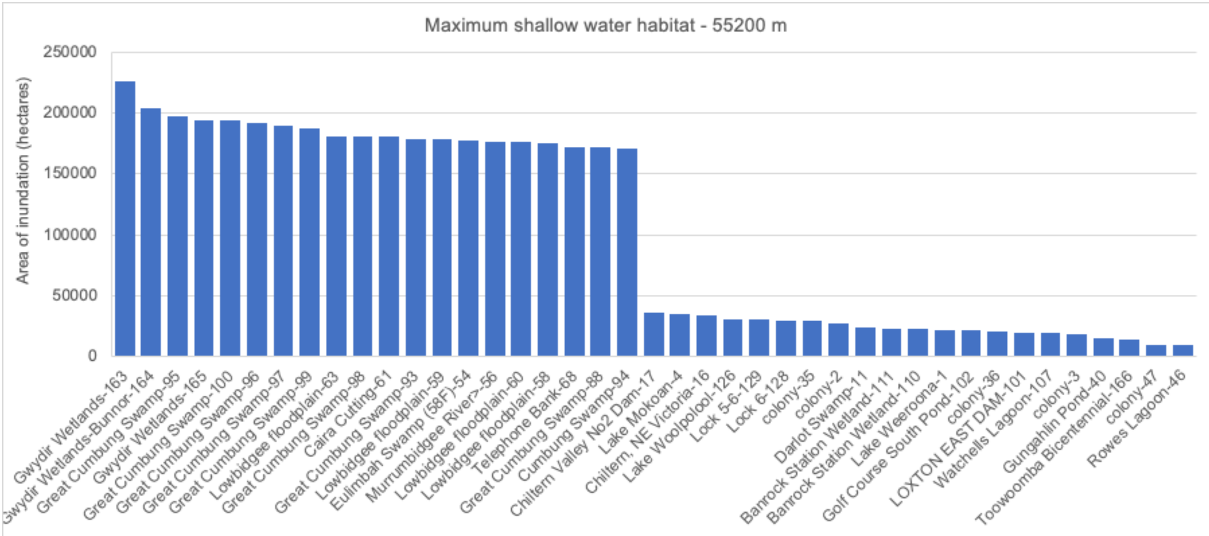

Figure 25. Maximum shallow water habitat in the maximum foraging distance for non-obligate wetland-feeders at the top 20 and bottom 20 colonies.

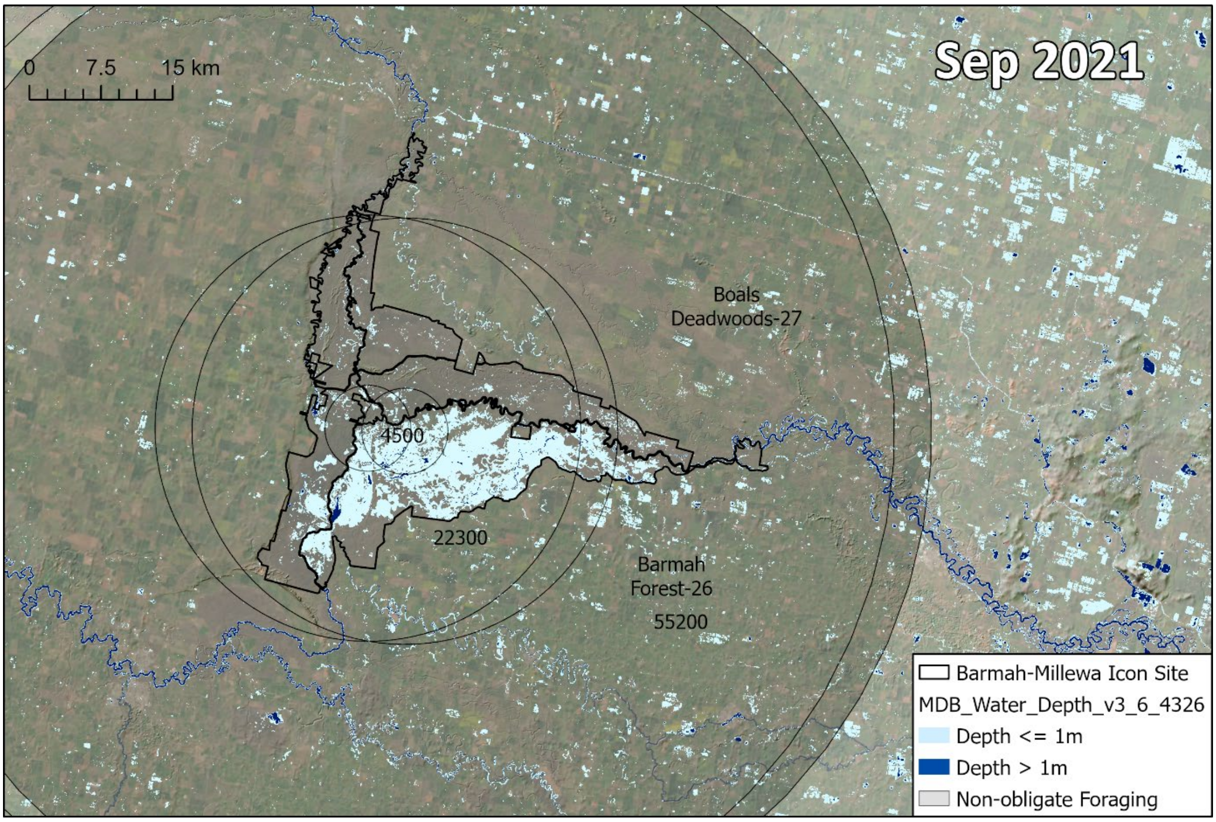

Figure 26. Non-obligate foraging colonies at Boals Deadwood and Barmah forest have regular extensive inundation of the inner circle to 4500m where nesting birds spend 50% of time and out to 22.3km (75% of time).

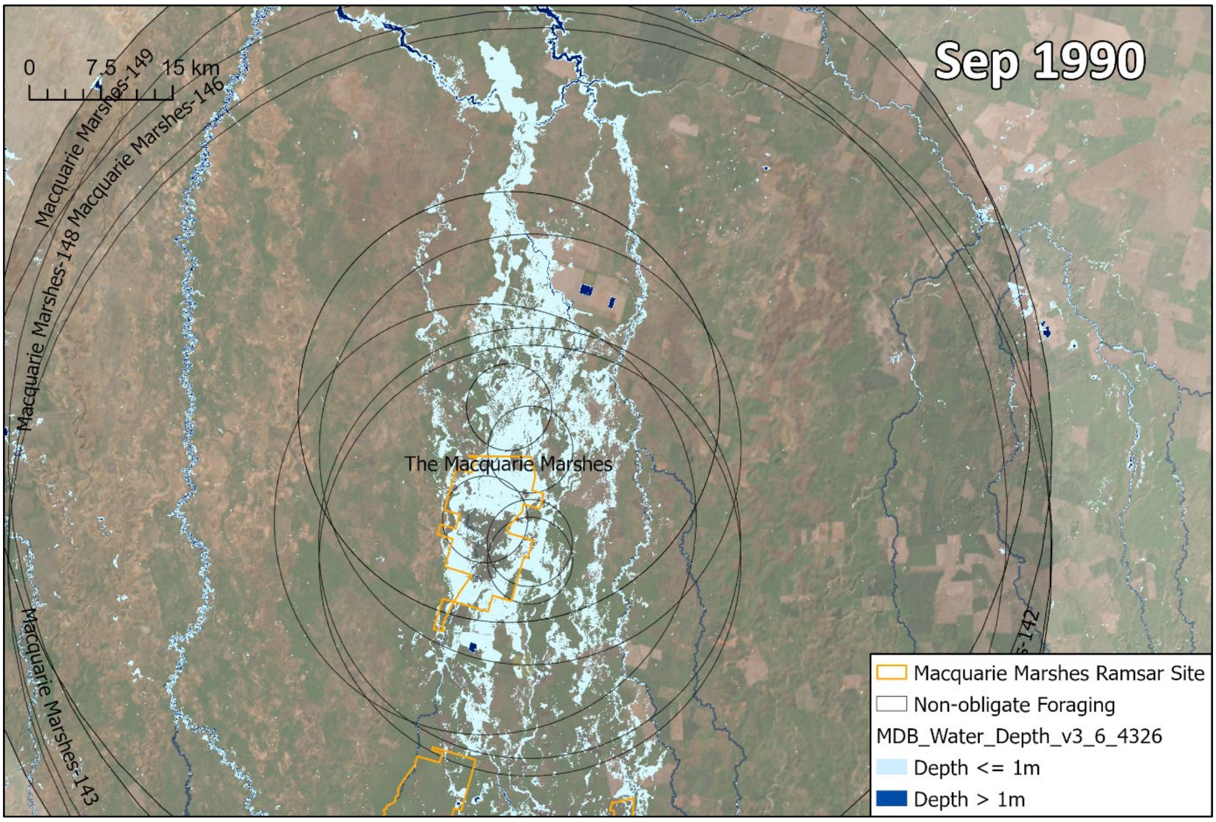

Figure 27. Non-obligate foraging colonies in the Maquarie Marshes (colonies 142, 143, 146, 148,149) centred on the marshes have 80%-90% of the inner foraging zone inundated during floods.

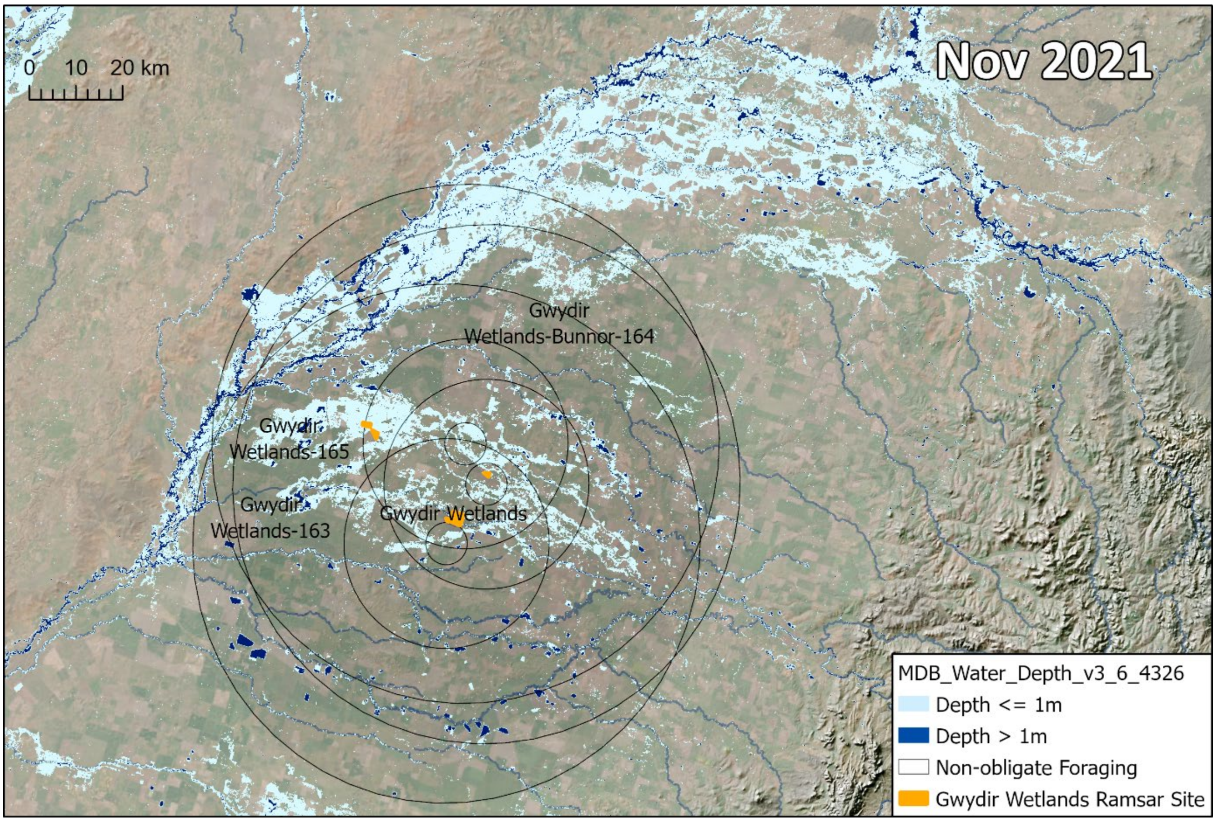

Figure 28. Non-obligate foraging colonies at the Gwydir wetlands have extensive areas of shallow foraging habitat along the floodplain and wetlands fringing the Barwon and Boomi River in the outer foraging zone.

3.3.3 Foraging habitat around active breeding colonies

Each of the colony locations supports breeding only when conditions are suitable and environmental cues trigger colony establishment (Geering 1993, Leslie 2001, Brandis 2010). We attempted to explore the differences in the extent and duration of foraging habitat around active breeding colonies compared to when there was no breeding occurring. The data, however, proved insufficient for this task.

Breeding records for each colony are very sparse, with records of breeding of target species at 144 colonies for the obligate wetland-feeding group and 89 colonies for the non-obligate wetland feeding group. Of these the majority had records for only a single breeding event, 60% of the colony locations with records of obligate wetland-feeding breeding and 70 % of the colony locations with records of non-obligate wetland-feeding breeding (Figure 29). The maximum number of breeding events over the 35-year record was seven for the obligate wetland-feeding group and eight for the non-obligate wetland feeding group (Figure 30) both at the same location; Lowbidgee Floodplain colony 71.

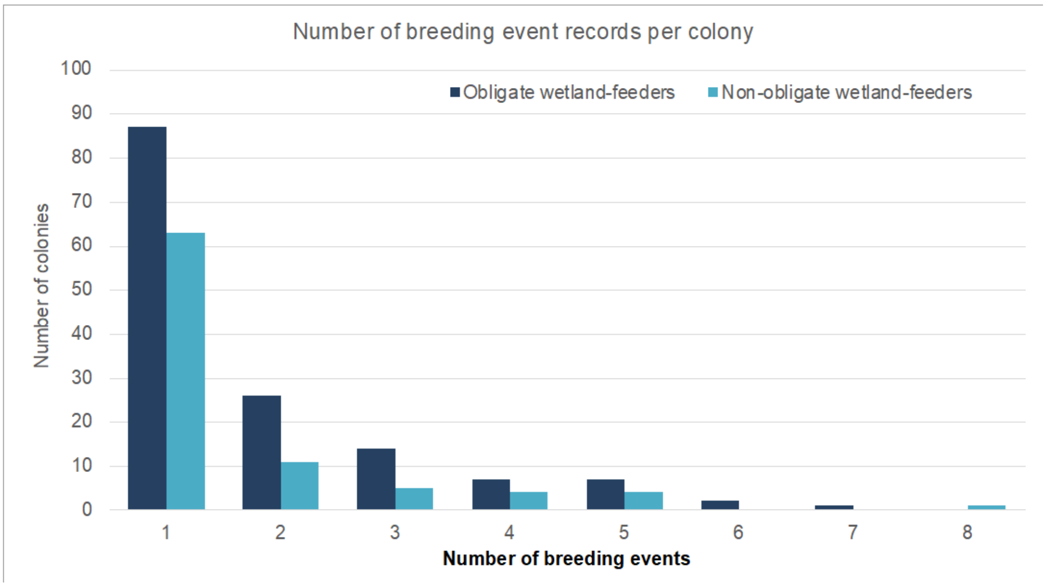

Figure 29. Number of recorded breeding events per colony for each functional group (1988 to 2022).

In terms of breeding across years, there are more colonies with recorded breeding of the target species at the beginning of the record (1988 to 1993) than in more recent years, including the post Millennium drought flood years (Figure 30). Whether this reflects actual breeding or sampling effort is not known.

