Environmental benefits assessment – Waterbirds

Project area – Yarrawonga to Wakool reach of the Murray River

Final report

June 2022

Compiled by: Bino, G., Spencer. J., Brandis, K., and Thomas, R. (2022). *Environmental benefits assessment – Waterbirds. Phase 2 – Project area Yarrawonga to Wakool reach of the Murray River.* Final report. June 2022. Prepared by University of New South Wales and NSW Department of Planning and Environment for the NSW Reconnecting River Country Program.

Acknowledgements: We acknowledge Yorta Yorta Nation and Bangerang People as traditional owners and custodians of the Barmah-Millewa Forest, and the Barapa Barapa people and Yorta Yorta Nation as traditional owners of the Gunbower-Koondrook-Perricoota Forests and surrounding country. We pay respect to Elders past, present and future and acknowledge their deep cultural, social, environmental, spiritual and economic connection to their lands and waters. We also recognise the unique, diverse and enduring knowledge of First Nations peoples.

This project was funded by the *Reconnecting River Country Program* coordinated by the NSW Government.

Richard Kingsford and John Porter (UNSW) provided aerial survey data for the Barmah-Millewa Forest and Gunbower-Koondrook-Perricoota Forests. These aerial surveys were funded through Murray-Darling Basin Authority (MDBA) programs including the Basin-wide *Targeted Wetland Survey* and *Specified Environmental Asset* program, and *The Living Murray* Program. The Living Murray is a joint initiative funded by the New South Wales, Victorian, South Australian, Australian Capital Territory and Commonwealth governments, coordinated by the Murray–Darling Basin Authority (MDBA). Waterbird ground surveys in Barmah-Millewa Forest were undertaken by many people including David Leslie (NSW Forestry Corporation), Rick Webster (NPWS/ Ecosurveys), Alison Borrell (NPWS/ Forests and Floodplains), Lachlan Webster (Ecosurveys), Alex Wilkinson (Ecology and Heritage Partners) through funding from *The Living Murray Program* coordinated by NSW National Parks and Wildlife Service (NPWS), and previous NSW Forestry Corporation (FCNSW) managed monitoring programs. Keith Ward (Goulburn-Broken Catchment Management Authority) also shared colonial waterbird records for Barmah-Millewa Forest. Our thanks also to the MDBA and Jean Dind (FCNSW) for providing waterbird monitoring data for Koondrook-Perricoota Forest collected as part of *The Living Murray* initiative.

We thank Carmen Amos, Cristina Venables, Samantha Dawson, Jessica Heath, Amelia Walcott, Thomas Job, Markus Bauerle and Nick Streeton (DPE) for providing project support. Our thanks also to Paul Childs, James Dyer, Mark Henderson (DPE), Keith Ward, Tim Barlow (GBCMA), Jean Dind (FCNSW), Wil Allen (NPWS) and Alison Borrell (Murray-Darling Wetlands Working Group) who provided feedback on the content and results contained in this report in late March 2022.

Cover image: *Aerial view of Reedbed Swamp in Millewa Forest with nesting ibis* (Credit: R. Francis, UNSW, February 2021).

Executive Summary

The Waterbird Environmental Benefits Assessment (EBA) project is part of the NSW *Reconnecting River Country Program* which aims to improve wetland and floodplain connectivity in southern NSW. The EBA project is focused on the River Murray and Murrumbidgee River systems. In this report we assessed the likely benefits to waterbirds from relaxed constraint options in the Murray River System between Yarrawonga and Wakool only. Results for the Murrumbidgee system are presented in a separate report.

We used available aerial and ground survey data to model waterbird responses (species richness, abundance and colonial waterbird breeding activity) to river flows and inundated area in Barmah-Millewa Forest and Gunbower-Koondrook-Perricoota Forest in the Mid-Murray. Both wetland areas are important waterbird areas in the Murray-Darling Basin and are recognised internationally under the Ramsar Convention.

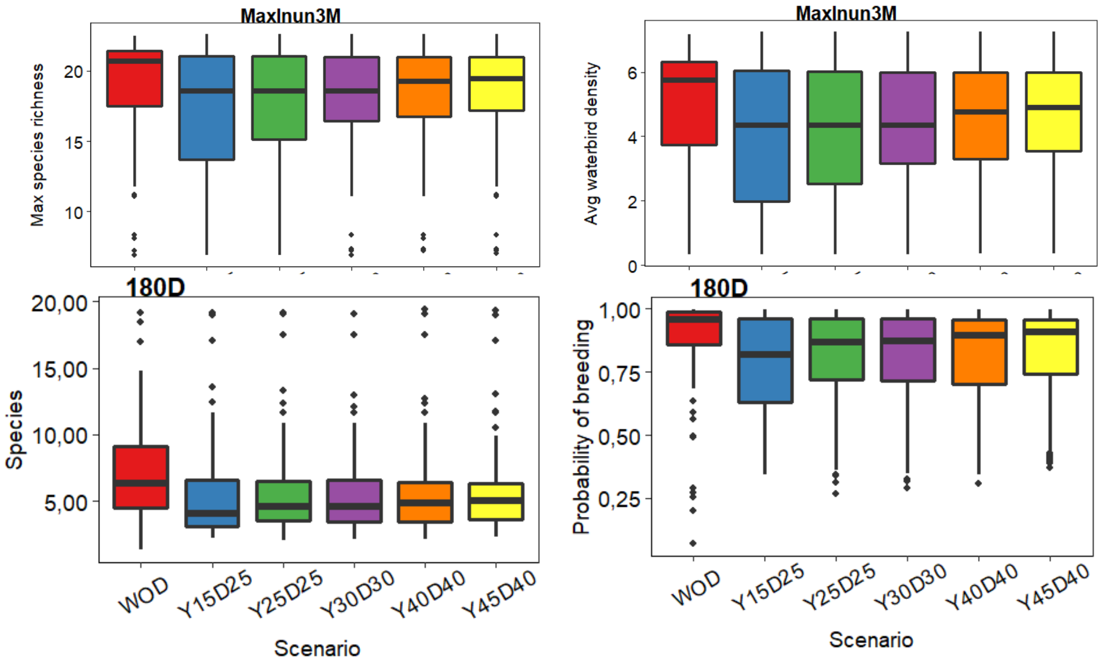
Ground survey data was used to develop predictions of waterbird species richness and waterbird abundance (represented as waterbird density) in Barmah-Millewa Forest. Aerial survey data was used to develop predictions of waterbird species richness and total waterbird abundance for Gunbower-Koondrook-Perricoota Forest. A combination of all records (including aerial and ground survey data) was used to compile presence/absence data for colonial waterbird breeding in Barmah-Millewa Forest. Expected benefits for waterbirds where then assessed for each of the flow scenarios based on the best flow predictor variable determined from the observed data. These were compared to both the base case (or current constraints) and without development scenarios to determine the relative benefits of the four relaxed constraint flow scenarios.

The best predictors of waterbird responses in Barmah-Millewa Forest were maximum inundated area and cumulative river flows 180 days prior to spring. We linked the modelled inundated and flow data for each constraint to predicted waterbird responses in Barmah-Millewa Forest. Compared to current constraints there were small increases in median waterbird species richness (4-5%) and waterbird density (10-13%) in Barmah-Millewa Forest for the highest relaxed constraint scenarios of 40,000 and 45,000 ML/day downstream of Yarrawonga Weir. The probability of colonial waterbird breeding in Barmah-Millewa Forest also increased for all relaxed constraint scenarios compared to current constraints from a 6%

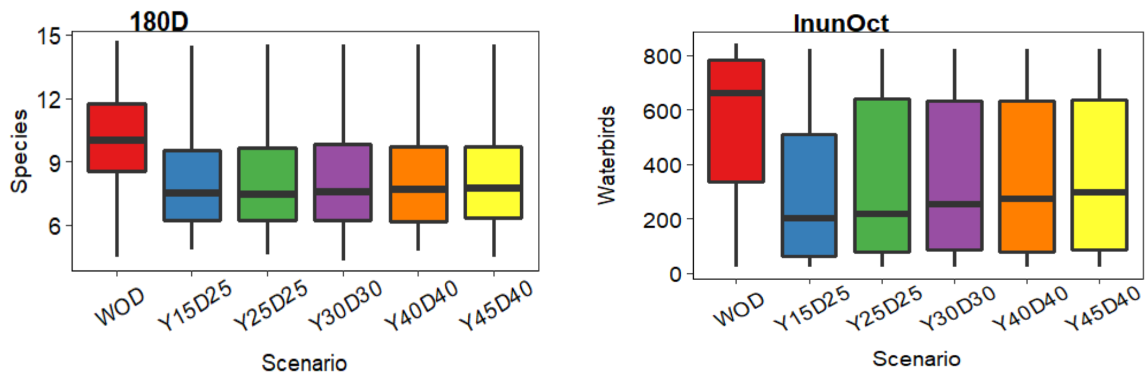
increase for the lowest scenario (25,000 ML/day) to a 11% increase for the highest scenario (45,000 ML/day downstream of Yarrawonga).

The best predictors for waterbird responses in Gunbower-Koondrook-Perricoota Forest were cumulative river flows 180 days prior to spring aerial surveys and inundated area at the time of the surveys. We observed small increases in the median number of species (1-4% compared to current constraints) and median waterbird abundance (8-48% compared to current constraints) in Gunbower-Koondrook-Perricoota Forest with increased relaxation of constraints. The largest predicted benefits were for the highest relaxed constraint scenarios of 45,000 ML/day downstream of Yarrawonga (which equates to 35,000 ML/day downstream of Torrumbarry Weir the nearest river gauge to the forest).

We also examined the modelled river flow and modelled inundation data to assess changes to the availability of waterbird habitat in Barmah-Millewa and Gunbower-Koondrook-Perricoota forests under different relaxed constraints scenarios. The number of days when small overbank events were recorded, which would inundate greater areas of the forests, increased for all the relaxed constraints scenarios compared to current constraints. This included events that would be of suitable duration and magnitude to initiate small-scale colonial waterbird breeding. The relaxation of constraints in the Mid Murray is likely to provide cumulative benefits to waterbird populations by inundating these important wetland areas more frequently. This would maintain and improve the condition of the feeding and breeding waterbird habitat, and in turn, support improvements in waterbird populations, a key objective of the Basin Plan.



Summary of predicted number of species (top left), waterbird density (top right) and number of breeding species (lower left) probability of colonial waterbird breeding (lower right) in Barmah-Millewa Forest under the flow scenarios. Inundated area in the 3 months prior to spring ground surveys was used as the predictor for species richness and waterbird density. Cumulative river flows in the 180 days prior the start of the breeding season was used as the main predictor for the probability of breeding and number of breeding species.



Summary of predicted number of waterbird species (left) and total waterbird abundance (left) in Gunbower-Koondrook-Perricoota Forest under the flow scenarios. Cumulative river flows in the 180 days prior to the spring aerial surveys was used as the main predictor species richness. Inundated area at the time of the aerial surveys in October was used as the main predictor for waterbird abundance.

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List of acronyms

AIC	Akaike's Information Criterion
BC Act	Biodiversity Conservation Act (NSW)
BM	Barmah-Millewa Forest
BWS	Basin Wide Environmental Watering Strategy
CAMBA	China-Australia Migratory Bird Agreement
CEWO	Commonwealth Environmental Water Office
DEM	Digital Elevation Model
DPE	Department of Planning and Environment (NSW)
EBA	Environmental Benefits Assessment
EPBC Act	Environmental Protection and Biodiversity Conservation Act (Commonwealth)
EWKR	Environmental Water and Knowledge Research Project
FCNSW	Forestry Corporation of NSW
GB	Gunbower Forest
JAMBA	Japan-Australia Migratory Bird Agreement
KP	Koondrook-Perricoota Forest
LTWP	Long Term Water Plan
MDBA	Murray-Darling Basin Authority
ML	Megalitre
NDVI	Normalised Difference Vegetation Index
NPWS	National Parks and Wildlife Service (NSW)
RiM-FIM	River Murray Floodplain Inundation Model
ROKAMBA	Republic of Korea-Australia Migratory Bird Agreement
RRCP	*Reconnecting River Country* Program
TLM	*The Living Murray* Program
UNSW	University of New South Wales
WOD	Without Development

1. Background

1.1 Waterbird benefits assessment

The Waterbird Environmental Benefits Assessment (EBA) Project is part of the NSW *Reconnecting River Country Program* (RRCP) which aims to improve wetland and floodplain connectivity in southern NSW. The Waterbird EBA Project is part of a suite of environmental assessment projects developed to assess the likely benefits of relaxed constraint options in the Murray and Murrumbidgee River Systems. The RRCP is focused on relaxing or removing constraints to allow for more efficient delivery of water for the environment in key project areas including:

- Hume to Yarrawonga (Murray River)
- Yarrawonga to Wakool (Murray River)
- Murrumbidgee River

In this report we evaluate the potential benefits of relaxing constraints in the Mid-Murray (the Yarrawonga to Wakool project area only) for waterbird communities. This is part of Phase 2 of the Waterbird EBA Project which aimed to provide a detailed assessment of the potential benefits of relaxed constraints and increased suitable habitat on waterbird communities. It follows on from preliminary analysis completed under Phase 1 of the project (Spencer et al. 2020). In this Phase 2 report we assessed the likelihood of increases in waterbird species richness, abundance and breeding in key wetlands because of the relaxation of constraints. The Yarrawonga to Wakool project area includes the Barmah-Millewa and Gunbower-Koondrook-Perricoota Forests (Figure 1) which are identified as important waterbird areas in the Murray-Darling Basin (MDBA 2019). These sites are also listed as sites of international importance under the Ramsar Convention and identified as nationally important wetlands (DAWE 2005).

Waterbird populations are in poor condition across the Murray Darling Basin (Kingsford et al. 2017). Changes in hydrology in the Murray River have directly impacted colonial nesting waterbirds in Barmah-Millewa Forest meaning it supports significantly less colonial waterbird breeding than historically recorded (Leslie 2001). Koondrook-Perricoota Forest has also supported many colonial waterbird nesting sites in the past, but there have been few recorded events in the last 20 years (Hutton 2017).

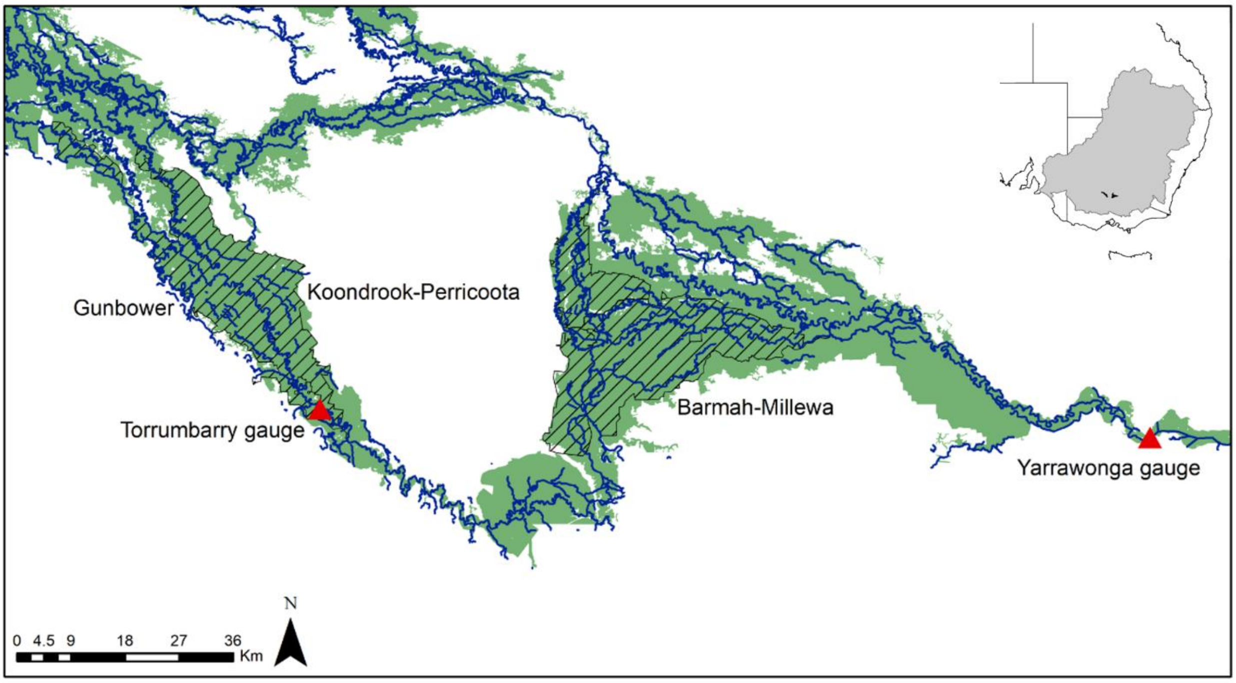


Figure 1 Locations of Barmah-Millewa Forest and Gunbower-Koondrook-Perricoota Forest (hatched areas) and main river gauges (red triangles) in the Yarrawonga to Wakool project area in the Mid-Murray within the Murray-Darling Basin (inset).

1.2 Relaxed constraints scenarios

Four relaxed constraints scenarios were investigated as part of the Waterbird EBA Project to determine the impacts of each scenario on the availability of waterbird habitat in each wetland area. For the Yarrawonga to Wakool stretch of the Murray River the current temporary operational limit is 15,000 ML/day. Increased limits of 25,000 ML/day, 30,000 ML/day, 40,000 ML/day and 45,000 ML/day for the River Murray downstream of Yarrawonga Weir (Figure 1) and the aligning increased limits of 25,000 ML/day, 30,000 ML/day, 40,000 ML/day and 40,000 ML/day at Doctors Point were investigated (Table 1). Relaxation of constraints to these limits could be achieved through removing a combination of physical, operation and/or policy constraints in this project area.

The current flow constraint downstream Yarrawonga Weir in the Murray River is designed to limit impacts on adjacent agricultural land. To manage this constraint, flows are often delivered to low-lying wetlands in either Millewa or Barmah forests. It is expected that removal of constraints to permit a higher flow rate would allow a greater area of the forest to be inundated for longer periods, providing benefits for a range of wetland-dependent species including waterbirds. At flow rates of 15,000 ML/day flows can enter low-lying parts of Barmah-Millewa Forest. It is not until flows exceed more than 45,000 ML/day that larger areas (60%) of the forest are inundated (Hale and Butcher 2011a). Although flows can also be directed and retained in low-lying wetlands using regulators and other infrastructure.

Flows into Gunbower-Koondrook-Perricoota Forest are measured at the Murray River downstream of the Torrumbarry Weir (Figure 1). At flow rates of about 12,500 ML/day downstream of Torrumbarry Weir flows can enter Swan Lagoon in Koondrook-Perricoota Forest, with flows above 18,000 ML/day needed for flows to spill from the lagoon and connect to several other oxbow lagoons in the rest of the forest (J. Dean, FCNSW pers. comm 2022). Larger flows greater than 35,000 ML/day are thought to inundate more than 80% of the forest (Harrington and Hale 2011). Waterbodies in Gunbower Forest can receive environmental water via Gunbower Creek in the northern part of the forest.

Flood enhancement works have been undertaken by the Forestry Corporation of NSW (FCNSW) to enable regulated delivery of water into the more parts of Koondrook-Perricoota forest under lower river flows. However, these works cannot be fully operated at present due to landholder impacts of flows upstream and downstream of the forest. The NSW RRCP is investigating options to provide higher river flows to the river adjacent to the forest to enable natural flow paths to connect and inundate the Koondrook-Perricoota forest.

Table 1 Project areas in the River Murray, and proposed flow limit options, included in the Reconnecting River Country Program

Scenario name	**Flow limit for each relaxed constraint scenario by project area**	
	Flow limit at Doctors Point (409017; Hume to Yarrawonga reach) ML/day	Flow limit at d/s Yarrawonga Weir (409025; Yarrawonga to Wakool reach) ML/day
Y15D25 (Current)	25,000	15,000
Y25D25	25,000	25,000
Y30D30	30,000	30,000
Y40D40	40,000	40,000
Y45D40	40,000	45,000

Flow thresholds for bankfull, small, medium and large overbank flows at the Yarrawonga gauge are documented in the NSW Murray-Lower Darling Long Term Water Plan (LTWP) (DPIE 2020) which specifies the river flows at which wetland habitat in Barmah-Millewa Forest and Gunbower-Koondrook-Perricoota Forest are inundated (see Table 2; Figure 2). Bankfull events can occur around 10,000-12,000 ML/day that can inundate low-lying parts of Barmah-Millewa Forest. Small overbank events into Barmah-Millewa Forest occur downstream of Yarrawonga Weir at 15,000 ML/day -50,000 ML/day, medium overbank events at greater than 50,000 ML/day up to 80,000 ML/day and large overbank events occur at flows greater than 80,000 ML/day at the Yarrawonga Weir gauge (DPIE 2020).

Higher flow rates are needed to influence flows into Gunbower-Koondrook-Perricoota Forest measured at the gauge downstream of Torrumbarry Weir (Table 2). Overbank events occur when flows are greater than 25,000 ML/day with small overbank events between 25,000-40,000 ML/day, medium overbank events between 40,000-55,000 ML/day and flows greater than 55,000 ML/day needed for large overbank events (DPIE 2020).

Table 2 Summary of flow threshold estimates (ML/D) from DPIE (2020) for relevant flow categories (bankfull, small, medium and large overbank events) that can inundate the main study areas Barmah-Millewa Forest and Gunbower* and Koondrook-Perricoota^ Forests. Large overbank events in both wetland areas are driven by large rainfall events in the upper Murray catchment.

Wetland area	River gauge where threshold measured	Bankfull	Small overbank	Medium overbank	Large overbank
Barmah-Millewa Forest	River Murray d/s Yarrawonga (409025)	10,000-15,000	>15,000-50,000	>50,000-80,000	>80,000
Gunbower-Koondrook-Perricoota Forest	River Murray d/s Torrumbarry (409207)	16,000-18,000* 22,000-25,000^	>25,000-40,000	>40,000-55,000	>55,000

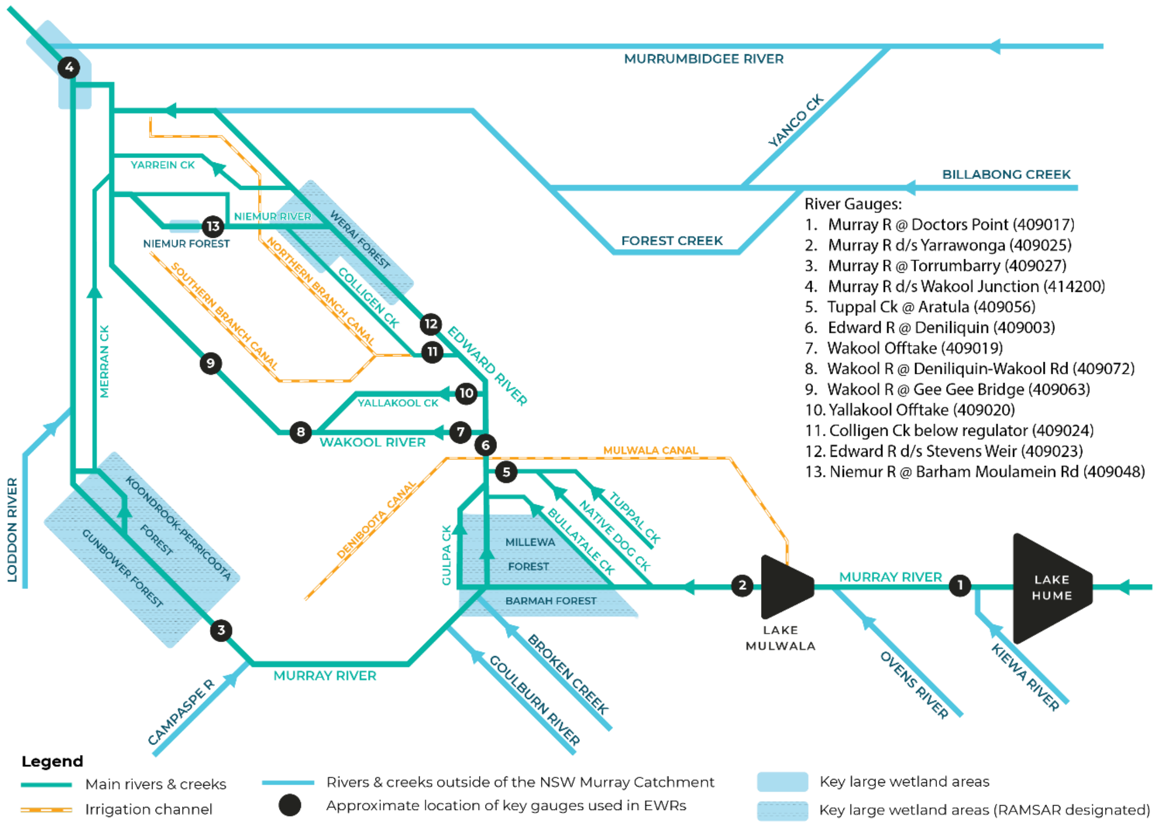


Figure 2 Schematic diagram showing main watercourses and gauges in the mid-Murray region including Barmah-Millewa Forest and Gunbower-Koondrook-Perricoota Forests. Reproduced from DPIE (2020).

1.3 Expected waterbird responses

Floodplain wetlands in the Murray-Darling Basin support a diverse range of waterbird species. Many species are highly mobile, undergoing periods of movement between different wetland regions to access suitable feeding and breeding habitats. Most waterbirds depend on aquatic food sources including wetland vegetation, aquatic invertebrates, fish and/or frogs (Kingsford and Norman 2002). Broadly, waterbird species can be grouped into five functional groups or guilds according to their foraging habitat preferences. This includes ducks and small grebes, herbivores, piscivores (or fish-eating waterbirds), large waders and shorebirds (or small waders) (see Kingsford et al. 2020). Variations in morphology and foraging techniques have allowed many species to co-exist in the same habitats. For example, many large waders, shorebird species and herbivores prefer to feed on the muddy edges of open waterbodies or shallow vegetated marshes, while deeper water foragers including some ducks, grebe and fish-eating (piscivores) species prefer to feed in large open lakes and lagoons (Figure 3).

Waterbird species found in the Murray-Darling Basin can also be grouped according to their breeding strategy as either colonial, non-colonial or non-breeding. Colonial species can sometimes nest in very large mixed species colonies when widespread inundation occurs. These include egrets, ibis, spoonbills, cormorants, pelicans, and herons. Most waterfowl and resident shorebird species can be described as non-colonial species as they breed across a wetland complex (rather than in high densities in a location) when suitable habitat is inundated. Migratory shorebirds can also be observed feeding in some floodplain wetlands in the Murray-Darling Basin during spring and summer months, but they do not breed in Australia, instead they migrate each year to breeding habitat in the Northern Hemisphere during austral autumn and winter months.

We expect increases in the frequency, duration and magnitude of overbank events in key sites will contribute to Basin-wide (MDBA 2019) and catchment-specific objectives set for waterbirds in NSW Murray Lower Darling LTWP (DPIE 2020) (Table 3). However, the expected responses of waterbirds to relaxation of flow constraints are likely to be complex and intricately linked with patterns in the availability of different wetland habitat types (Figure 3).

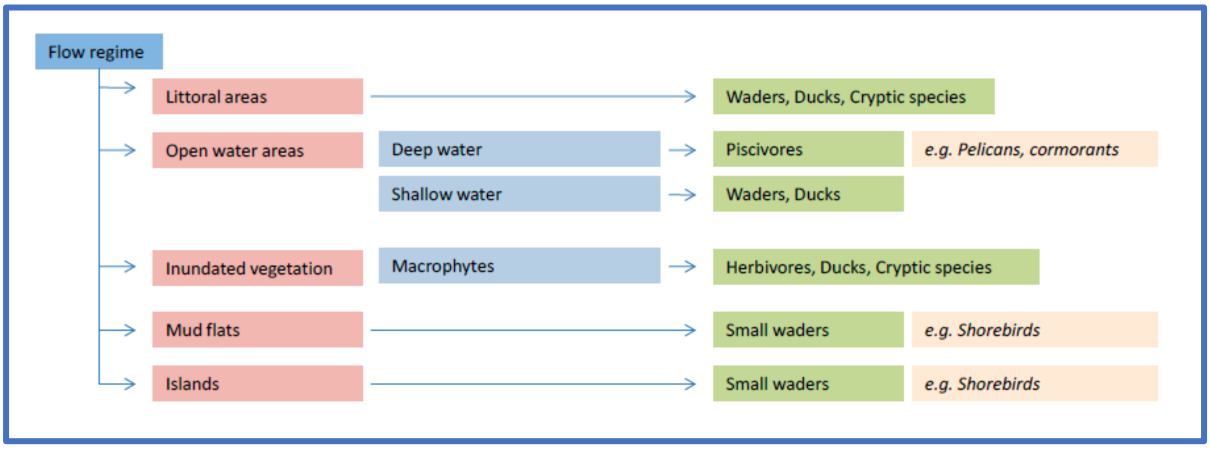


Figure 3 Waterbird species can be grouped according to their habitat requirements which is influenced by the flow regime (reproduced from Brandis et al. 2009). For example, large waders such as spoonbills feed in shallow vegetated wetlands, while many piscivores, including pelicans and cormorants, feed in deeper more open waterbodies, and shorebirds (or Small Waders) prefer open waterbodies with shallow muddy shorelines.

Table 3 NSW Murray-Lower Darling Long Term Water Plan (LTWP) waterbird objectives and MDBA Basin Wide Environmental Watering Strategy (BWS) expected environmental outcomes supported by the Reconnecting River Country Program. See more detailed information on waterbird objectives and flow categories from the LTWP in Appendix 1.

LTWP objective ID	LTWP objective	BWS Expected waterbird outcomes
WB1	Maintain the number and type of waterbird species	The number and type of waterbird species present in the Basin will not fall below current observations
WB2	Increase total waterbird abundance	There is a significant improvement in waterbird populations in the order of 20 to 25% over the baseline scenario, with increases in all waterbird functional groups
WB3	Increase breeding activity in non-colonial nesting waterbirds	Breeding abundance (nests and broods) for all of the other functional groups to increase by 30–40% compared to the baseline scenario, especially in locations where the Basin Plan improves over-bank flows
WB4	Increase opportunities for colonial nesting waterbird breeding	Breeding events (the opportunities to breed rather than the magnitude of breeding per se) of colonial nesting waterbirds to increase by up to 50% compared to the baseline scenario
WB5	Maintain the extent and improve condition of waterbird habitats	Not specified in BWS but this habitat objective underpins four expected outcomes listed above

It is anticipated that waterbirds may benefit in two ways to relaxation of constraints downstream of Yarrawonga Weir including: 1) increases in abundance and 2) increases in breeding opportunities. There may be also localised increases in species richness in individual wetland sites where there are changes in habitat structure due to changes to the flow regime. We also anticipate that increases in the availability of inundated wetland habitat will result in localised increased abundance of waterbirds.

We anticipate that increased flow volumes will more frequently meet the flow thresholds required for small-scale colonial waterbird breeding allowing both Barmah-Millewa Forest and Koondrook-Perricoota Forest to contribute to increased opportunities for breeding in the Murray-Darling Basin. Previous work by Leslie (2001) and Arthur et al. (2012) has demonstrated positive associations between higher river flows and the occurrence of waterbird breeding in the Barmah-Millewa Forest. The success of breeding events is linked to the magnitude and duration of inundation of key breeding sites and surrounding foraging habitat. Inundation of these habitats is needed over the breeding cycle from nest building, egg laying, chick rearing through to fledging to support successful breeding. This is where relaxation of constraints may provide greater management options for delivering flows to extend natural inundation of active colony sites and surrounding habitat.

Certainty around waterbird responses to the relaxation of constraints is potentially lower than for other ecological responses being evaluated as part of the EBA project. Waterbirds are highly mobile organisms that make decisions around habitat use, which wetland to use, when, where and for what purpose (i.e., foraging, roosting, or nesting). The decision-making process is complex and can be influenced by factors in the larger landscape beyond the wetland scale (Kingsford and Norman 2002; Kingsford et al. 2010; Bino et al. 2020).

The availability of other suitable habitat may influence the use of Barmah-Millewa and Gunbower-Koondrook-Perricoota forests by waterbirds including the timing of when habitat becomes available (prior or post flooding of other wetlands in the Murray River Catchment and in other parts of the Murray-Darling Basin). Waterbird responses to relaxation of constraints may also be subdued in the short- to medium-term due to the impact of low population numbers. Long-term aerial surveys have shown that waterbird populations are severely degraded across the Murray-Darling Basin (Kingsford et al. 2017) with continued declines in waterbird abundance recorded in the most recent spring surveys (Porter et al. 2021) (see Figure 4).

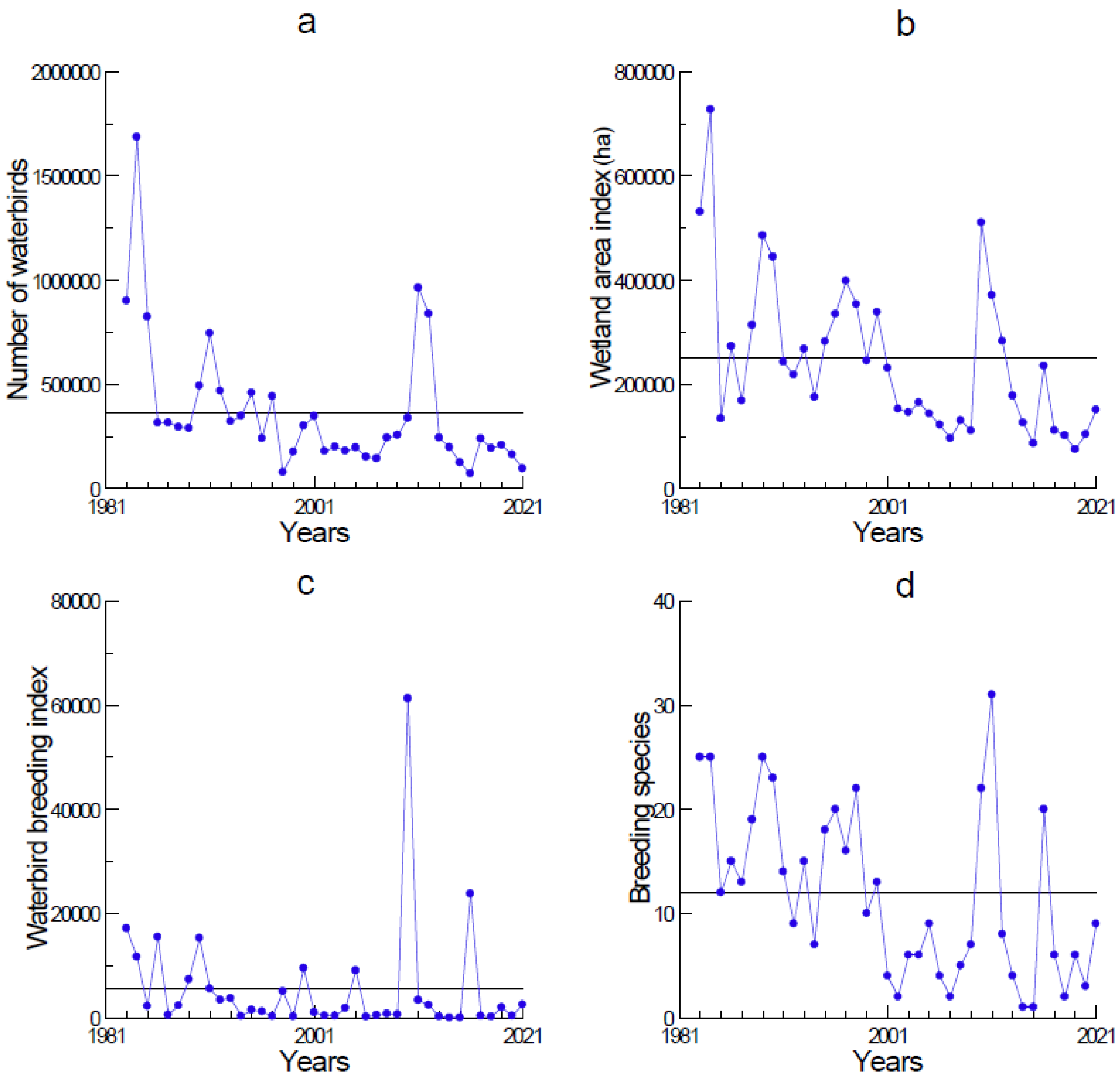


Figure 4 Changes over time in a) total waterbird abundance, b) wetland area index, c) waterbird breeding index and d) number of waterbird breeding species recorded in the Eastern Australian Waterbird Aerial Survey (1983-2021). The horizontal lines show long-term averages. These long-term aerial surveys are made up of ten aerial survey bands (each 30km in width), every two degrees of latitude, that cross Eastern Australia. They monitor up to 2000 wetlands in the bands and provide estimates for up to 50 waterbird species each October each year. Reproduced from Porter et al. (2021).