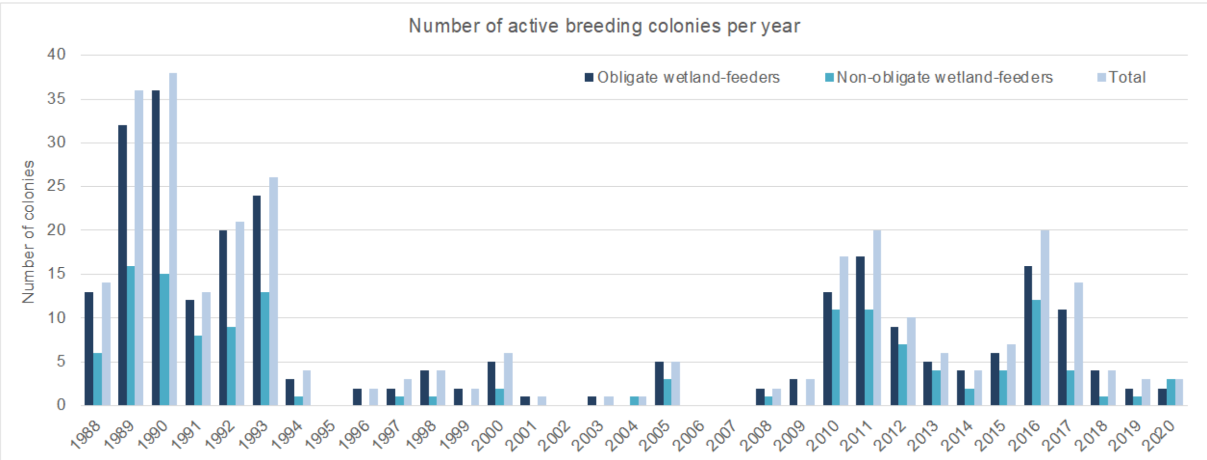

Figure 30. Records of the number of active breeding colonies per year.

What we do know is that there are many breeding events that are missing from the data set we have complied (which used several known databases including MDBA aerial surveys and ALA records). For example, there are two colonies located in Boal's Deadwood in Barmah Forest, colony 21 and colony 27. Records compiled from databases indicate just four breeding events in these two colonies (combined; Figure 31 and Figure 32) in 2003, 2012, 2014 and 2015. The only species recorded were Australian white ibis and straw-necked ibis. There are, however, references in written reports (that have not been uploaded into any database that we could find) of royal spoonbill breeding in this location in 2002, 2005 and 2010 and ibis breeding in 2005 and 2010 (O'Connor and Ward 2003, Ward 2014). There are further records of colonial nesting of ibis, egrets and spoonbills in Barmah Forest in several years, but the exact location within the forest is not provided (Ward 2014).

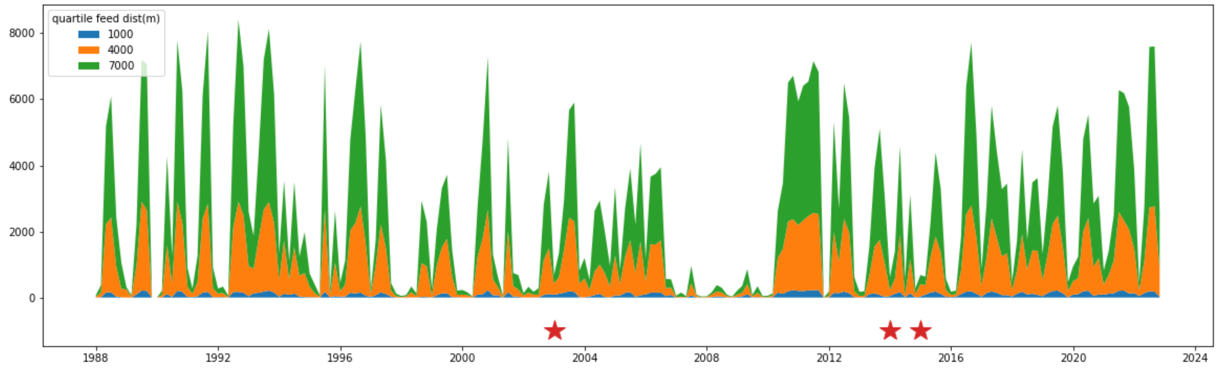

Figure 31. Shallow water habitat at Boal's Deadwood colony 27, with breeding records shown as stars.

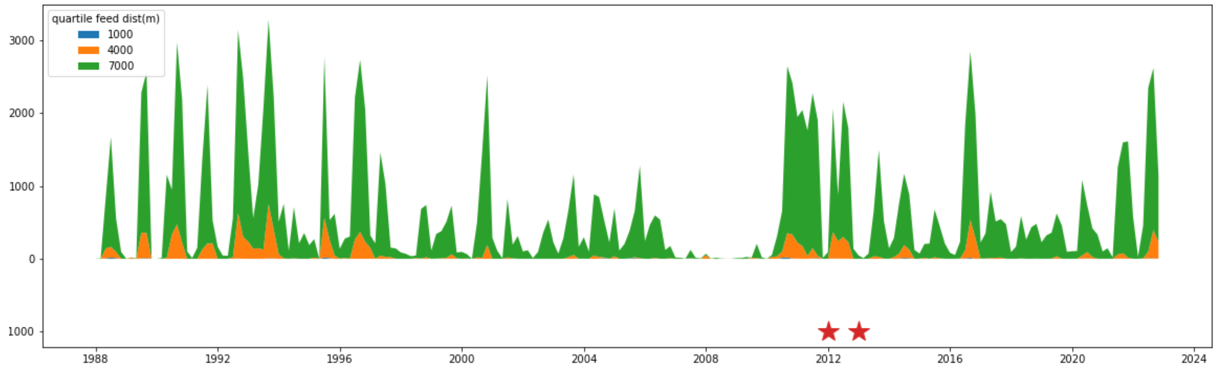

Figure 32. Shallow water habitat at Boal's Deadwood colony 21, with breeding records shown as stars.

It is expected that this omission of breeding events from colony records is relatively extensive. This is because an observation of no breeding cannot be treated as a true zero in comparing breeding to non-breeding sites. As a consequence, there is currently no mechanism to evaluate relationships between the extent of foraging habitat around active colonies and breeding event occurrence or size.

4 Quality of foraging habitat

4.1 Indicators of foraging habitat quality

While we have defined foraging habitat extent for the target species as the area of shallow water within foraging distances, the quality of that habitat is dependent on a large number of other factors. A recent review identified several direct habitat measures for waterbirds (Mott et al. 2023). Those relevant to foraging habitat for the target species include:

- Food availability (e.g. prey animal biomass) – there is evidence from studies of egrets and ibis that prey availability influences both condition and reproductive success (Herring et al. 2010, Herring and Gawlik 2013).
- Primary productivity (e.g. normalised difference vegetation index NDVI) – on the assumption that increased productivity drives increased prey availability and waterbird condition (e.g. Karikkudy 2011).
- Predation pressure (e.g. predator density, proportion of nests predated) – there is evidence form other (non-target) species that predator avoidance reduces foraging time (Maslo et al. 2012).
- Vegetation type and structure – matched to foraging habitat preferences of target species.
- Disturbance (e.g. distance to footpaths, roads) – the presence of people and vehicles can impact foraging behaviour in some species including egrets and herons (Rodgers Jr and Schwikert 2002, Stolen 2003).
- Foraging substrate (e.g. sediment grain size, organic carbon content) – invertebrate prey biomass can be influenced by sediment characteristics (Yates et al. 1993).
- Land use (proportion of non-natural land use) – based on the assumption that inundated non-natural land uses provide lower quality forage.
- Water chemistry (salinity, nutrient concentrations, turbidity) – can influence prey type and availability.

The list of potential foraging habitat indicators for which there is adequate data at the scale of the Basin is limited. While many of the indicators listed above may be appropriate for detailed, site-scale investigations, there are only a small number for which land-scape scale data were available:

- Primary productivity – as indicated by NDVI
- Land use
- Vegetation type and structure, as indicated by preferred ANAE types for each functional group.

For the purposes of this foraging habitat assessments habitat quality was measured based on the following assumptions:

1. Shallow water habitat close to colony locations is preferred, reducing the energy costs of foraging at greater distances.
2. With respect to habitat type, there is a hierarchy of better to worse quality of: preferred ANAE type, other ANAE types, shallow water inundation in non-aquatic ecosystems.

3. Higher productivity (as indicated by NDVI) represents better foraging habitat quality than lower productivity.
4. The presence of high intensity land uses within the foraging distances reduces foraging habitat quality.

4.2 Preferred ANAE types

4.2.1 What are the preferred ANAE types?

An approximation of preferred habitats and their locations for each functional group was derived by intersecting ANAE polygons with species presence observations from available data sources. The most common habitat type(s) for each group were labelled as "preferred ANAE" (Table 5`).

Table 5. List of preferred ANAE types for each functional group.

Obligate wetland-feeders	Non-obligate wetland-feeders
Lp1.1: Permanent lake	F2.4: Shrubland riparian zone or floodplain
Pp4.2: Permanent wetland	Lp1.1: Permanent lake
F1.2: River red gum forest riparian zone or floodplain	Pp4.2: Permanent wetland
F2.4: Shrubland riparian zone or floodplain	Pt1.8.2: Temporary shrub swamp
F1.8: Black box woodland riparian zone or floodplain	F2.2: Lignum shrubland riparian zone or floodplain
F2.2: Lignum shrubland riparian zone or floodplain	F1.8: Black box woodland riparian zone or floodplain
Pt2.2.2: Temporary sedge/grass/forb marsh	Pt2.2.2: Temporary sedge/grass/forb marsh
Pt1.8.2: Temporary shrub swamp	Pt3.1.2: Clay pan
Pt1.7.2: Temporary lignum swamp	F1.2: River red gum forest riparian zone or floodplain
Pt1.1.2: Temporary river red gum swamp	Pt2.3.2: Freshwater meadow
Pt3.1.2: Clay pan (temporary shallow ponds)	Pt1.7.2: Temporary lignum swamp

4.2.2 Preferred ANAE types for obligate wetland-feeders

The mean extent of foraging habitat in the inner foraging zone for obligate wetland-feeders ranges from over 80 hectares at Charcoal Swamp in Gunbower Forest, to less than one hectare at 38 wetlands spread across the Basin (Figure 33).

It is perhaps, however, more useful to look at changes in quality foraging habitat at each colony over time. At Charcoal Swamp, for example, the shallow inundated habitat is of preferred ANAE only in the inner zone (Figure 34). There was a clear decline in the extent of foraging habitat during the Millennium Drought, and while the frequency of foraging habitat provision has recovered, there has been a 24% decline in the duration of foraging habitat extent (2013 to 2022 compared to 1988 to 1997).

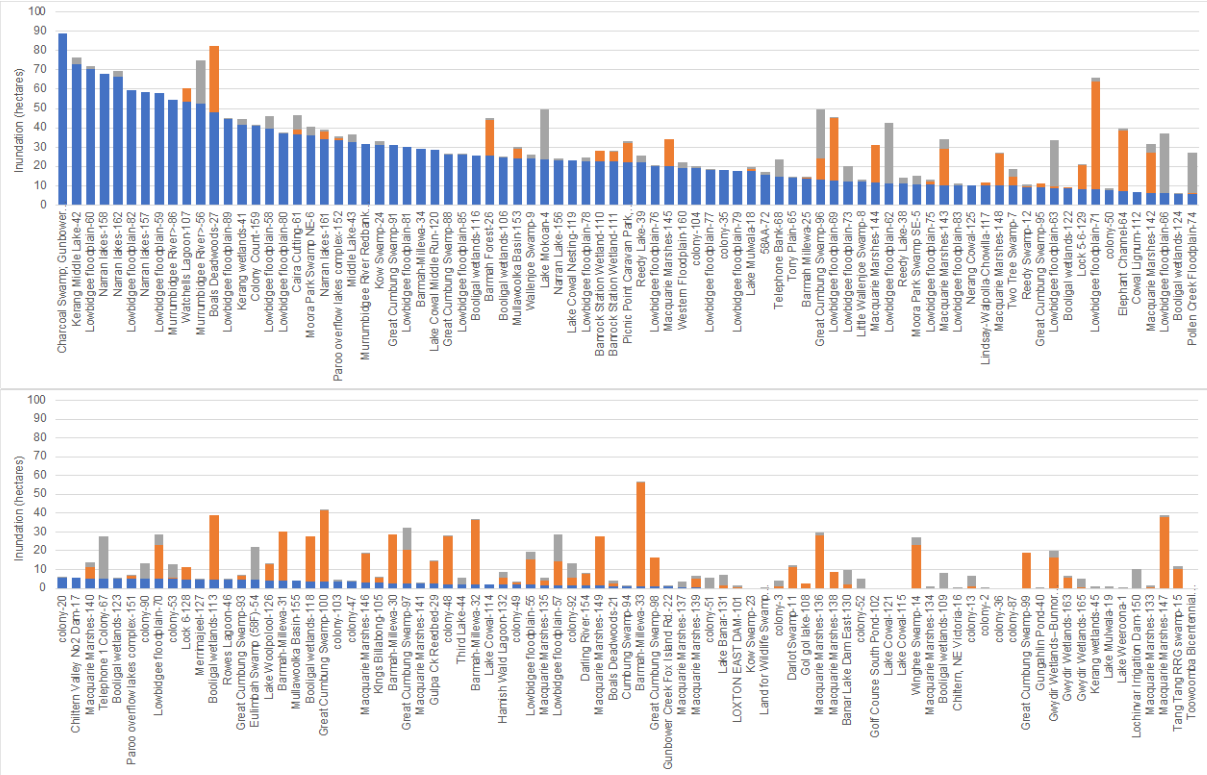

Figure 33. Waterbird foraging habitat extent at all 166 colonies in three habitat quality classes (preferred ANAE, other ANAE and non-ANAE) in the inner zone for the obligate wetland-feeding group from 1988 to 2022.

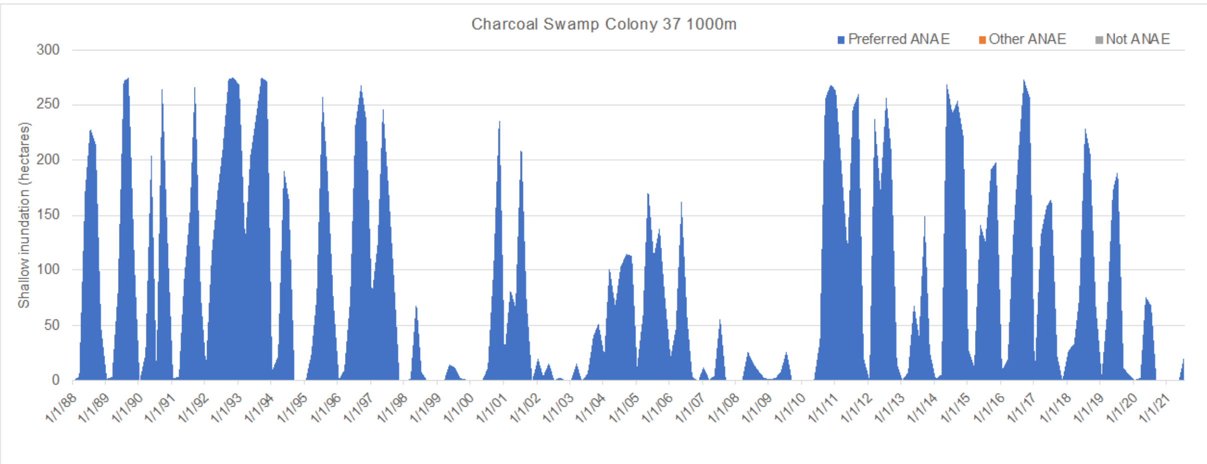

Figure 34. Waterbird foraging habitat extent at Charcoal Swamp (colony 37) in the inner zone for the obligate wetland-feeding group from 1988 to 2022.

The Macquarie Marshes (colony 148) has a greater proportion of other ANAE in the inner zone foraging habitat (Figure 35). In this instance there has been a 30% decline in preferred ANAE foraging habitat and a 20% decline in the provision of foraging habitat in other ANAE types (1988-1997 compared to 2013-2022).

Lake Mokoan (colony 4) represents a different scenario (Figure 36). This former water storage has now been rehabilitated to more natural wetland system. As a consequence, despite increasing dry conditions in a post 1997 climate in Victoria (DELWP 2016), there has been a 30% increase in the provision of preferred ANAE foraging habitat at this site.

The Lowbidgee Floodplain colony (59) represents one of the biggest declines in the provision of waterbird foraging habitat in the inner zone for obligate-wetland feeders (Figure 37). From 1988 to 1997, on average there was 125 hectares of foraging habitat in the inner zone, by 2013 to 2022, this had declines to just 29 hectares (a 77% decline).

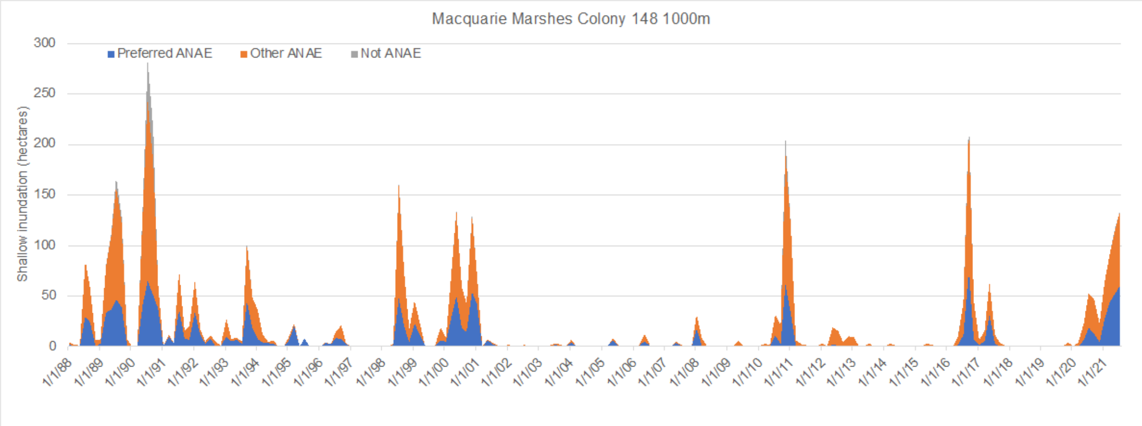

Figure 35. Waterbird foraging habitat extent at Macquarie Marshes (colony 148) in the inner zone for the obligate wetland-feeding group from 1988 to 2022.

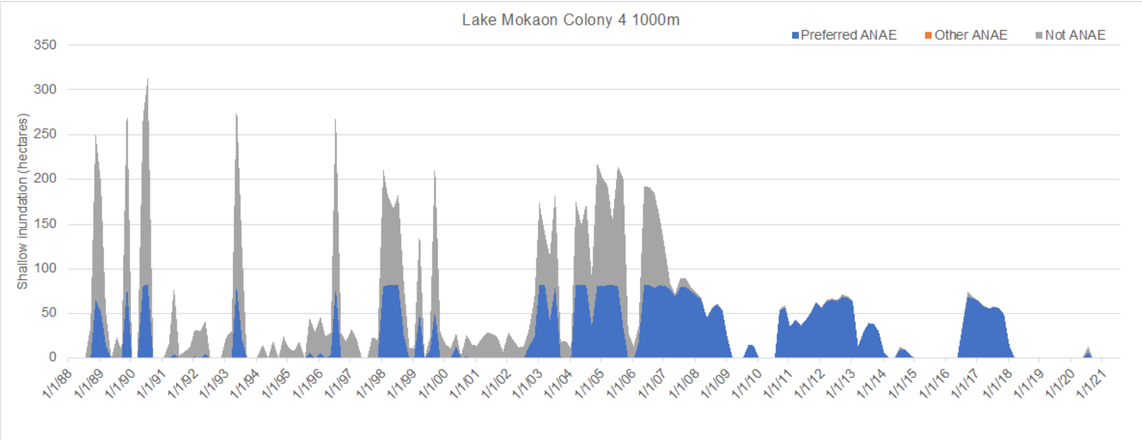

Figure 36. Waterbird foraging habitat extent at Lake Mokoan (colony 4) in the inner zone for the obligate wetland-feeding group from 1988 to 2022.

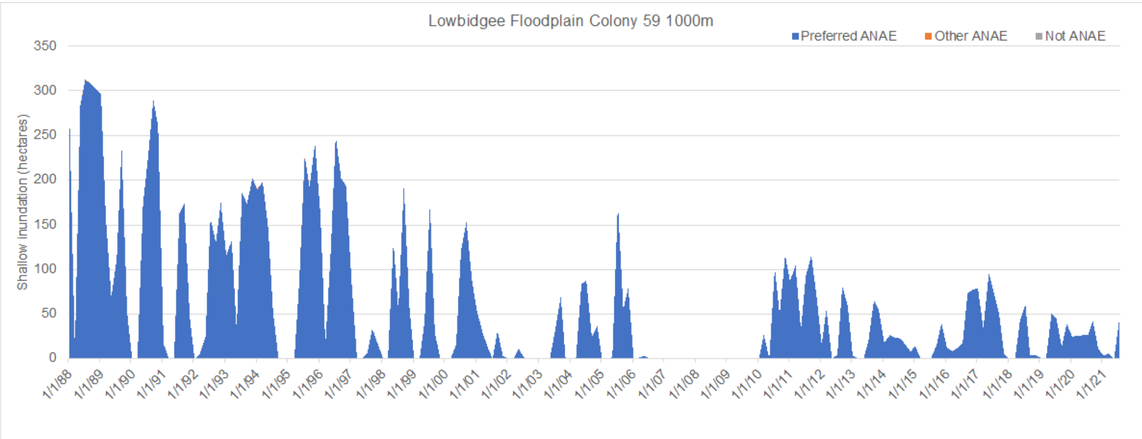

Figure 37. Waterbird foraging habitat extent at Lowbidgee Floodplain (colony 59) in the inner zone for the obligate wetland-feeding group from 1988 to 2022.

Overall, there has been a decline (> 1 hectare) in preferred ANAE foraging habitat in the inner foraging zone for obligate-wetland feeders at around half (85) of the colony locations (Figure 38). This ranges from nearly 100 hectares at colony 59 on the Lowbidgee floodplain, to very small changes at a large number of sites. Conversely, there has been an increase in average preferred ANAE foraging habitat at 29 colony locations, including several lake systems (e.g Kow Swamp, Lake Mokoan, Lake Cowal). It is possible that at these locations there has been an increase in shallow water and a decline in deeper water habitat.

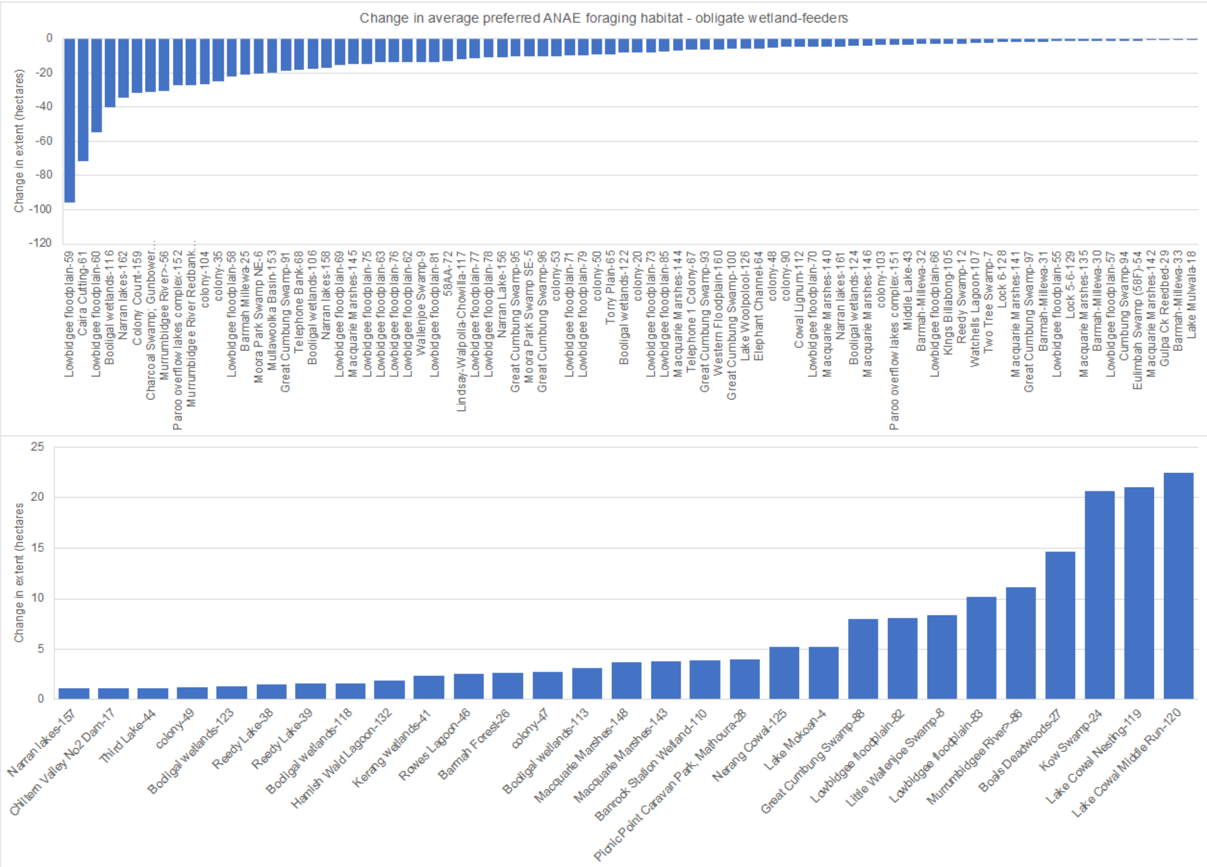

Figure 38. Change in the average extent of foraging habiat in preferred ANAE in the inner zone for obligate-wetland feeders (1988-97 compared to 2013-22). Colonies with less than one hectare change not shown.

4.2.3 Preferred ANAE types for non-obligate wetland-feeders

The mean extent of foraging habitat in the inner foraging zone for non-obligate wetland-feeders ranges from over 800 hectares at Narran Lakes (colony 157), to less than one hectare at 10 wetlands spread across the Basin including Toowoomba Bicentennial Bird Habitat in Queensland and Lake Weeroona in Victoria (Figure 39).

Extent of preferred ANAE foraging habitat over time various significantly between colony locations. At Narran Lakes (colony 157) for example, the majority of foraging habitat in the inner foraging zone for non-obligate feeders is in preferred ANAE types (Figure 40). The site is highly variable in foraging habitat extent over time, but there has been a 25% decline in foraging habitat in the last ten years compared to 1988-97.

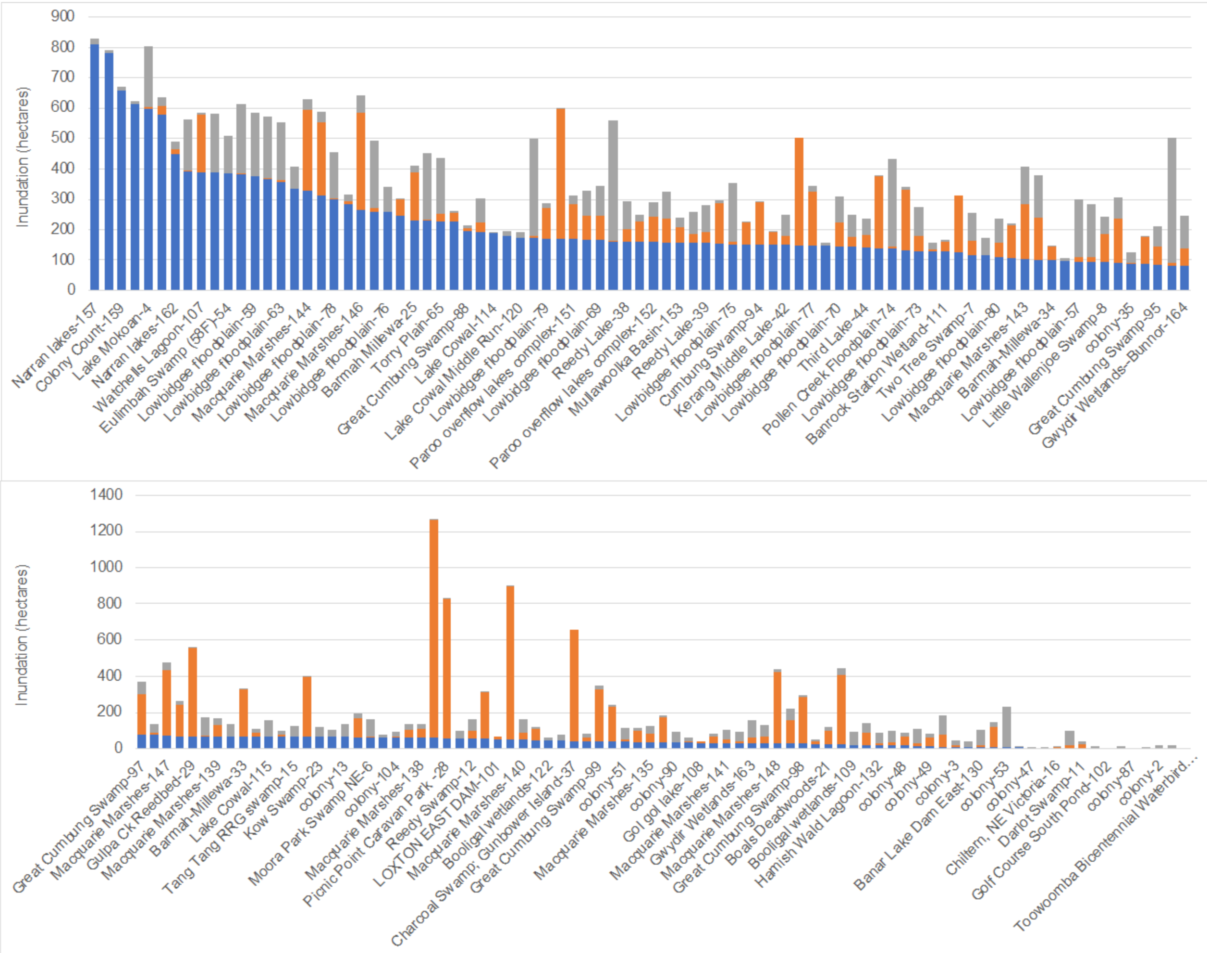

Figure 39. Waterbird foraging habitat extent at all 166 colonies in three habitat quality classes (preferred ANAE, other ANAE and non-ANAE) in the inner zone for the non-obligate wetland-feeding group from 1988 to 2022.