2. Methods

2.1 Study sites

2.1.1 Barmah-Millewa Forest

Barmah-Millewa Forest, located in the Mid-Murray region (Figure 5) covers 66,000 hectares and spans the NSW-Victorian border between Tocumwal, Deniliquin and Echuca. The Millewa group of forests are part of the Ramsar-listed NSW Central Murray Forests, while Barmah Forest, in the Victorian section of the forest, is separately listed under the Ramsar Convention. Combined, the Barmah-Millewa Forest is recognised as one of six icon sites through the MDBA's *The Living Murray Program* (TLM). Part of the reason for its listing includes the support of unique wetlands, including some of Australia's largest river red gum *Eucalyptus camaldulensis* forests, threatened waterbird species and colonial waterbird breeding (RIS 2012; Hale and Butcher 2011). The Millewa Forest is protected as part of the Murray Valley National Park and is listed as a priority asset for waterbirds and environmental water delivery by NSW Department of Planning and Environment (DPE) and partners (DPIE 2020). On the Victorian side the forest is protected in the Barmah National Park and part of the River Murray Reserve and is a priority wetland for the Victorian Environmental Water Holder and partners (DELWP 2021).

Both Barmah and Millewa Forests provide important habitat for waterbirds (see Appendix 2) in the Murray-Darling Basin. The forest is identified as an important asset for recovery of waterbird populations in the Basin (MDBA 2019). The site provides breeding habitat for colonial waterbird species, including ibis, spoonbills, egrets and herons, and the nationally endangered Australasian bittern *Botaurus poiciloptilus* (Plate 1). The forest also supports waterbird species listed as vulnerable in NSW and migratory species (see Appendix 2). Prior to river regulation it is thought that colonially-nesting waterbird species would have bred in Barmah-Millewa Forest almost annually. Changes to the flooding regime of the forest including reduced frequency, magnitude, duration and altered timing of flows has reduced opportunities for successful breeding (Leslie 2001).

Low annual rainfall (<400 mm) (BOM 2022) means that the forest is dependent on high river flows in the Murray River initiated from heavy rainfall upstream. Naturally the forest would have flooded regularly following high river flows in winter and spring. The construction of major dams including Hume Reservoir and Dartmouth Dam have reduced the size and frequency of natural winter/spring floods in the Barmah-Millewa Forest (Kingsford 2000). Inundation of the forest depends on overbank flooding below Yarrawonga Weir when flows exceed the river channel capacity. This upper limit in channel capacity influences how the weir is operated and how water for the environment can be delivered to the forest to maintain its high ecological values.

There are numerous water management structures involved in the delivery of water to Millewa Forest. A proportion of the Murray River flows that exceed 30,000 ML/day downstream from Yarrawonga Weir flow northward into the Edward River (through eastern Millewa and the Bullatale and Native Dog creeks) (see Figure 2) and southward through Barmah Forest around the Barmah Choke. The travel time from Yarrawonga Weir to Millewa Forest is generally around 3-4 days (P. Childs, DPE pers. comm. 2021) and Yarrawonga Weir downstream gauge (409025) is crucial for informing the management of flows that inundate the forest. When flows are above 15,000 ML/day all structures in the forest are open allowing greater areas of wetland habitat to be inundated (K. Ward, GBCMA, pers. comm. 2022).

Plate 1 Reed Beds in Millewa Forest regularly supports colonial waterbird breeding when inundated over spring and summer months. This site also provides important habitat for the nationally endangered Australasian bittern (Credit: Kate Brandis, UNSW, November 2015).

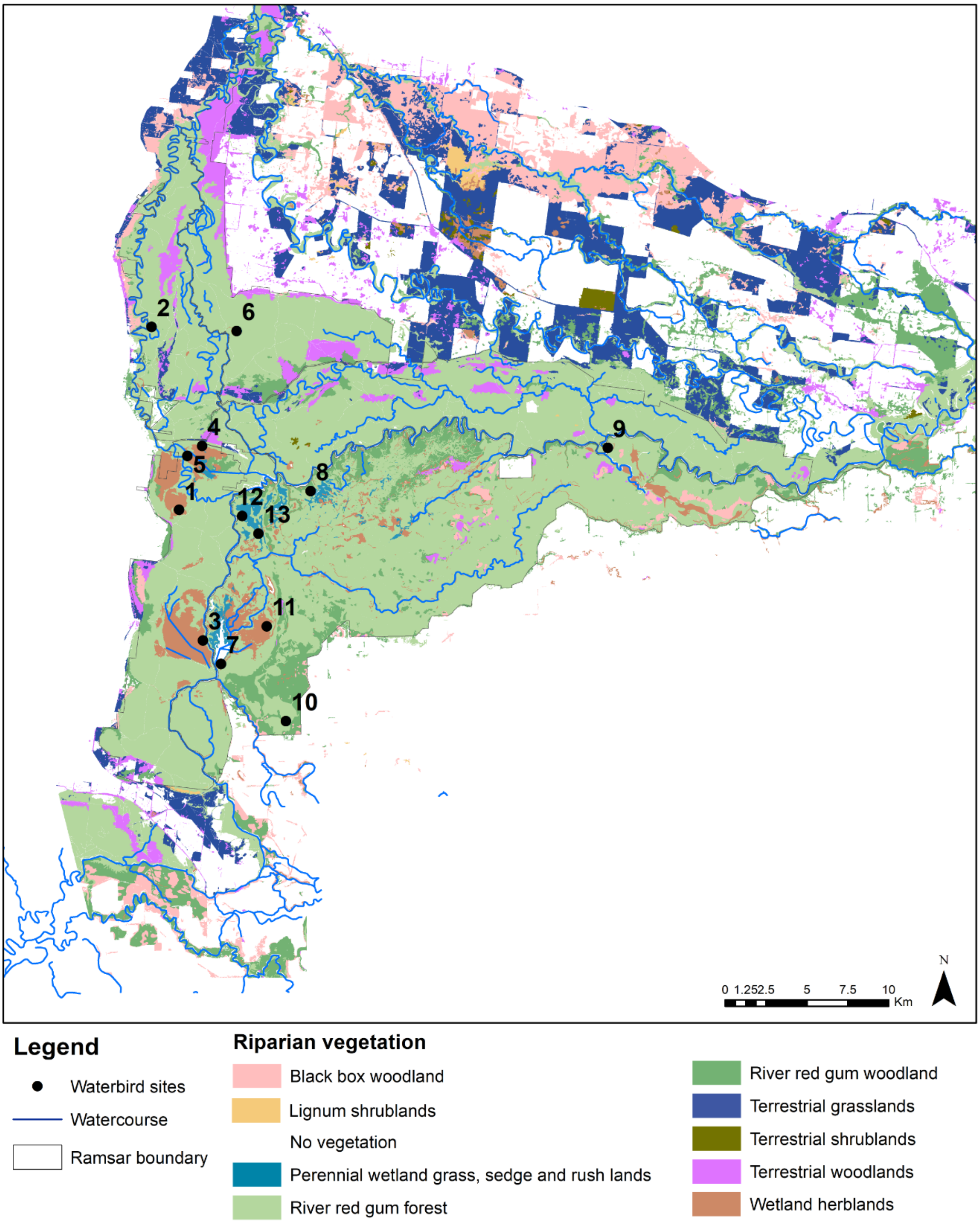


Figure 5 Barmah-Millewa Forest and Ramsar site on the River Murray. Locations of key wetlands including waterbird ground survey sites in Barmah-Millewa Forest 1. Duck Lagoon, 2. Horseshoe Lagoon, 3. Moira Lake, 4. Reed Beds North, 5. Reed Beds South, 6. St Helena Swamp, 7. Barmah Lake, 8. Boals Deadwood, 9. Bunyip Hole, 10. Goose Swamp, 11. Steamer Plain, 12. Top Island, 13. Pig Hole.

2.2.2 Gunbower-Koondrook-Perricoota Forest

The Koondrook-Perricoota Forest is an extensive area of river red gum forest and woodlands. Together with Gunbower Forest on the southern bank of the Murray River in Victoria, it forms a TLM icon site and is the second-largest red gum forest in Australia, covering over 32,000 hectares along the Murray River (Watts et al. 2017). The Koondrook-Perricoota Forest comprises part of the NSW Central Murray State Forest Ramsar site, the largest complex of tree-dominated floodplain wetlands in southern Australia. The site contains rare wetland types within the Riverina bioregion, particularly floodplain lake and floodplain meadows and reed swamps (Harrington and Hale 2011). Gunbower Forest on the Victorian side of the Murray River was separately listed under Ramsar in 1982 (Hale and Butcher 2011b), and supports river red gum, black box (*E. largiflorens*) and grey box (*E. microcarpa*) communities interspersed by lakes, swamps and lagoons at lower elevations (MDBA 2012).

When inundated Gunbower and Koondrook-Perricoota forests can provide important habitat for waterbirds. At least 40 waterbird species were recorded in the forests over the 2007-2021 period including waterfowl (ducks, waterhens) and colonially-nesting species (egrets, cormorants and herons) (see Appendix 2). Key waterbird assets within Koondrook-Perricoota include creeks and lagoons including Horseshoe Lagoon, Swan Lagoon, Pollack Lagoon and Pollack Swamp (Plate 2, Figure 6) which have supported waterbird breeding in the past (Disher 2000; Hutton 2017). Waterbodies in Gunbower Forest that can receive environmental water via Gunbower Creek and provide habitat for waterbirds include: Black Swamp, Reedy Lagoon and Little Reedy Wetland Complex (Figure 6) (VEWH 2022).

Significant water resource development in the 1900's has altered the flow and flooding regime of these wetlands. Large scale floods that inundate Gunbower-Koondrook-Perricoota Forest are the result of large rainfall events in the upper catchment, but environmental water has also been delivered in recent years. The TLM Program aims to restore wetland condition in this site and other Murray icon sites through the provision of environmental water. One of the key ecological objectives for the Gunbower-Koondrook-Perricoota icon site is that there is "successful breeding of thousands of colonial waterbirds in at least 3 in 10 years" (MDBA 2012).

Plate 2 Pollack Lagoon and surrounding area provides important waterbird habitat in Koondrook-Perricoota Forest and has supported breeding of colonially-nesting waterbirds in recent years (Credit: Jean Dind, FCNSW, January 2020).

The forests have supported many colonial nesting sites in the past but there are few records of breeding in the last 20 years. The most recent records in Koondrook-Perricoota Forest were in 2016-2017 and 2017-2018 after large-scale natural flooding in the Mid-Murray in late 2016. In the last five years colonial waterbird nesting has mainly been confined to the Pollack area (Figure 6) of Koondrook-Perricoota Forest, which has supported small numbers of nesting egrets and herons (Hutton 2017; 2018b; 2021).

Waterbird habitat in the Gunbower-Koondrook-Perricoota Forest consists of river red gum forests and floodplain marshes including some permanent wetlands in Gunbower Forest. The intermittently flooded wetland areas in Koondrook-Perricoota can support waterbirds when they are inundated. Environmental water delivery into the northern part of Koondrook-Perricoota forest has been managed using private irrigation infrastructure in recent years (Hutton 2019). Inflows have been delivered via a pumping station on the Murray River upstream of Barham directly into Pollack Lagoon and Pollack Swamp (Figure 6). During natural high flows this wetland area fills from the adjacent Barbers Creek via Pollack Creek (Hutton 2019). Koondrook-Perricoota can also be watered using the Torrumbarry weir pool upstream of the river gauge which was done successfully in late winter-spring 2014 and spring 2019 (J.

Dyer, DPE, pers. comm. 2022) as part of an option originally identified in the development of the flood enhancement works (MDBC 2006).

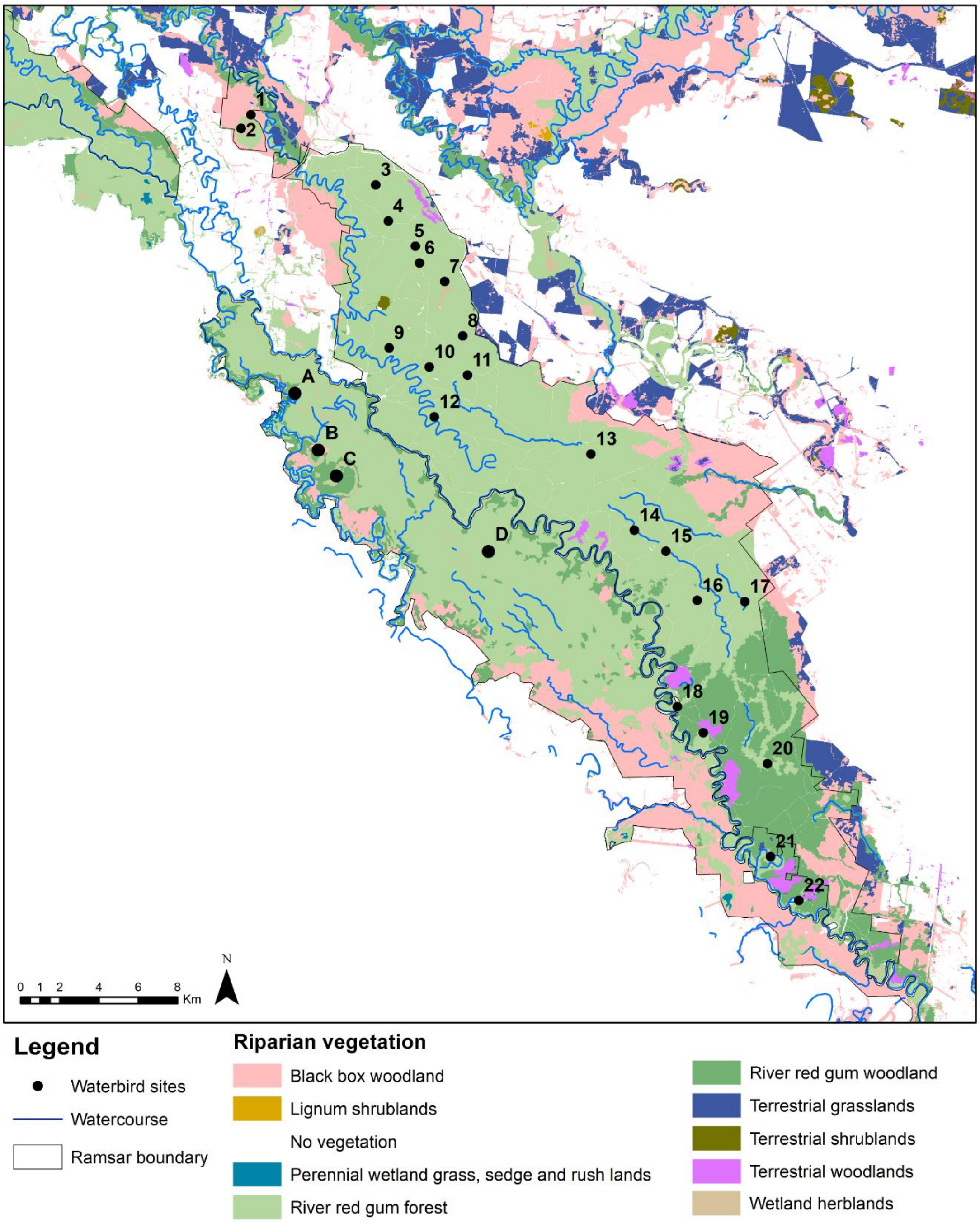


Figure 6 Gunbower-Koondrook-Perricoota Forests and Ramsar sites in the Mid-Murray. Locations of key wetlands in Koondrook-Perricoota Forest located in NSW: 1. Pollack Lagoon, 2. Pollack Swamp, 3. Sandpit Trail, 4. Long Lagoon, 5. IU Rookery, 6. Smokehouse Lagoon, 7. The Rookery, 8. McMahons Waterhole, 9. Moorings Lagoon, 10. Mosses Lagoon, 11. McMahons Creek, 12. Barbers Lagoon, 13. Myloc Creek, 14. Pennyroyal Lagoon, 15. Belbins Waterhole, 16. Smoke Waterhole, 17. Clarkes Lagoon, 18. Dead River Lagoon, 19. Horseshoe Lagoon, 20. Allens Waterhole, 21. Swan Lagoon, 22. Broken River. Locations of four key wetlands in Gunbower Forest in Victoria that can receive environmental water and provide waterbird habitat: A. Little Gunbower Creek Complex, B. Black Swamp, C. Reedy Lagoon, and D. Little Reedy Wetland Complex.

2.2 *River flow data*

Observed and modelled river flow data and inundation extent data were available for both wetland areas. This included daily flow data for the Murray River recorded downstream of Yarrawonga Weir (gauge 409025) (for Barmah-Millewa Forest) and downstream of Torrumbarry Weir (gauge 409207) (for Gunbower-Koondrook-Perricoota Forest) (sourced from Water NSW (2021)).

The downstream Yarrawonga Weir gauge (409025) is the main gauging point at which flows into Barmah-Millewa Forest and surrounding creek systems are measured (Figure 1). We collated flow volumes measured at the Yarrawonga Weir gauge and calculated cumulative flow volumes corresponding with the dates of annual spring aerial and ground surveys (see further detail below).

Flows into Gunbower-Koondrook-Perricoota Forest are measured at the gauge downstream of Torrumbarry Weir (409207) located near the south-eastern end of the forests (Figure 1). The flows recorded downstream of Torrumbarry Weir are dependent on flows from the Murray River at Barmah but also heavily dependent on flows from the Goulburn River that meets the Murray River (Figure 2) near Echuca and operation of water management infrastructure. As done for Barmah-Millewa, we collated flow volumes measured at the nearest river gauge and calculated cumulative flow volumes corresponding with the dates of waterbird aerial surveys for Gunbower-Koondrook-Perricoota Forest (see below).

Modelled river flow data was available from the Murray River Source Model version 7 (MDBA 2022) for downstream of Yarrawonga Weir and downstream of Torrumbarry Weir for the 1895-2019 period. There were four hydrological modelled scenarios (completed in the Murray River Source in late January 2022) (MDBA 2022) available to investigate likely benefits to waterbirds under different relaxed constraints scenarios (Table 4). These relaxed constraint scenarios were compared to a without development (WOD) and base case (current) scenario.

The Source Model represents historic climate for the 1/7/1895-30/6/2019 period, with water regulating infrastructure, water sharing policies and water recovery for the environment as it exists on 1 January 2021 and all environmental water managed as a single portfolio. The model considers combined inflows from the Murray and Goulburn Rivers and the delivery strategy is not to deliver in summer months to limit blackwater risks (MDBA 2022). The modelling tries to represent appropriate environmental water delivery options, either on the back of existing flows (to extend duration of natural high flow and medium flow events) or to create new events, with the focus on small and medium overbank events (MDBA 2022).

Table 4 Flow scenarios assessed as part of the Waterbird EBA Project and relationships between the two main gauges in the study area. (For each scenario flows are specified for Doctors Point (D) and downstream Yarrawonga Weir (Y). Relationships at the gauges are based on median estimates of flow limits from the DPE flow peak tracking tool (DPE 2022a).

Scenario name	Flows at Doctors Point (409017) ML/day	Flows at d/s Yarrawonga Weir (409025) ML/day	Flows at d/s Torrumbarry Weir (409207) ML/day
Y15D25 (Current)	25,000	15,000	13,000
Y25D25	25,000	25,000	23,000
Y30D30	30,000	30,000	27,000
Y40D40	40,000	40,000	32,000
Y45D40	40,000	45,000	34,000

2.3 Inundated wetland area

To determine the inundation extent across the Barmah-Millewa and Gunbower-Koondrook-Perricoota forests, water maps were derived from the Landsat (TM-5, ETM+7, OLI 8) (1987-2021) and Sentinel-2 satellite archives (2015-2021) (DPE 2022b). Near cloud free satellite images were automatically downloaded from the USGS (United States Geological Survey's) Earth Explorer website (http://earthexplorer.usgs.gov) and from the Copernicus Sentinel Open Access Hub (https://scihub.copernicus.eu/dhus/#/home) as orthorectified images. These images were then processed to standardised surface reflectance (Flood et al. 2013). During the period between 2011 and 2013 satellite images were only available from the Landsat ETM+7 sensor which had missing data due to the scan line corrector error.

From each surface reflectance image, a water index was generated using linear discriminant analysis (Fisher et al. 2016). A threshold approach was used to classify pixels as water or non-water, using threshold values that allowed for the inclusion of mixed pixels because an open water classifier is known to underestimate flood extent in vegetated floodplain wetlands (Thomas et al. 2015). Inundation extent estimates for Gunbower-Koondrook-Perricoota Forest were from cloud-free spring images only and, therefore, we may have underestimated the area inundated at the time of the surveys. Relationships between observed river flows and inundated area are shown in Figure 7 and Figure 8 (and in more detail in Appendix 3).

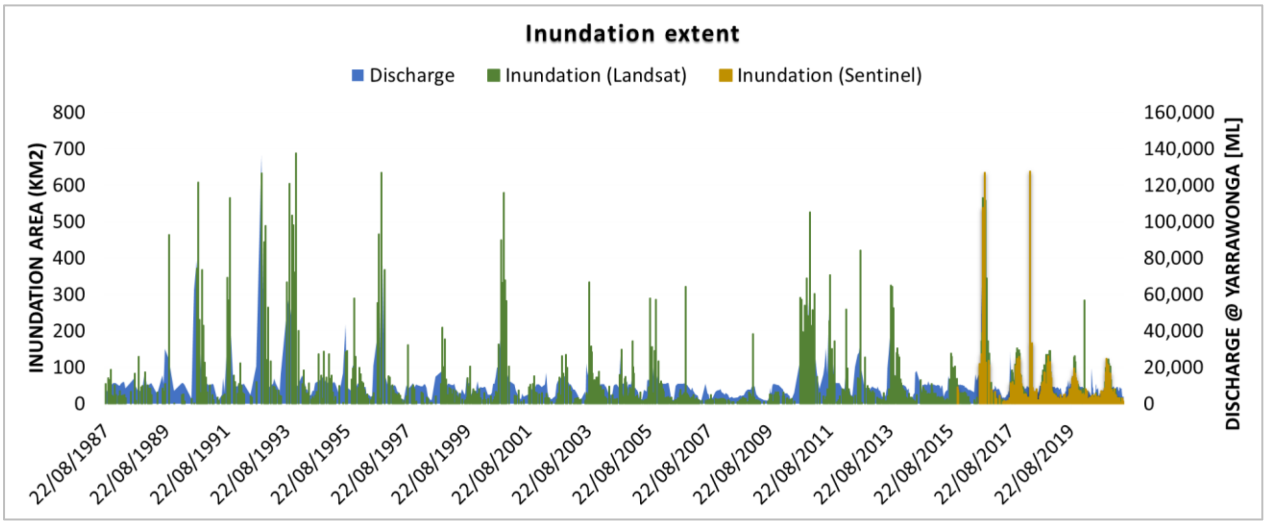


Figure 7 Maximum daily river flow (ML/day) measured each month in the Murray River downstream of Yarrawonga Weir (409025), estimated area of inundation in Barmah-Millewa Forest based on Landsat (1987-2021) and Sentinel imagery (2015-2021).

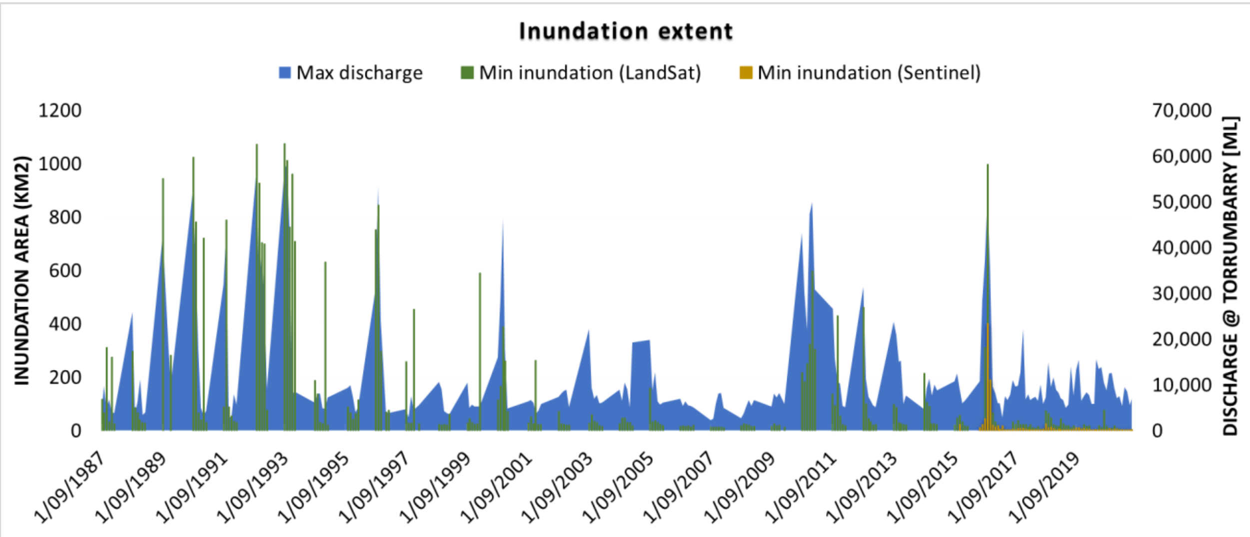


Figure 8 Maximum daily river flow (ML/day) measured each month in the Murray River downstream of Torrumbarry Weir (409207) and estimated minimum area of inundation in Gunbower-Koondrook-Perricoota Forest based on Landsat (1987-2021, spring-summer months only) and Sentinel imagery (2015-2021, all months).

Modelled inundated area was available from the River Murray Floodplain Inundation Model (RiM-FIM) (zone 2 of the model covers Millewa Forest, zone 3 clip covers Barmah Forest and zone 7 clip represents most of Gunbower-Koondrook-Perricoota Forest) and updated hydraulic modelling for both wetland areas created for the purpose of the EBA project. The RiM-FIM inundation model was originally created by Overton et al. (2006) to support environmental water management in the River Murray. It links measurements of water height at flow gauges to the extent of inundation mapped from Landsat satellite images to predict the distribution of inundation across the floodplain (at 5m spatial resolution) using a lidar digital elevation model (DEM) (Sims et al. 2014).

2.4 Waterbird survey data

2.4.1 Aerial surveys

Aerial surveys of Barmah-Millewa Forest and Gunbower-Koondrook-Perricoota Forests have been completed by the University of New South Wales (UNSW) (Kingsford et al. 2020) each spring from 2007 to 2020 as part of the *The Living Murray*, *Specified Environmental Assets* and *Targeted Wetland* programs funded by the MDBA. The aerial surveys are done from fixed-wing aircraft using two observers to independently count waterbirds in the wetlands at a height of 30-46 m, within 150 m of the wetland's shoreline where waterbirds are concentrated (Kingsford et al. 2020). All waterbirds are identified to species, except small grebes (Australasian little grebe, hoary headed grebe), small egrets (cattle egret, little egret and Intermediate egret), terns and migratory shorebirds (Charadriformes) which cannot be consistently identified from the air and were instead grouped (Kingsford et al. 2020). The forests on both sides of the NSW-Victorian border are surveyed during these fixed-wing aerial surveys. We used this aerial survey data to develop predictive relationships for Barmah-Millewa and Gunbower-Koondrook-Perricoota forests.

Annual helicopter surveys of Gunbower-Koondrook-Perricoota Forest were also commissioned by FCNSW each year from 2014 to 2020 (not including 2017). These surveys were funded through the TLM program and typically flown in November/December (Dind 2021). Multiple parallel transects were flown over the forest and all waterbird species were recorded during the survey. These transects are approximately 1km apart and each transect is around 55km long. During these helicopter surveys additional targeted surveys of key sites were also surveyed after the completion of the survey transects. The surveys were flown at consistent speed (typically 20-30 knots during waterbird counting) and height (around 40m above ground level, 5-10m above canopy height (Dind 2021). Data for Gunbower Forest was not available for every year as the focus of the FCNSW surveys is key wetland sites in Koondrook-Perricoota Forest. While we used the FCNSW survey data to investigate current condition of the forest we did not use the aerial survey data to develop predictive relationships between waterbirds and flows.

2.4.2 Ground surveys

On ground surveys have been completed in Barmah-Millewa Forest from 1999-2000 onwards (see TLM annual reports e.g., Webster 2008; Webster 2013; Borrell 2018; Webster and Borrell 2020; Ecology and Heritage partners 2021). Quarterly ground surveys of six wetlands in the Millewa Forest and seven wetlands in the Barmah Forest were completed as part of this TLM condition monitoring. Additional event-based ground surveys of active colonial waterbird breeding sites were completed in some years as part of intervention monitoring (e.g., Borrell and Webster 2016). These surveys were funded through the TLM monitoring coordinated by NSW National Parks and Wildlife Service (NPWS).

The ground survey sites covered a range of habitat types and were accessible during a range of flow conditions (Webster 2008) (Table 5, Figure 5). Ground survey sites in Millewa Forest include: Reed Beds South, Reed Beds North, Moira Lake, Duck Lagoon, Horseshoe Lagoon and St Helena Swamp (Figure 5Figure 5, Appendix 4). The Reed Beds Complex and Moira Lake in Millewa Forest retain water for the longest periods. Horseshoe Lagoon and Duck Lagoon are serviced by Gulpa Creek which is influenced by the main river channel flowing from the Murray River at Picnic Point immediately downstream from the Edward River Offtake. St Helena Swamp fills from the Edward River downstream from the Edward River Offtake. A further 6 sites were monitored in Barmah Forest which include: Barmah Lake, Boals Deadwood Swamp, Bunyip Hole, Goose Swamp, Pig Hole and Steamer Plain (see Figure 5 and Appendix 4). One additional site in Barmah Forest, Top Island (Figure 5) has been surveyed from October 2015 onwards (Table 5).

Table 5 Barmah-Millewa Forest TLM condition monitoring waterbird ground survey sites, estimated survey areas (in hectares) and survey coverage between 1999-2021. Every site was surveyed over three periods (1999/2000 – 2002/2003; 2007/2008-2012/2013; 2015/2016 – ongoing) unless otherwise indicated.

Management Unit	Site Code	Site Name	Survey Area (ha)	Spring survey coverage
Millewa Forest	DUC	Duck Lagoon	53.7	Spring 1999 – ongoing
	HSL	Horseshoe Lagoon	11.2	Spring 1999 – ongoing
	MOI	Moira Lake	474.6	Spring 1999 – ongoing
	RBN	Reed Beds North	34.6	Spring 1999 – ongoing
	RBS	Reed Beds South	25.3	Spring 1999 – ongoing
	STH	St Helena Swamp	8.3	Spring 2014 – ongoing
Barmah Forest	BAL	Barmah Lake	58.9	Spring 1999 – ongoing
	BDW	Boals Deadwood	29.5	Spring 2001 – ongoing
	BYH	Bunyip Hole	3.3	Spring 1999 – ongoing
	GOS	Goose Swamp	16.8	Spring 1999 – ongoing
	PHL	Pig Hole	12.8	Spring 1999-2016 only
	STP	Steamer Plain	41.1	Spring 1999 – ongoing
	TOP	Top Island	5.0	Spring 2015 – ongoing

Ground survey data was available for parts of Koondrook-Perricoota Forest for 10 water years in the 2007-2008 to 2020-2021 period. Typically, these surveys have been done in summer months (December-February) but in the earlier years spring, autumn and winter counts were also completed (Webster, unpublished data 2008-2012). These surveys were focused on Pollack Lagoon and Swan Lagoon only (Figure 6). From 2017-2018 monitoring sites were set up at 20 sites across the forest (Dind 2021). Site selection was based on records by Disher (2000) and local knowledge of the forest on sites that had historically supported colonial waterbird breeding.

Over the 2017-2021 period Pollack Lagoon, Pollack Swamp and Swan Lagoon consistently held water while the remaining ground survey sites contained varying amounts of water or were dry over this period (GHD 2015, FCNSW 2019; Dind 2020; 2021). Targeted ground surveys were also undertaken in the Pollack area from 2016 onwards to assess waterbird responses including colonial-nesting activity, to flows and to guide environmental water delivery (Hutton 2017-2021). While we examined this ground survey data to investigate current condition of the forest we did not use this data to develop predictive relationships between waterbirds and flows.