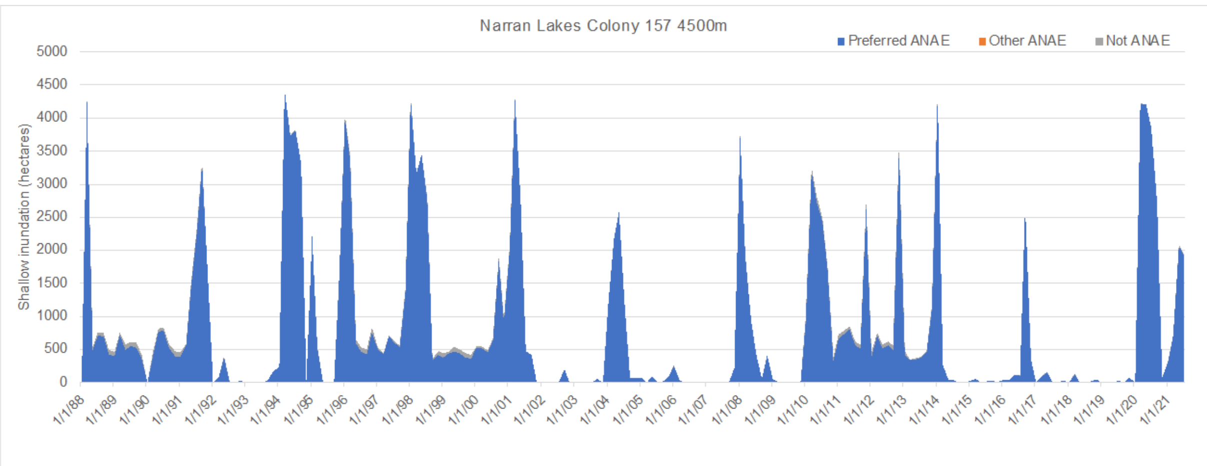

Figure 40. Waterbird foraging habitat extent at Narran Lakes (colony 157) in the inner zone for the non-obligate wetland-feeding group from 1988 to 2022.

The majority of foraging habitat in the inner foraging zone at Picnic Point (on the Murray near Barmah Forest) is in non-preferred ANAE types (Figure 41). There has been little change in average foraging habitat extent over time at this site. In contrast, Caira Cutting (colony 61) has had a significant decline in the duration and frequency of foraging habitat extent (Figure 42). On average, there has been over 300 hectares less preferred ANAE foraging habitat extent in the inner foraging zone in the past ten years (compared to 1988-97) representing a 43% decline.

There has been a large increase in foraging habitat at Barren Box Swamp (colony 92, Figure 43). This former water storage underwent a significant redevelopment in 2006, with one third of the waterbody returned to intermittent wetland. This is reflected in a greater than 300 hectare increase in average foraging habitat at the colony location, representing a 470% increase in shallow water habitat.

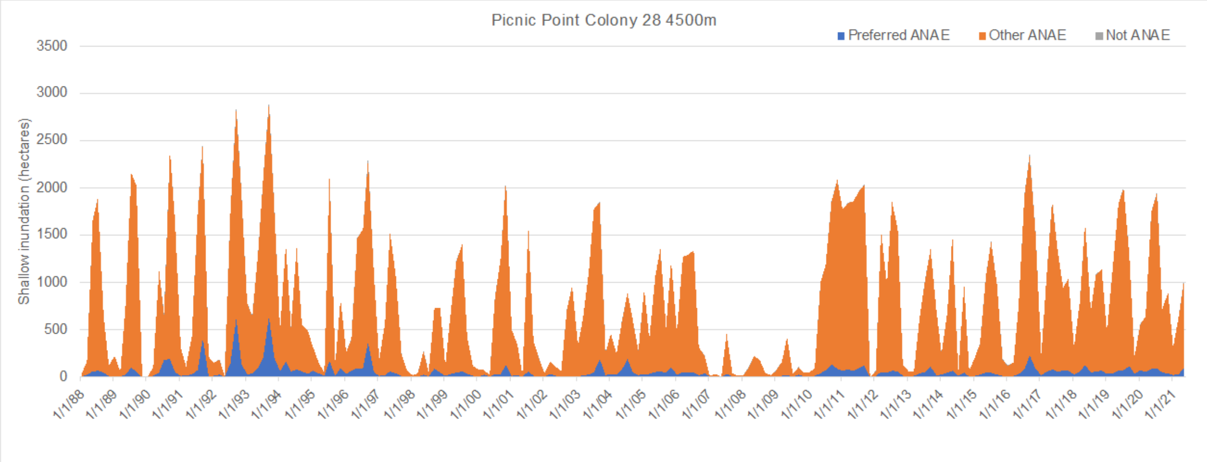

Figure 41. Waterbird foraging habitat extent at Picnic Point (colony 28) in the inner zone for the non-obligate wetland-feeding group from 1988 to 2022.

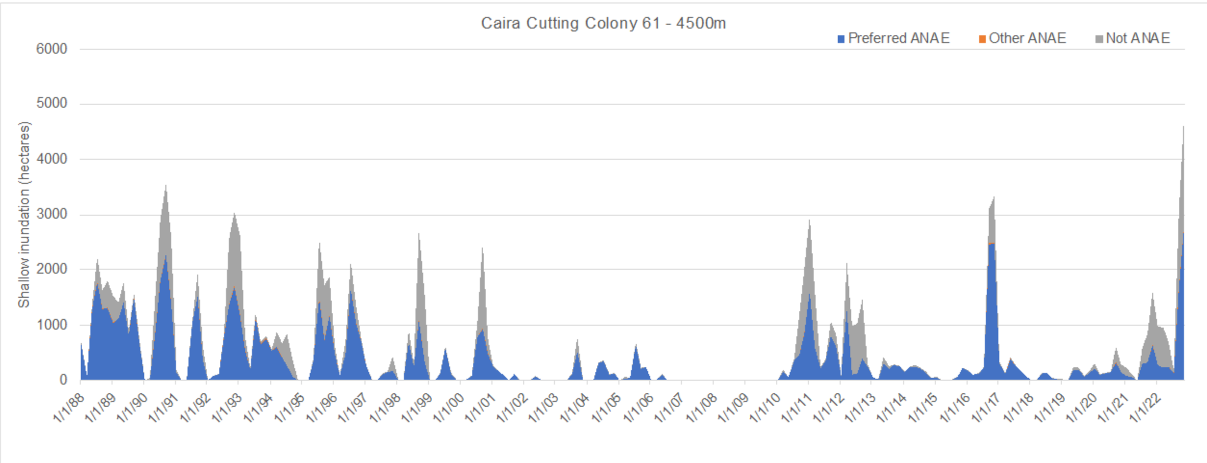

Figure 42. Waterbird foraging habitat extent at Caira Cutting (colony 61) in the inner zone for the non-obligate wetland-feeding group from 1988 to 2022.

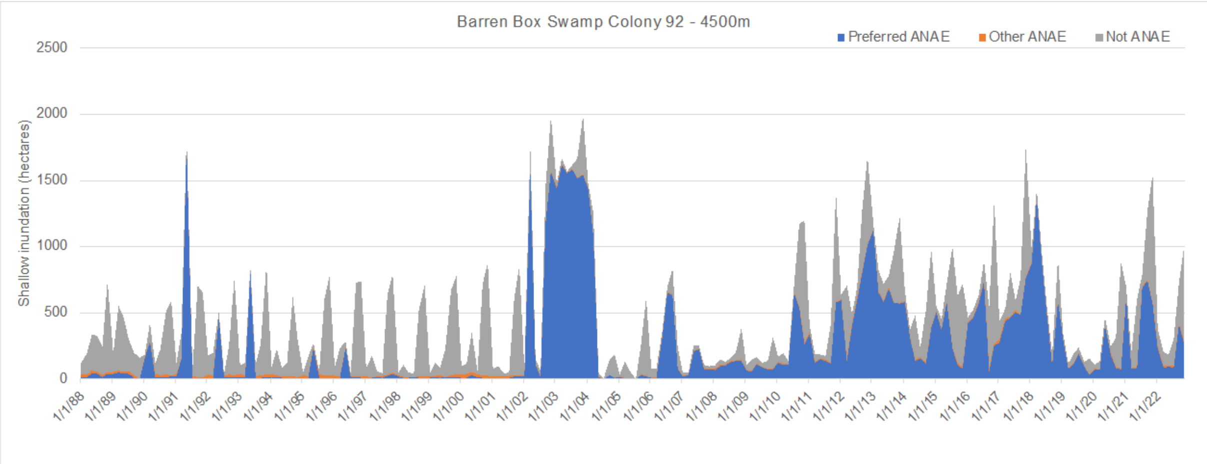

Figure 43. Waterbird foraging habitat extent at Barren Box Swamp (colony 92) in the inner zone for the non-obligate wetland-feeding group from 1988 to 2022.

There has been a decline (> 1 hectare) in preferred ANAE foraging habitat in the inner foraging zone for non-obligate-wetland feeders at nearly 80% (111) of the colony locations (Figure 44). This ranges from over 300 hectares at colony 61, to very small changes at a large number of sites. Conversely, there has been an increase in average preferred ANAE foraging habitat at 40 colony locations, including several lake systems (e.g. Barren Box Swamp, Lake Mokoan, Lake Cowal).

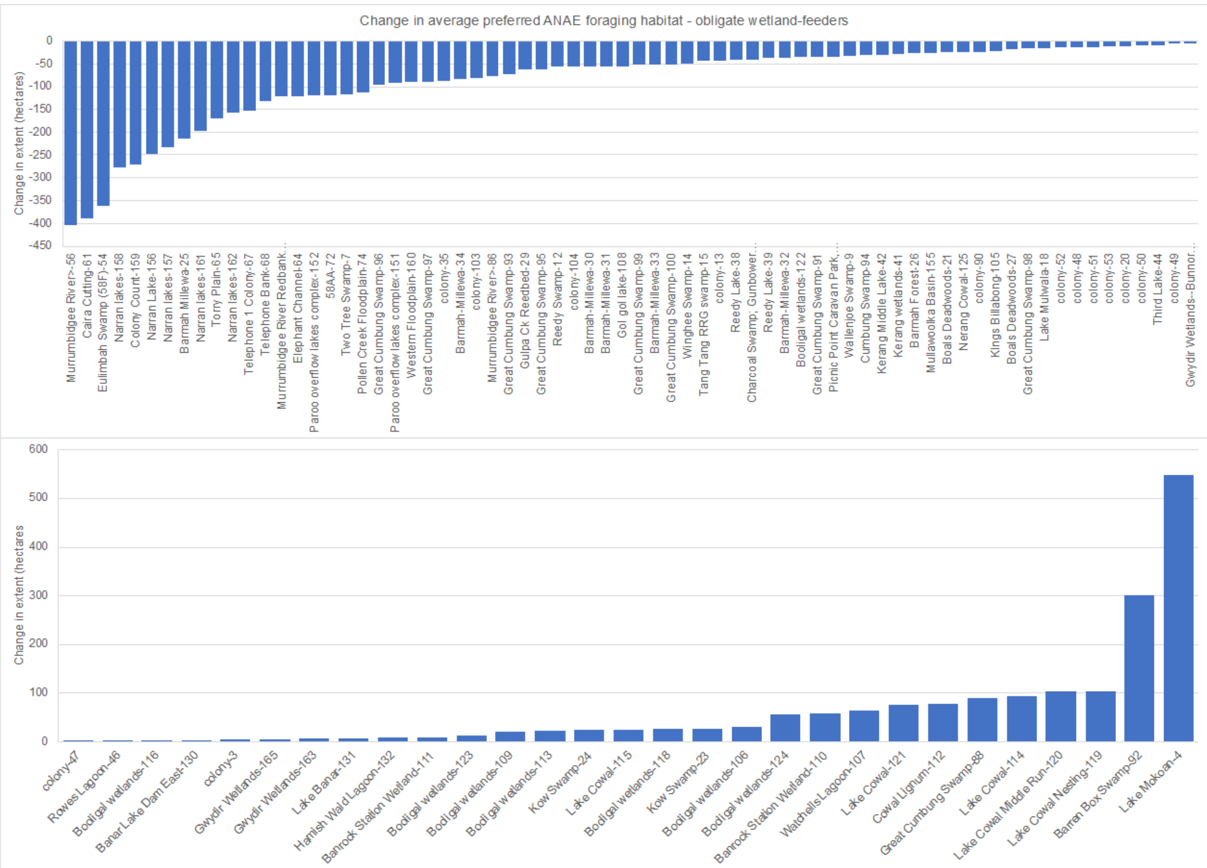

Figure 44. Change in the average extent of foraging habiat in preferred ANAE in the inner zone for non-obligate-wetland feeders (1988-97 compared to 2013-22). Colonies with less than one hectare change not shown.

4.3 Land use

Land use in the foraging zones was explored using the Catchment Scale Land Use of Australia (DOE 2017). This provided a coarse indication of the types of inundated habitats in the "not ANAE" category. The area of different land use types within foraging zones varied within colonies depending on their location in the Basin (Figure 45 and Figure 46). For example, the Kerang wetlands and several colony locations in the Murrumbidgee have substantive amounts of mapped irrigated pasture and cropping within colony foraging zones, many other sites (e.g. in the floodplain forests of the Murray) contain largely mapped wetlands in foraging zones. The static nature of the data set and coarse spatial scale did not lend itself to a useful measure of foraging habitat quality.

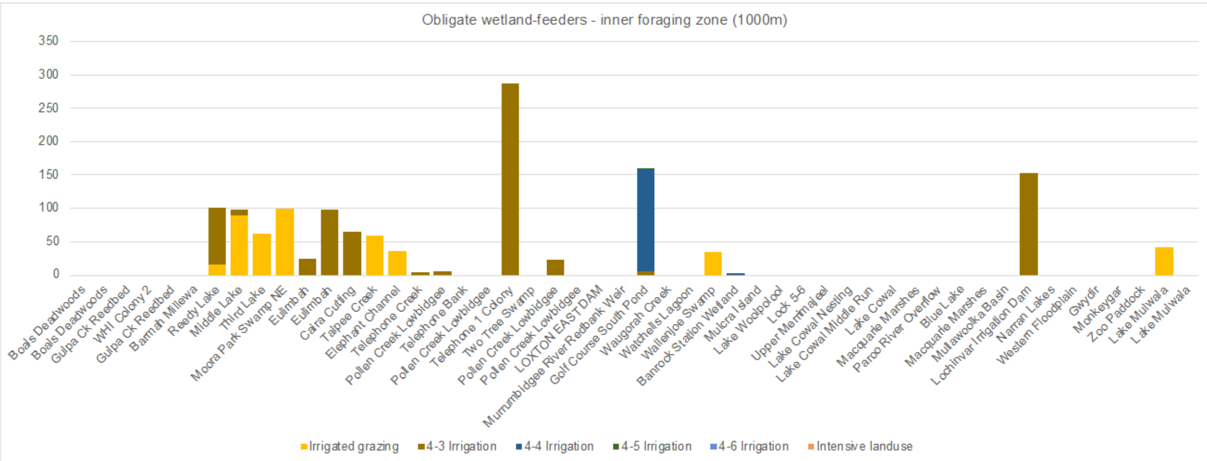

Figure 45. Proportion of irrigated and intensive land uses in foraging zones of a selection of breeding colonies for obligate wetland-feeders.

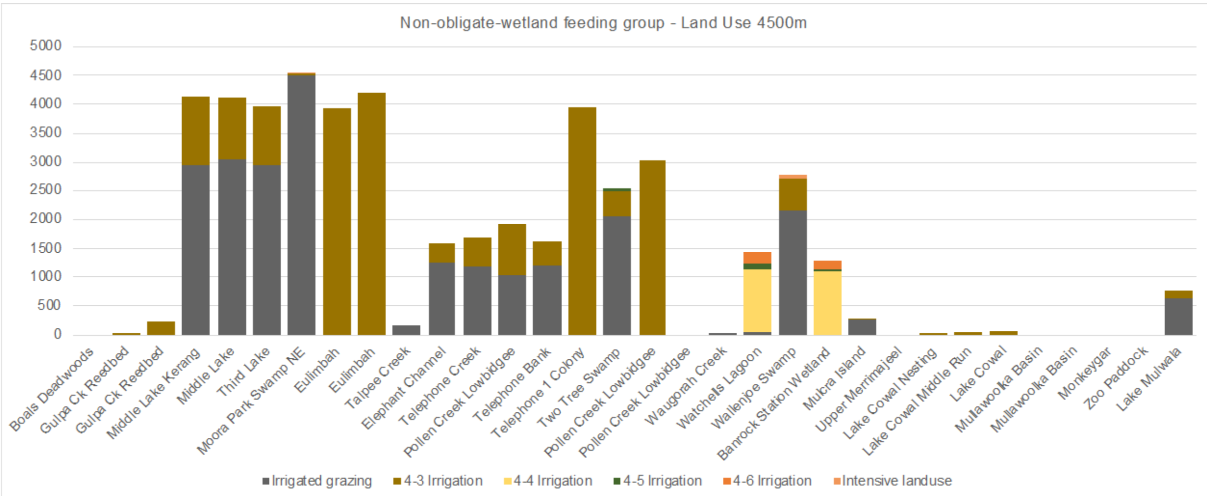

Figure 46. Proportion of irrigated and intensive land uses in foraging zones of a selection of breeding colonies for non-obligate wetland-feeders.