2.4.3 Colonial waterbird breeding records

We collated waterbird breeding records sourced from available aerial and ground survey programs and historical records to determine the presence of breeding of 16 colonially-nesting species in the Barmah-Millewa Forest. This included records of colonial waterbird breeding from:

- Leslie (2001), Brandis (2010), Ward (2011) and Spencer (2017)
- Waterbird aerial survey data – Murray-Darling Basin Environmental Asset and The Living Murray (TLM) icon site surveys (Kingsford et al. 2020).
- Waterbird ground condition monitoring data available for Barmah-Millewa Forest from TLM surveys and previous monitoring programs 1999-2021 (e.g., Webster 2008; Webster 2013; Borrell 2018; Webster and Borrell 2020; Ecology and Heritage partners 2021)
- Waterbird TLM intervention ground monitoring data (e.g., Borrell and Webster 2016), Goulburn-Broken Catchment Management Authority monitoring observations (e.g., Ward 2021) and recent TLM funded colony drone surveys conducted by Francis and Brandis (2021).
- Other complementary monitoring including the Commonwealth Environmental Water Office (CEWO) Environmental Water and Knowledge Research Project (EWKR) (McGinness et al. 2019).

2.5 Analyses

2.5.1 Relationships between observed data

We analysed observed waterbird data from Barmah-Millewa and Gunbower-Koondrook-Perricoota forests collected as part of annual surveys. We looked at patterns in numbers of species, total abundance, and abundance of each functional response group (ducks, herbivores, large waders, piscivores) in response to cumulative river flows and inundated area (for a given mapped image date) using Generalized Linear Models with a QuasiPoisson distribution (R Development Core Team 2022). Shorebirds were not recorded regularly in the wetland areas and so this group was not included in the either the aerial or ground survey functional group analysis.

We calculated cumulative flows at 10, 30, 60, 90, 120 and 180 days prior to the aerial and ground surveys for each water year using data from the main river gauges to investigate flow predictors of waterbird responses (Table 6). For Barmah-Millewa Forest we used estimated area of inundation from Landsat imagery to calculate maximum inundation area for each water year and for three months preceding the aerial and ground surveys. Due to limited availability of mapping across the water year for Gunbower-Koondrook-Perricoota Forest we used estimates of inundated area for mapped dates in October each year closest to the time of the spring aerial surveys (Table 6). Many of the images covering Gunbower-Koondrook-Perricoota Forest were cloud effected and so we used the image with the smallest inundated area in October (a cloud free image) for each year to minimise the potential for overestimating total inundated area.

Modelling of waterbird responses to river flows and inundated area for Gunbower-Koondrook-Perricoota Forest was focused on the long-term aerial survey data only (Kingsford et al. 2020). There were only three ground survey sites in the Koondrook-Perricoota Forest that had repeat surveys over the 2008-2021 period (Pollack Lagoon, Pollack Swamp, Swan Lagoon) (see details on ground survey data coverage above). We were also unable to undertake detailed analysis of breeding responses in Gunbower-Koondrook-Perricoota Forest because of too few breeding records for the past 20 years.

For waterbird ground survey data collected in Barmah-Millewa Forest, we analysed annual waterbird responses at both the individual wetland scale and the entire floodplain scale recorded during spring ground surveys only. At the floodplain scale, we adjusted for survey effort by estimating waterbird densities for each of the 13 survey sites by dividing total waterbird abundance by the delineated survey area (in hectares) (Webster, R. pers. comm, 2015) (see Table 5). At the wetland scale we modelled waterbird abundances in response to cumulative flow volumes with an interaction term with wetland, thereby allowing for differential responses in each wetland. At the floodplain scale, we used the annual average waterbird density across the 13 wetlands and the maximum waterbird species recorded across all the 13 wetlands combined. For both scales, we also modelled waterbird responses for four functional response groups as well as for total waterbird species. For the wetland scale, we modelled waterbird responses using Generalized Linear Models using Generalized Linear models, using a Quasi-Poisson distribution (R Development Core Team 2022).

For the Barmah-Millewa Forest colonial waterbird breeding analysis, we calculated 10, 30, 60, 90, 120 and 180-day cumulative river flows prior to the 1st of November each year. This date represented the approximate start of nesting for most species in most years in the historical colonial waterbird breeding dataset with the start date of breeding not consistently recorded in early years. This approach was undertaken to represent conditions in the forest that would have triggered colonial waterbird breeding. We also included estimated area of inundation determined from Landsat imagery to calculate maximum inundation area for each water year and for three months preceding the breeding season (August-October).

We used available colonially-nesting waterbird breeding records to investigate how river flow and floodplain inundation influenced the likelihood of breeding in 16 colonial waterbird breeding species. Historical breeding records for Barmah-Millewa Forest were available back to 1905 (Leslie 2001; Ward 2011) but we were limited to the period from 1961 onwards due to lack of gauged river flow data pre-1960. We focused on the presence/absence of breeding only as the historical data series was not comprehensive enough to have consistent records of failed and successful events. We used Generalized Linear Models, with a Binomial distribution to analysis waterbird breeding responses to flows and inundation area (R Development Core Team 2022). We modelled number of breeding species and individual breeding species responses for 13 colonially-nesting species in total (see Table 9) that had sufficient records (>10 years) using Generalized Linear Models with a Poisson distribution (R Development Core Team 2022).

Given high correlation among cumulative flows explanatory variables (see Appendix 3), we limited models to only a single explanatory variable. We evaluated model performance of each explanatory variable using the Akaike's Information Criterion (AICc), considering best fit models within ΔAICc≤2. Analyses were implemented in R (R Development Core Team, 2022). We were not able to make combined models incorporating the flow and inundation variables to look at the best predictors due to too few data. Rather we developed individual response models using the cumulative river flow and inundated area predictors (Table 6).

Table 6 Explanation of model codes used in the analysis.

Model Code	Details
	Cumulative river flows
10D	Cumulative river flows at nearest gauge 10 days prior to the survey date/ start of breeding season
30D	Cumulative river flows at nearest gauge 30 days prior to the survey date/ start of breeding season
60D	Cumulative river flows at nearest gauge 60 days prior to the survey date/ start of breeding season
90D	Cumulative river flows at nearest gauge 90 days to the survey date/ start of breeding season
120D	Cumulative river flows at nearest gauge 120 days to the survey date/ start of breeding season
180D	Cumulative river flows at nearest gauge 180 days to the survey date/ start of breeding season
	Inundated area
MaxInun	Maximum inundated area is from the mapped image date with the largest inundated area in the water year (Jul-Jun)
MaxInun3M	Maximum inundated area is based on the mapped image date with the largest inundated area in the 3 months prior to the surveys/ start of breeding season
InunOct	Minimum inundated area closest to the time of the spring aerial surveys (Gunbower-Koondrook-Perricoota only)

2.5.2 Comparison of flow scenarios

We compared predicted waterbird responses (species richness, abundance, breeding (Barmah-Millewa only)) for each flow scenario. To do so, we used response models developed as part of this project which identified to the best single parameter (either flows or inundation) for predicting waterbird responses. We used the modelled Source river flow time series (1896-2019) and predicted inundation extents from the RiM-FIM modelling (1896-2019) to generate predicted flows and inundation for the 124-year time series (noting we did not include the first year (1895) of the modelled time series). The predicted waterbird responses for the modelled time series were summarised in box plots and kernel density plots which show the distribution of the modelled response variables for each scenario.

We also examined modelled river flow data to determine the likelihood of changes to the availability of waterbird habitat in Barmah-Millewa Forest and Koondrook-Perricoota Forest under different relaxed constraints scenarios. Defined flow thresholds from the LTWP (DPIE 2020) (see Table 2) were used to assess the influence on the flow scenarios on the number of flow events for bankfull, small overbank, medium overbank and large overbank events.

A spells analysis was also undertaken to determine the number of small and medium-sized overbank events of different durations that would inundate Barmah-Millewa Forest and Gunbower-Koondrook-Perricoota Forest. The spells analysis identified events of different durations (in days) with a new event defined as any event where the overbank thresholds were met at the main river gauges more than 5 days after another event. There was a within event gap tolerance of 5 days. This meant the flow could drop below the threshold for up to 5 days and even if it goes back up again it will not break the event. We did not incorporate seasonality of flows in this analysis and events were spilt across water years. However, we did look at the frequency and duration of different flow events of different magnitudes across the modelled flow time series (1896-2019) in terms of differences across the pre-breeding season (August-October) and calendar year (January-December).

The upper limit of targeted flow extents in Barmah-Millewa Forest determined by hydraulic modelling was used to assess whether key waterbird sites were likely to be inundated under available flow scenarios. Locations of key waterbird sites in both study areas were overlayed with predicted inundated wetland extent under current constraints and relaxed constraint scenarios that were available from a combination of RiM-FIM and hydraulic modelling outputs made available to the EBA project. The hydraulic model outputs provided to the EBA project were limited to Barmah-Millewa Forest and Koondrook-Perricoota Forest (only). A combination of RiM-FIM and hydraulic modelling outputs was also available that covered both Gunbower and Koondrook-Perricoota forests. These outputs provided the most reliable upper end (conservative) estimates of predicted inundated areas for all flow scenarios, however, the hydraulic model outputs (alone) do not represent the influence infrastructure has on flow delivery options or on maintaining inundation of key sites.

3. Results – Barmah-Millewa Forest

3.1 Current condition

Sixty-one waterbird species have been recorded in Barmah-Millewa Forest in the last decade (Appendix 2) and this site regularly supports the nationally endangered Australasian bittern. Recent aerial surveys have shown the forest can support a range of waterbird species including large numbers of large waders, such as ibis, egrets and spoonbills, in years when the forest is inundated. For example, numbers of large waders peaked in spring 2012 and spring 2016 following high natural river flows (Figure 9). Numbers of waterbird species were relatively low in the 2007-2010 period at the end of the millennium drought but have remained relatively stable from 2011 onwards (Figure 9).

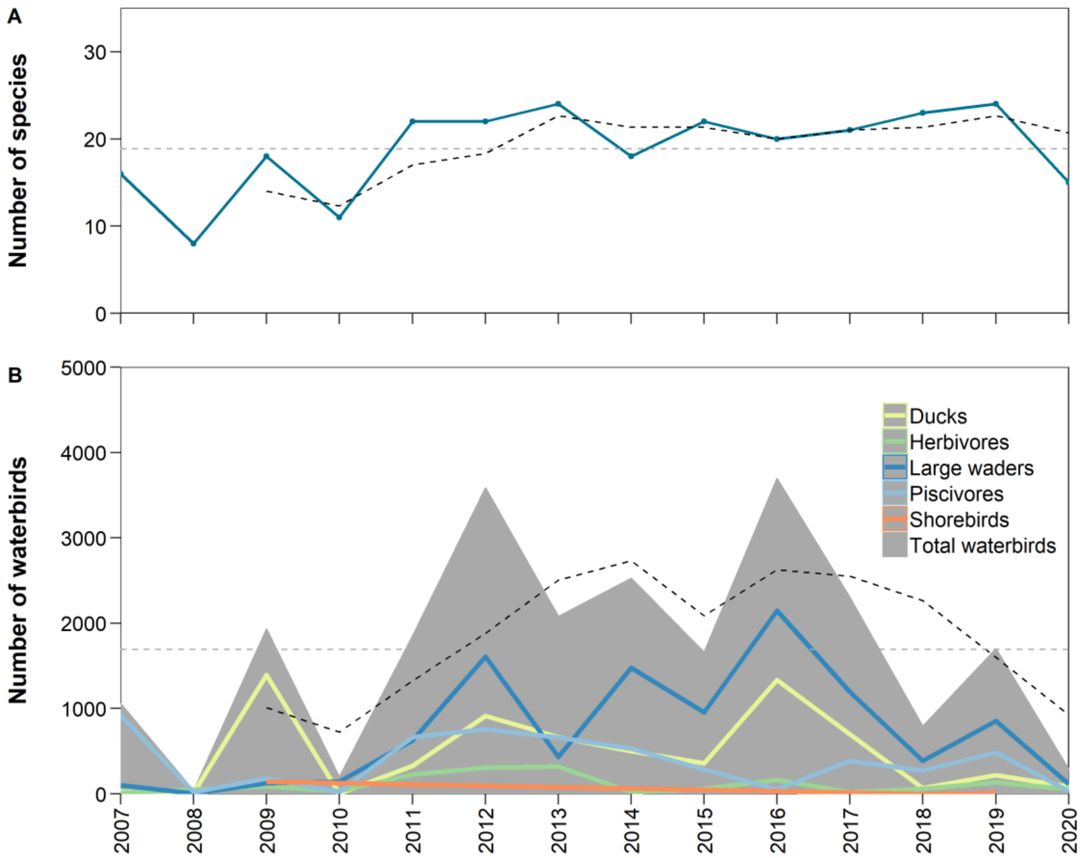


Figure 9 Total number of waterbird species – solid blue line (A) and total waterbird abundance (filled grey area (including abundance of each functional group) (B) recorded during annual spring aerial surveys of Barmah-Millewa Forest (Kingsford et al. 2020). The grey dotted line in each figure represents the long-term average, and the black dotted line is the 3-year rolling average for the 2007-2020 period.

Several sites across Barmah-Millewa have supported colonial waterbird breeding in the past. Locations where birds have been confirmed breeding include main depressions and lagoons, with large areas of common reed on both sides of the river (see Table 7). Many of these sites have been used over multiple years and following large overbank events, these sites have supported several thousand straw-necked ibis, intermediate egrets, nankeen night-herons and little pied cormorants.

Millewa Forest has at least 17 known colonial waterbird breeding sites including cormorant and darter nesting sites in lakes and lagoons, and larger ibis and spoonbill colonies in the Reedbed complex in most years when the site is inundated. Barmah Forest also supports colonial waterbird breeding at several locations (at least 19 sites have been documented). This includes nesting ibis and spoonbills in Reedy Lagoon and Boals Deadwood in recent years and Barmah Lake and Top Island (Figure 5) in the last decade (see Table 7).

In the last two decades widespread colonial waterbird breeding activity in Barmah-Millewa Forest was recorded in 2000, 2005, 2010-11, 2016-2017 (and most recently in 2021-2022) when colonies of egrets, herons and ibis established. These events coincided with large overbank flows that inundated large parts of the forest for many months. Large and medium overbank flows occurred more frequently prior to 2000 and there was a long interval with minimal overbank flows entering the forest in the 2007-2010 period (Figure 10).

In the 2000 event there was an estimated 400 nests of intermediate egrets at Moira Lake (Millewa Forest), and around 2,000-3,000 nankeen night-heron nests recorded across multiple sites in the forest including Porters Plain (Millewa Forest). There was also a record of more than 1,000 pairs of egrets and night-herons nesting in 2005-2006 in Barmah Forest and around 2,500 nankeen night-heron nests near Picnic Point were recorded in 2010-2011 along with several hundred nesting egrets.

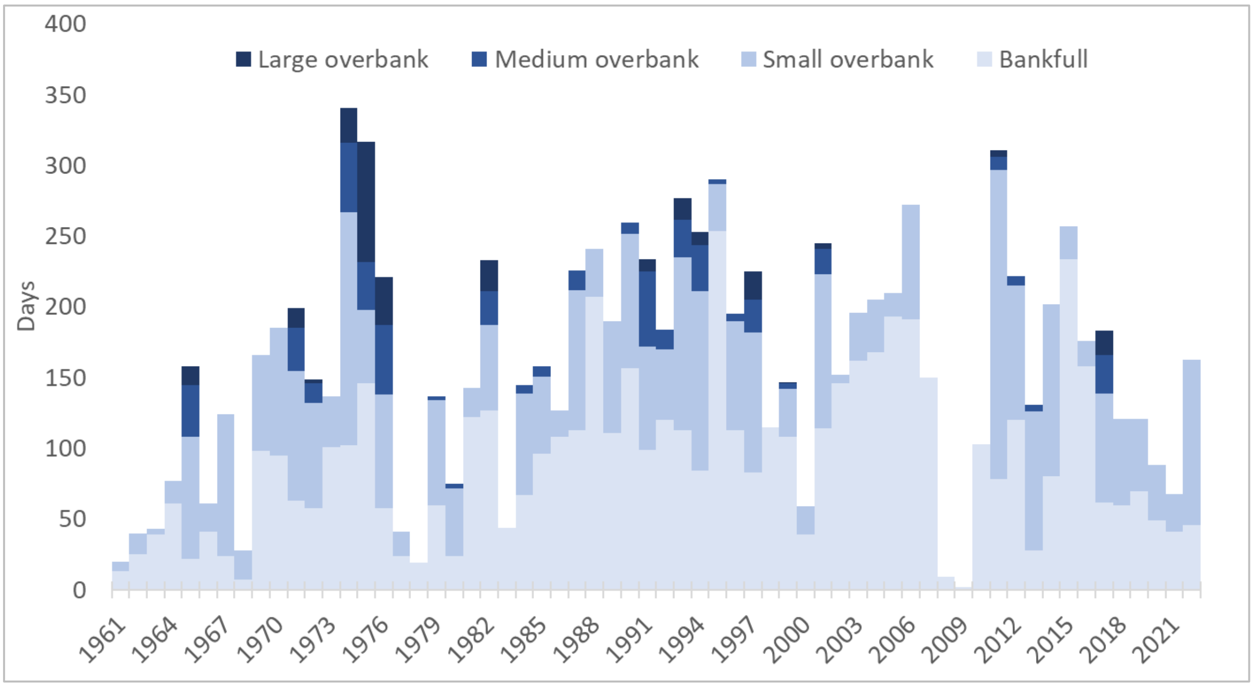


Figure 10 Number of days flows in the River Murray downstream of Yarrawonga Weir met thresholds for bankfull (10,000-15,000 ML/Day), small (>15,000-50,000 ML/Day), medium (>50,000-80,000 ML/day) and large (>80,000 ML) overbank events in the 1961-2021 period.

Millewa Forest and the neighbouring Niemur Precinct also supported several thousand nesting nankeen night-herons in the 2016-2017 flood event as well as nesting ibis and egrets. Little pied cormorants, little black cormorants, Australian white ibis and straw-necked ibis, for example, can nest regularly in Barmah-Millewa Forest after smaller and medium overbank events when the main lagoons and wetlands are filled over spring and summer months. Species like cattle egrets, yellow-billed spoonbills, pied cormorants, and glossy ibis have only bred in small numbers in Barmah-Millewa Forest and in fewer locations. There are at least 8 colony sites in Barmah Forest and 3 colony sites in Millewa Forest that have not been used in the last decade (see Table 7). The Duck Lagoon colony site was damaged by bushfire in 2008 and it took a few years for vegetation to re-establish for ibis and spoonbill nesting (P. Childs, DPE, pers. comm. 2022).

Table 7 Locations where colonial waterbirds have been confirmed breeding in Barmah-Millewa Forest (records for the 1905-2021 period) including total number of species recorded breeding at each site and the water year each colony site was last active. Shaded sites have not been active in the last decade.

Colony site name	Number of breeding species over entire breeding record	Water Year when breeding activity was last recorded
Barmah Forest		
Barmah Lake	10	2011/12
Boals Deadwood	5	2020/21
Budgee Creek	2	1979/80
Bullock Creek	6	1979/80
Bunyip Hole	7	2015/16
Cucumber Gully	1	1993/94
Doctor Point Swamp	4	2011/12
Goose Swamp	1	2010/11
Green Deadwoods	2	2000/01
Island Lagoon	2	1979/80
Opposite Picnic Point	3	2016/17
Pig Hole	2	2011/12
Reedy Lake	2	2020/21
Smith's Creek	2	1970/71
Steamer's Plain	2	2020/21
Tarma	2	1974/75
Top Lake	1	2000/01
Top Island	2	2011/12
War Plain	4	2011/12
Millewa Forest		
Algeboia Plain	8	2010/11
Benarca	1	2020/21
Black Swamp	8	2018/19
Coppingers Lagoon	5	2016/17
Dora Creek	N/A	1981/82
Duck Lagoon	12	2016/17
Edward River	1	2000/01
Gulpa Creek Wetlands	8	2016/17
Horseshoe Lagoon	2	2011/12
Moira Lake	9	2011/12
Picnic Point	2	2020/21
Porters Plain	4	2010/11
Reedbed Swamp	10	2020/21
St Helena Swamp	10	2020/21
Swifts Road	1	2000/01
Warrick Creek Reedbed	2	2016/17
White Swamp	3	2016/17

3.2 *Species richness*

We used estimates of total numbers of waterbird species determined from annual spring aerial (Figure 11 and Figure 12) and ground (Figure 13) surveys to investigate relationships between species richness and cumulative river flows and inundation extent. This approach showed there were generally more waterbird species recorded in Barmah-Millewa Forest with increasing river flows and area of inundation. Overall, 180-day cumulative river flows and maximum inundated area 3 months prior to the surveys were the best predictors for species richness based on the long-term aerial and ground survey data (see Table 8). Further examination of the ground survey data showed there were nuances in waterbird species responses at a wetland site level which influenced total species richness in relation to flows (Figure 13). This was expected to a large degree as each survey site differs in habitat structure (see Appendix 4) and patterns of inundation (frequency and duration).

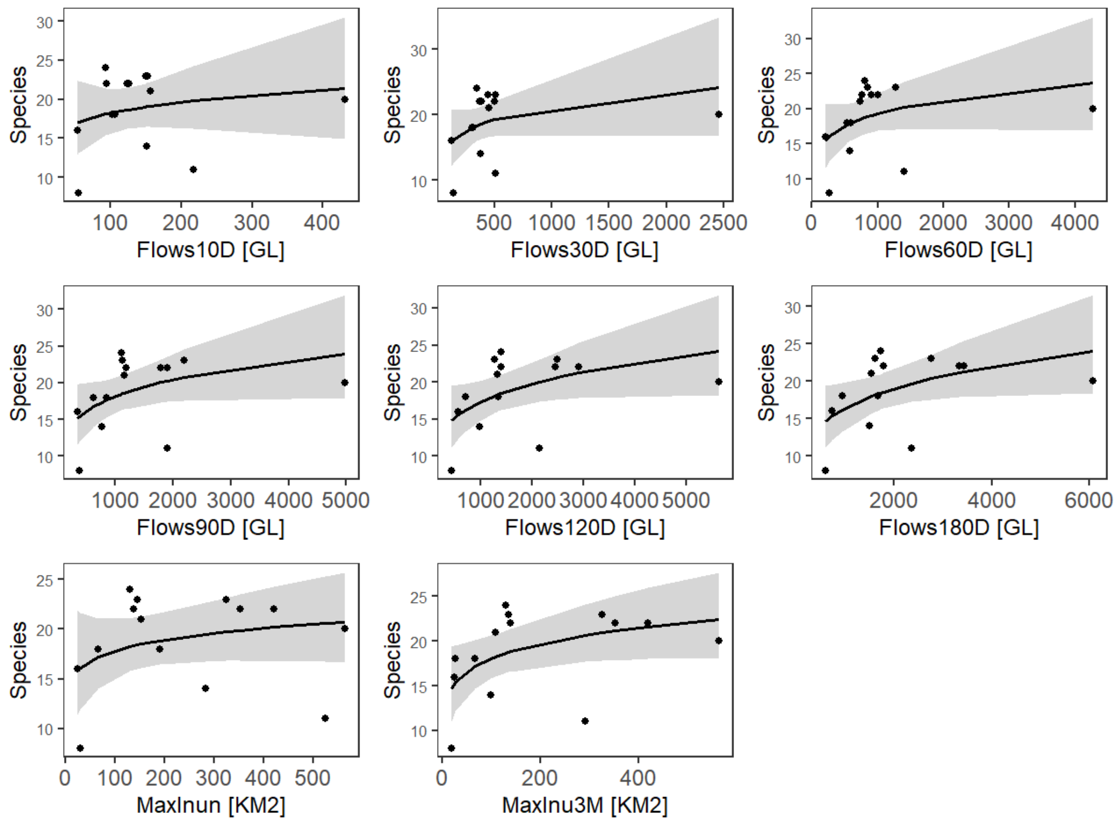


Figure 11 Waterbird species richness recorded in aerial surveys in the Barmah-Millewa forest each spring over the 2007-2020 period in relation to cumulative river flows 10, 30, 60, 90, 120 and 180 days, and maximum inundation extent over the entire water year (MaxInun) and maximum inundation extent 3 months prior (MaxInun3M, August-October) preceding the aerial surveys. The shaded areas represent the confidence intervals around the line of best fit.

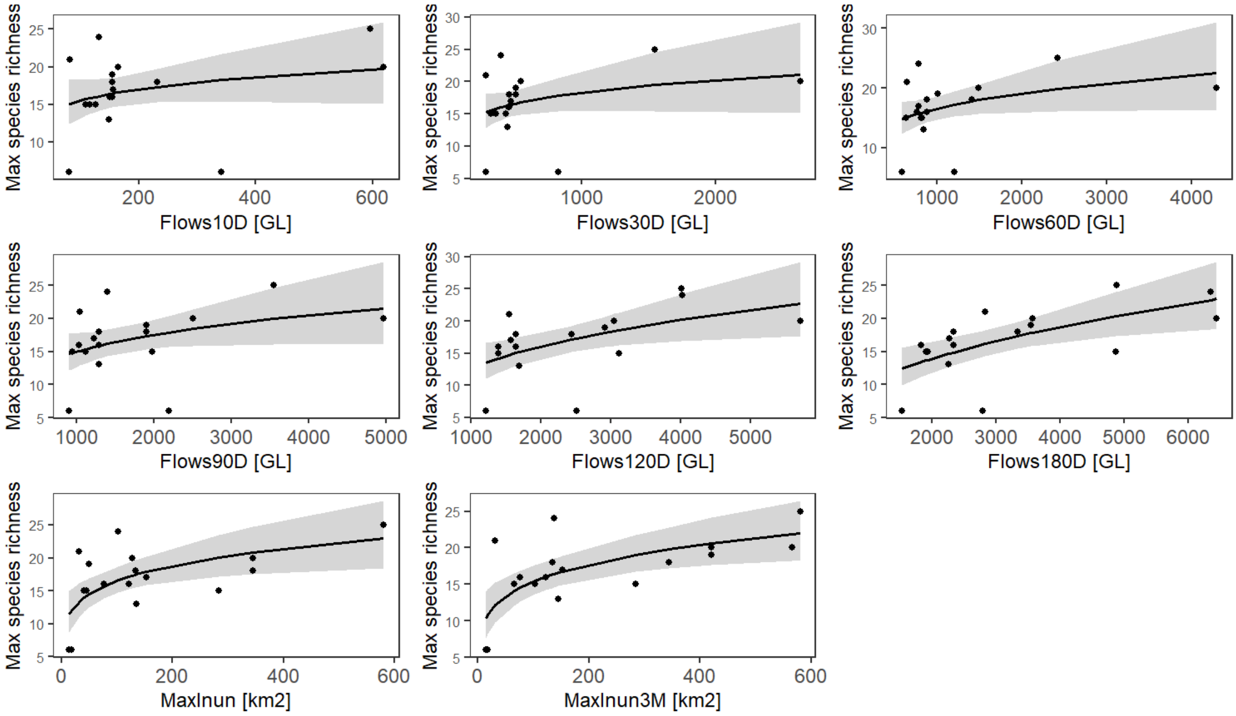


Figure 12 Waterbird species richness recorded in ground surveys in the Barmah-Millewa Forest each spring over the 1999-2020 period in relation to cumulative river flows 10, 30, 60, 90, 120, 180 days preceding the surveys, maximum inundation extent across the water year (MaxInun) and maximum inundation extent 3 months prior (MaxInun3M, August-October) preceding the ground spring surveys. The shaded areas represent the confidence intervals around the line of best fit.

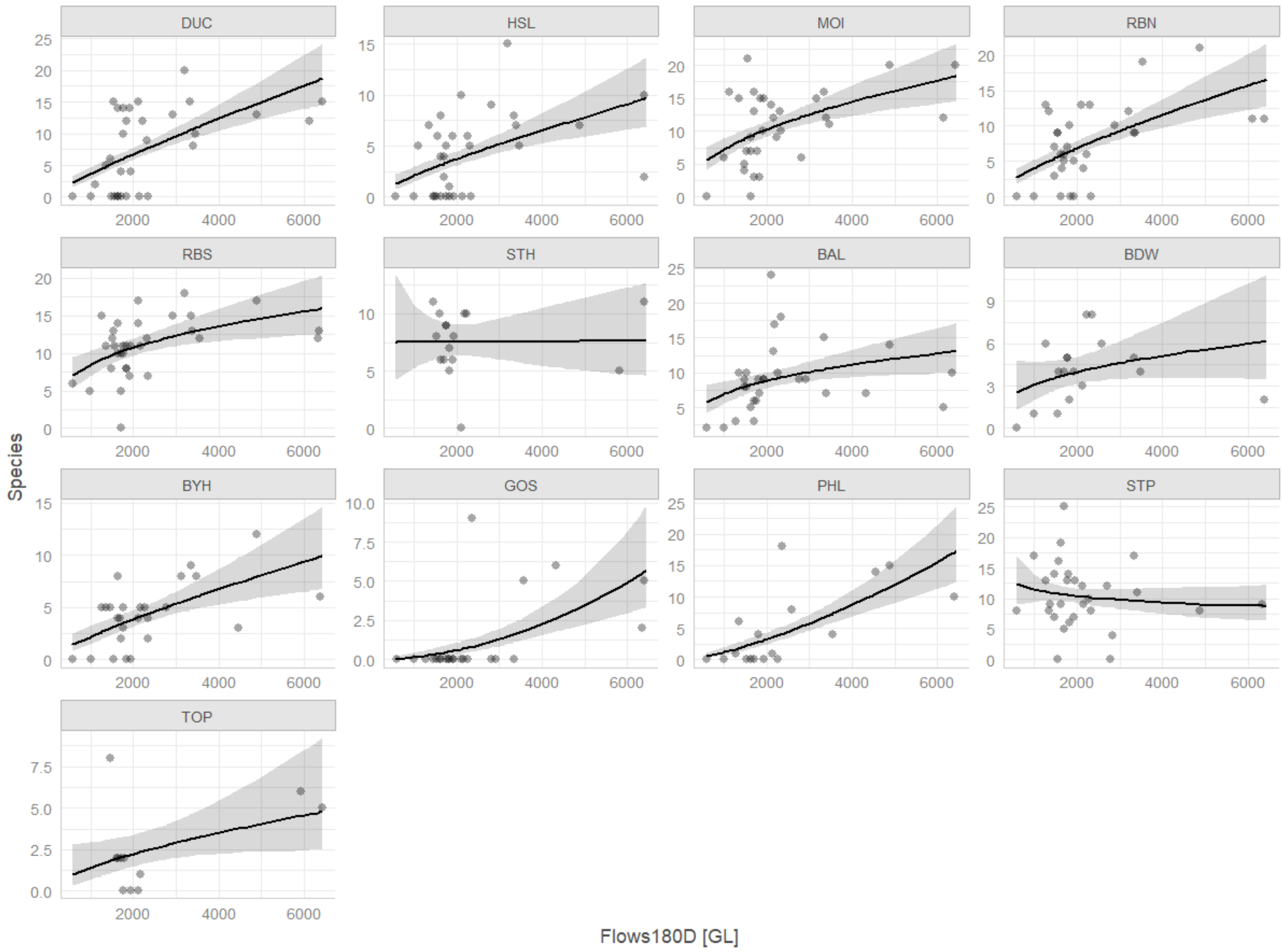


Figure 13 Waterbird species richness recorded in 13 ground survey sites in the Barmah-Millewa Forest each spring over the 1999-2020 period in relation to cumulative river flows 180 days preceding the surveys. Millewa Forest ground survey sites included Duck Lagoon (DUC), Horseshoe Lagoon (HSL), Moira Lake (MOI), Reed Beds North (RBN), Reed Beds South (RBS), and St Helena Swamp (STH). Barmah Forest ground survey sites included Barmah Lake (BAL), Boals Deadwood (BDW), Bunyip Hole (BYH), Goose Swamp (GOS), Pig Hole (PHL), Steamer Plain (STP) and Top Island (TOP). The shaded areas represent the confidence intervals around the line of best fit.

3.3 *Waterbird abundance*

We used estimates of total waterbird abundance for Barmah-Millewa Forest determined from annual spring aerial (Figure 14) and ground (Figure 15) surveys. We evaluated associations between waterbird abundance and habitat availability using cumulative river flows and inundated area. This approach showed there was generally higher waterbird abundance with increasing inundation extent for the 3 months prior to the surveys and in response to cumulative river flows of 180 days (Table 8). Further examination of the ground survey data showed there were nuances in waterbird abundance responses at a site level which influenced total numbers of waterbirds (see Figure 16) and total numbers of each guild in relation to cumulative flows (see Appendix 5). This can be explained to some degree by position of each site in the landscape and complexities in how water can be delivered to parts of the system, including the Reed Beds and Boals Deadwoods wetlands, using regulators and other infrastructure that can be used to deliver and maintain inundation of habitats.

Table 8 Summary of single-parameter model performance for total waterbird abundance and abundance of each of the five waterbird guilds based on available aerial and ground survey data collected for Barmah-Millewa Forest. Note the inundation model MaxInun3M represents maximum inundated extent in three months (Aug-Oct) prior to spring waterbird surveys.

Waterbird response variable	Top performing model	R^2
Aerial data – Floodplain scale		
Total number of species	180D, MaxInun3M	0.11
Total waterbird abundance	MaxInun3M	0.27
Total duck abundance	120D	0.31
Total herbivore abundance	MaxInun3M	0.34
Total large wader abundance	180D	0.48
Total piscivore abundance	10D	0.20
Ground data – Survey site scale		
Max species richness	180D	0.45
Total waterbird abundance	180D	0.20
Total duck abundance	MaxInun3M	0.07
Total herbivore abundance	180D	0.09
Total large wader abundance	180D	0.26
Total piscivore abundance	180D	0.22
Ground data – Floodplain scale		
Max species richness	MaxInun3M	0.52
Total waterbird abundance	MaxInun3M	0.67
Total duck abundance	MaxInun3M	0.73
Total herbivore abundance	MaxInun3M	0.90
Total large wader abundance	MaxInun3M, 120D	0.49-0.50
Total piscivore abundance	MaxInun3M	0.54

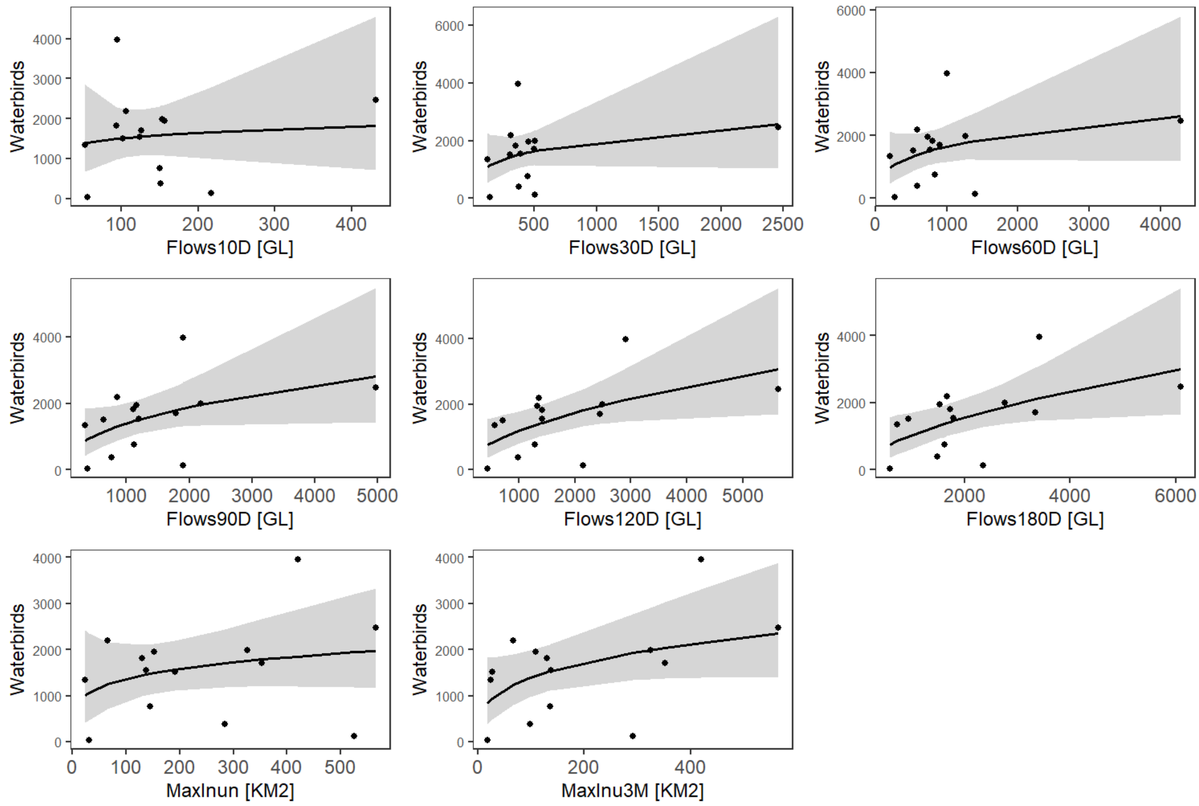


Figure 14 Total waterbird abundance recorded in aerial surveys (Kingsford et al. 2020) in the Barmah-Millewa forest each spring over the 2008-2020 period in relation to cumulative river flows 10, 30, 60, 90, 120 and 180 days preceding the surveys and maximum inundation extent over the entire water year (MaxInun) and 3 months (August – October, MaxInun3M) prior to the surveys. The shaded areas represent the confidence intervals around the line of best fit.

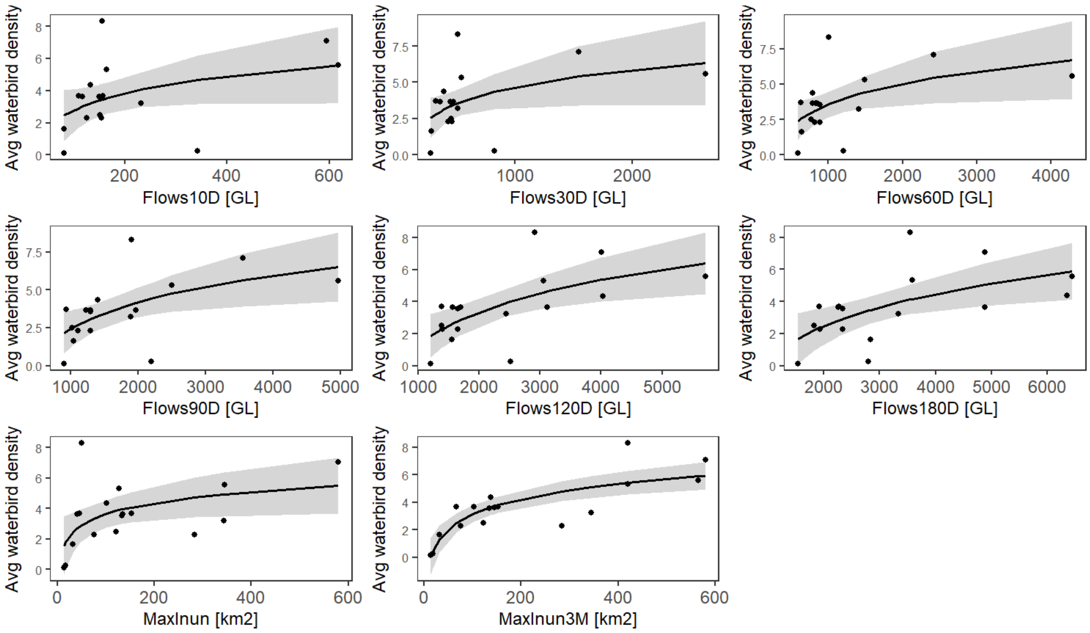


Figure 15 Average (across wetlands) waterbird density recorded in ground surveys in the Barmah-Millewa Forest (1999-2021) in relation to cumulative river flows preceding the spring ground surveys and maximum inundation extent over the month of October (Inun) and the maximum inundation extent in the August – October period (MaxInun3M) preceding the surveys.

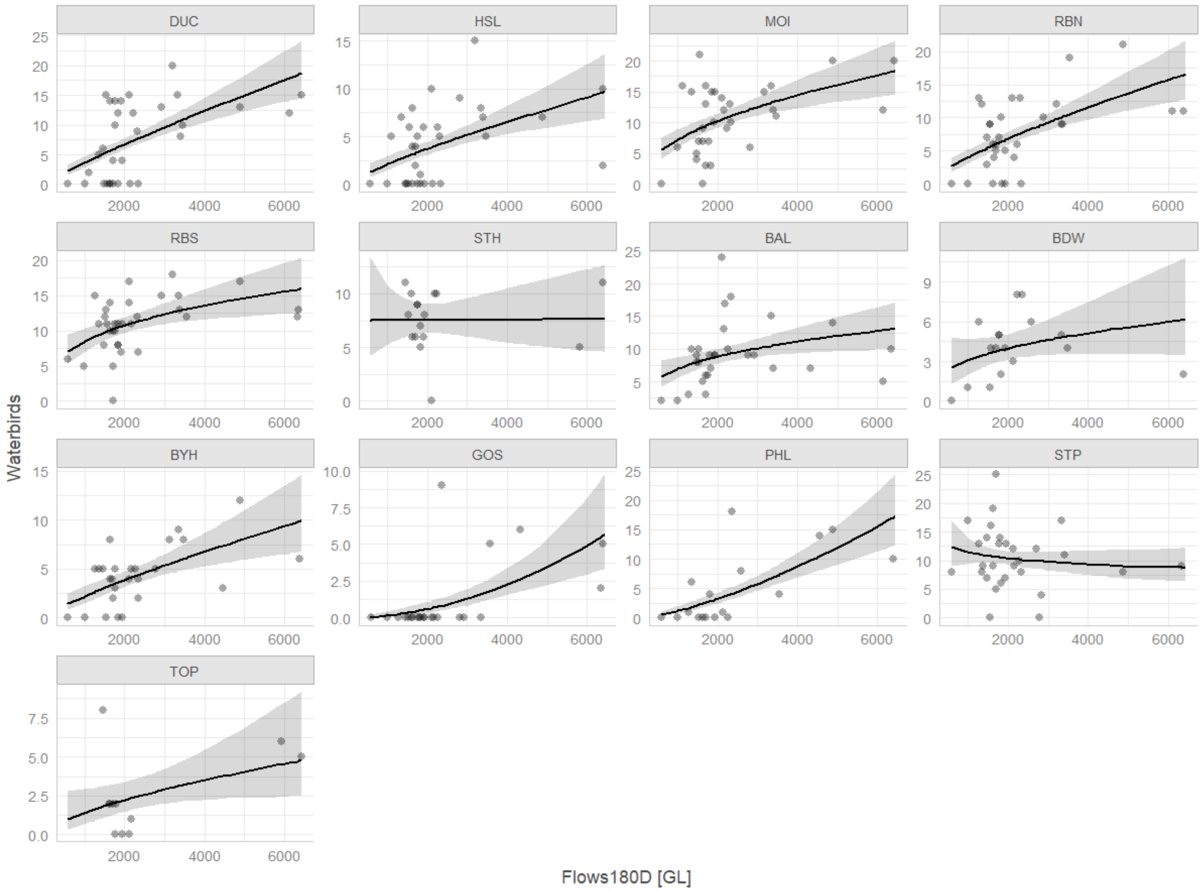


Figure 16 Total waterbird abundance recorded in spring ground surveys in the Barmah-Millewa Forest (1999-2021) in relation to cumulative river flows 180 days preceding the surveys. Millewa Forest ground survey sites included Duck Lagoon (DUC), Horseshoe Lagoon (HSL), Moira Lake (MOI), Reed Beds North (RBN), Reed Beds South (RBS), and St Helena Swamp (STH). Barmah Forest ground survey sites included Barmah Lake (BAL), Boals Deadwood (BDW), Bunyip Hole (BYH), Goose Swamp (GOS), Pig Hole (PHL), Steamer Plain (STP) and Top Island (TOP). Note that St Helena Swamp surveys commenced in spring 2014 and Top Island ground surveys commenced in spring 2015 (see Methods).

3.4 Colonial waterbird breeding

Colonial waterbird breeding is known to be closely linked to cumulative river flows as many species breed in response to large flows that inundate suitable nesting habitat. Based on studies in Barmah-Millewa (Arthur et al. 2012, Leslie 2001) and similar studies elsewhere (e.g., Brandis et al. 2018, Kingsford and Auld 2005) key metrics that are known to influence colonial waterbird breeding responses include cumulative river flows preceding the breeding season, flows over the breeding period, and the timing of flows that inundate key waterbird feeding and breeding habitats.

Colonial waterbird breeding in Barmah-Millewa can be quite regular, almost every 1-2 years in some periods, although there is a paucity of records pre-1980 for some species, and there were few records of breeding during the millennium drought period (2001-2009) (Figure 17). When examining the historical breeding records for Barmah-Millewa Forest for the whole 60-year period, we found 45 years of probable breeding (38 years of confirmed breeding) (1961-2021). Overall, the frequency of colonial waterbird breeding records was 7.5 years in 10 years (or 6.3 years in 10 years for confirmed records).

Previous studies have shown that colonially breeding ibis (straw-necked ibis and Australian white ibis) respond to threshold flow volumes as a trigger for nesting in Barmah-Millewa (Leslie 2001, Arthur et al. 2012). These thresholds have been quantified as exceedance of two flow volumes: (1) the total volume of flow > 2,300,000 megalitres (ML) for 6 months before breeding (July-December), and (2) flow > 15,000 ML per day for 30-50 days, measured downstream of Yarrawonga Weir (Leslie 2001; Arthur et al. 2012). In addition to suitable flow timing, the duration of flood events can determine the success of breeding with longer floods providing greater opportunities for building up of condition, courtship, construction of nests and egg laying, incubation, rearing and fledging of chicks (Brandis and Bino 2016).

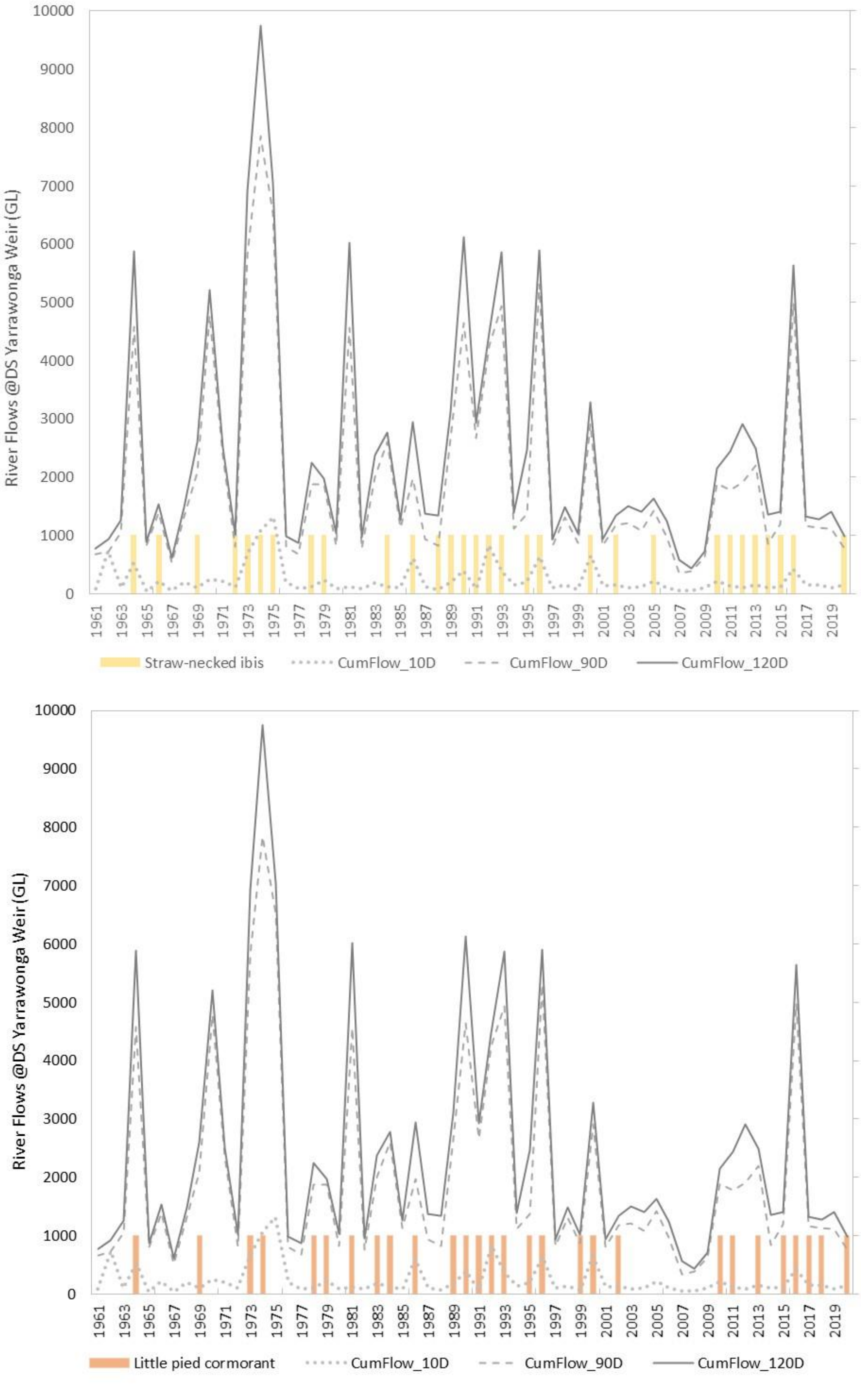


Figure 17 Occurrence of breeding records of straw-necked ibis (Large wader) and little pied cormorant (Piscivore), two common colonial waterbird species, in Barmah-Millewa Forest over the 1961-2021 period in relation to cumulative river flows at Yarrawonga (409025) preceding the main breeding period (10 days (10D), 90 days (90D) and 120 days (120D)).

We used presence/absence data for colonial waterbird breeding species in Barmah-Millewa Forest to model the impact of cumulative river flows and inundated wetland area on breeding responses including likelihood of breeding (Figure 18), and total number of breeding species over spring and summer (Figure 19). This approach suggested that a range of cumulative flow time intervals performed equally well in explaining the likelihood of colonial waterbird breeding and total number of breeding species in Barmah-Millewa Forest (Table 9 and Table 10).

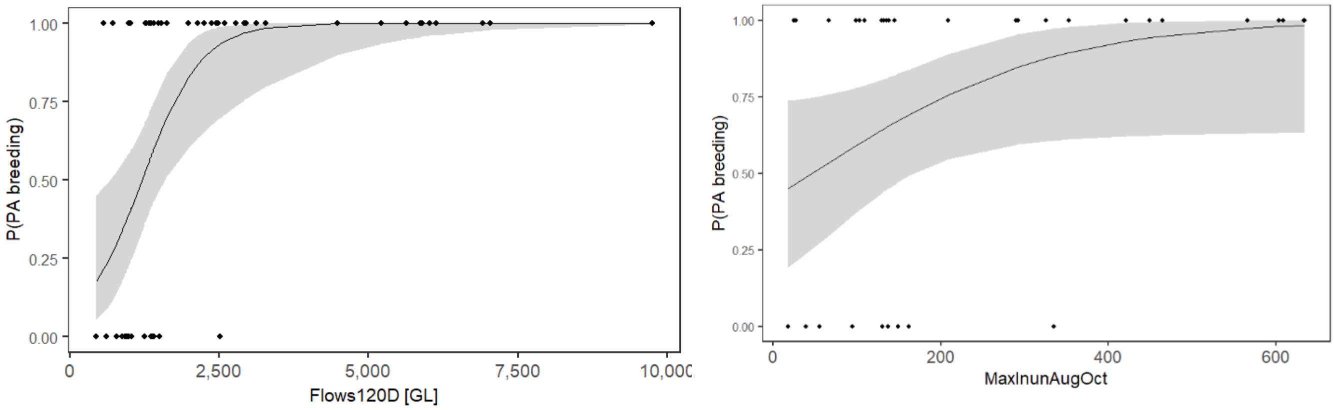


Figure 18 Modelled probability (0-1) of confirmed colonial waterbird breeding of any species (n=16) in Barmah-Millewa Forest in relation to (*left*) cumulative flows over the preceding 120 days prior to spring downstream of Yarrawonga Weir (409025, 1961-2021) and (*right*) maximum inundation extent (calculated from Landsat satellite derived inundation maps) preceding the main breeding season (August-October between 1987-2021).

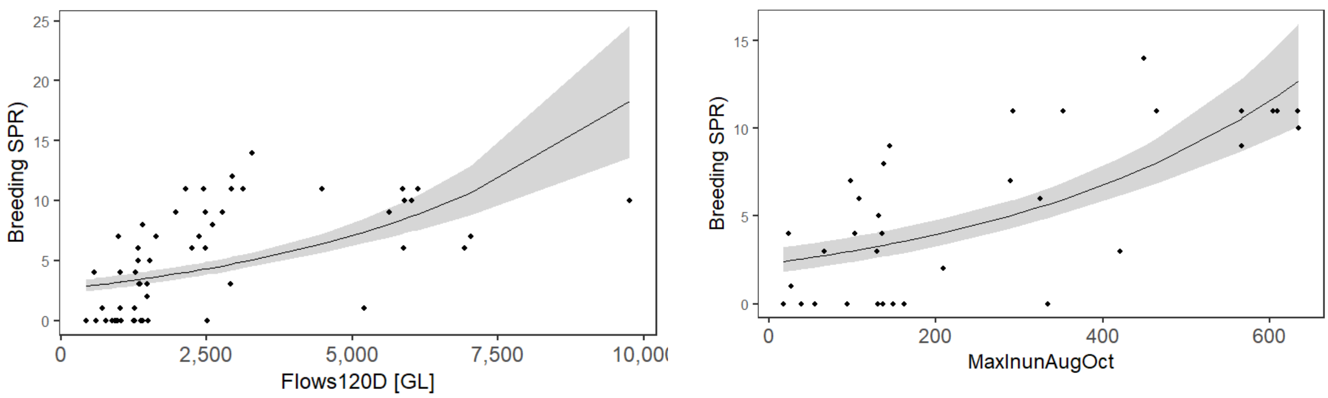


Figure 19 Total number of colonial waterbird species recorded in Barmah-Millewa Forest period in relation to (*left*) cumulative flows over the preceding 120 days prior to spring downstream of Yarrawonga Weir (409025, 1961-2021) and (*right*) maximum inundation extent (calculated from Landsat satellite derived inundation maps) preceding the breeding season (months of August-October between 1987-2021).

Table 9 Summary of single parameter model performance for colonial waterbird breeding (1961-2021).

Waterbird species	Top performing flow models (≤2AIC)	R^2 values	Number of years with confirmed records (^All records)
All species (P/A)	120D,180D,90D	0.29-0.31	41 (46)
Number of breeding species	120D	0.83	-
Piscivores			
Pied cormorant*	180D,120D,90D,10D,60D, null	0.00-0.06	4 (4)
Great cormorant	180D,120D,90D	0.18-0.20	16 (16)
Little pied cormorant	180D,120D,90D	0.23-0.26	28 (33)
Little black cormorant	90D,120D,60D,30D,180D	0.06-0.07	29 (30)
Darter	120D,90D,180D,60D,30D	0.05-0.07	20 (23)
Large waders			
Cattle egret*	10D	0.18	4 (4)
Intermediate egret	10D,180D,120D,90D	0.23-0.24	19 (27)
Little egret	10D	0.16	11 (14)
Great egret	180D,10D,120D	0.42-0.43	25 (30)
White-necked heron	120D,90D,60D,180D	0.15-0.18	15 (19)
Nankeen night-heron	All	0-0.05	25 (30)
Royal spoonbill	All	0-0.02	29 (30)
Yellow-billed spoonbill*	30D, null, 60D	0-0.05	7 (9)
Glossy ibis*	10D,180D,120D	0.08-0.11	4 (4)
Straw-necked ibis	10D	0.30	30 (34)
Australian white ibis	120D,180D	0.32-0.33	35 (38)

*Species excluded from further analysis due to insufficient data <10 years of confirmed breeding records in the 60 years of records. ^Number of years where it is likely that breeding occurred, but records are only probable were also modelled. For example, there are 41 years with confirmed records of breeding and an additional five years where it probable some colonial waterbird breeding occurred in Barmah-Millewa Forest.

Many but not all species attempted to breed when there were suitable flow events. However, there were differences among the species in terms of the best-fitting models (see Table 9 and Table 10). For piscivore species that regularly breed in Barmah-Millewa forest including little pied cormorant (28 confirmed years of breeding) the cumulative river flows of longer duration (>90 days) were the best predictors of breeding response (Figure 20, Table 9). For large wader species including straw-necked ibis (30 years of confirmed breeding records), great egret (25 years of confirmed breeding), intermediate egret (19 years of confirmed records) and little egrets (11 years of confirmed records) shorter cumulative flows of 10 days duration could also be linked to recorded breeding responses (Figure 21, Table 9).

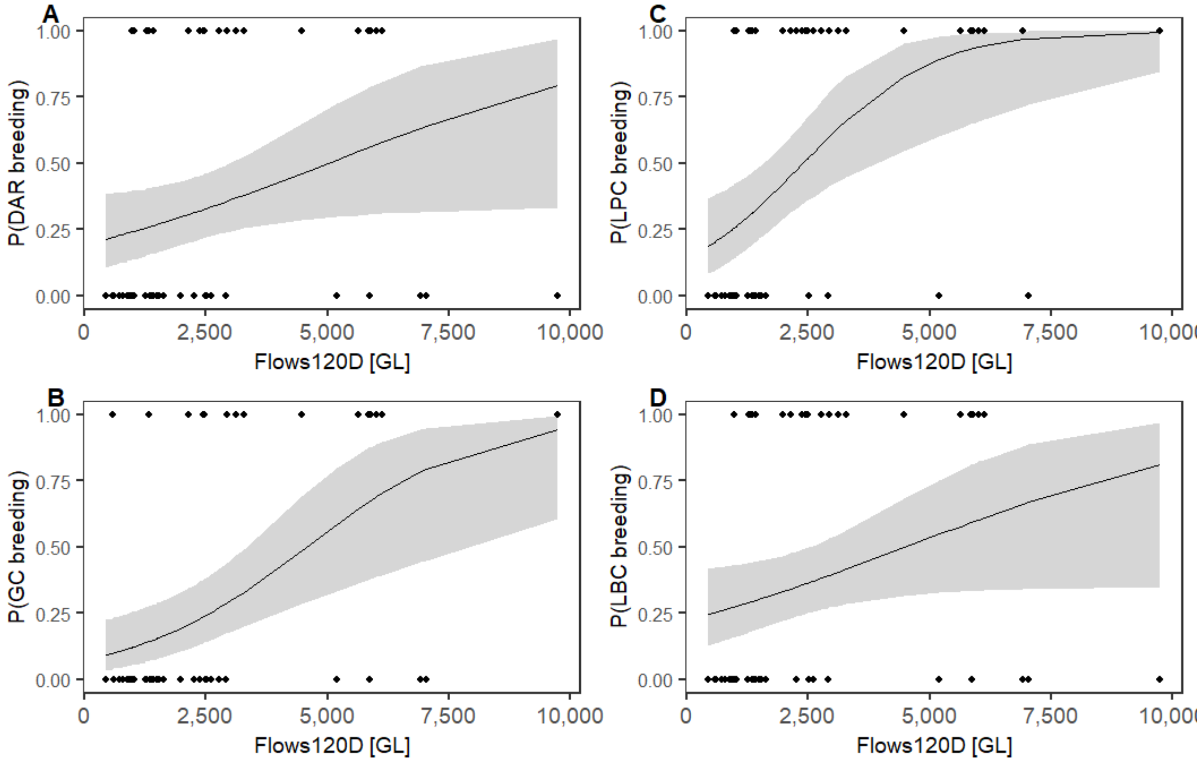


Figure 20 Piscivore breeding responses ((1) present and absence (0)) in relation to flow volumes, in this example 120-day cumulative river flows. A – Australian darter (DAR), B – great cormorant (GC), C – little pied cormorant (LPC), D – little black cormorant (LBC).

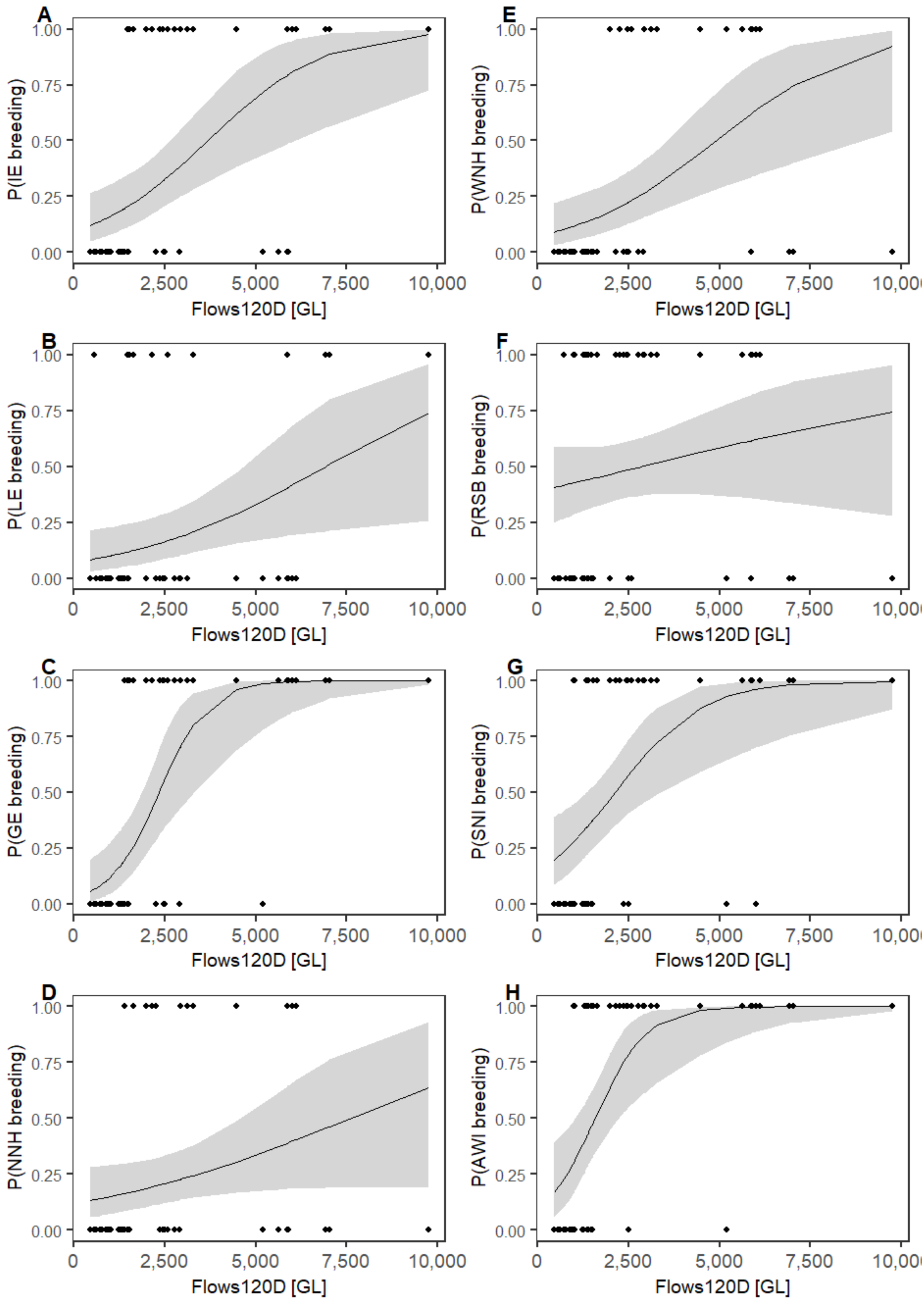


Figure 21 Large wader breeding response ((1) present and absence (0)) in relation to flow volumes, in this example 120-day cumulative river flows. A -Intermediate egret (IE), B – Little egret (LE), C – Great egret (GE), D – Nankeen night-heron (NNH), E – White-necked heron (WNH), F –Royal spoonbill (RSB), G – Straw-necked ibis (SNI), H – Australian white ibis (AWI).

When inundated area was included the likelihood of breeding in intermediate egrets (8 years of confirmed records) and nankeen night-herons (9 years of confirmed records), which are both large wader species that can nest together in the same colonies, was linked to the magnitude of wetland inundation in the months prior to the breeding season (see Table 10).

Table 10 Summary of single parameter flow model performance for colonial waterbird breeding (1987-2021, including inundation extent).

Waterbird species	Top performing flow models (≤2AIC)	R^2 values	Number of years with confirmed records (^All records)
All species (P/A)	180D,120D	0.20-0.18	25 (28)
Number of breeding species	180D, MaxInun3M	0.86-0.85	-
	Piscivores		
Pied cormorant*	180D,120D,90D,10D,60D, null	0.00-0.05	2 (2)
Great cormorant	180D,120D,90D	0.43-0.44	13 (13)
Little pied cormorant	90D,30D,180D,60D,10D	0.35-0.39	18 (20)
Little black cormorant	30D,90D	0.44-0.47	17 (20)
Darter	180D,90D,10D,30D,120D,60D	0.34-0.36	16 (19)
	Large waders		
Cattle egret*	null,10D	0-0.03	2 (2)
Intermediate egret	MaxInun3M	0.27	8 (12)
Little egret*	null,10D,180D	0-0.01	4 (5)
Great egret	180D,90D,120D	0.51-0.52	13 (15)
White-necked heron	120D,180D	0.60-0.61	9 (12)
Nankeen night-heron	MaxInun3M	0.29	9 (10)
Royal spoonbill	180D,120D,90D	0.32-0.34	23 (24)
Yellow-billed spoonbill*	180D,30D,120D,90D, MaxInun3M,60D	0.08-0.12	4 (5)
Glossy ibis*	10D, null, 60D,30D,90D,120D	0-0.07	2 (2)
Straw-necked ibis	180D	0.54	19 (20)
Australian white ibis	180D,120D,90D	0.38-0.41	23 (24)

*Species excluded from further analysis due to insufficient data <5 years of confirmed breeding records in the 33-year period. ^Number of years where it is likely that breeding occurred, but records are only probable were also modelled. For example, there are 41 years with confirmed records of breeding and an additional five years where it probable some colonial waterbird breeding occurred in Barmah-Millewa Forest.

3.5 *Comparison of flow scenarios*

3.5.1 Predicted waterbird responses

The best predictor of waterbird species richness and abundance in Barmah-Millewa Forest was maximum inundated area in the 3 months prior to the spring surveys. The best predictor for the presence of colonial waterbird breeding was cumulative river flows 180 days prior to November each year. Overall, there was very little difference in the median values of predicted inundated area between current constraints of 15,000 ML/day (Y15D25) and the lower relaxed constraint scenarios of 25,000 ML/day (Y25D25) and 30,000 ML/day (Y30D30) downstream of Yarrawonga Weir. The median inundated area only increased for the higher relaxed constraint scenarios of 40,000 ML/day (Y40D40) and 45,000 ML/day (Y45D40) downstream of Yarrawonga. However, predicted cumulative river flows increased in moderate years (median, 50th percentile) for the lowest relaxed constraint scenario of 25,000 ML/day and above (Figure 22). There were also increases in predicted inundated area and predicted cumulative river flows in the drier years (25th percentile) for all the relaxed constraint scenarios compared to current constraints (Figure 22).

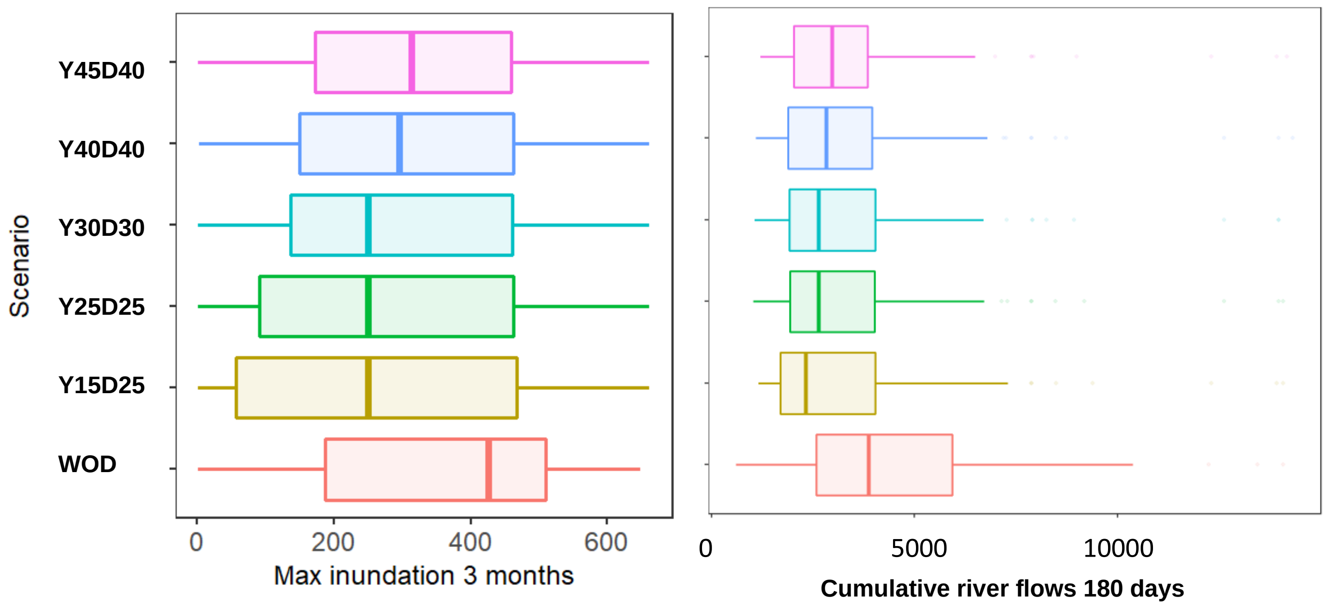


Figure 22 Boxplots showing variation in the key predictor of waterbird responses (maximum inundated area 3 months prior to the surveys (*left*) and cumulative river flows 180 days preceding the spring ground surveys (*right*) under each of the flow scenarios.