4.4 NDVI

The Normalized Difference Vegetation Index (NDVI) is commonly used to estimate vegetation productivity. It is a simple ratio applied to satellite imagery that quantifies the difference in red light (absorbed by chlorophyl in actively growing healthy vegetation) and near-infrared (reflected by vegetation). NDVI was measured as a surrogate for productivity within each waterbird colony foraging zone using Google Earth Engine to calculate the mean value in each zone per year for the period 1986-2021. Data are obtained from two different satellites to represent the full time period.

- 1986_2000 - NOAA AVHRR satellite https://developers.google.com/earth-engine/datasets/catalog/NOAA_CDR_AVHRR_NDVI_V5
- 2001_2022 – MODIS satellite https://developers.google.com/earth-engine/datasets/catalog/MODIS_061_MOD13Q1

The data sets are not directly comparable with NDVI values obtained from AVHRR being approximately 50% of MODIS (a function of the data ranges as provided in Google's earth engine data library). Each data set is therefore standardised to range 0-1 before appending them together to represent annual productivity in each foraging zone.

Productivity within foraging zones was explored in several ways. Maximum NDVI in inner foraging zones varied considerably at colony locations. For example, in the inner foraging zone for non-obligate wetland-feeders, maximum NDVI ranged from over 0.7 at several colony locations in the mid-Murray to < 0.3 at inland locations in western NSW such as the Paroo Overflow Lakes (Figure 47). We also explored changes over time in NDVI at individual locations (see Figure 48 and Figure 49) and tried to find links between foraging habitat extent and NDVI within individual colony locations (Figure 50).

It seems likely that the annual time scale of the NDVI is inadequate as an indicator of foraging habitat quality. The issue of productivity within foraging habitat should be explored further if finer scale (temporal and spatial) measures of productivity become available.

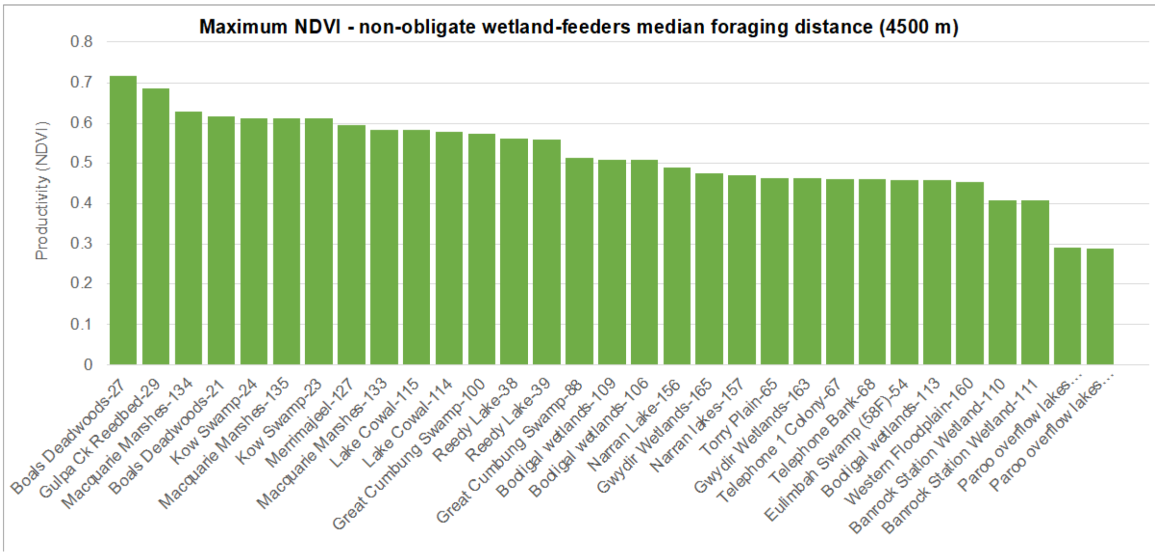

Figure 47. Maximum annual NDVI in the inner foraging zone for non-obligate wetland-feeders at the highest and lowest 15 colony locations.

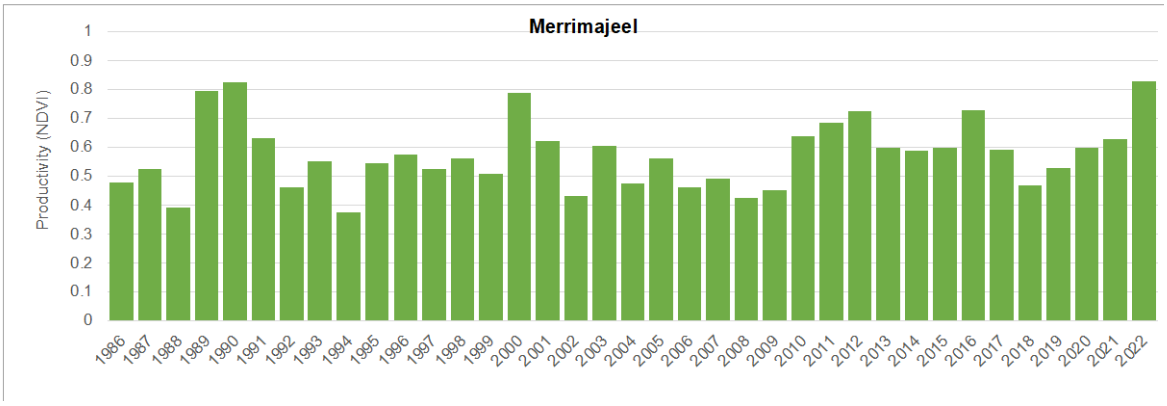

Figure 48. Annual NDVI at the Merrimajeel in the inner foraging zone for non-obligate wetland-feeders 1988 to 2022.

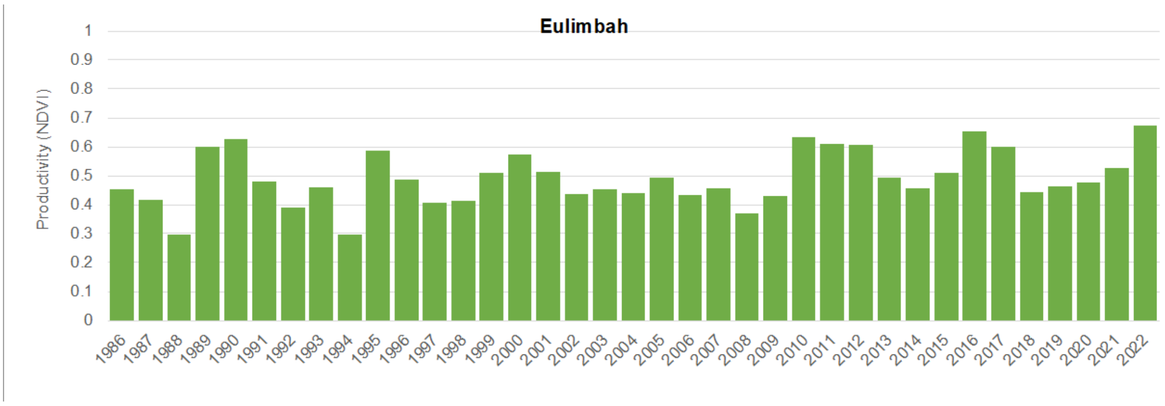

Figure 49. Annual NDVI at Eulimbah (colony 54) in the inner foraging zone for non-obligate wetland-feeders 1988 to 2022.

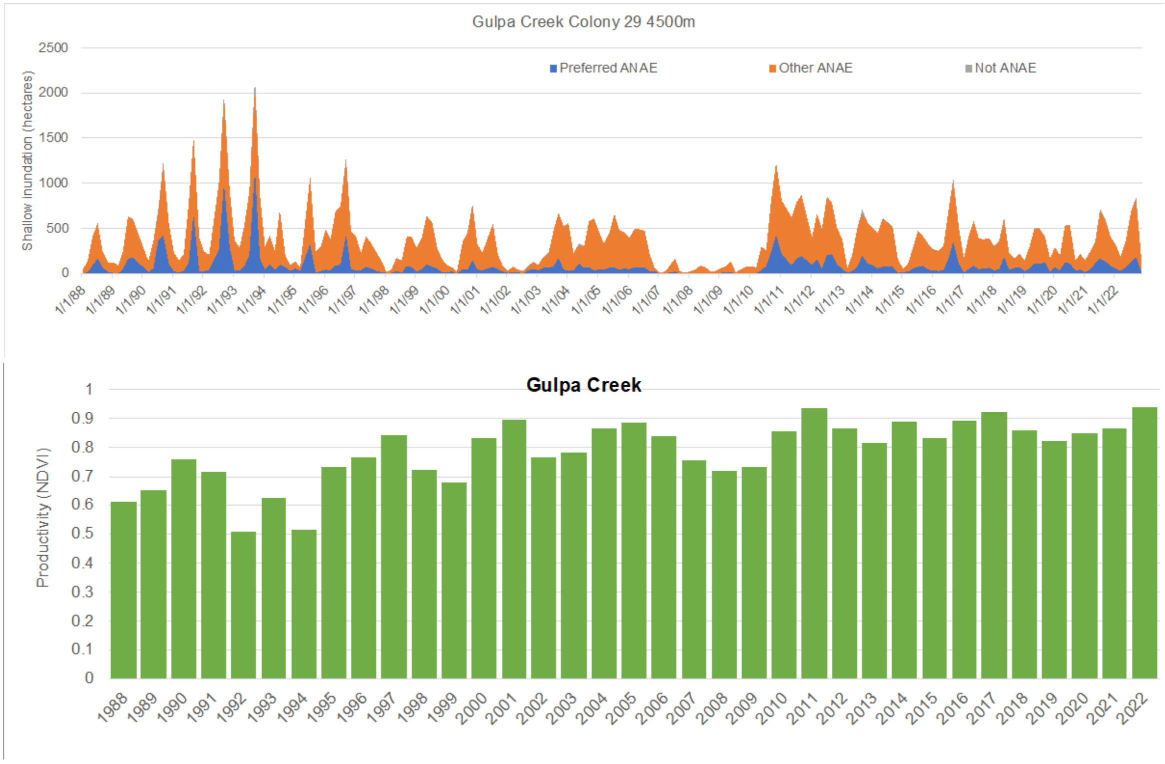

Figure 50. Waterbird foraging habitat (top) and NDVI (bottom) at Gulpa Creek (colony 29) in the inner foraging zone for non-obligate wetland-feeders 1988 to 2022.

5 Priorities for environmental water

5.1 How can mapped foraging habitat help inform environmental water?

The indicators of waterbird foraging habitat around colonies that have sufficient confidence in to inform environmental watering priorities are foraging distance (it is assumed that closer to colony locations is preferred) and ecosystem type (with preferred ANAE types a higher priority than other aquatic ecosystems, and any aquatic ecosystem preferred over non-ANAE inundation). Environmental water for improving the provision of foraging habitat around active colonies should be provided to colonies where delivering additional water is likely to result in increased shallow water habitat immediately during courtship / nest establishment, during breeding or post breeding while young are still present at the site. Priority for environmental water is for the obligate wetland-feeding group as non-obligate species are able to utilise other habitats. This has been explored by considering the duration and extent of foraging habitat in inner foraging zones, in preferred ANAE types on the managed floodplain.

5.1.1 What is the managed floodplain?

The current best estimate of the area of the Basin that is in scope for environmental water management is the Basin-wide watering strategy managed floodplain (MDBA 2019a). The managed floodplain (Figure 51) maps the area where floodplain vegetation can be influenced with the 2075 GL of environmental water under the Basin Plan (MDBA 2019). It includes actively managed areas that can receive environmental water via large headwater storages or via the MDBA's "The Living Murray" 'environmental works' sites on the River Murray floodplain, and passively managed areas that receive environmental water via flow rules in water resource plans or via natural events.

5.1.2 What colonies support foraging habitat in inner zones on the managed floodplain?

The inner foraging zone for obligate wetland-feeders for 54 colony locations has no preferred ANAE shallow water habitat over the 35 year record. This includes a number of lakes in Victoria for which environmental water can be delivered, but that are not captured by the current management floodplain layer such as Winton Wetlands (Lake Mokoan) and the Kerang Lakes system. It also includes a few surprising sites including Booligal Wetlands (colony 109) and Boal's Deadwood (colony 21) (see limitations section 6.1.4). This may reflect the classification of wetland habitats in the ANAE, which for some locations are based on limited data, or inaccuracies in shallow water inundation under dense vegetation.

The remaining 112 colony locations have supported at least one hectare of foraging habitat in the inner foraging zone (Figure 52). This ranges from over 300 hectares at several colonies such as Narran Lakes and the Lowbidgee Floodplain, to < 10 hectares at a number of locations such as Lake Cowal (colony 15) and Kings Billabong (colony 105).

In the inner foraging zone for non-obligate wetland-feeders there is no foraging habitat in mapped ANAE types (preferred or other) for 33 colony locations. There is some preferred ANAE foraging habitat at each of the other colony locations ranging from over 4000 hectares at Narran Lakes to much smaller extents at most colonies (Figure 53).

It is important to note that Figure 52 and Figure 53 are not ranked lists of priorities, they are merely an indication of the potential foraging habitat that could be provided on the managed floodplain near colony locations. There are many other factors that need to be considered when determining priorities for environmental water to support waterbird foraging around breeding colony locations (see section 5.2 below).