We linked the modelled inundated and flow data for each constraint to predicted waterbird responses in Barmah-Millewa Forest. Overall, these analyses indicated there were small increases in the median number of species (4-5%) and median waterbird density (10-13%) with increased relaxation of constraints downstream of Yarrawonga Weir of 40,000 and 45,000 ML/day (Figure 13 and Table 11).

The large error bars shown in Figure 23 represent natural high variability of flows and flooding in the system over 124 years. While the median (P50) and 75th percentile (P75) do not change greatly across the flow scenarios the minimum number of species (represented by the 25th percentile, P25) does increase with greater relaxation of constraints (Table 11). The 75th percentile (P75) represents wetter years when large natural flows are dominating the system. While the 25th percentile (P25) and 10th percentile (P10) represent the drier years where relaxing constraints would provide greater capacity for managed delivery of small and medium overbank flows.

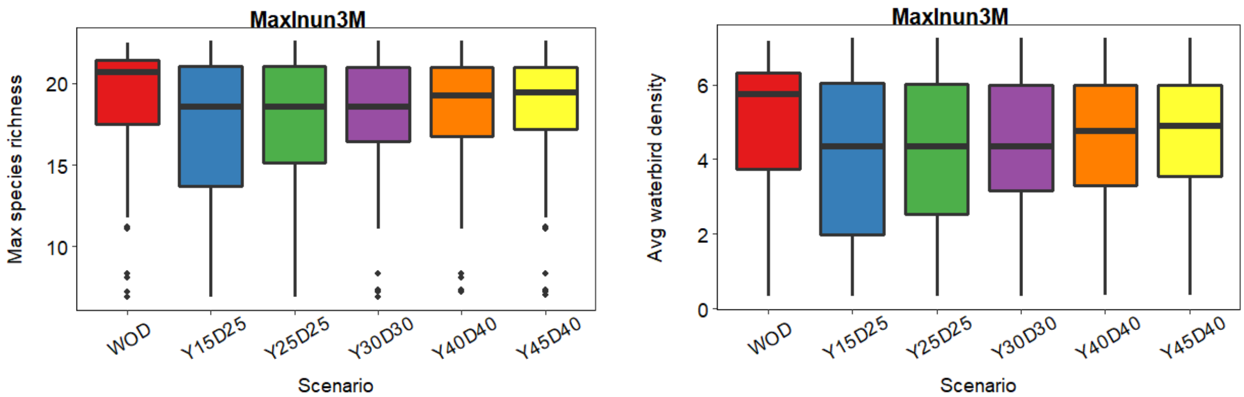
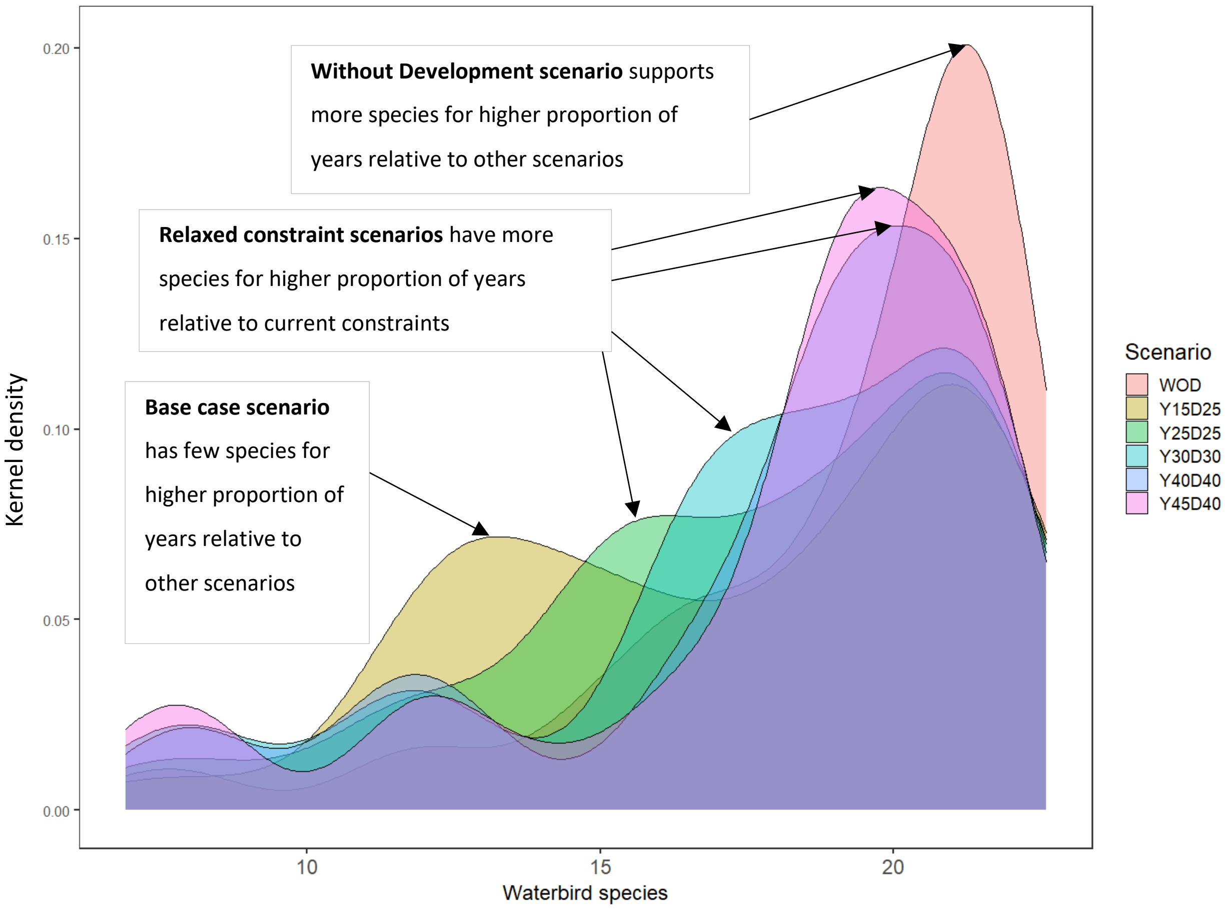


Figure 23 Predicted waterbird responses in Barmah-Millewa Forest based on the best predictor variable (MaxInun3M) for number of species (*left*) and waterbird density (birds/ha) (*right*) for the 1896-2019 period for all flow scenarios. Note that the modelled time series assumes current levels of river regulation and water extraction throughout the whole period. The base case (Y15D25) therefore does not represent actual waterbird populations under observed historical flows.

Table 11 Mean predicted species richness and waterbird density (birds/ha) plus standard deviation (SD) values and percentiles (including median, P50) are presented for each flow scenario based on the best predictor of waterbird responses (maximum inundation 3 months prior to surveys). Note that modelled responses are based on ground survey data for Barmah-Millewa Forest.

Scenario	Mean	SD	P10	P25	P50	P75	P90
Number of species							
WOD	19.11	3.43	14.48	17.51	20.69	21.45	21.89
Y15D25	17.33	4.01	12.23	13.70	18.56	21.07	21.66
Y25D25	17.65	3.88	11.86	15.12	18.56	21.03	21.57
Y30D30	17.68	4.08	11.12	16.43	18.56	21.00	21.61
Y40D40	18.03	4.00	11.24	16.73	19.22	21.02	21.55
Y45D40	18.03	4.09	11.77	17.18	19.44	20.99	21.59
Waterbird density							
WOD	4.97	1.77	2.27	3.73	5.75	6.32	6.66
Y15D25	4.02	2.06	1.46	1.97	4.33	6.03	6.49
Y25D25	4.17	1.95	1.35	2.54	4.33	6.00	6.41
Y30D30	4.22	1.95	1.14	3.15	4.33	5.98	6.45
Y40D40	4.40	1.90	1.17	3.31	4.75	6.00	6.40
Y45D40	4.42	1.90	1.32	3.55	4.89	5.97	6.43

To investigate patterns in waterbird responses we also looked at the frequency of predicted species richness and waterbird density values in more detail over the 1895-2019 period (Figure 24). The kernel density plots demonstrate how the largest relaxed constraint scenarios equivalent of 40,000 ML/day and 45,000 ML/day downstream of Yarrawonga Weir (scenarios Y40D40, and Y45D40, respectively), are likely to provide the most benefits for waterbirds in terms of increased species richness and abundance in Barmah-Millewa Forest (Figure 24).



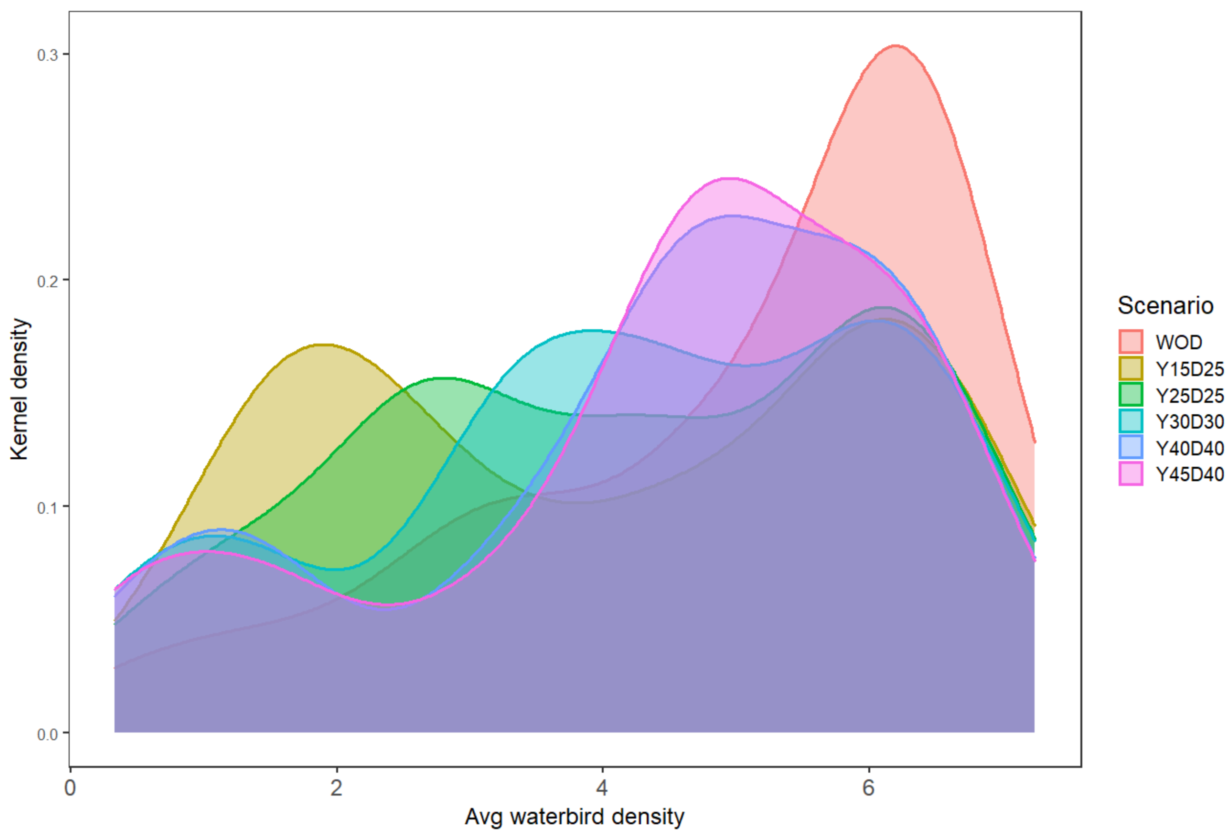


Figure 24 Summary of modelled waterbird species richness (*upper*) and waterbird density (birds/ha) (*lower*) in Barmah-Millewa Forest in each flow scenario across the modelled time series (1896-2019) when using maximum inundated area 3 months prior to surveys as the main predictor of waterbird response.

We used the same approach to compare waterbird breeding responses under the different flow scenarios. There was some increase in the probability of colonial waterbird breeding (6-11% compared to current constraints) and number of breeding species (12-24%) with increased relaxation of constraints of 25,000 ML/day and higher downstream of Yarrawonga weir (Figure 25 and Figure 26). These relative increases were in years with median (P50) conditions (Table 12). We did not observe similar changes predicted for the years that would be very wet (P75 and P90) or years that would be extremely dry (P10) (Table 12).

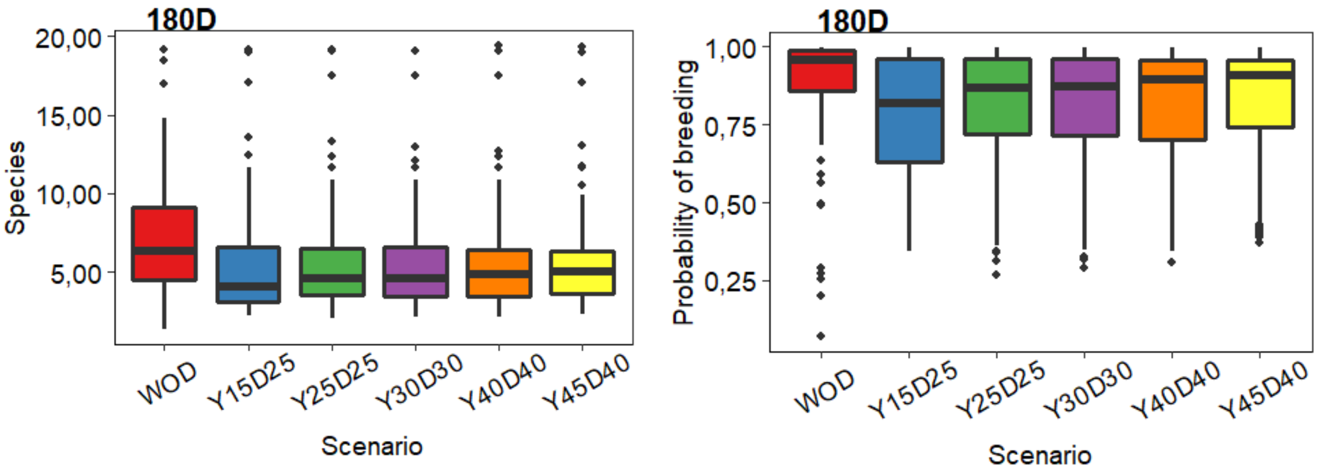
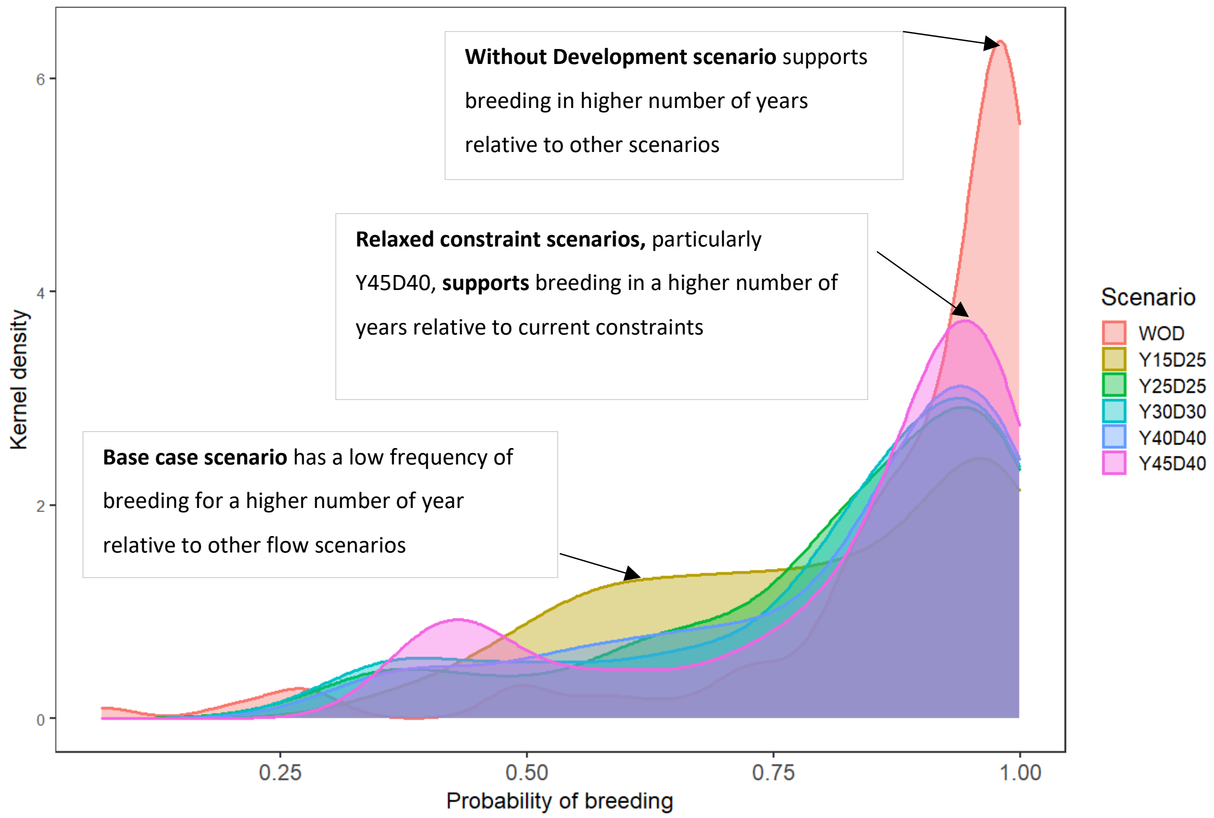


Figure 25 Predicted colonial waterbird responses in Barmah-Millewa Forest based on the best predictor variable (Flows180D) for number of breeding species (*left*) and probability of breeding (*right*) for the 1896-2019 period for all flow scenarios. Note that the modelled time series assumes current levels of river regulation and water extraction throughout the whole period. The base case (Y15D25) therefore does not represent actual waterbird breeding under observed historical flows.

Table 12 Mean predicted probability of colonial waterbird breeding and number of breeding colonial waterbird species in response to 180 days cumulative river flows are presented plus standard deviation (SD) values and percentiles (including median, P50) for each flow scenario (1896-2019).

Scenario	Mean	SD	P10	P25	P50	P75	P90
				Probability of breeding			
WOD	0.88	0.18	0.72	0.86	0.96	0.99	0.99
Y15D25	0.79	0.18	0.52	0.63	0.82	0.96	0.99
Y25D25	0.81	0.19	0.5	0.72	0.87	0.96	0.99
Y30D30	0.81	0.2	0.48	0.71	0.87	0.96	0.99
Y40D40	0.81	0.19	0.52	0.70	0.89	0.96	0.99
Y45D40	0.82	0.19	0.45	0.74	0.91	0.96	0.99
				Number of species			
WOD	7.03	3.49	3.48	4.45	6.32	9.11	11.67
Y15D25	5.38	3.3	2.73	3.10	4.07	6.54	9.68
Y25D25	5.55	3.2	2.68	3.48	4.54	6.51	9.73
Y30D30	5.56	3.19	2.62	3.45	4.56	6.54	9.72
Y40D40	5.6	3.19	2.75	3.41	4.83	6.43	9.75
Y45D40	5.61	3.1	2.54	3.61	5.03	6.28	9.5



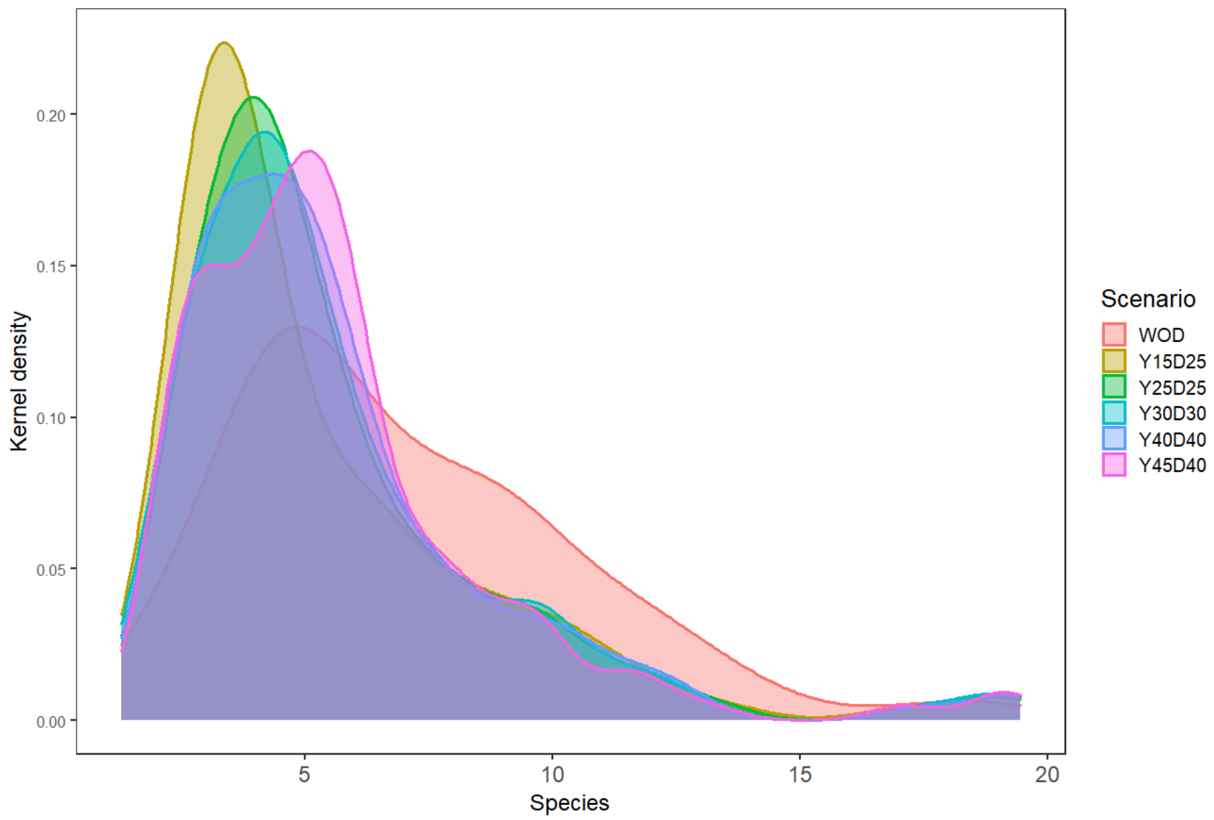


Figure 26 Summary of modelled probability of waterbird breeding (*upper*) and number of breeding species (*lower*) in Barmah-Millewa Forest in each flow scenario across the modelled 100 year-time series when using cumulative river flows 180 days prior to surveys as the main predictor of waterbird response.

3.5.2 *Predicted changes in habitat availability*

We also examined the modelled river flow data to determine the likelihood of changes to the availability of waterbird habitat in Barmah-Millewa Forest under different relaxed constraints scenarios. Flow thresholds defined in the LTWP (DPIE 2020) (see Table 2) were used to assess the influence of the flow scenarios on the number of flow events for bankfull, small overbank, medium overbank and large overbank events.

The bankfull events would inundate low-lying creeks and lagoons within Barmah-Millewa Forest which is key delivery strategy under current constraints. There was no obvious increase in bankfull events under relaxed constraints scenarios (Figure 27). However, the number of days when small overbank events, which would inundate greater areas of the forest, were recorded downstream of Yarrawonga Weir increased for all the relaxed constraints scenarios compared to current constraints (Figure 27). As expected, the modelled relaxed constraint scenarios did not influence the number of days of large overbank flows (Figure 27) as these larger flows are more heavily influenced by significant rainfall events in the upper catchment.

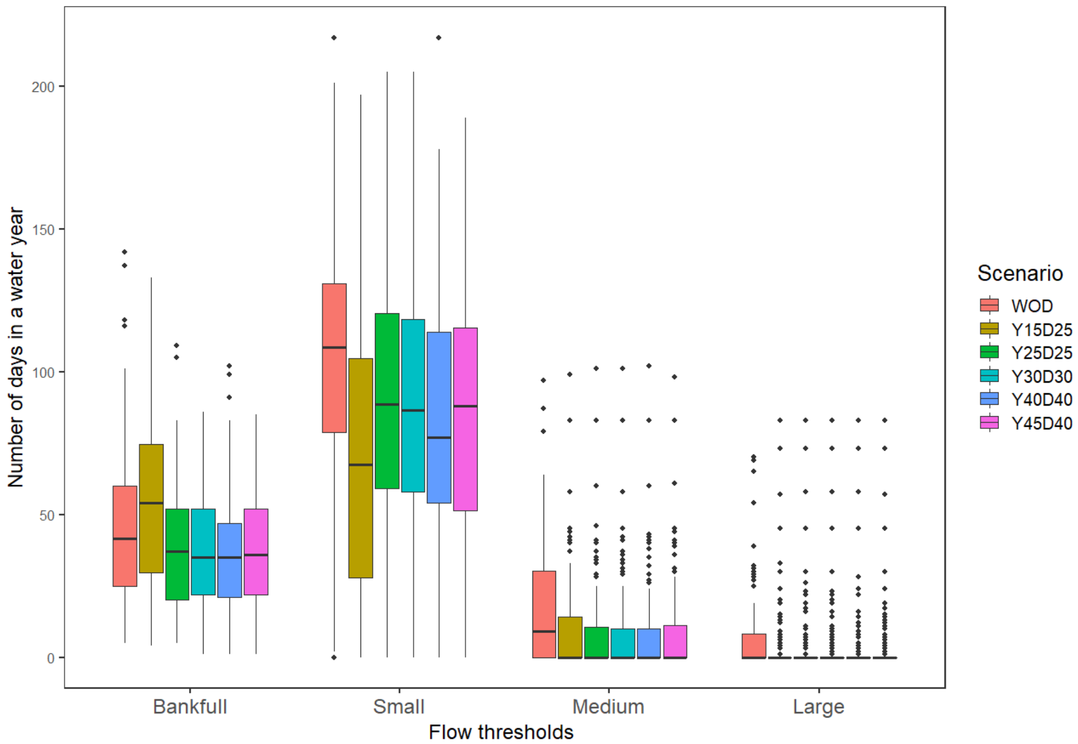


Figure 27 Number of bankfull, small overbank, medium overbank and large overbank events predicted to inundate parts of the Barmah-Millewa Forests under the different flow scenarios over the modelled 1896-2019 period at River Murray downstream of Yarrawonga Weir.

Further analysis was undertaken using a spells analysis to determine the number of small and medium-sized overbank events of different durations that would inundate Barmah-Millewa Forest. This analysis indicated that the relaxed constraints options could influence the number of small overbank flow events of more than 30 days and less than 60 days in length with increasing number of small overbanks of this duration with greater relaxed constraints. It was only the largest relaxed constraint scenario (45,000 ML/day at Yarrawonga) that could influence the number of days of medium-sized overbank events (Figure 28).

We undertook further analysis of the flow scenario data to look at how the number of suitable flow events varied across the pre-breeding and calendar year under the different flow scenarios. We focused on the number of small overbank events of a minimum 15,000 ML/day in size and of suitable duration (>45 days) thought sufficient to support small-scale waterbird breeding (DPIE 2020) or extend the duration of large and medium overbank events. The average number of suitable flow events increased from 1 in a ten-year period in the baseline scenario (Y15D25) to an average of 4 events in 10 years in the 25,000 ML/day (Y25D25) and higher flow scenarios (Table 13). The minimum threshold specified in the LTWP for these types of flows to support colonial waterbird breeding is 3 in 10 years. This threshold of 15,000 ML/day for 45 days is also contingent on ongoing flows of 9,000 ML/day for 105 days to extend the duration of inundation in key feeding and breeding habitats (such as Reed Beds Swamp) in Barmah-Millewa Forest (DPIE 2020).

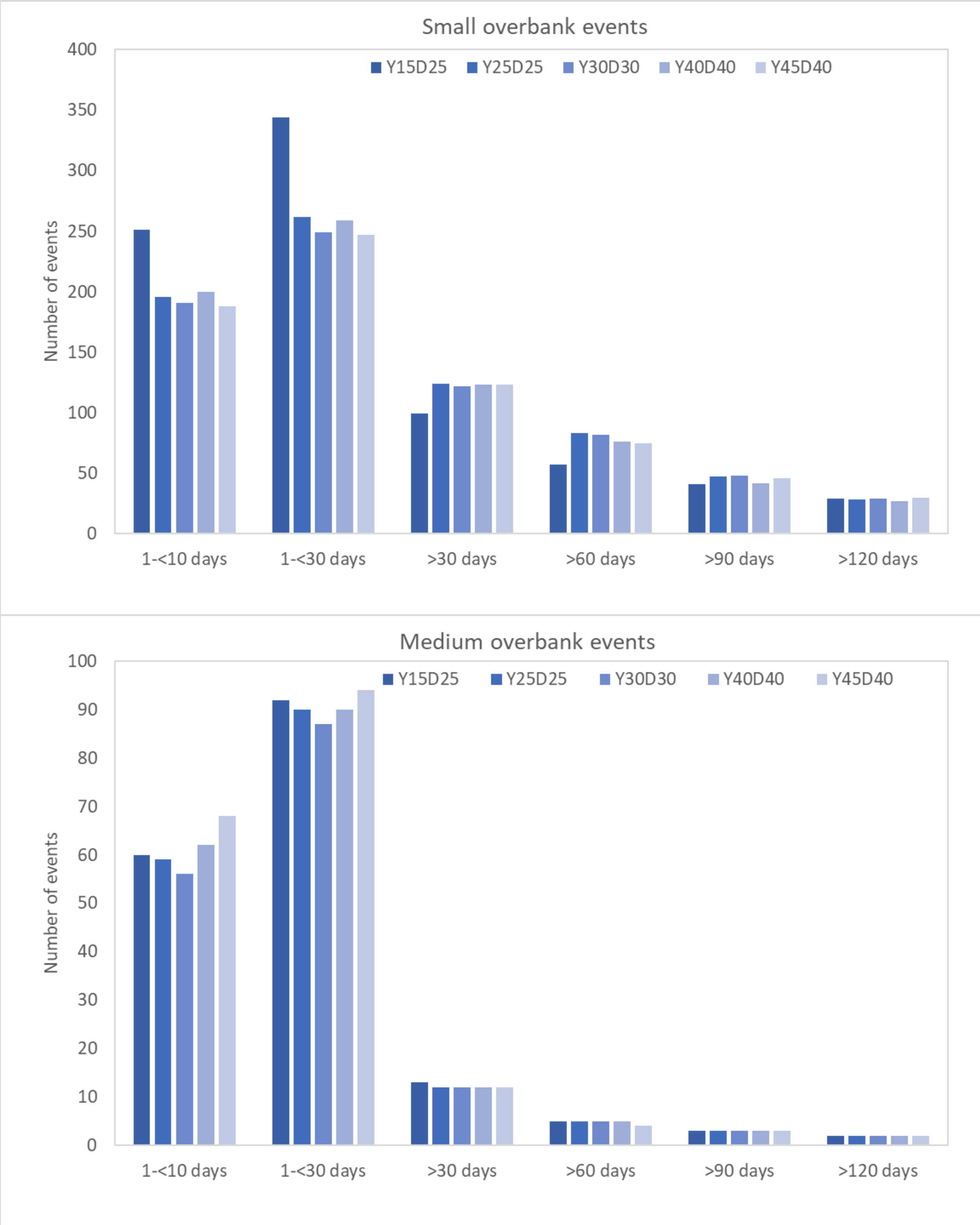


Figure 28 Results of spells analysis predicting number of events of different durations 1-10 days, 1-<30 days, more than 30 days, 60 days, 90 days and 120- days that would create small overbank events (≥15,000 ML/day) and medium overbank events (≥50,000 ML/day) in Barmah-Millewa Forest for the five flow scenarios (1896-2019). Note the y-axis are different scales in the two figures. By default, a 1-<30 days event, for example, must include the previous spell of a 10-day duration being achieved.

Table 13 Average number (per decade) of small overbank events of 15,000 ML/day or more that inundate Barmah-Millewa Forest under the modelled flow scenarios. Events of 45 days in duration were identified in the LTWP (DPIE 2020) as the minimum requirement for small-scale waterbird breeding (see detailed environmental water requirements (Appendix 1) and results of summary analyses in Appendix 6a).

Duration (days)	Y15D25	Y25D25	Y30D30	Y40D40	Y45D40
August to October 3 months prior to breeding season					
<=10	12	7	7	7	7
11-30	3	2	2	1	1
31-45	1	2	1	1	1
>45	**1**	**4**	**4**	**4**	**4**
All year (January-December)					
<=10	30	25	24	24	24
11-30	7	7	7	6	7
31-45	2	2	2	2	2
>45	**4**	**7**	**7**	**7**	**7**

The upper limit of targeted flow extents in Barmah-Millewa Forest was determined by hydraulic modelling developed for the EBA project. We used this information to assess whether key waterbird sites were likely to be inundated under available flow scenarios (15,000 ML/day (current constraints), 25,000 ML/day (Y25D25), 30,000 ML/day (Y30D30) and 40,000 ML/day (Y40D40) (Figure 29). Under current constraints (Y15D25) 10 of 13 waterbird sites were inundated in Barmah-Millewa Forest. This increased to 12 of the 13 sites for the Y25D25 scenario (25,000 ML/day downstream Yarrawonga Weir), and all waterbird sites were inundated in Barmah-Millewa Forest under the Y40D40 flow scenario (40,000 ML/day downstream of Yarrawonga Weir) (Figure 29). It is important to note that while these hydraulic model outputs provided to the EBA project provided the most reliable estimates of predicted inundated areas for all flow scenarios, they do not represent the influence infrastructure has on flow delivery options or on maintaining inundation of key sites in Barmah-Millewa Forest.