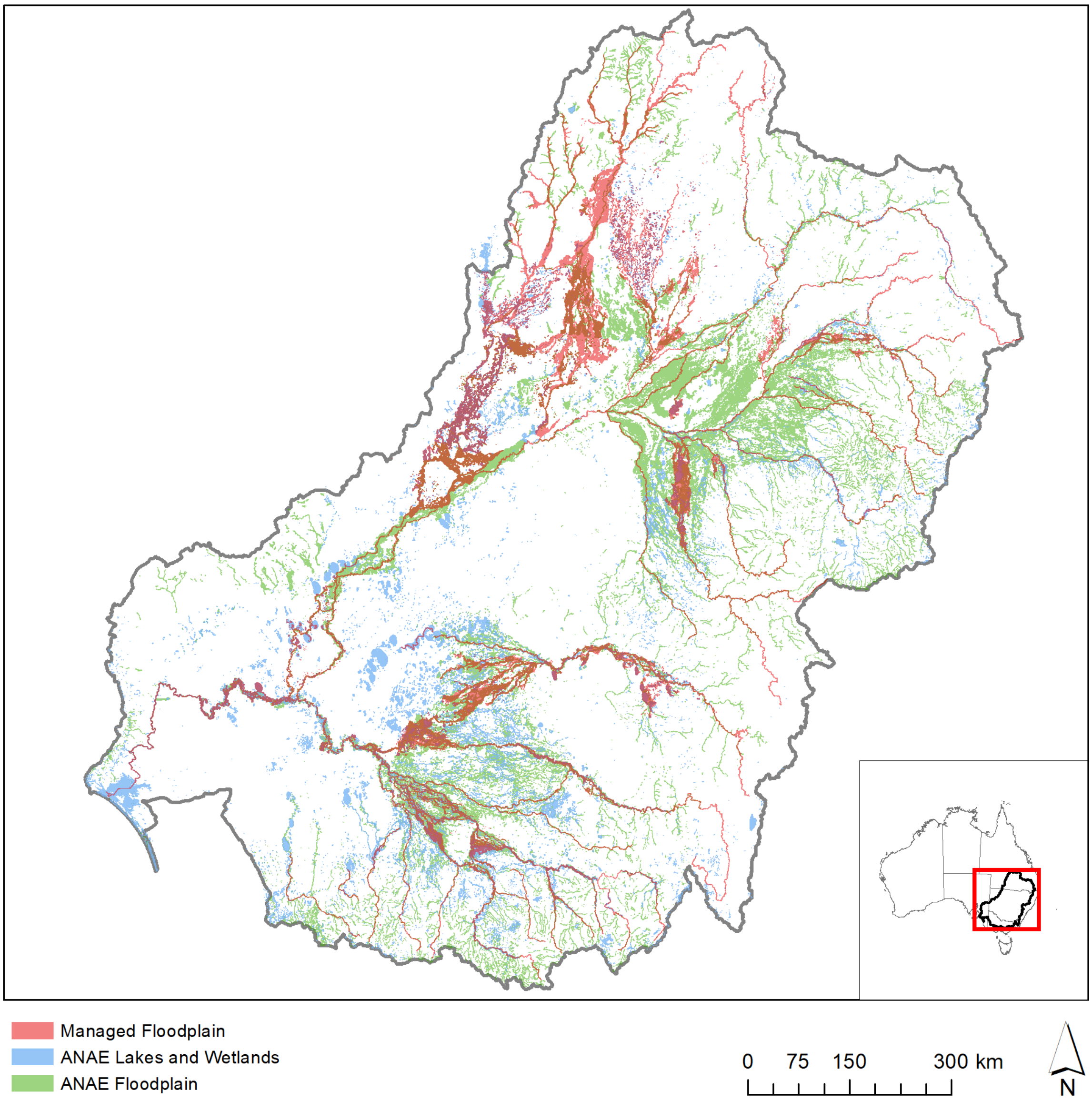

Figure 51. Spatial extent of the Basin-wide watering strategy managed floodplain compared to the extent of ANAE wetland and floodplain ecosystem types.

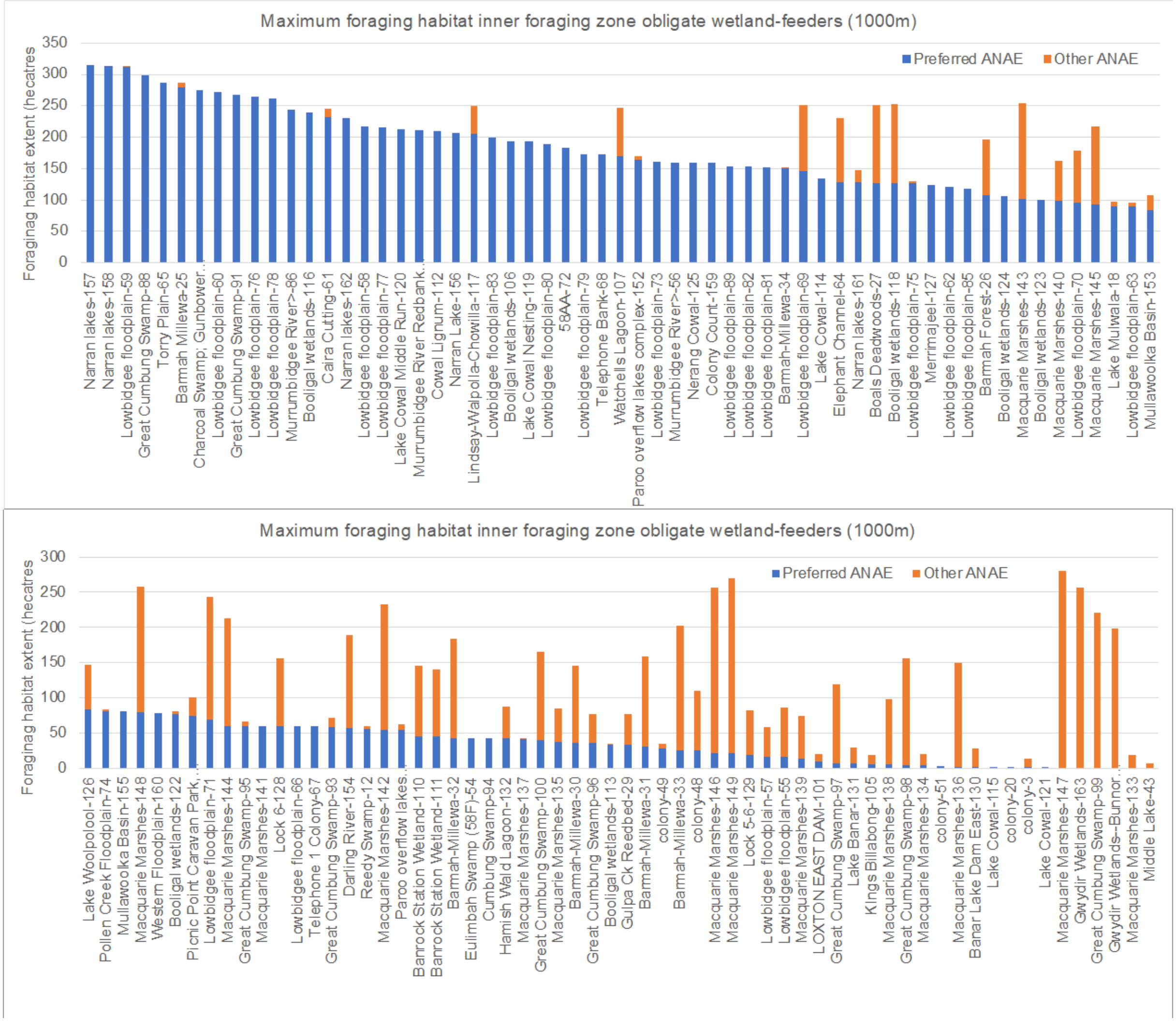

Figure 52. Maximum waterbird foraging habitat extent at colonies on the managed floodplain in the inner zone for the obligate wetland-feeding group from 1988 to 2022.

The maximum extent of foraging habitat on the managed floodplain in mapped ANAE does provide an indication of whether the provision of additional water is likely to result in increased shallow water habitat. For several colony locations, particularly those that are on the margins of lakes, more water may mean greater water depth and no influence, or in fact a reduction in shallow water habitat. For example, the time series of foraging habitat at Reedy Lake (colony 38; Figure 54) illustrates that there is a relatively constant amount of shallow water habitat around the lake margins of around 10 hectares, even during high rainfall years there is little change in the shallow water, making this site an unsuitable candidate for environmental water when the sole watering aim is the provision of foraging habitat (noting that environmental water may still be delivered to maintain breeding habitat).

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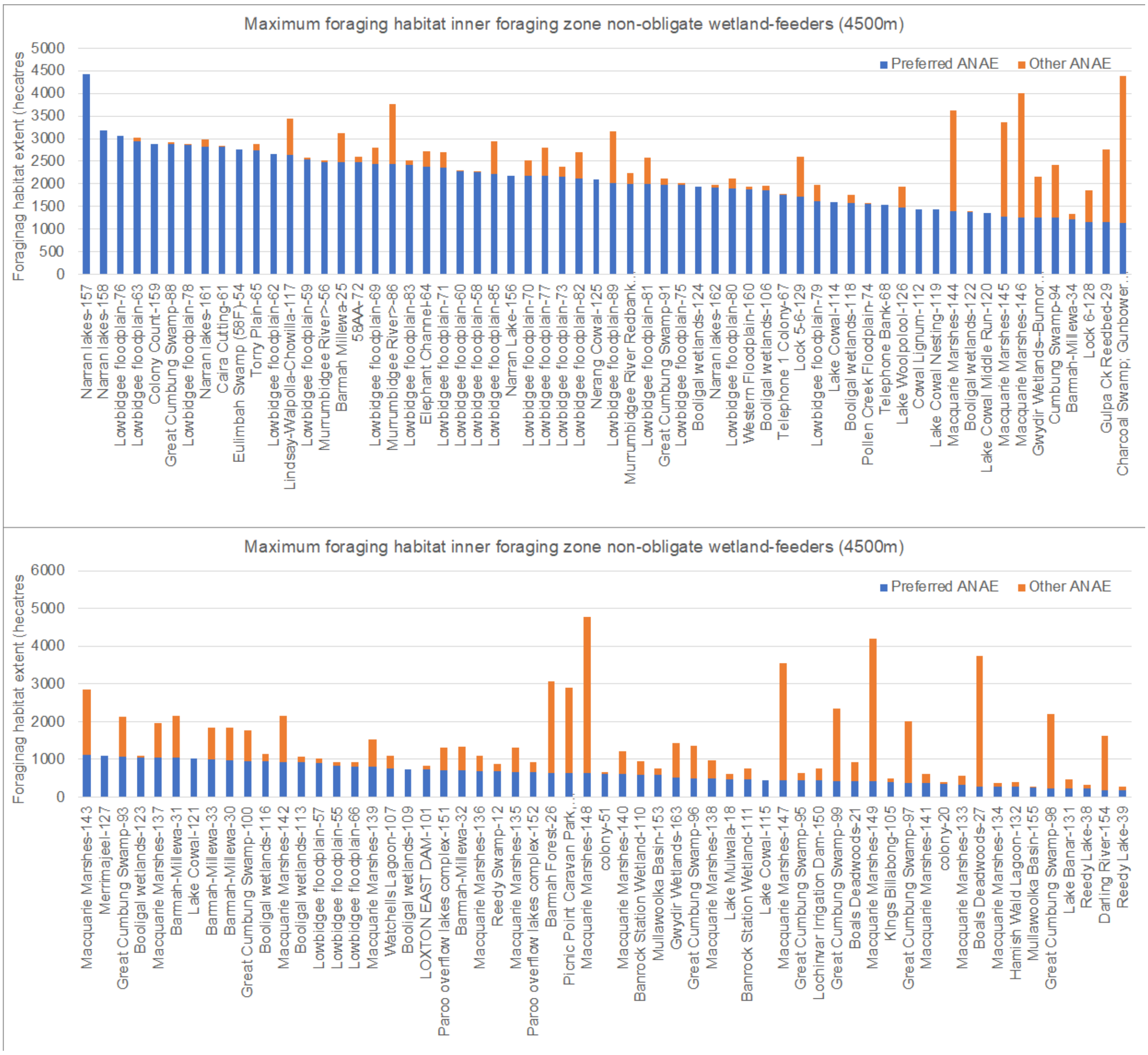

Figure 53. Maximum waterbird foraging habitat extent at colonies on the managed floodplain in the inner zone for the non-obligate wetland-feeding group from 1988 to 2022.

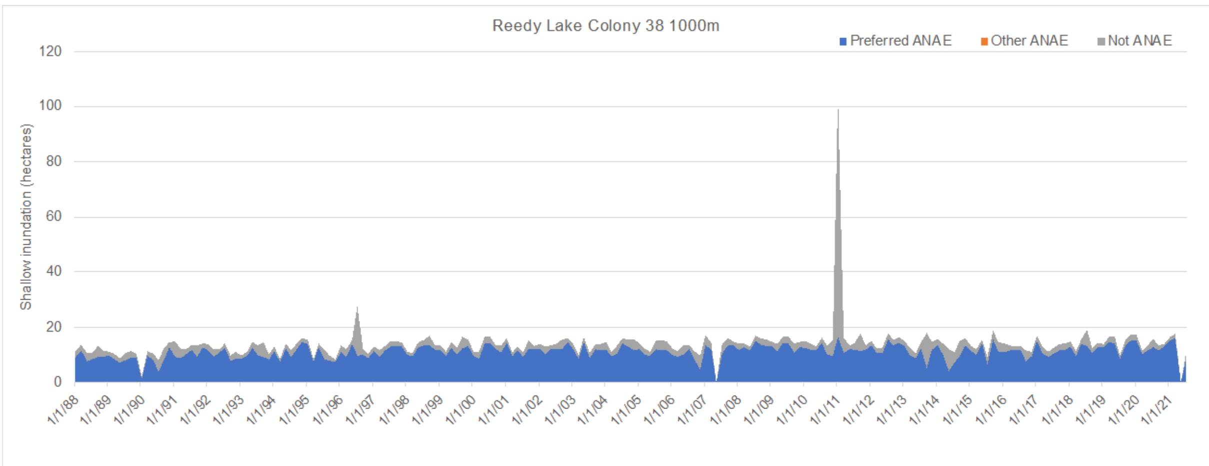

Figure 54. Waterbird foraging habitat extent at Reedy Lake (colony 38) in the inner zone for the obligate wetland-feeding group from 1988 to 2022.

5.2 Considerations for prioritisation of sites

This project has developed a method for identification of foraging habitats for potential management to support waterbirds to complete their whole lifecycle including nesting, raising chicks, and surviving juvenile and sub-adult years through to be coming breeding adults. In summary, it includes the following steps:

A. Define how far birds will likely travel to forage during each nest stage
B. Define preferred foraging habitat characteristics (e.g. ANAE types, water depths)
C. Define manageable foraging habitats (e.g. 'managed floodplain')
D. Map locations of foraging habitats around breeding sites within radii of how far birds will travel to forage, including:
    a. Where are the preferred foraging habitats?
    b. What quality / types are these habitats?
    c. Which locations are within the managed floodplain?
E. Calculate what proportion of the potential foraging areas within radii from breeding sites that preferred foraging habitats occupy
F. Calculate what proportion of foraging habitats are within the managed floodplain
G. Calculate how much potential foraging habitat is present and how much it fluctuates

We suggest the following steps for prioritisation of sites for environmental watering:

H. Compare:
    a. long-term foraging habitat availability within radii of breeding sites
    b. recent and current foraging habitat availability within radii of breeding sites
    c. bird abundance and life cycle stage
I. Select:
    a. Breeding sites currently active with nesting birds – prioritising, in a given year, those with higher abundances
    b. Breeding sites with proportionally less foraging habitat currently available
    c. Breeding sites where foraging habitat declines rapidly or is highly variable
J. Prioritise:
    a. Foraging sites within movement radii
    b. Foraging sites that best meet habitat preferences
    c. Foraging sites that are manageable / waterable
    d. Foraging sites that can be watered with appropriate timing, e.g.
        i. To support late nesting stages when there is demand for food from chicks & adults
        ii. To support juveniles as they learn to feed.

Where managers wish to support foraging sites between breeding events, we suggest prioritisation of:

1. Sites within the same regions as major breeding events
2. Sites within known common movement routes across the Murray-Darling Basin
3. Sites in the Northern Basin, since many species move north for winter
4. Sites that are known drought refugia.

The reasoning behind these steps is that to support waterbird populations long-term, we need to support birds to complete their whole lifecycle – including surviving their juvenile and sub-adult years through to becoming breeding adults. Huge quantities of food are needed for chicks and juveniles as well as their parents, and the further birds have to travel from their nests or roosts to get food, the more energy they waste and the more food they need. If we can ensure that foraging habitats (and food) are provided when and where they are needed, we will be better supporting the whole lifecycle and waterbird population maintenance.

An example of how these steps can be applied more broadly for water planning is presented in Figure 55 and Figure 56.

Antecedent conditions	Current conditions	Forecast conditions
• Wet sequence of years • Multiple large breeding events • Extended breeding seasons • Repeat breeding	• Neutral • Multiple large cohorts of juvenile and sub-adult birds (2-36 months old) needing food • Multiple large cohorts of adult birds rebuilding condition post-nesting needing food	• Drier • Fewer, smaller and shorter breeding events (most likely in the southern basin) - with breeding adults and chicks needing food • Large numbers of juvenile birds and recovering adults from 2023-24 and past seasons needing food

Figure 55. Example 1: water planning considerations for Basin waterbirds and their habitats 2023-24.