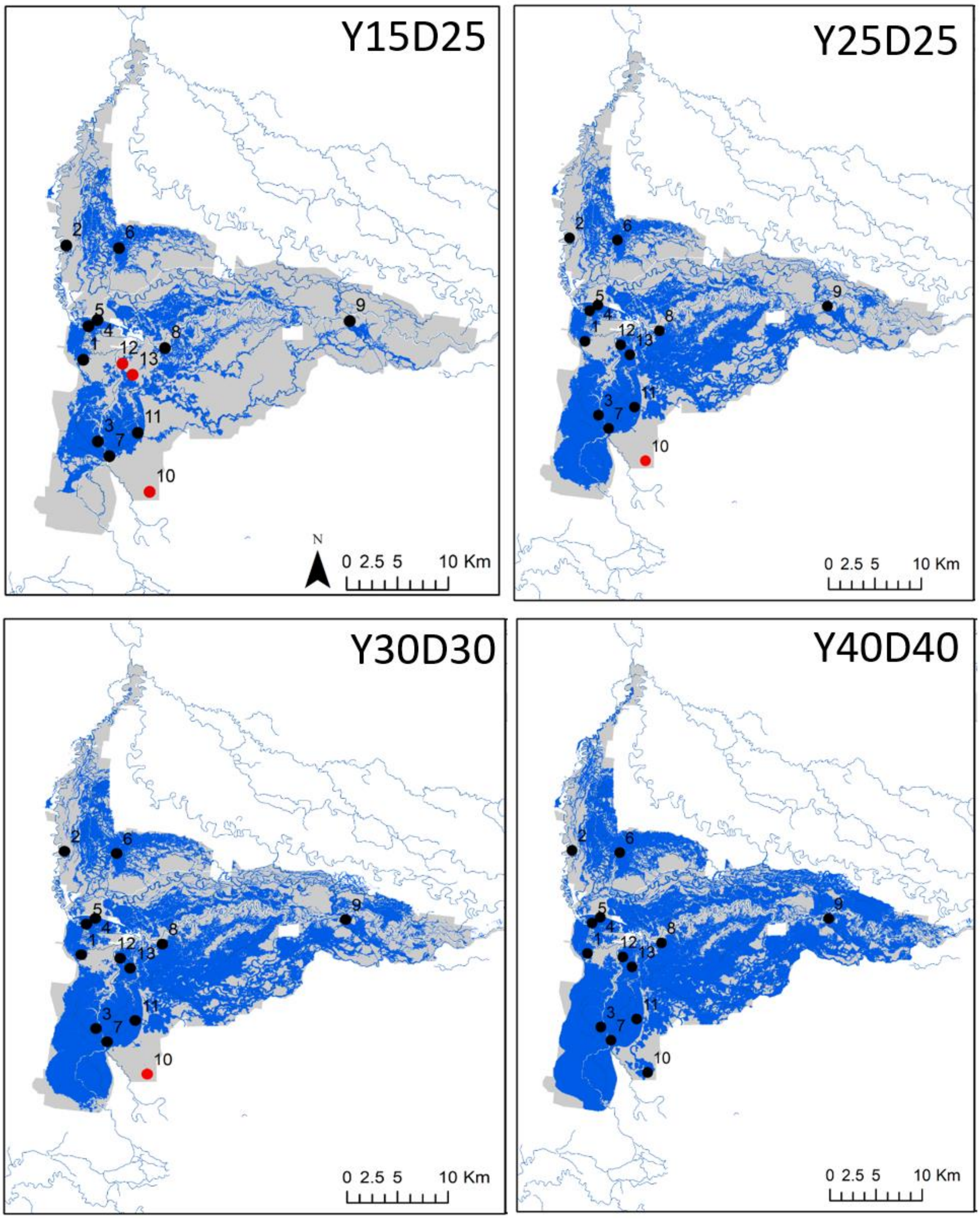


Figure 29 Upper limit of flow extent predicted under the Y15D25 (current constraints) and relaxed constraints (Y25D25, Y30D30 and Y40D40) in Barmah-Millewa Forest. Inundated waterbird sites coloured black, dry sites are coloured red. See Figure 5 for explanation of site numbers. Note that these maps show predicted inundated area without infrastructure being used and were used for the purpose of the waterbird EBA project only.

4. Results – Gunbower-Koondrook-Perricoota Forest

4.1 Current condition

At least 40 species of waterbirds have been recorded in Koondrook-Perricoota Forest in the last decade of monitoring (see Appendix 2). Annual spring aerial surveys have shown that the number of species and total abundance of waterbirds observed in Gunbower-Koondrook-Perricoota is typically low, and waterbird community is typically dominated by ducks (Figure 30). Waterbirds do use the forest when it is inundated. For example, there were high counts of waterbirds (mainly ducks) recorded at the time of UNSW aerial spring surveys in 2014 and 2016 when the forest was inundated (Figure 30). While the forest was inundated by a large overbank flows in spring 2016, the 2014 event was created by a smaller 25 GL commissioning flow over August-September 2014 that was delivered via the Koondrook-Perricoota offtake upstream of the Torrumbarry weir gauge (J. Dyer, DPE, pers. comms., 2022).

Complementary helicopter surveys in late spring-early summer also show that Koondrook-Perricoota forest waterbird community generally has low numbers of species and waterbird abundance with the duck guild making up 60-70% of observations in most years. However, during years when small managed flows (25-30 GL) are delivered to the forest waterbird abundance increased (e.g., in 2019) compared to drier years (e.g., 2018 and 2020) (Figure 31).

Historically there were at least 20 separate sites that supported colonially-nesting waterbirds in Koondrook-Perricoota Forest (Disher 2000) (see Figure 6) but there are few records of breeding in the last 20 years. The forest was extensively inundated because of high natural river flows in the Murray River in spring-summer 2010-11 and 2016-17 (Figure 32) and the wetland system also experienced overbank flows over spring-summer 2021-22. These events flood parts of the forest that have not been inundated in the intervening water years when only small areas of the forest can be inundated by managed flows (Dind 2021).

Large and medium overbank flows occurred more frequently prior to 2000 and there has been a long interval of minimal overbank flows into the forest over the 2000-2010 period (Figure 32). In the last 5 years there has been consistent small-scale breeding in the Pollack area including nesting nankeen night-heron, white-necked herons and eastern great egrets in response to overbank flows including environmental water delivery (Hutton 2021).

There has also been some evidence from recent ground surveys by Hutton (2020) of some localised increases in species richness in Pollack Lagoon and surrounding area following successive years of environmental water delivery. This included recent records of Australian little bittern *Ixobrychus dubius*, hoary-headed grebe *Poliocephalus poliocephalus*, pink-eared duck *Malacorhynchus membranaceus* and red-kneed dotterel *Erthrogonys cintctus* not recorded in the previous decade of surveys (Hutton 2020; Hutton 2021).

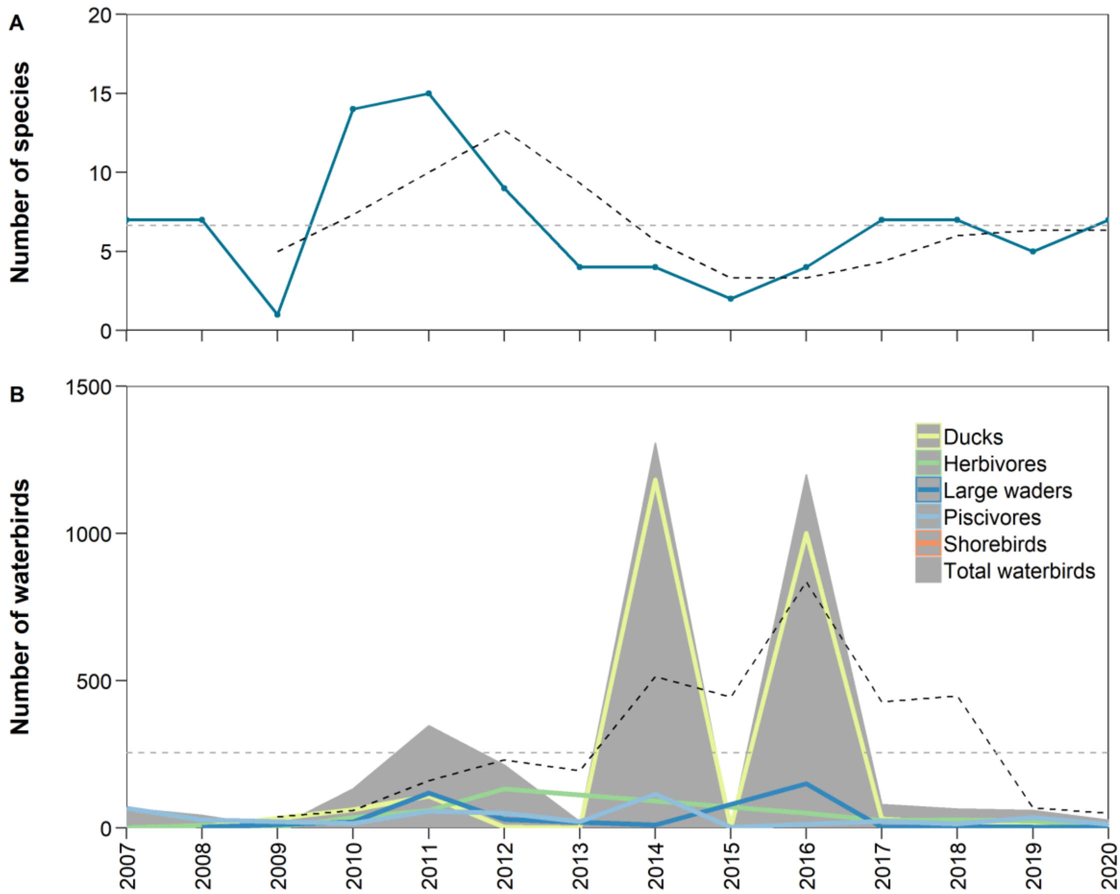


Figure 30 Total number of waterbird species – solid blue line (A) and total waterbird abundance (filled grey area (including abundance of each functional group) (B) recorded during annual (Oct-Nov) spring aerial surveys of Koondrook-Perricoota Forest (Kingsford et al. 2020). The grey dotted line represents the long-term average, and the black dotted line is the 3-year rolling average for the 2007-2020 period. Note that this aerial survey dataset covers both Gunbower and Koondrook-Perricoota Forests.

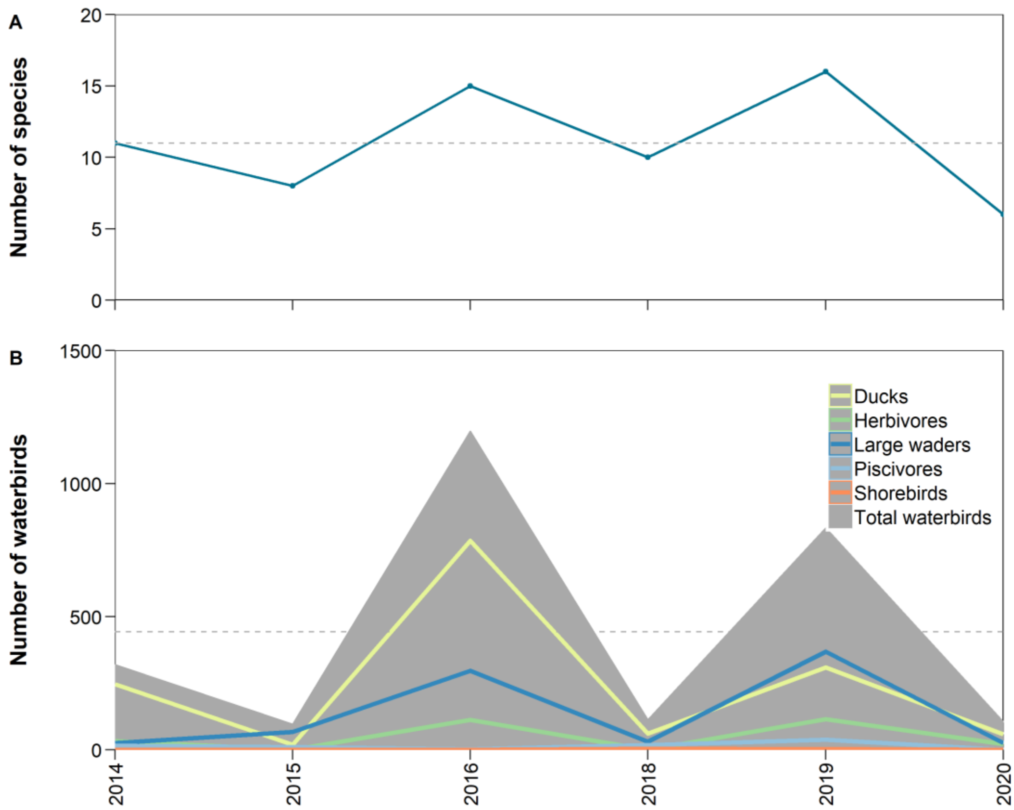


Figure 31 Total number of waterbird species – solid blue line (A) and total waterbird abundance (filled grey area (including abundance of each functional group) (B) recorded during annual (Nov-Dec) helicopter surveys of in Koondrook-Perricoota Forest (Dind 2021). The grey dotted line represents the average for the 2014-2020 period. Note that no surveys were completed in 2017.

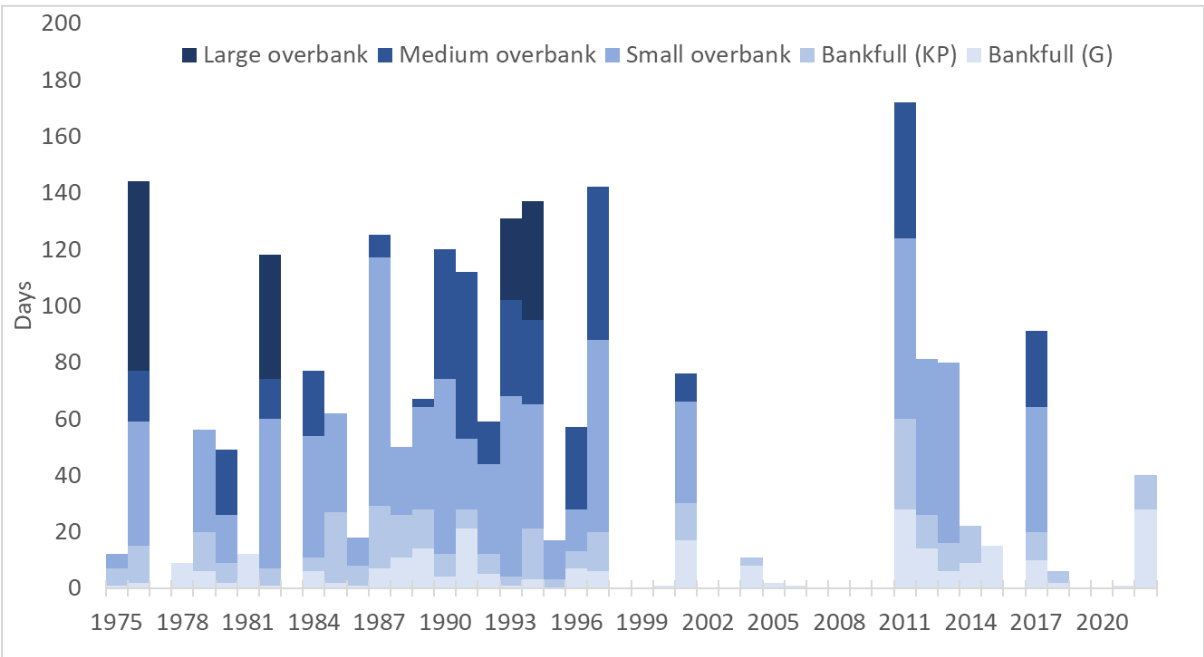


Figure 32 Number of days flows downstream of Torrumbarry Weir met thresholds for bankfull (16,000-18,000 (Gunbower) and 22,000-25,000 (Koondrook-Perricoota) ML/Day), small (>25,000-40,000 ML/Day), medium (>40,000-55,000 ML/Day) and large (>55,000 ML/Day) overbank events in the 1974-2021 period.

4.2 Species richness

We used estimates of total numbers of species determined from long-term annual spring aerial surveys to model the relationships between observed cumulative river flows and inundation extent with waterbird species richness. This approach showed there were generally more waterbird species recorded with increasing river flows and greater inundation of Gunbower-Koondrook-Perricoota Forest (Figure 33). A range of cumulative river flow models could explain the total number of species observed during UNSW long-term aerial surveys (see Table 14).

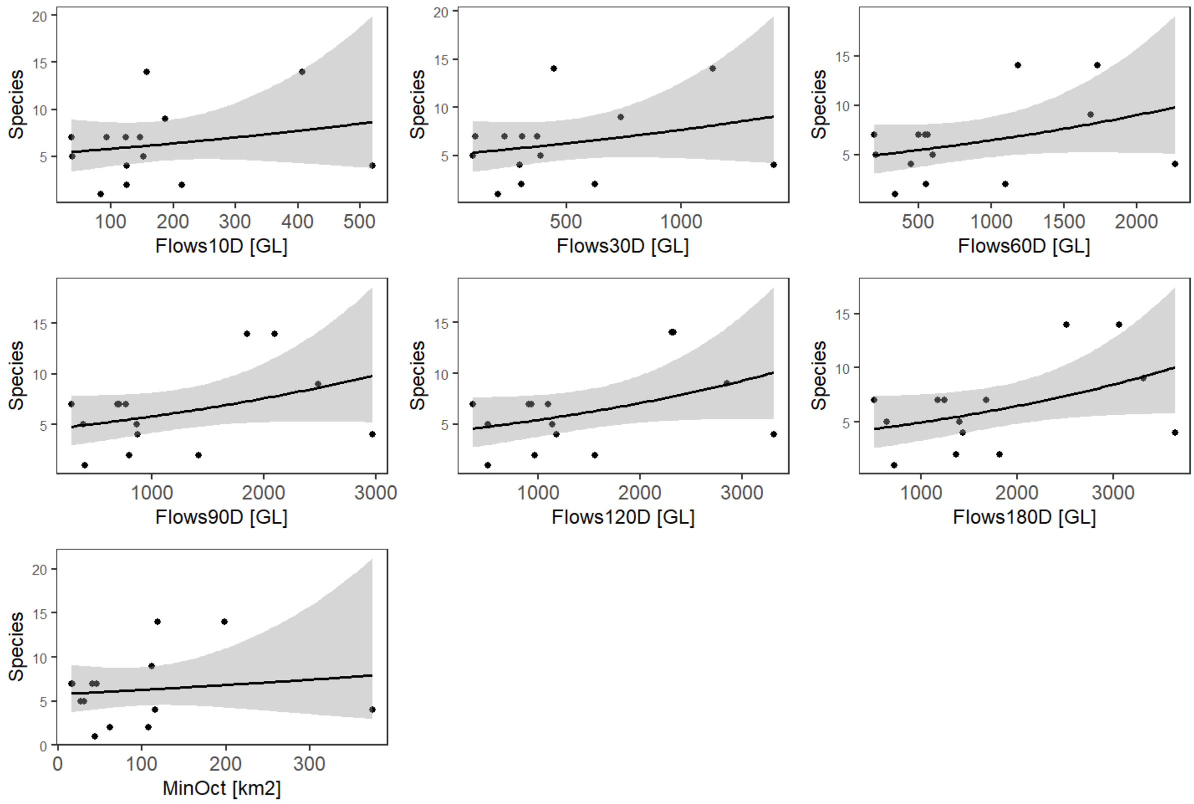


Figure 33 Waterbird species richness recorded in aerial surveys in the Koondrook-Perricoota Forest each spring over the 2007-2020 period in relation to cumulative river flows 10, 30, 60, 90, 120 and 180 days preceding to aerial surveys and inundation extent in October at the time of the spring surveys. The shaded areas represent the confidence levels around the line of best fit.

Table 14 Summary of single parameter flow model performance for total waterbird abundance and abundance of each of the five waterbird guilds based on available aerial survey data collected for Gunbower-Koondrook-Perricoota Forest. Note the inundation model InunOct represents the inundated extent in October at the time of the spring aerial surveys.

Waterbird response variable	Top performing model	R^2
Total number of species	180D,120D,90D,60D	0.20-0.15
Total waterbird abundance	InunOct	0.46
Total abundance of each guild		
Ducks	InunOct	0.43
Herbivores	180D	0.59
Large waders	180D	0.76
Piscivores	10D	0.06

4.3 Waterbird abundance

We used estimates of total waterbird abundance for Gunbower-Koondrook-Perricoota Forest determined from UNSW annual spring aerial surveys. We evaluated associations between waterbird abundance and habitat availability using cumulative river flows and wetland inundation extent. This approach showed there were generally higher waterbird abundance with increasing inundation extent at the time of the surveys in October (Figure 34, Table 14). Further examination of the aerial survey data showed there were nuances in waterbird abundance responses in terms of total abundance of each guild in relation to cumulative flows and inundated area (see Table 14 and Appendix 5).

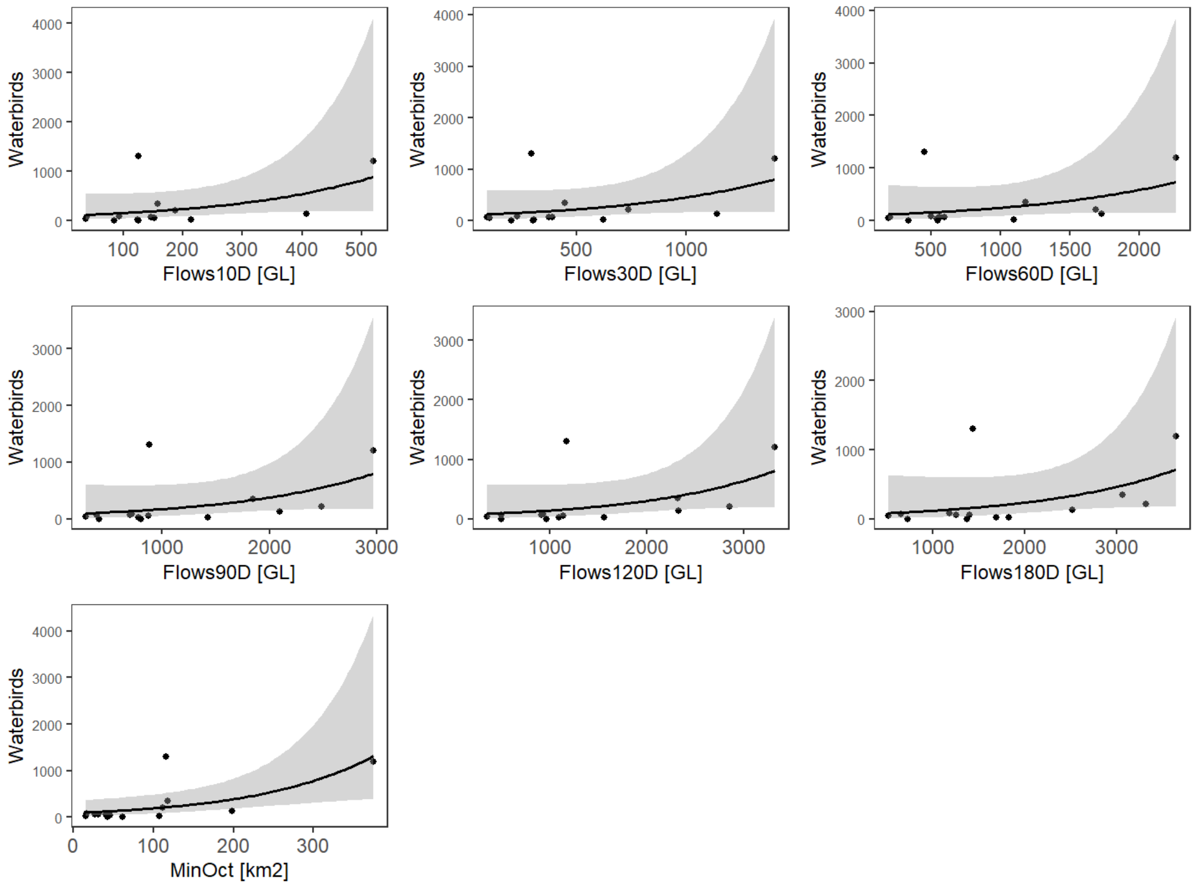


Figure 34 Total waterbird abundance recorded in aerial surveys (Kingsford et al. 2020) in the Koondrook-Perricoota Forest each spring over the 2007-2020 period in relation to cumulative river flows 10, 30, 60, 90, 120 and 180 days preceding the surveys and inundation extent in October at the time of the spring surveys. The shaded areas represent the confidence levels around the line of best fit.

4.4 *Comparison of flow scenarios*

4.4.1 Predicted waterbird responses

We looked at differences in the best predictor variables of waterbird responses in Gunbower-Koondrook-Perricoota Forest using the modelled inundation data and modelled river flow data. The best predictor of waterbird species richness in Gunbower-Koondrook-Perricoota Forest was cumulative river flows recorded at Torrumbarry gauge in the 180 days before the spring aerial surveys. The best predictor of total waterbird abundance was inundated area in Gunbower-Koondrook-Perricoota Forest at the time of the surveys.

Overall, there was very little difference in median cumulative river flows between current constraints (Y15D25) and the relaxed constraint scenarios. However, there were increases in median inundated area for all relaxed constraint scenarios with increasing inundated area predicted in Gunbower-Koondrook-Perricoota Forest with higher flow limits (Figure 35). There were also some increases in predicted inundated area in the drier years (25th percentile) for all the relaxed constraint scenarios compared to current constraints (Figure 35).

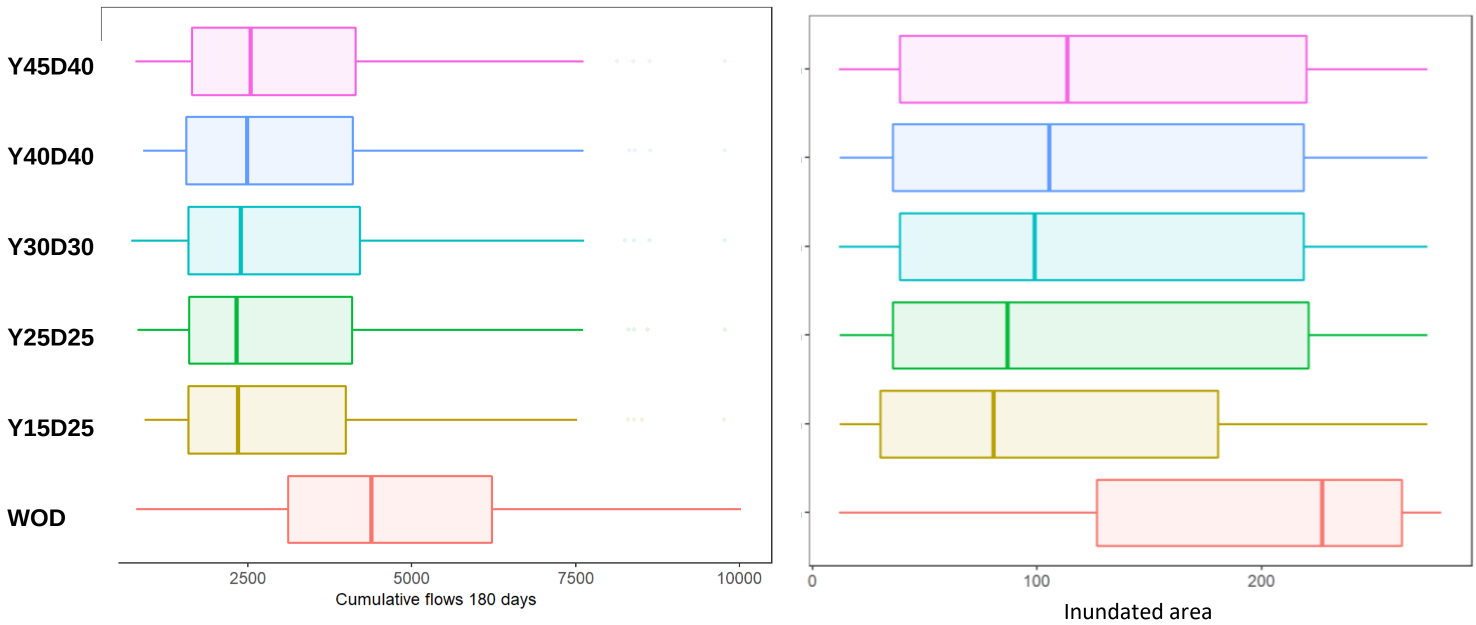


Figure 35 Boxplots showing variation in the key predictor of waterbird responses (cumulative river flows 180 days preceding the spring aerial surveys (*left*) and inundated area at the time of the surveys in October (*right*) under each of the flow scenarios.

We linked the modelled river flow and inundated area data for each scenario to predicted waterbird responses in Gunbower-Koondrook-Perricoota Forest. The analysis of modelled species richness and waterbird abundance (Figure 36) indicated small increases in the median number of species (1-4% compared to current constraints) and median waterbird abundance (8-48% compared to current constraints) with increased relaxation of constraints (Figure 36, Table 15).

To further investigate patterns in waterbird responses we also looked at the frequency of predicted species richness and waterbird abundance values over the 1895-2019 period in more detail (Figure 37). The kernel density plots demonstrate how the largest relaxed constraint scenarios equivalent of 30,000 ML/day and 35,000 ML/day downstream of Torrumbarry Weir (scenarios Y40D40, and Y45D40, respectively), are likely to provide the most benefits for waterbirds in terms of predicted increases in species richness and abundance in the forest (Figure 37).

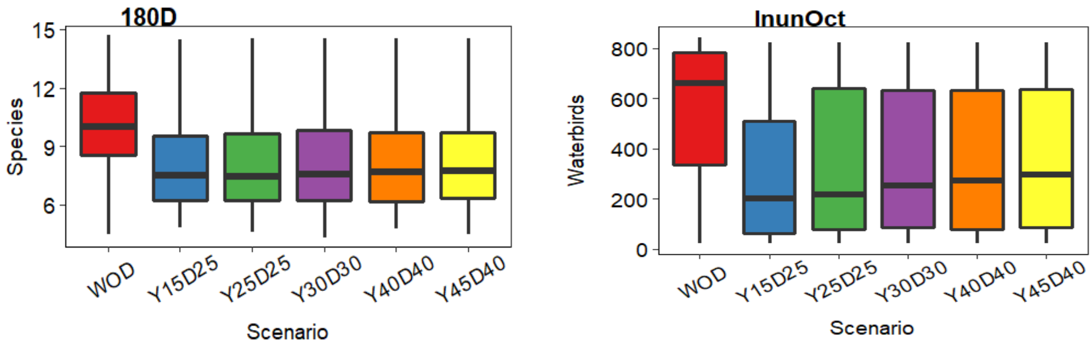


Figure 36 Predicted waterbird responses in Gunbower-Koondrook-Perricoota Forest for all flow scenarios for the 1896-2019 period based on the best predictor variable (Flows180D) for number of species (*left*) and inundated area in October each year for total waterbird abundance (*right*). Note that the modelled time series assumes current levels of river regulation and water extraction throughout the whole period. The base case (Y15D25) therefore does not represent actual waterbird populations under observed historical flows.

Table 15 Mean predicted species richness and waterbird abundance in Gunbower-Koondrook-Perricoota Forest (plus standard deviation (SD) values and percentiles are presented) for each flow scenario in response to 180 days cumulative flows (species richness) and inundated area in October (waterbird abundance). Note modelled responses are based on aerial survey data for the entire Gunbower-Koondrook-Perricoota Forest.

Scenario	Mean	SD	P10	P25	P50	P75	P90
Number of species							
WOD	10.01	2.13	7.18	8.53	10	11.76	12.77
Y15D25	8.05	2.24	5.61	6.23	7.48	9.57	11.17
Y25D25	8.12	2.27	5.44	6.26	7.45	9.67	11.24
Y30D30	8.13	2.28	5.56	6.25	7.55	9.8	11.22
Y40D40	8.15	2.26	5.54	6.17	7.69	9.69	11.23
Y45D40	8.16	2.25	5.51	6.33	7.76	9.74	11.23
Waterbird abundance							
WOD	561	263	101	337	662	782	822
Y15D25	311	284	54	64	201	508	796
Y25D25	335	287	54	78	218	641	796
Y30D30	343	281	23	86	253	634	796
Y40D40	354	281	29	78	273	634	796
Y45D40	361	277	29	86	297	638	787

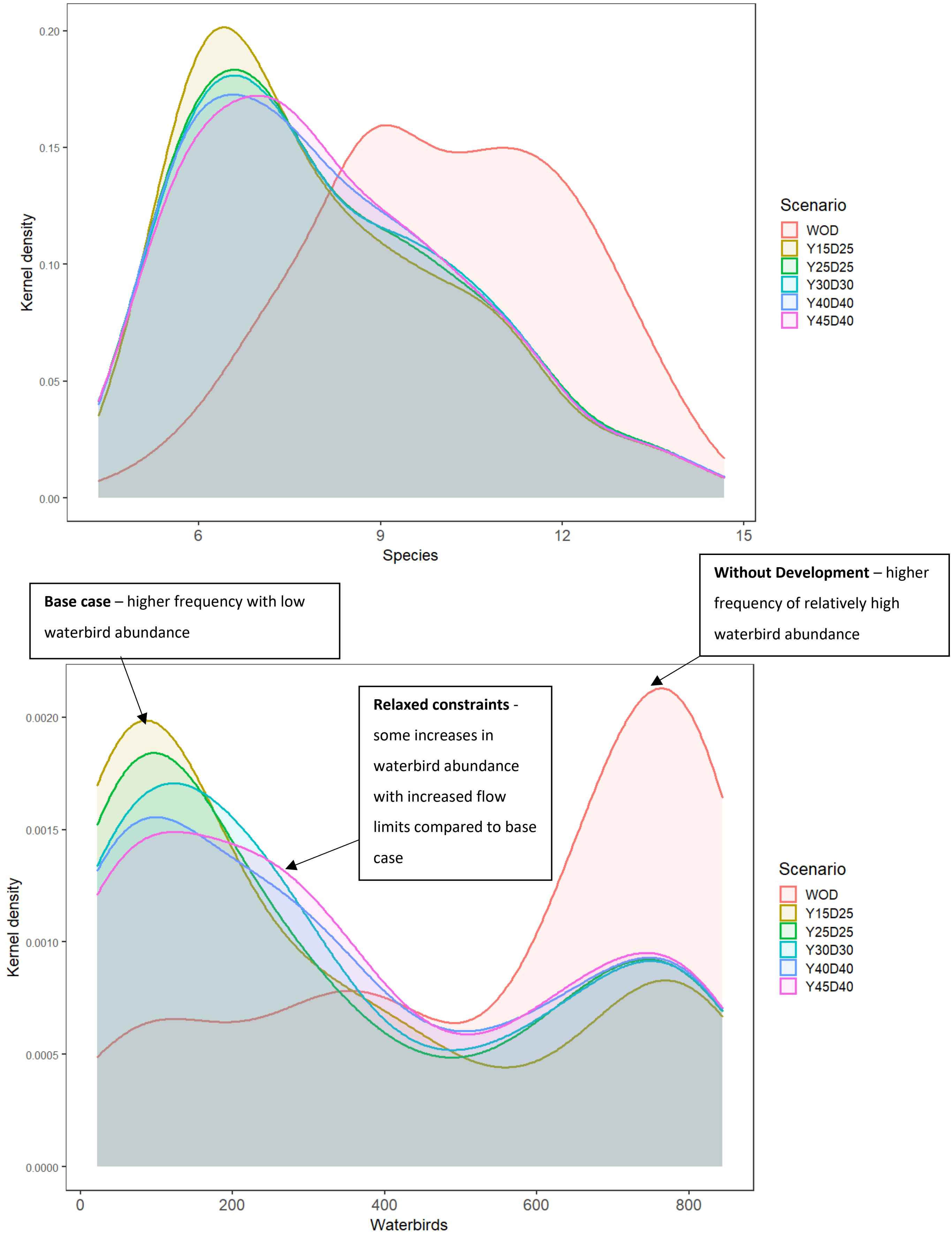


Figure 37 Summary of modelled waterbird species richness (*upper*) and waterbird abundance (*lower*) in Gunbower-Koondrook-Perricoota Forest in each flow scenario across the modelled time series (1896-2019) using the best predictor variables.