Forecast conditions

- Drier
- Smaller, shorter breeding events with adults and chicks needing food (mostly southern basin)
- Multiple large cohorts of naïve juvenile birds from previous and 2023-2024 seasons needing food to survive over the next 3+ years
- Multiple large cohorts of adult breeding birds needing to rebuild body condition

Lifecycle stages:

1. Breeding adults and chicks

- Species
- Locations
- Timing

2. Juveniles and sub-adults (2-36 months)

- Species
- Locations
- Timing

3. Adults post-breeding

- Species
- Locations
- Timing

Support completion of breeding if it occurs

- Species: Colonial nesters or at-risk species
- Locations: Wetlands where breeding starts naturally, operational delivery is feasible, and there is sufficient foraging habitat
- Timing: To final juvenile departures from breeding wetland (species and location dependent), e.g:
  - Royal spoonbills: through summer & autumn
  - Straw-necked ibis: through summer

Support foraging habitats and food abundance

- Species: Prioritise ‘obligate’ shallow wetland feeders e.g. Spoonbills; non-obligates will benefit
- Locations: preferred foraging habitat types, a) in and near active or recently active breeding wetlands; b) MDB flyway wetlands; c) northern basin wetlands
- Timing: the autumn and winter post-breeding; during and within first three years of breeding events; stagger watering of different wetlands over time to maximise productivity and foraging opportunities; include some watering in autumn, winter and spring where possible

Figure 56. Example 2 - water planning considerations for Basin waterbirds and their habitats 2023-24.

6 Limitations and recommendations

There are several significant limitations with the method as applied in this development trial that result in low confidence in the mapped outputs. Most of these will be addressed with improved data in the future.

6.1.1 Colony locations

Spatially representing colony locations was limited due to several factors. Aerial survey data is often attributed to single point locations within large wetland complexes. For example, nest and brood counts from the aerial surveys of the Macquarie Marshes are attributed to a single centroid coordinate that does not reflect where the colonies are located. Similarly, for breeding records in the ALA, the location recorded is more likely to be where the observer was standing (or parked their vehicle) than the actual location of the observed nest or bird. Colony coordinates in the dataset compiled by Hale et al. (2023) may be inaccurate by anywhere from a few metres to over 50 km. This is because a few breeding colony observations are assigned to the centroid of a wetland complex (rather than the true breeding colony latitude and longitude).

Initially the project team undertook a process of manually moving colony locations from the data set to where local knowledge suggest that they would be. This process, however, was abandoned as it would have made the method presented here unrepeatable.

Recommendation: We suggest refining and reviewing data and observations to produce a more accurate and validated spatio-temporal dataset of true colony locations.

6.1.2 Breeding records

We attempted to explore the differences in the extent and duration of foraging habitat around active breeding colonies compared to when there was no breeding occurring. The data, however, proved insufficient for this task. The authors are aware of many breeding events that are missing from the data set complied from the sources used in this project. These breeding events are often documented in unpublished reports or are simply expert knowledge and are not represented in public databases. It would be useful to collate these records to explore potential relationships between foraging habitat extent or quality to breeding event occurrence, initiation, completion, or size.

Recommendation: We suggest a project to review all available literature, published and unpublished, together with an expert knowledge survey, to compile a validated and peer-reviewed database of breeding records matched to true colony locations over time.

6.1.3 Summarising over many years vs examining individual events

It has been suggested that when the data is summarised over many years, insights into the relative importance of particular breeding sites and patterns of inundation around them during small vs large inundation events and small vs large breeding events may be lost. Some sites do not have active breeding very often because of huge changes in flows and habitat availability (e.g. the Gwydir, for which the only breeding event records in last ten years were 2011/12 before the more recent 2021/22 and 2022/23 breeding. Because they are so variable in flows, the average area of shallow water habitat over several decades may not capture links between large flood events and breeding events. In addition, care needs to be taken regarding using maximum inundation area to represent foraging habitat availability for the entire breeding event. This is because inundation area may change rapidly during different breeding stages.

Recommendation: In future, it would be useful to extract test case years and/or sites selected by local water managers, to identify areas inundated around various breeding events and implications for foraging habitat availability and quality. The 2010-2022 period has been suggested, for which there is detailed data on flows and breeding and during which environmental water has been frequently used to support waterbirds. Selecting years with large flows or inundation events may also be useful.

6.1.4 Shallow water mapping

Our measurement of shallow water foraging habitat area can be an underestimate because we are not able to reliably distinguish the places or times when persistent cloud cover or satellite image artefacts prevent mapping of surface water. The inundation depth mapping includes areas of steep or elevated terrain that are consistently designated 'No Data' across most dates. Where these occur within foraging zones they can be treated as 'zero depth' as these areas are unlikely to pond or hold flood waters (e.g. the hills to the east of Narran Lakes, Figure 57). In these cases, our measurement of shallow water foraging habitat is unaffected by the missing data. In contrast, many dates also have transient patches of 'No Data' that occur in locations where cloud cover or satellite imaging artefacts persist for the duration of the two-month measuring period (e.g. west and east of Narran Lakes in Figure 58). In these obscured areas there may be significant surface water present that is not mapped, and our measured foraging habitat will be an under-estimate. We were not able to adjust our estimate for cloud cover because we have no way of differentiating cloud cover from the dry elevated terrain scenario shown in Figure 57.

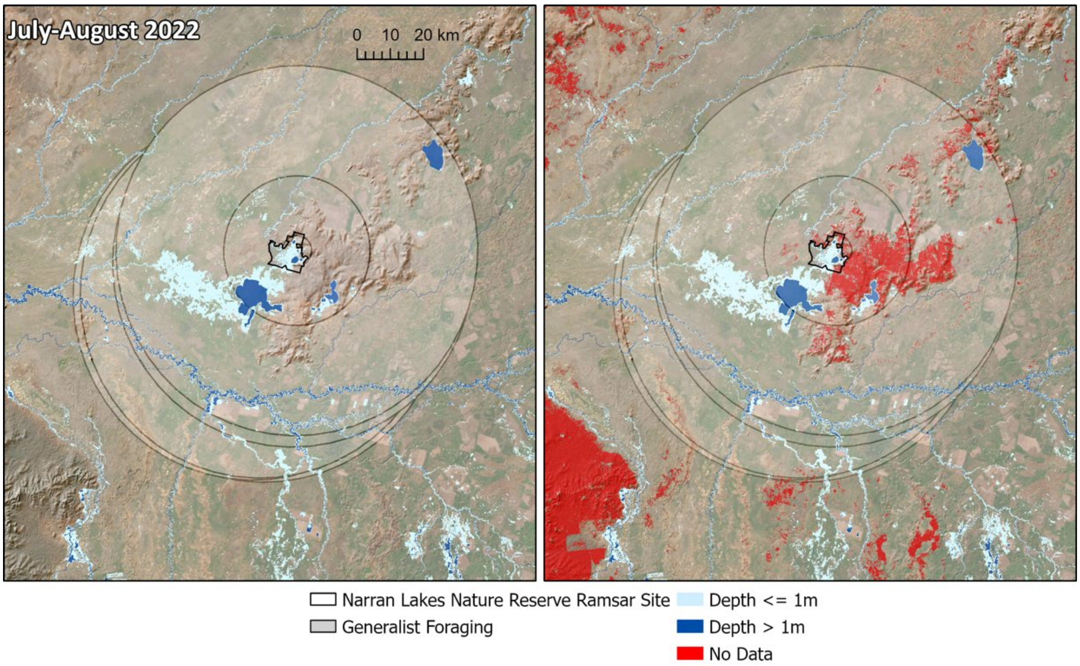

Figure 57. CSIRO two-montly inundation to 1 July 2022. The left image shows elevated terrain to the east and southwest of Narran Lakes that is consistently masked as “No Data” across multiple dates (right image).

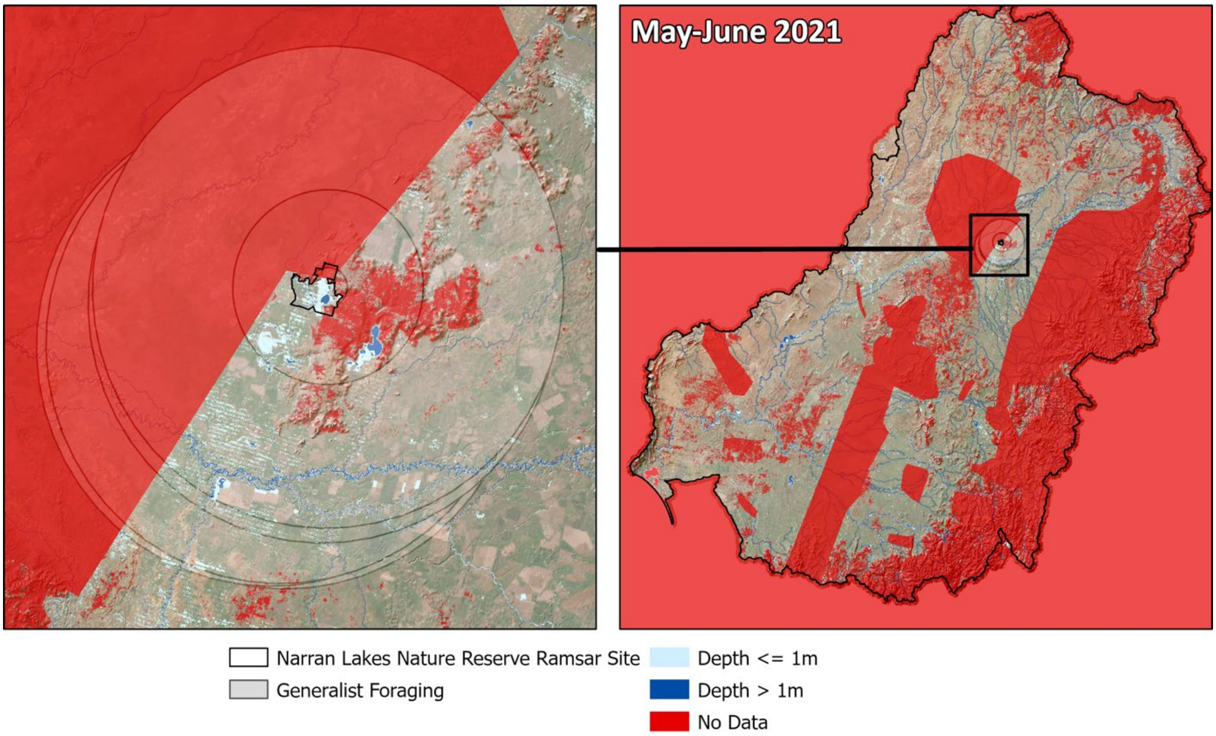

Figure 58. CSIRO two-montly inundation to 1 May 2021 showing the extent of ‘No Data’ in regions with cloud cover or imaging artefacts that persist for the two-month sampling interval required to generate each map; also in areas of steep or elevated terrain, and areas outside of the Basin.

The CSIRO two-monthly maximum flood water depth spatial timeseries for the MDB is a new data set that facilitates exploration of spatial patterns in water depth at spatial scales that was not practical previously. We observed that the depth extent mapping under-represented densely vegetated wetland areas that are often preferred sites for waterbird breeding. This was particularly evident in the Macquarie Marshes and in the Booligal Wetlands (Figure 59). The problem of vegetation obscuring detection of water from satellites is a recurring issue with remote sensed mapping of water. In developing their Wetland Insights Tool (WIT), Geoscience Australia recognised a similar limitation in the Digital Earth Australia Water Observations from Space mapping, and augmented the WIT with a Tasseled-Cap Wetness index specifically to quantify the extent of water underlying vegetation (Dunn et al. 2019). The CSIRO flood extent mapping employs a similar approach using CSIRO’s Multi-Index Mapping (MIM) that allocates the best performing water index from a panel that includes Tasseled-Cap Wetness, with an aim of providing more accurate inundation mapping under different contexts (Ticehurst et al. 2022). Our observations suggest there is some scope to fine tune the water extent mapping to improve detection of water in vegetated wetlands where waterbirds commonly breed.

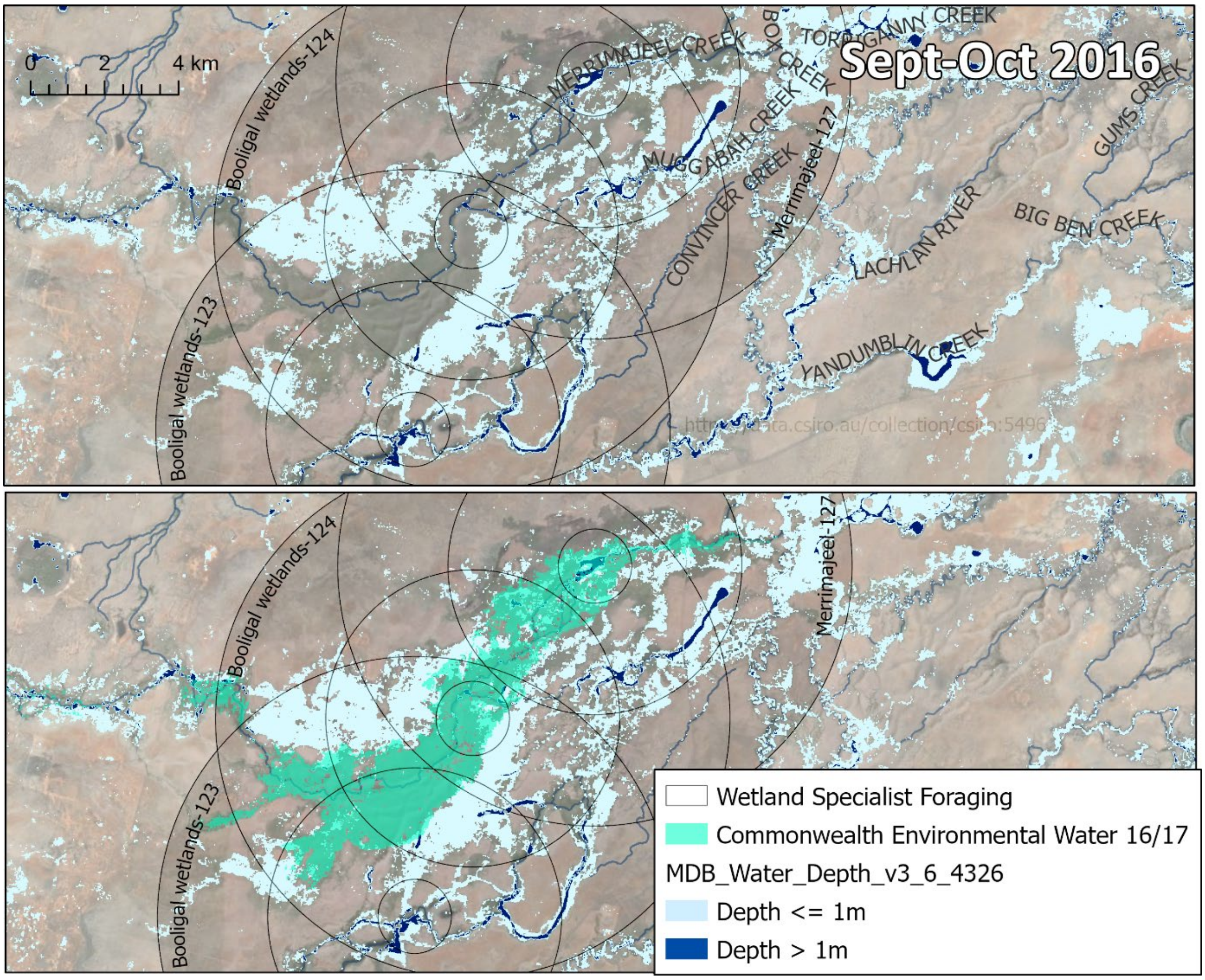

Figure 59. Shallow water extent in the core waterbird breeding habitat along Merrimajeel Creek in the Booligal Wetlands is under represented in the two-monthly maximum flood depth mapping. Inundation of flows containing Commonwealth environmental water mapped during the same period show these areas as flooded.

Recommendation: In identified wetlands where inundated vegetations is underrepresented , review the calibration of the CSIRO MIM method indices used in these particular locations. A correction to the extent mapping could then be integrated into the flood depth mapping when it is next generated. A direct comparison of water extent measured by Geosciences WIT tool and the MIM extent for individual ANAE polygons could identify specific areas to investigate further.

Recommendation: We suggest incorporation of new shallow water mapping products into this method as they become available. We also suggest that results of this method always be checked by experts with local knowledge of flooding patterns in and around dense vegetation.

6.1.5 Foraging distance radii

The statistics used to define foraging distance radii in development of this method are sourced from recent research by CSIRO using satellite tracking (McGinness et al. in prep.; McGinness et al. 2019; funded by CEWH as part of their Monitoring, Evaluation and Research program). This research is ongoing, and with new data collection is producing new statistics that are more robust, based on larger sample sizes of more nesting events within and across species and breeding sites.

Recommendation: These new statistics should be incorporated into any future iteration of this method or approach. This will be particularly important for the obligate wetland-feeders, which at the time of this current project were based on relatively small sample sizes.

In the current project, foraging flight distances associated with the immobile chick phase were selected as the most appropriate because this phase is the most vulnerable and requires foraging habitat and food to support both growing chicks and adults, and it is also the phase for which the most robust data were available for calculation of statistics.

Recommendation: In future, we suggest using 'overall' distance statistics describing entire nesting events, unless watering is specifically targeted to a particular nesting stage.

Recommendation: Together with use of new foraging radii statistics as described above, it will be important to emphasise that watering of wetlands in a wider radius than the closest radii explored here will also have value, as that is how water managers will likely identify sites additional to breeding sites to target with e water or other management intervention. It may be possible to explore cost/benefit analysis to identify sites to target management decisions within these wider radii.

Provision of environmental water to increase foraging habitat for later stages (one to three years) to ensure recruitment was identified as a priority by environmental water managers. While this was beyond what could be achieved in this current project, it represents an area of potential future research and one for which an application of a method similar to that developed here could potentially be applied.

Recommendation: There could be opportunities to adapt the method to assist in identifying watering priorities for recruitment of juveniles and subadults into the breeding program when larger sample size statistics are available. We recommend that such an approach could include consideration of: a) the length of time that juveniles remain near colony locations where they hatched, where they forage, and if foraging habitat availability influences dispersal away from the area; and b) where juveniles are most likely to forage during and after dispersal, and if there are locations in the Basin that are regularly visited and could be targeted with environmental water to improve foraging habitat and food availability at key times.

7 References

Arthur, A.D., Reid, J.R.W., Kingsford, R.T., McGinness, H.M., Ward, K.A., and Harper, M.J. (2012). Breeding Flow Thresholds of Colonial Breeding Waterbirds in the Murray-Darling Basin, Australia. Wetlands 32(2): 257–265.

Barker, R.D. and Vestjens, W.J.M. (1990). The food of Australian birds 2. Passerines. CSIRO PUBLISHING.

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

Bino, G., Steinfeld, C., and Kingsford, R.T. (2014). Maximizing colonial waterbirds' breeding events using identified ecological thresholds and environmental flow management. Ecological Applications 24(1): 142–157.

Boulton, A.J. and Brock, M.A. (1999). Australian freshwater ecology : processes and management / Andrew J. Boulton, Margaret A. Brock. Gleneagles Publishing, Mt Osmond, S. Aust. :

Brandis, K. (2010). Colonial waterbird breeding in Australia: Wetlands, water requirements and environmental flows. University of NSW.

Brandis, K.J., Spencer, J., Wolfenden, B., and Palmer, D. (2020). Avian-botulism risk in waterbird breeding colonies and implications for environmental water management. Marine and Freshwater Research 71(2): 179–190. CSIRO.

Brooks, S. (2021). Australian National Aquatic Ecosystem (ANAE) Classification of the Murray-Darling Basin v3.0. Commonwealth Environmental Water Office, Department of Agriculture, Water and the Environment, Australia., Canberra, Australia. Available at: http://www.environment.gov.au/fed/catalog/search/resource/details.page?uuid=%7B9A26F3E7-DDE4-483B-A85C-06F9DF663124%7D. Last accessed 16 May 2023.

Butler, R.W. (1994). Population regulation of wading Ciconiiform birds. Colonial Waterbirds: 189–199. JSTOR.

Carrick, R. (1959). The food and feeding habits of the Straw-necked Ibis, *Threskiornis spinicollis* (Jameson), and the White Ibis, *T. molucca* (Cuvier) in Australia. CSIRO Wildlife Research 4(1): 69–92. CSIRO Publishing.

Carrick, R. (1962). Breeding, movements and conservation of ibises (Threskiornithidae) in Australia. CSIRO Wildlife Research 7(1): 71–88. CSIRO Publishing.

DELWP. (2016). Guidelines for Assessing the Impact of Climate Change on Water Supplies in Victoria. Department of Environment, Land, Water and Planning, Melbourne, Victoria.

DOE. (2017). Catchment Scale Land Use of Australia 2017. Australian Government Department of Environment.

Dutson, G., Garnett, S., and Gole, C. (2009). Australia's Important Bird Areas: Key sites for conservation. Birds Australia.

Garnett, S.T., Duursma, D.E., Ehmke, G., Guay, P.-J., Stewart, A., Szabo, J.K., Weston, M.A., Bennett, S., Crowley, G.M., and Drynan, D. (2015). Biological, ecological, conservation and legal information for all species and subspecies of Australian bird. Scientific data 2(1): 1–6. Nature Publishing Group.

Geering, D.J. (1993). The effect of drought-breaking rain on the re-establishment of egret colonies in north coastal New South Wales. Corella 17: 47–51.

Geering, D.J., Maddock, M., Cam, G.R., Ireland, C., Halse, S.A., and Pearson, G.B. (1998). Movement patterns of Great, Intermediate and Little Egrets from Australian breeding colonies. Corella 22: 37–45. Australian Bird Study Association.

Hale, J., Bond, N., Brooks, S., Capon, S., Grace, M., Guarino, F., James, C., King, A., McPhan, L., Mynott, J., Stewardson, M., and Thurgate, N. (2020). Murray–Darling Basin Long Term Intervention Monitoring Project — Basin Synthesis Report. Report prepared for the Agriculture, Water and

the Environment, Commonwealth Environmental Water Office. Centre for Freshwater Ecosystems, Latrobe University, Albury, NSW.
Hale, J., Brooks, S., Campbell, C., and McGinness, H. (2023). Assessing Vulnerability for use in Determining Basin-scale Environmental Watering Priorities. A Report to the Commonwealth Environmental Water Office. Canberra, ACT.
Hale, J. and Butcher, R. (2011). Ecological Character Description for the Barmah Forest Ramsar Site. Department of Sustainability, Environment, Water, Population and Communities, Canberra.
Herring, G. and Gawlik, D.E. (2013). Differential physiological responses to prey availability by the great egret and white Ibis. The Journal of wildlife management 77(1): 58–67. Wiley Online Library.
Herring, G., Gawlik, D.E., Cook, M.I., and Beerens, J.M. (2010). Sensitivity of nesting Great Egrets (*Ardea alba*) and White Ibises (*Eudocimus albus*) to reduced prey availability. The Auk 127(3): 660–670. Oxford University Press.
Jaensch, R. (2002). Ecological Requirements and Guilds of Waterbirds Recorded at the Menindee Lakes System, NSW. Wetlands International Oceanica.
Karikkudy, J.K. (2011). Seasonal and interannual variability of NDVI and waterbird abundance and diversity in Fuente de Piedra Lagoon, Spain. Master's Thesis, University of Twente.
Kingsford, R., Bino, G., Porter, J., and Brandis, K. (2014). Waterbird Communities in the Murray-Darling Basin, 1983-2012. Australian Wetlands, Rivers and Landscapes Centre, University of New South Wales, Canberra, ACT.
Kingsford, R.T., Curtin, A.L., and Porter, J. (1999). Water flows on Cooper Creek in arid Australia determine 'boom' and 'bust' periods for waterbirds. Biological Conservation 88(2): 231–248.
Kingsford, R.T. and Norman, F.I. (2002). Australian waterbirds — products of the continent's ecology. Emu 102(1): 47–69.
Kingsford, R.T., Roshier, D.A., and Porter, J.L. (2010). Australian waterbirds – time and space travellers in dynamic desert landscapes. Marine and Freshwater Research 61(8): 875–884.
Leigh, C., Sheldon, F., Kingsford, R.T., and Arthington, A.H. (2010). Sequential floods drive 'booms' and wetland persistence in dryland rivers: a synthesis. Marine and Freshwater Research 61(8): 896–908. CSIRO.
Leslie, D.J. (2001). Effect of river management on colonially-nesting waterbirds in the Barmah-Millewa forest, south-eastern Australia. Regulated Rivers: Research & Management 17(1): 21–36.
Lowe, K.W. (1982). Feeding behaviour and diet of royal spoonbills *Platalea regia* in Westernport Bay, Victoria. Emu 82(3): 163–168. CSIRO Publishing.
Marchant, S. and Higgins, P.J. (1990). Handbook of Australian, New Zealand and Antarctic birds Part A, Vol. 1. Ratites to ducks. Oxford Univ. Press, Melbourne.
Maslo, B., Burger, J., and Handel, S.N. (2012). Modeling foraging behavior of piping plovers to evaluate habitat restoration success. The Journal of Wildlife Management 76(1): 181–188. Wiley Online Library.
McGinness, H. (2016). Waterbird responses to flooding, stressors and threats. A literature review prepared for the Murray–Darling Freshwater Research Centre as part of the Environmental Water Knowledge and Research Project. CSIRO, Canberra, ACT.
McGinness, H., Brandis, K., Robinson, F., Piper, M., O'Brien, L., Langston, A., Hodgson, J., Wenger, L., Martin, J., Bellio, M., Callaghan, D., Webster, E., Francis, R., McCann, J., Lyons, M., Doerr, V., Kingsford, R., and Mac Nally, R. (2019). Murray–Darling Basin Environmental Water Knowledge and Research Project Waterbird Theme Research Report. Centre for Freshwater Ecosystems, Latrobe University, Albury, NSW.
MDBA. (2018). Icon site condition: The Living Murray. Murray-Darling Basin Authority, Canberra, ACT.
MDBA. (2019a). Basin-wide environmental watering strategy. Australian Government, Canberra, ACT.
MDBA. (2019b). BWS waterbird areas based on UNSW Waterbird survey areas (MDBA_2019_polygons.shp). Unpublished data set provided by the Murray-Darling Basin Authority. Last accessed 2 November 2020.

Mott, R., Prowse, T.A., Jackson, M.V., Rogers, D.J., O'Connor, J.A., Brookes, J.D., and Cassey, P. (2023). Measuring habitat quality for waterbirds: A review. Ecology and Evolution **13**(4): e9905. Wiley Online Library.

Murray, C.G., Loyn, R.H., Kasel, S., Hepworth, G., Stamation, K., and Hamilton, A.J. (2012). What can a database compiled over 22 years tell us about the use of different types of wetlands by waterfowl in south-eastern Australian summers? Emu - Austral Ornithology **112**(3): 209–217.

O'Connor, P. and Ward, K. (2003). Waterbird Monitoring in Barmah Forest, 2002-2003. Department of Sustainability and Environment, Tatura, Victoria.

Office of Environment and Heritage. (2012). Macquarie Marshes Ramsar Site: Ecological Character Description Macquarie Marshes Nature Reserve and U-block Components. Office of Environment and Heritage, Sydney, NSW.

Paton, D.C., Bailey, C.P., and Northeast, P.J. (2011). Waterbird responses to Goolwa Channel water-level management and Barrage releases, and developing habitat suitability models for waterbirds in the Coorong and Lower Lakes. University of Adelaide, Adelaide, SA.

Recher, H.F., Holmes, R.T., Davis Jr, W.E., and Morton, S. (1983). Foraging behavior of Australian herons. Colonial Waterbirds: 1–10. JSTOR.

Reid, J., Arthur, T., and McGinness, H.M. (2009). Waterbirds. *In* Ecological Outcomes of Flow Regimes in the Murray-Darling Basin. Report prepared for the National Water Commission by CSIRO Water for a Healthy Country Flagship. *Edited by* I. Overton, M.J. Colloff, T.M. Doody, B. Henderson, and S. Cuddy. CSIRO, Canberra.

Reid, J.R.W., Colloff, M.J., Arthur, A.D., and McGinness, H.M. (2013). Influence of Catchment Condition and water resource development on waterbird assemblages in the Murray-Darling Basin, Australia. Biological Conservation **165**: 25–34.

Rodgers Jr, J.A. and Schwikert, S.T. (2002). Buffer-zone distances to protect foraging and loafing waterbirds from disturbance by personal watercraft and outboard-powered boats. Conservation Biology **16**(1): 216–224. Wiley Online Library.

Roshier, D.A., Robertson, A.I., and Kingsford, R.T. (2002). Responses of waterbirds to flooding in an arid region of Australia and implications for conservation. Biological Conservation **106**(3): 399–411. Elsevier.

Stolen, E.D. (2003). The effects of vehicle passage on foraging behavior of wading birds. Waterbirds **26**(4): 429–436. BioOne.

Taylor, I.R. and Taylor, S.G. (2015). Foraging habitat selection of Glossy Ibis (*Plegadis falcinellus*) on an Australian temporary wetland. Waterbirds **38**(4): 364–372. BioOne.

Teng, J., Penton, D., Ticehurst, C., Sengupta, A., Freebairn, A., Marvanek, S., King, D., and Pollino, C. (2023). Two-monthly Maximum Flood Water Depth Spatial Timeseries for the MDB. CSIRO.

Vestjens, W.J.M. (1975). Feeding behaviour of spoonbills at Lake Cowal, NSW. Emu **75**(3): 132–136. CSIRO Publishing.

Ward, K. (2014). Colonial waterbird breeding in Barmah–Millewa Forest and the use of environmental water. Goulburn Broken CMA, Shepparton.

Wassens, S., Poynter, C., Brooks, S., and McGinness, H. (2021). Basin-scale evaluation of 2019–20 Commonwealth environmental water: Species Diversity. Flow-MER Program. Commonwealth Environmental Water Office (CEWO): Monitoring, Evaluation and Research Program, Department of Agriculture, Water and the Environment, Australia. 104pp.

Wen, L., Macdonald, R., Morrison, T., Hameed, T., Saintilan, N., and Ling, J. (2013). From hydrodynamic to hydrological modelling: Investigating long-term hydrological regimes of key wetlands in the Macquarie Marshes, a semi-arid lowland floodplain in Australia. Journal of Hydrology **500**: 45–61.

Wen, L., Saintilan, N., Reid, J.R., and Colloff, M.J. (2016). Changes in distribution of waterbirds following prolonged drought reflect habitat availability in coastal and inland regions. Ecology and evolution **6**(18): 6672–6689.

Yates, M.G., Goss-Custard, J.D., McGrorty, S., Lakhani, K.H., Durell, S.L.V.D., Clarke, R.T., Rispin, W.E., Moy, I., Yates, T., and Plant, R.A. (1993). Sediment characteristics, invertebrate densities and shorebird densities on the inner banks of the Wash. Journal of Applied Ecology: 599–614. JSTOR.