4.4.2 Predicted changes in habitat availability

We examined modelled river flow data for the downstream gauge of the Torrumbarry Weir to assess the likelihood changes to the availability of waterbird habitat in Gunbower-Koondrook-Perricoota Forest under different constraints relaxed scenarios. We used defined flow thresholds from the LTWP (DPIE 2020) to relate the four flow scenarios to flows at the Torrumbarry river gauge (see Table 2). There was some increase in the number of days of small overbank flows for the Y30D30 scenario (equivalent of 25,000 ML/day downstream of Torrumbarry Weir) and higher scenarios (Y40D40 and Y45D40) compared to current constraints (Y15D25) and the Y25D25 scenario (equivalent of 20,000 ML/day downstream of Torrumbarry Weir) (Figure 38). The modelled relaxed constraint scenarios did not influence the number of days of medium or large overbank flows (Figure 38), which are more heavily influenced by significant rainfall events in the upper catchment.

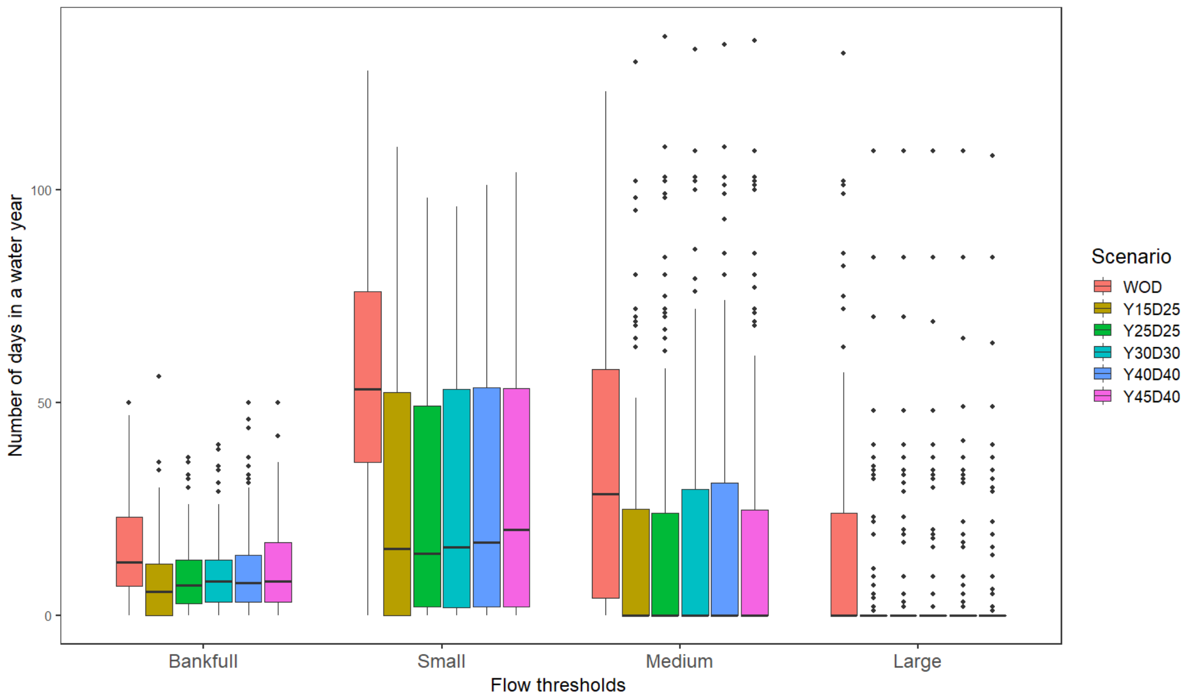


Figure 38 Number of bankfull, small overbank, medium overbank and large overbank events predicted downstream of Torrumbarry Weir that could inundate parts of Gunbower-Koondrook-Perricoota Forest under the different flow scenarios over the modelled 1895-2019 period.

A spells analysis was undertaken to determine the number of small and medium-sized overbank events of different durations that would inundate Gunbower-Koondrook-Perricoota Forest. This analysis indicated that the relaxed constraints options had most influence on the number of small overbank flow events of less than 30 days in length with increasing number of small overbanks of this duration with increased relaxation of constraints (Figure 39). The spells analysis showed that the relaxed constraints options have minimal impact on the number of medium-sized overbank events of different durations (Figure 39).

We undertook further analysis of the flow scenario data to look at how the frequency of small overbank events varied across the pre-breeding season (August-October) and each year (January-December) (Table 16). The number of small overbank events of a minimum 25,000 ML/day in size with a short duration (less than or equal to 10 days) to support small-scale waterbird breeding or extend the duration of larger overbank events increased from on average 2 events in 10 years in the baseline scenario (Y15D25) to an average of 3 in 10 years under the Y40D40 and Y45D45 flow scenarios (August-October).

Table 16 Average number (per decade) of small overbank events of 25,000 ML/day or more downstream of Torrumbarry Weir that would inundate Gunbower-Koondrook-Perricoota Forest under the modelled flow scenarios (see results of summary analyses in Appendix 6b).

Duration (days)	Y15D25	Y25D25	Y30D30	Y40D40	Y45D40
August to October					
<=10	2	2	2	3	3
11-30	1	2	2	2	2
31-45	0	0	0	0	0
>45	1	1	1	1	1
All year (January-December)					
<=10	4	5	5	5	5
11-30	2	4	4	4	4
31-45	1	1	1	1	1
>45	**3**	**3**	**3**	**4**	**4**

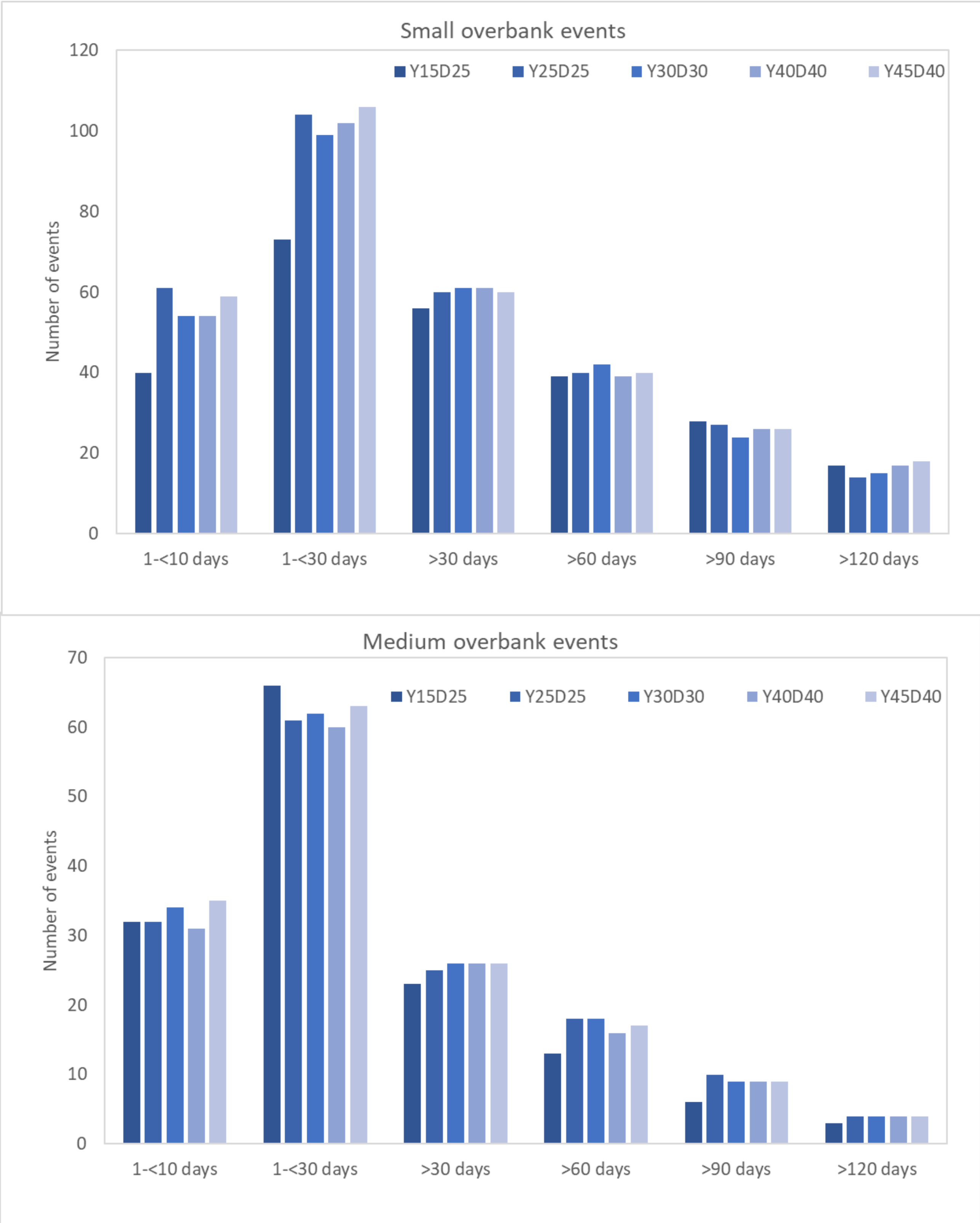


Figure 39 Results of spells analysis predicting number of events of different durations 1-10 days, 1-<30 days, more than 30 days, 60 days, 90 days and 120 days that would create small overbank events (≥25,000-40,000 ML/day) and medium overbank events (≥40,000 – 55,000 ML/day) in Gunbower-Koondrook-Perricoota Forest for the five flow scenarios (1896-2019). The relaxed constraints options have most influence on the number of small overbank flow events of relatively short duration (less than 30 days in length) and the number of medium sized events of more than 30 days or more under relaxed constraints.

The upper limit of targeted flow extents was determined by hydraulic modelling provided to the EBA project for the Koondrook-Perricoota Forest area only. This mapping was used to determine whether key waterbird sites in Koondrook-Perricoota were likely to be inundated under available flow scenarios compared to the current constraint downstream of Yarrawonga Weir which does not allow for inundation of the Koondrook-Perricoota Forest unless infrastructure is utilised. Note the four relaxed constraints scenarios represent a lower flow volume downstream of Torrumbarry Weir which is the nearest gauge to the forest: 20,000 ML/day (Y25D25), 25,000 ML/day (Y30D30), 30,000 ML/day (Y40D40), and 35,000 ML/day (Y45D40).

Using the outputs of the hydraulic modelling it was possible to look at predicted upper limit of targeted flow extent across the forest with increasing relaxed constraints without the use of infrastructure. At Koondrook-Perricoota Forest 18/22 waterbird sites are inundated at 20,000ML/day (Y25D25), this increased by three sites (19/22) at flows 25,000 ML/day downstream of Torrumbarry Weir (Y30D30) (Figure 40). Flows greater than 25,000 ML/day do not result in the inundation of any additional defined waterbird sites, but an increasing area of the floodplain forest becomes inundated under higher relaxed constraints (Figure 41).

The hydraulic model outputs provided to the EBA project provided most reliable estimates of the predicted upper limit of targeted flow predicted extent for all flow scenarios. However, it is important to note that these areas do not account for the influence of infrastructure on delivery of flows and for retaining water on the floodplain. The predicted extent using infrastructure in combination with relaxed constraints represents the maximum inundation extent that could be achieved for both areas of the forest (see for example Figure 41). In this example much larger areas of the wider Gunbower-Koondrook-Perricoota Forest complex are inundated in the Y30D30 and Y40D40 flow scenarios (Figure 41).

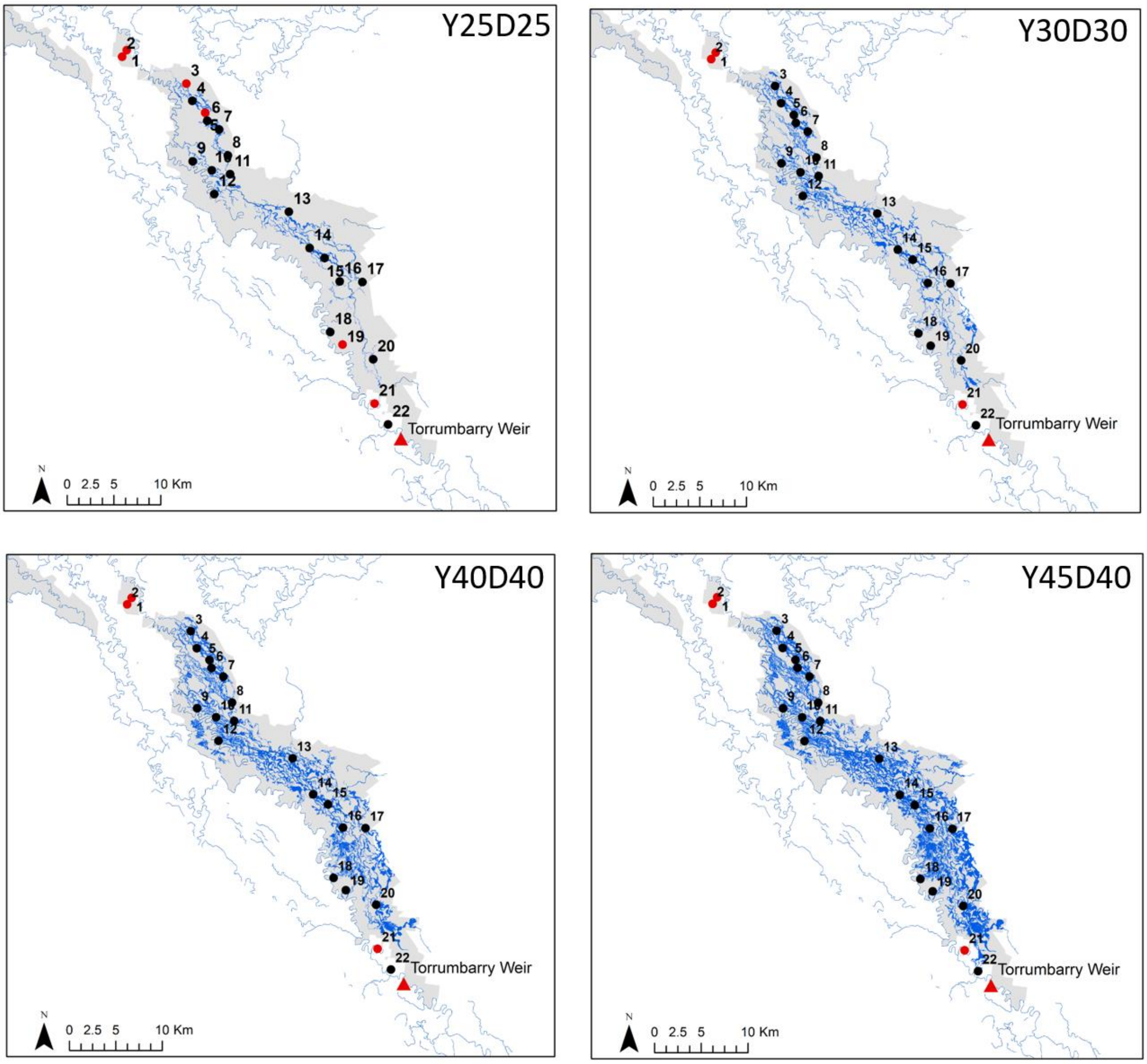


Figure 40 Upper limit of targeted flow extent predicted for Koondrook-Perricoota Forest (only) under the Y25D25 relaxed constraint scenario (left panel), Y30D30 relaxed constraint scenario (middle panel) and Y40D40 relaxed constraint scenario (right panel). Inundated waterbird sites coloured black, dry sites are coloured red, Koondrook-Perricoota Forest is shaded light grey. See Figure 6 for explanation of site codes. Note that these maps show predicted inundated area without infrastructure being used and were used for the purpose of the waterbird EBA project only.

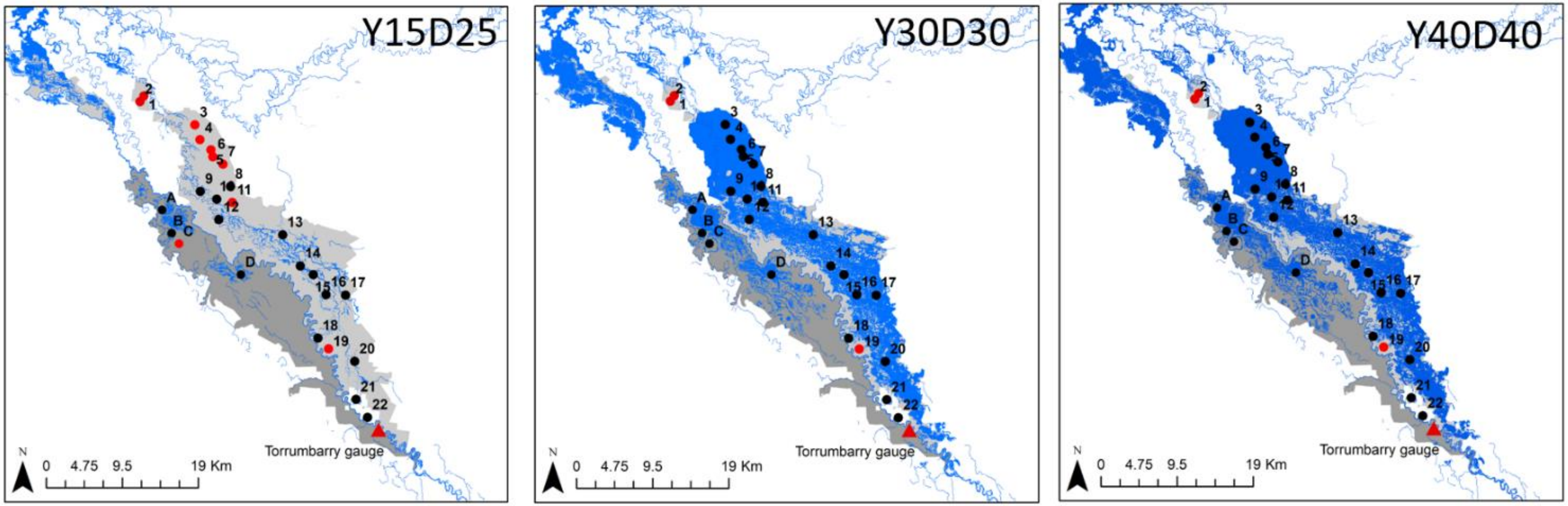


Figure 41 Upper limited of targeted flow extent in Gunbower-Koondrook-Perricoota Forest that would be inundated under the current and relaxed constraint scenarios when infrastructure is in use. This predicted extent is combination of outputs from RiM-FIM and hydraulic mapping and so covers both sides of the river (Koondrook-Perricoota is coloured light grey and Gunbower Forest is shaded dark grey). Inundated waterbird sites coloured black, dry sites are coloured red. See Figure 6 for explanation of site codes for Gunbower Forest and Koondrook-Perricoota Forest.

5. Discussion

We anticipated that waterbirds would benefit from relaxation of constraints downstream of Yarrawonga Weir in the Mid-Murray region because of greater availability of feeding and breeding habitat over spring and summer months. We also expected localised increases in species richness at individual wetland sites where there are changes in habitat structure and condition due to more frequent inundation.

Our analysis indicated there were incremental benefits for each relaxed constraint scenario considered in our analysis with increasing flow volumes and greater floodplain inundation. The most immediate benefits were from the lowest scenario (25,000 ML/day at Yarrawonga) which would support increases in the number and duration of small overbank events suitable for small-scale colonial waterbird breeding in Barmah-Millewa Forest. Further relaxation of constraints up to 40,000 ML/day and 45,000 ML/day downstream of Yarrawonga would provide additional benefits to waterbirds by allowing larger areas of Barmah-Millewa Forest and the neighbouring Gunbower-Koondrook-Perricoota Forest to be inundated, which would provide greater habitat availability for a range of waterbird species in the Mid-Murray region.

The relationships between waterbird species richness and abundance and the main predictors (river flows and inundation area) were not as strong for the Gunbower-Koondrook-Perricoota Forest area as for Barmah-Millewa Forest, but we think that the relaxation of constraint to 40,000 ML/day or 45,000 ML/day at Yarrawonga will be most apparent for Gunbower-Koondrook-Perricoota Forest. Many parts of the forest are in poor condition and this site currently has the most restricted options for delivery of overbank flows. It currently has open lagoons with limited understorey vegetation due to changes to the natural flow regime which have reduced the frequency and duration of inundation (P. Childs, DPE, pers. comm. 2022).

The predicted inundation extents from the available hydraulic modelling indicated that most waterbird sites in Barmah-Millewa Forest can be inundated under the Y25D25 flow scenario and a large majority of sites in Koondrook-Perricoota Forest can be inundated under the Y30D30 flow scenario. There was only one site in Barmah-Millewa Forest, Goose Swamp, that was not inundated under the lowest relaxed constraint scenarios. Goose Swamp is in the southern part of Barmah Forest and has supported some colonial waterbird breeding in the past. The most recent record being in 2010-11 after large-scale natural flooding across the

Mid-Murray region. However, this site is also influenced by flows from other inflow points in the southern part of Barmah-Millewa Forest including Broken Creek and by major flooding in the Goulburn River (K. Ward GBCMA, pers. comm. 2022).

Water delivery mechanisms are also used to complement high river flows to extend the duration of inundation at colonial waterbird breeding sites. For instance, when infrastructure for directing flows and maintaining wetland inundation are used a much larger area of Gunbower-Koondrook-Perricoota Forest can be inundated under the relaxed constraint scenarios (see Figure 41). There are also additional management options for directing flows using infrastructure into at least 2 of the remaining sites at Koondrook-Perricoota (which includes key waterbird habitats Pollack Lagoon and Pollack Swamp), not represented in available modelling. This environmental water management approach has been used in recent years, with flows delivered to support waterbird habitat in the northern part of Koondrook-Perricoota Forest using private infrastructure (Hutton 2019) and to parts of Gunbower Forest using Gunbower Creek (VEHW 2022).

We found that the predicted areas from the inundation modelling were useful for assessing the distribution of inundation in Barmah-Millewa and Gunbower-Koondrook-Perricoota forests but not at sufficient scale to determine if colony sites were inundated for adequate depth and duration needed to support successful waterbird breeding. Typically, colonial waterbirds require several months of inundated habitat to support successful rearing of their young (Brandis and Bino 2016; Brandis et al 2018; Leslie 2001). However, we anticipate that increased flow volumes under relaxed constraints will more frequently meet the flow thresholds required for small overbank flows allowing both Barmah-Millewa Forest and Gunbower-Koondrook-Perricoota Forest to contribute to increased opportunities for waterbird breeding in the Murray-Darling Basin. In our analyses we found with increasing relaxation of constraints downstream of Yarrawonga Weir there was a greater number of individual flow events (and increased number of days) where the threshold for small overbank flows were met compared to current constraints.

The relaxed constraints options will provide greater management options for delivering flows to extend natural inundation of active colony sites and surrounding habitat in both wetland systems. Under suitable conditions managed flow deliveries in early spring with greater relaxation of constraints are also likely to initiate small-scale colonial waterbird breeding including nesting cormorants, egrets and ibis. It is likely that these smaller breeding events will become increasing important for maintaining viable waterbird populations in the Murray-Darling Basin alongside periodic boom years where large-scale breeding is triggered by widespread natural flooding (Brandis et al. 2021). The Murray-Lower Darling LTWP outlines the target to support small-scale colonial waterbird breeding in at least two sites including parts of Barmah-Millewa Forest (Reed Beds Swamp, Duck Lagoon, St Helena Swamp) and Koondrook-Perricoota Forest (Pollack Swamp) in the 2019-2024 period (DPIE 2020).

Small overbank events and bankfull events that inundate waterbird habitats on the floodplain can also promote the survival of young waterbirds in years following large-scale flooding which may contribute to overall increases in waterbird populations in the Murray-Darling Basin. These types of flow events also provide opportunities for non-colonial waterbird species including waterfowl to feed and breed in parts of Barmah-Millewa and Gunbower-Koondrook-Perricoota forests. The delivery of small overbank events will also support the health of nesting vegetation and neighbouring foraging areas including open lagoons and marsh grasslands, sedgelands and rushes in years of low water availability when these habitats are at risk of declining in condition. Long dry spells without any floodplain inundation can have implications for the condition of waterbird nesting habitat, food availability, opportunities for breeding and, therefore, broader waterbird populations (Brandis et al. 2018; Brandis et al. 2021; Jenkins and Boulton 2007).

In our assessment of likely benefits of relaxed flow constraints for waterbirds in the Barmah-Millewa and Gunbower-Koondrook-Perricoota forests we did not consider the influence of climate change on predicted waterbird outcomes, or the influence of other processes including siltation of breeding habitat for example. We also did not consider the influence of habitat availability in other parts of the Basin on observed and modelled waterbird responses in our study sites. It is likely that any benefits for waterbirds will be cumulative with improved wetland condition in the neighbouring Gunbower-Koondrook-Perricoota Forest area providing benefits to waterbirds breeding in the nearby Barmah-Millewa Forest and vice-versa. Although our analyses considered each wetland area in isolation their proximity in the Yarrawonga to Wakool section of the Murray River would mean many waterbird species are likely to move easily between the systems if inundated wetland habitat is available.

6. References

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7. Appendices

Appendix 1 Description of flow categories

Flow categories that can inundate Barmah-Millewa (BM) and Gunbower (GB) - Koondrook-Perricoota (KP) forests based on environmental water requirements for the Murray River Yarrawonga to Barmah LTWP planning unit. Sourced from LTWP (DPIE 2020).

LTWP Objectives	Flow category	Flow threshold minimum (ML/day)	EWR codes	Timing	Duration	Minimum frequency	Maximum frequency	Max Inter event frequency
WB1,2,5 habitat	Large Fresh	12,000 (BM & GBKP)	LF2	Oct-Apr	5 days	3 in 10 years	6 in 10 years	2 years
WB1,2,5 habitat	Large Fresh	12,000 (BM & GBKP)	LF4	Aug-Mar	120 days	3 in 10 years	6 in 10 years	3 years
WB1,2,5 habitat	Bankfull	10,000 (BM) 16,000 (GB)	BK1	Aug-Mar/Apr	10-45 days	2 in 10 years	8 in 10 years	2-3 years
WB1,2,5 habitat	Bankfull	29,000 (BM) 22,000 (KP)	BK2	Aug-Nov	15 days	5 in 10 years	10 in 10 years	3 years
WB1-5 incl. small scale colonial waterbird breeding	Small overbank	15,000 (BM)* 25,000-33,000 (GBKP)	OB1-OB2	Aug-Nov	45 days *followed by 9,000 for 105 days	3 in 10 years	10 in 10 years	2-5 years
WB1-5 incl. large scale colonial waterbird breeding	Medium overbank in combination with natural events	50,000-60,000 (BM) 40,000-45,000 (GBKP)	OB7-OB8 (BM) OB3-OB4 (GBKP)	Jul-Feb	7-30 days	2 in 10 years	5 in 10 years	4-10 years
WB1-5 incl. large scale colonial waterbird breeding	Large overbank in combination with natural events	80,000-100,000 (BM) 40,000-55,000 (GBKP)	OB9-10 (BM) OB3-OB5 (GBKP)	Anytime	3-45 days	1 in 10 years	2 in 10 years	7-14 years

Appendix 2 List of waterbird species

List of waterbird species recorded at Barmah-Millewa Forest during aerial and ground surveys^ completed between 2007-2021.

Common Name	Scientific Name	Guild	Status*
Australasian Grebe	*Tachybaptus novaehollandiae*	Ducks and small grebes	
Hoary-headed Grebe	*Poliocephalus poliocephalus*	Ducks and small grebes	
Australasian Shoveler	*Anas rhychotis*	Ducks and small grebes	
Blue-billed Duck	*Oxyura australis*	Ducks and small grebes	v
Chestnut Teal	*Anas castanea*	Ducks and small grebes	
Freckled Duck	*Stictonetta naevosa*	Ducks and small grebes	v
Grey Teal	*Anas gracilis*	Ducks and small grebes	
Hardhead	*Aythya australis*	Ducks and small grebes	
Musk Duck	*Biziura lobata*	Ducks and small grebes	
Pacific Black Duck	*Anas superciliosa*	Ducks and small grebes	
Pink-eared Duck	*Malacorhynchus membranaceus*	Ducks and small grebes	
Australian Spotted Crake	*Porzana fluminea*	Ducks and small grebes	
Buff-banded Rail	*Gallirallus philippensis*	Ducks and small grebes	
Spotless Crake	*Porzana tabuensis*	Ducks and small grebes	
Australian Shelduck	*Tadorna tadornoides*	Herbivore	
Australian Wood Duck	*Chenonetta jubata*	Herbivore	
Black Swan	*Cygnus atratus*	Herbivore	
Black-tailed Native-hen	*Tribonyx ventralis*	Herbivore	
Dusky Moorhen	*Gallinula tenebrosa*	Herbivore	
Eurasian Coot	*Fulica atra*	Herbivore	
Magpie Goose	*Anseranas semipalmata*	Herbivore	v
Plumed Whistling-Duck	*Dendrocygna eytoni*	Herbivore	
Purple Swamphen	*Porphyrio porphyrio*	Herbivore	
Australasian Bittern	*Botaurus poiciloptilus*	Large wader	E, e
Australian Little Bittern	*Ixobrychus dubius*	Large wader	
Australian White Ibis	*Threskiornis molucca*	Large wader	
Brolga	*Grus rubicunda*	Large wader	v
Cattle Egret	*Bubulcus ibis*	Large wader	
Eastern Great Egret	*Ardea modesta*	Large wader	
Glossy Ibis	*Plegadis falcinellus*	Large wader	Bonn
Intermediate Egret	*Ardea intermedia*	Large wader	
Little Egret	*Egretta garzetta*	Large wader	
Nankeen Night-Heron	*Nycticorax caledonicus*	Large wader	
Royal Spoonbill	*Platalea regia*	Large wader	
Straw-necked Ibis	*Threskiornis spinicollis*	Large wader	
White-faced Heron	*Egretta novaehollandiae*	Large wader	
White-necked Heron	*Ardea pacifica*	Large wader	
Yellow-billed Spoonbill	*Platalea flavipes*	Large wader	
Australasian Darter	*Anhinga novaehollandiae*	Piscivore	
Australian Pelican	*Pelecanus conspicillatus*	Piscivore	

Common Name	Scientific Name	Guild	Status*
Australian Gull-billed Tern	*Gelochelidon nilotica*	Piscivore	
Caspian Tern	*Hydroprogne caspia*	Piscivore	J
Great Cormorant	*Phalacrocorax carbo*	Piscivore	
Great Crested Grebe	*Podiceps cristatus*	Piscivore	
Little Black Cormorant	*Phalacrocorax sulcirostris*	Piscivore	
Little Pied Cormorant	*Phalacrocorax melanoleucos*	Piscivore	
Pied Cormorant	*Phalacrocorax varius*	Piscivore	
Silver Gull	*Chroicocephalus novaehollandiae*	Piscivore	
Whiskered Tern	*Chlidonias hybrida*	Piscivore	
Black-fronted Dotterel	*Elseyornis melanops*	Shorebird	
Black-winged Stilt	*Himantopus himantopus*	Shorebird	
Double-banded Plover	*Charadrius bicinctus*	Shorebird	
Latham's Snipe	*Gallinago hardwickii*	Shorebird	J, R
Marsh Sandpiper	*Tringa stagnatilis*	Shorebird	J, C, R
Masked Lapwing	*Vanellus miles*	Shorebird	
Red-capped Plover	*Charadrius ruficapillus*	Shorebird	
Red-kneed Dotterel	*Erthrogonys cintctus*	Shorebird	
Red-necked Avocet	*Recurvirostra novaehollandiae*	Shorebird	
Red-necked Stint	*Calidris ruficollis*	Shorebird	J, C, R
Sharp-tailed Sandpiper	*Calidris acuminata*	Shorebird	J, C, R

^Sources of records included TLM ground survey data collected by Webster, Borrell and others; and UNSW aerial survey data. *Status: Endangered (E) species listed under Commonwealth Environmental Protection and Biodiversity (EPBC) Act 1999. Threatened species listed under NSW Biodiversity Conservation (BC) Act 2016 (e = endangered, vulnerable). Migratory species listed under Convention of Migratory Species (Bonn), Japan-Australia Migratory Bird Agreement, JAMBA (J), China-Australia Migratory Bird Agreement, CAMBA (C) and/or Republic of Korea-Australia Migratory Bird Agreement, ROKAMBA (R).

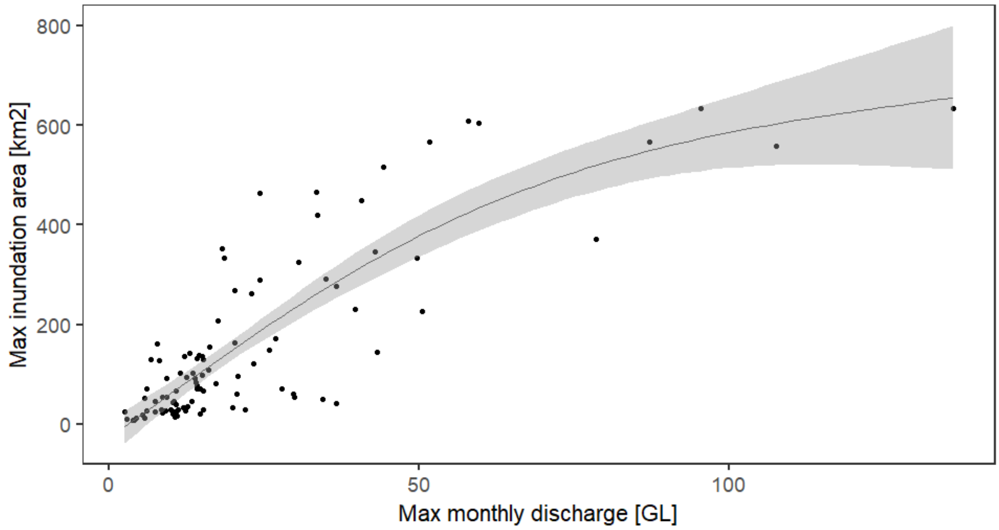
List of waterbird species recorded at Gunbower-Koondrook-Perricoota Forest during aerial and ground surveys^ completed between 2007-2021

Common Name	Scientific Name	Guild	Status*
Australasian Grebe	*Tachybaptus novaehollandiae*	Ducks and small grebes	
Hoary-headed Grebe	*Poliocephalus poliocephalus*	Ducks and small grebes	
Australasian Shoveler	*Anas rhychotis*	Ducks and small grebes	
Blue-billed Duck	*Oxyura australis*	Ducks and small grebes	v
Chestnut Teal	*Anas castanea*	Ducks and small grebes	
Grey Teal	*Anas gracilis*	Ducks and small grebes	
Hardhead	*Aythya australis*	Ducks and small grebes	
Pacific Black Duck	*Anas superciliosa*	Ducks and small grebes	
Pink-eared Duck	*Malacorhynchus membranaceus*	Ducks and small grebes	
Baillon's Crake	*Porzana pusilla*	Ducks and small grebes	
Spotless Crake	*Porzana tabuensis*	Ducks and small grebes	
Australian Shelduck	*Tadorna tadornoides*	Herbivore	
Australian Wood Duck	*Chenonetta jubata*	Herbivore	
Black Swan	*Cygnus atratus*	Herbivore	
Black-tailed Native-hen	*Tribonyx ventralis*	Herbivore	
Dusky Moorhen	*Gallinula tenebrosa*	Herbivore	
Eurasian Coot	*Fulica atra*	Herbivore	
Purple Swamphen	*Porphyrio porphyrio*	Herbivore	
Australian Little Bittern	*Ixobrychus dubius*	Large wader	
Australian White Ibis	*Threskiornis molucca*	Large wader	
Eastern Great Egret	*Ardea modesta*	Large wader	
Glossy Ibis	*Plegadis falcinellus*	Large wader	Bonn
Intermediate Egret	*Ardea intermedia*	Large wader	
Nankeen Night-Heron	*Nycticorax caledonicus*	Large wader	
Royal Spoonbill	*Platalea regia*	Large wader	
Straw-necked Ibis	*Threskiornis spinicollis*	Large wader	
White-faced Heron	*Egretta novaehollandiae*	Large wader	
White-necked Heron	*Ardea pacifica*	Large wader	
Yellow-billed Spoonbill	*Platalea flavipes*	Large wader	
Australasian Darter	*Anhinga novaehollandiae*	Piscivore	
Australian Pelican	*Pelecanus conspicillatus*	Piscivore	
Great Cormorant	*Phalacrocorax carbo*	Piscivore	
Great Crested Grebe	*Podiceps cristatus*	Piscivore	
Little Black Cormorant	*Phalacrocorax sulcirostris*	Piscivore	
Little Pied Cormorant	*Phalacrocorax melanoleucos*	Piscivore	
Pied Cormorant	*Phalacrocorax varius*	Piscivore	
Black-fronted Dotterel	*Elseyornis melanops*	Shorebird	
Black-winged Stilt	*Himantopus himantopus*	Shorebird	
Masked Lapwing	*Vanellus miles*	Shorebird	
Red-kneed Dotterel	*Erthrogonys cintctus*	Shorebird	

^Sources of records included ground survey data collected by Webster (unpubl. data 2008-2012), GHD (2015), Dind (2020, 2021), FCNSW (2019), Hutton (2017, 2018a,b, 2019, 2020, 2021) (Koondrook only), and aerial survey data collected by Kingsford et al. (2020), GHD (2015), Dind (2020, 2021) and FCNSW (2019) (both Gunbower and Koondrook-Perricoota Forests). *Status: Species listed under Convention of Migratory Species (Bonn).

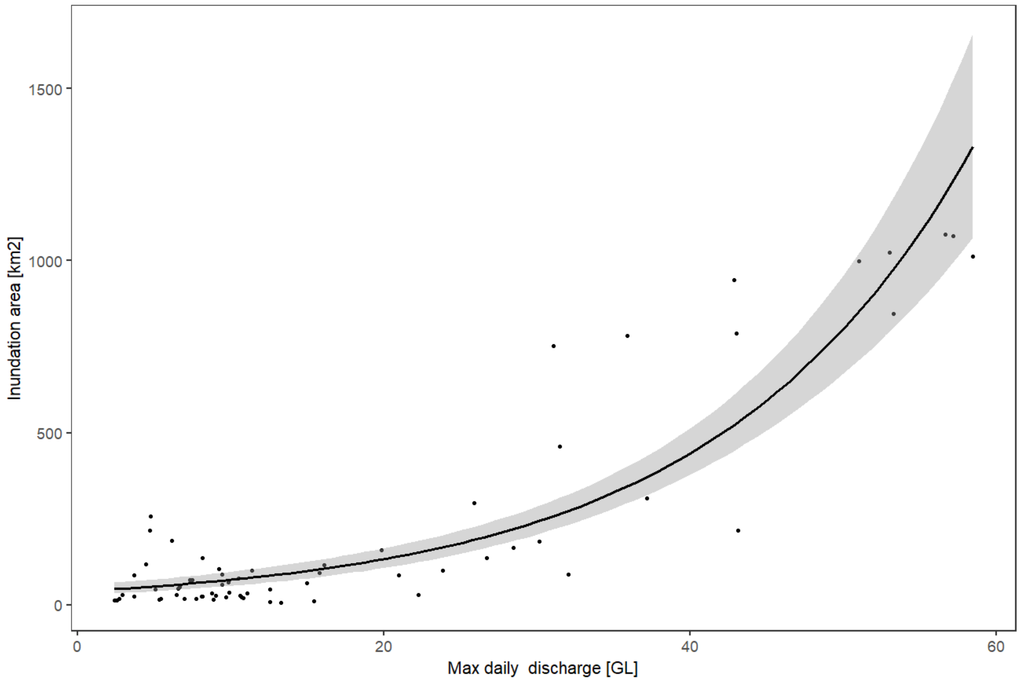
Appendix 3 Relationships between river flows and inundated area

Barmah-Millewa Forest



Maximum discharge rate (GL/day) recorded over August-October downstream of Yarrawonga Gauge (409025) and maximum inundated area in Barmah-Millewa Forest calculated from Landsat satellite derived inundation maps (1987-2021) and Sentinel (2015-2021) imagery.

Gunbower-Koondrook-Perricoota Forest



Maximum discharge rate (GL/day) recorded over August-October downstream of Torrumbarry Weir (409207) and minimum estimated area of inundation in October each year for Gunbower-Koondrook-Perricoota Forest based on mapping of Landsat (1988-2021) and Sentinel (2015-2021) imagery.

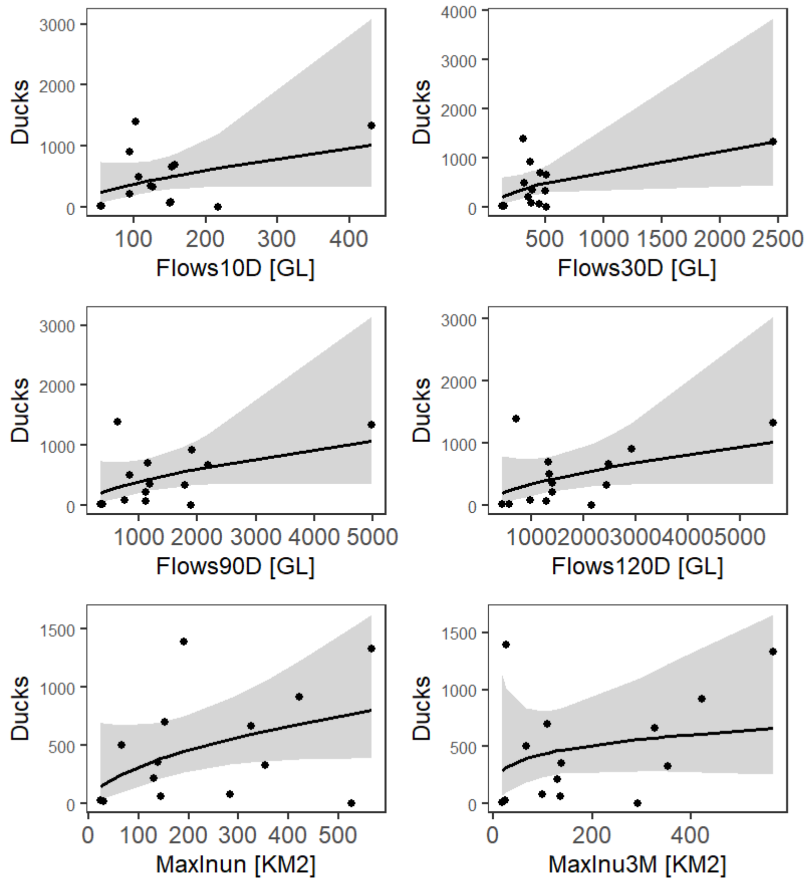
Appendix 4 Barmah-Millewa Ground Survey Sites

Waterbird ground survey sites in Millewa Forest (clockwise from top left: Duck Lagoon, Horseshoe Lagoon, Reed Beds South, St Helena Swamp, Moira Lake, Reed Beds North) (Credit: Alison Borrell, NSW NPWS, January 2017).

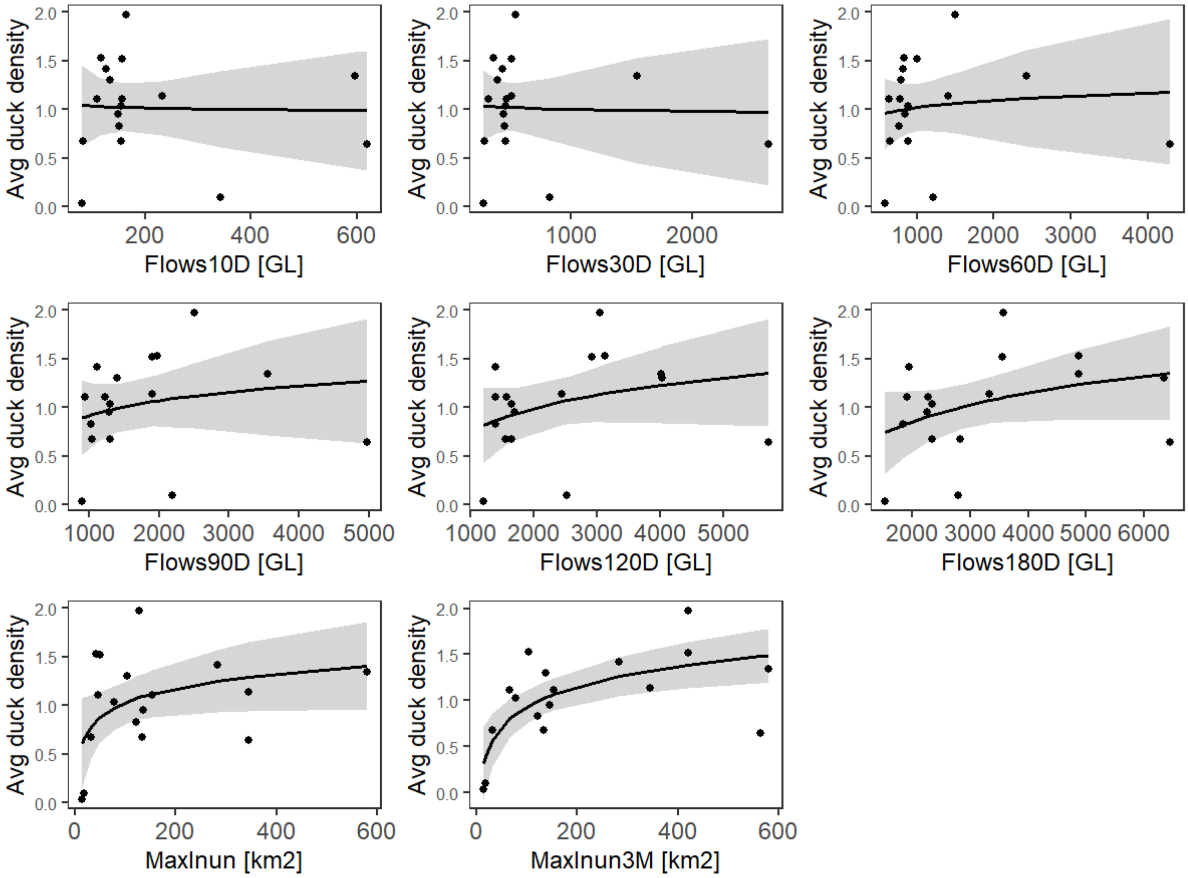
Waterbird ground survey sites in Barmah Forest (clockwise from top left: Barmah Lake, Boals Deadwood, Bunyip Hole, Goose Swamp, Pig Hole, Steamers Plain) (Credit: Alison Borrell, NSW NPWS, January 2017).

Appendix 5a Model results – Barmah-Millewa Forest

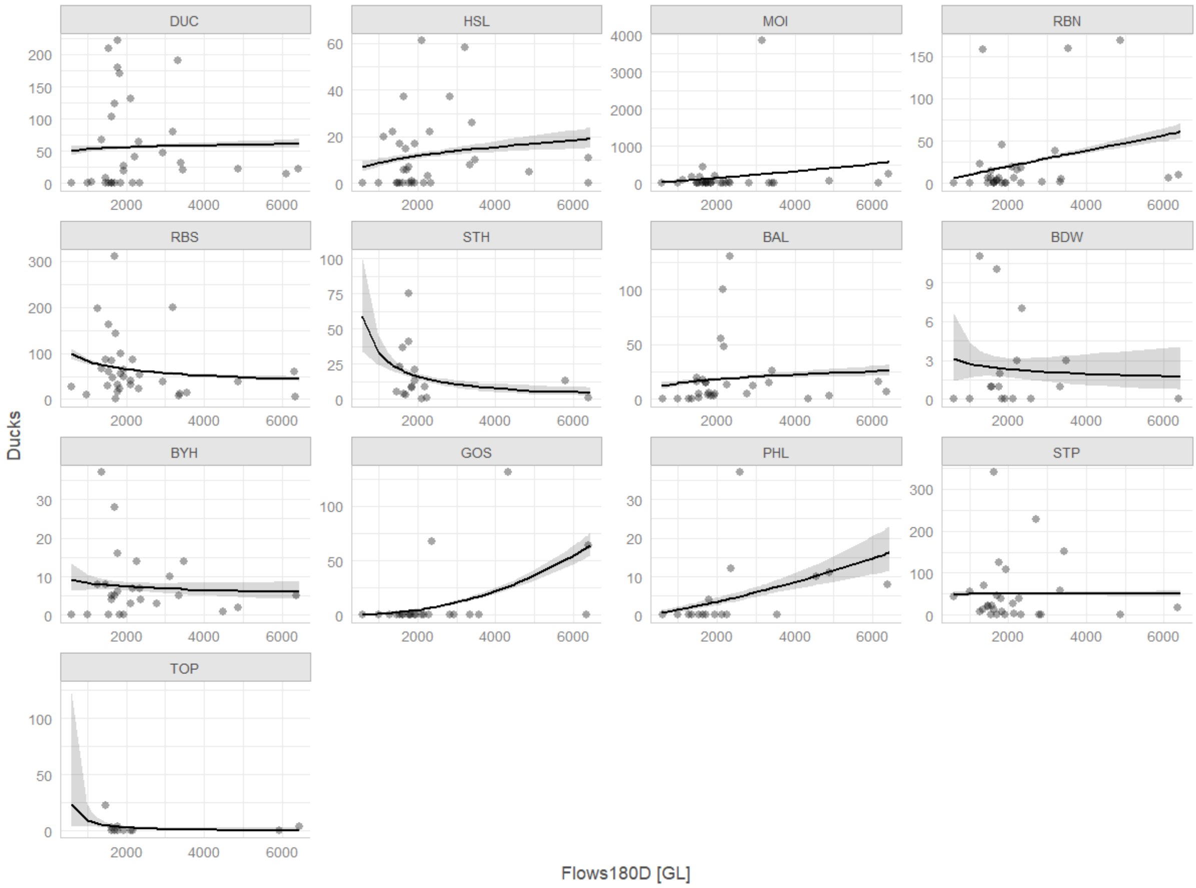
Ducks



Total numbers of ducks recorded in aerial surveys in the Barmah-Millewa forest each spring over the 2007-2020 period in relation to cumulative river flows 10, 30, 60, 90, 120 and 180 days preceding the spring surveys and maximum inundation extent over the entire water year (MaxInun) and the months of August – October (MaxInun3M).

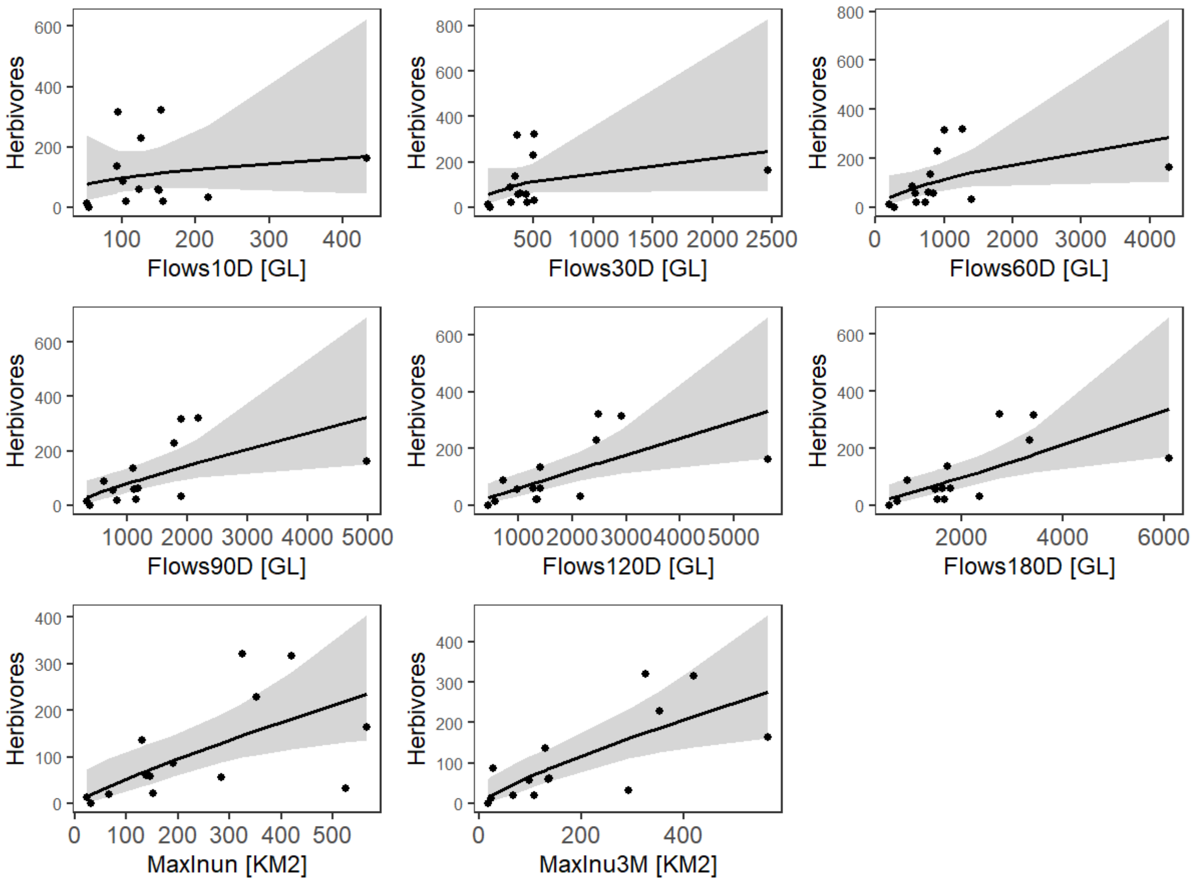


Average (across wetlands) duck density recorded in ground surveys in the Barmah-Millewa Forest (1999-2021) in relation to cumulative river flows preceding to ground surveys and maximum inundation extent over the month of October (Inun) and the months of August – October (MaxInun3M).

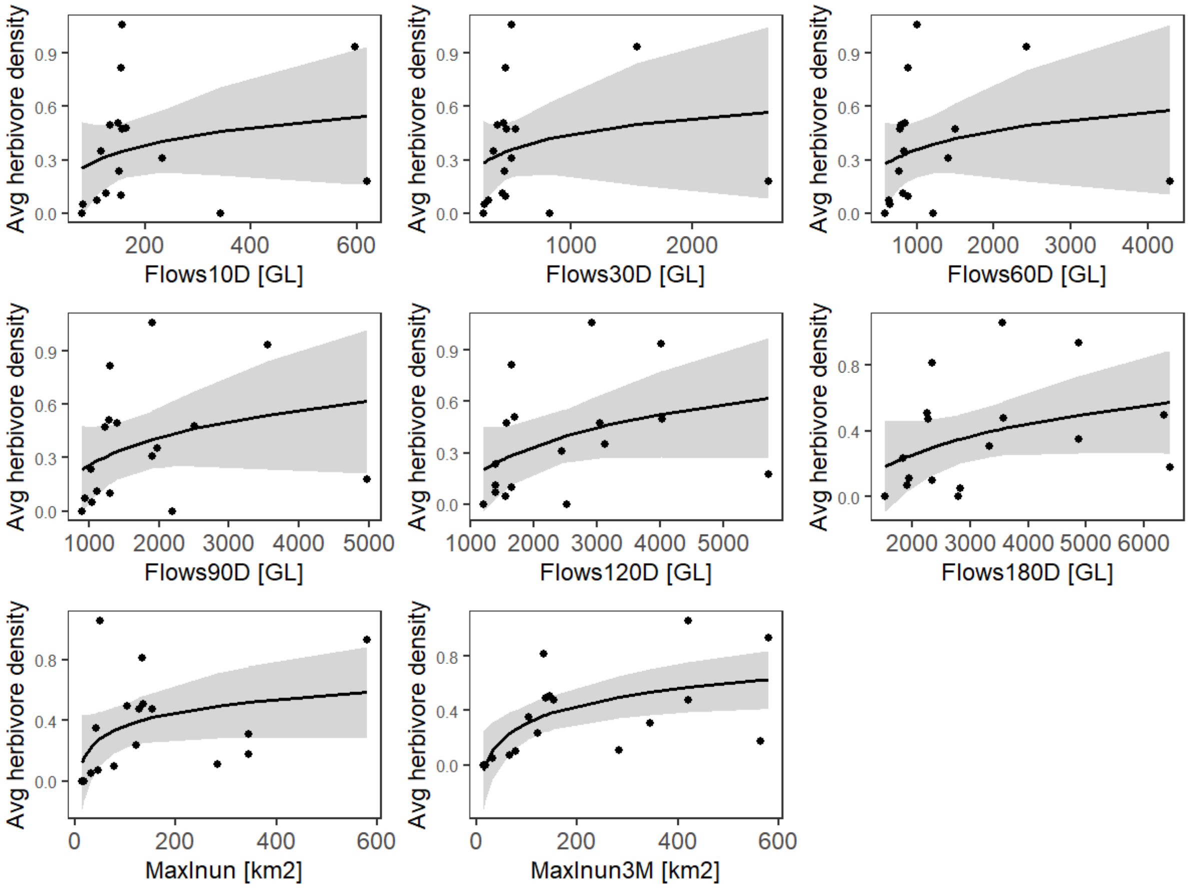


Total duck abundance recorded in ground surveys in the Barmah-Millewa Forest (1999-2021) in relation to cumulative river flows 180 days preceding the surveys. Millewa Forest ground survey sites included Duck Lagoon (DUC), Horseshoe Lagoon (HSL), Moira Lake (MOI), Reed Beds North (RBN), Reed Beds South (RBS), and St Helena Swamp (STH). Barmah Forest ground survey sites included Barmah Lake (BAL), Boals Deadwood (BDW), Bunyip Hole (BYH), Goose Swamp (GOS), Pig Hole (PHL), Steamer Plain (STP) and Top Island (TOP).

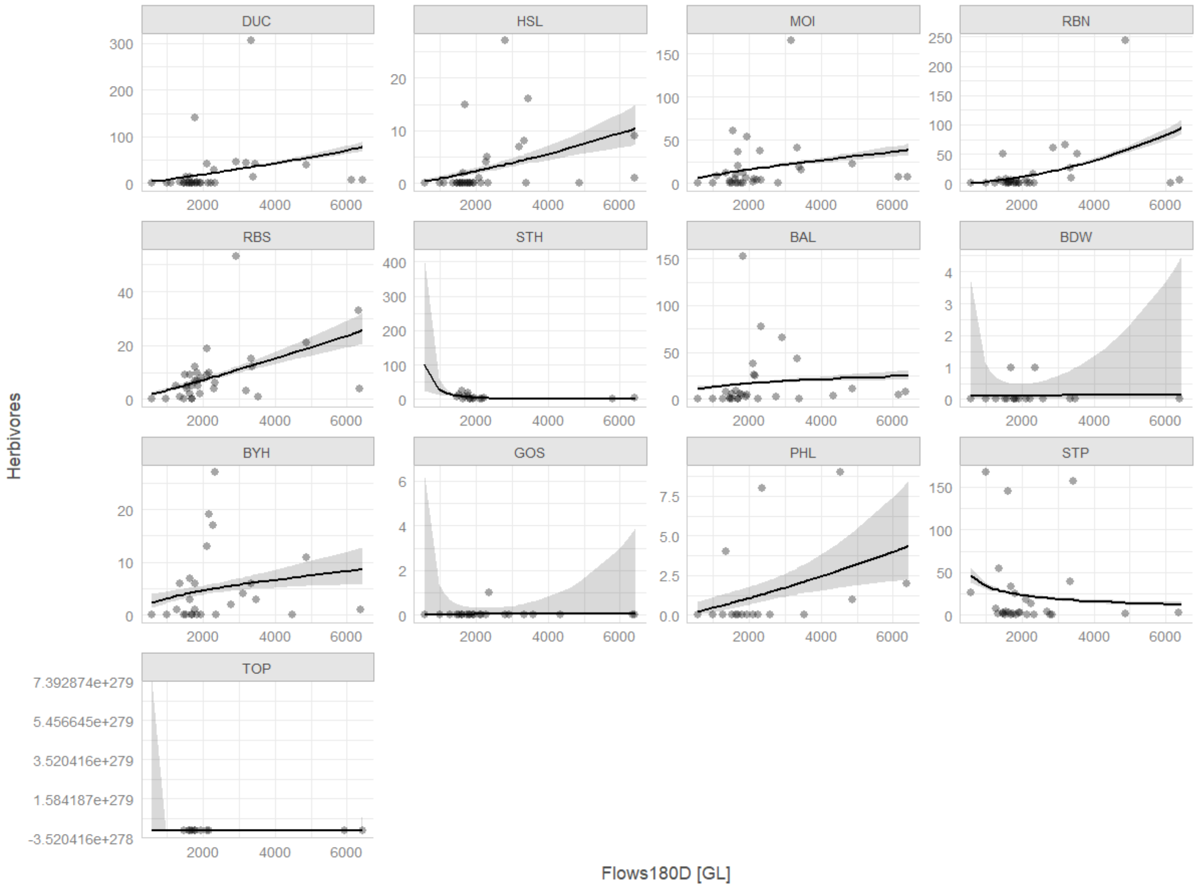
Herbivores



Total numbers of herbivores recorded in aerial surveys in the Barmah-Millewa forest each spring over the 2008-2020 period in relation to cumulative river flows 10, 30, 60, 90, 120 and 180 days preceding the surveys and maximum inundation extent over the entire water year (MaxInun) and the months of August – October (MaxInun 3M).

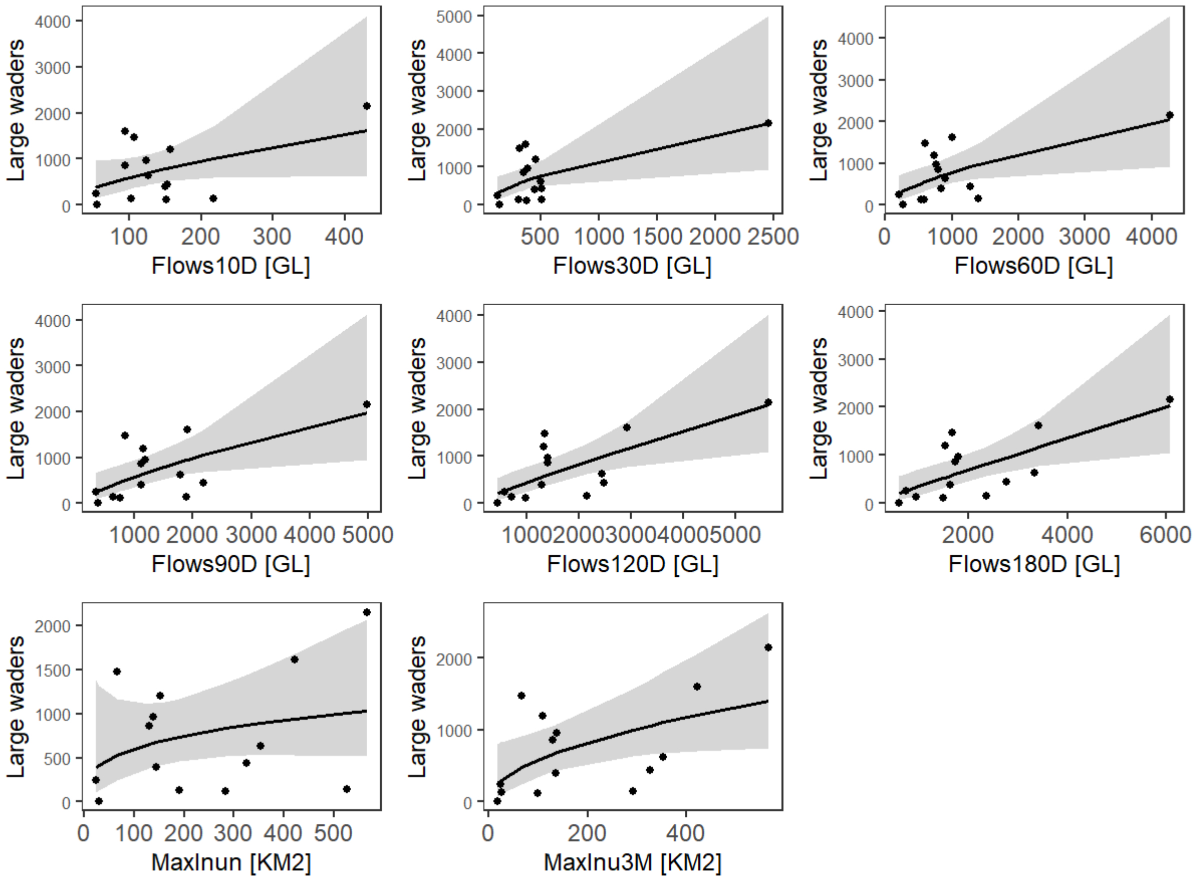


Average (across wetlands) herbivore density recorded in ground surveys in the Barmah-Millewa Forest (1999-2021) in relation to cumulative river flows preceding to ground surveys and maximum inundation extent over the month of October (Inun) and the months of August – October (Inun 3M).

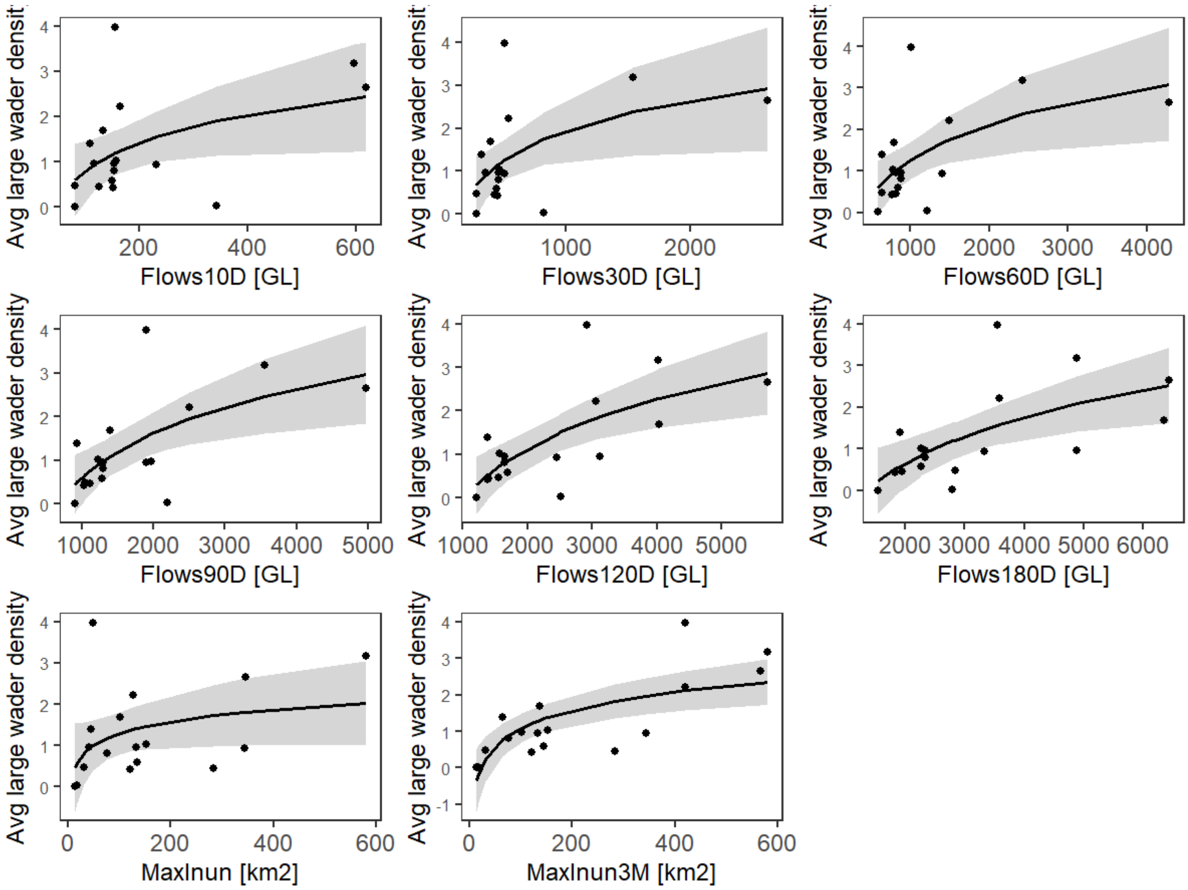


Total herbivore abundance recorded in ground surveys in the Barmah-Millewa Forest (1999-2021) in in relation to cumulative river flows 180 days preceding the surveys. Millewa Forest ground survey sites included Duck Lagoon (DUC), Horseshoe Lagoon (HSL), Moira Lake (MOI), Reed Beds North (RBN), Reed Beds South (RBS), and St Helena Swamp (STH). Barmah Forest ground survey sites included Barmah Lake (BAL), Boals Deadwood (BDW), Bunyip Hole (BYH), Goose Swamp (GOS), Pig Hole (PHL), Steamer Plain (STP) and Top Island (TOP).

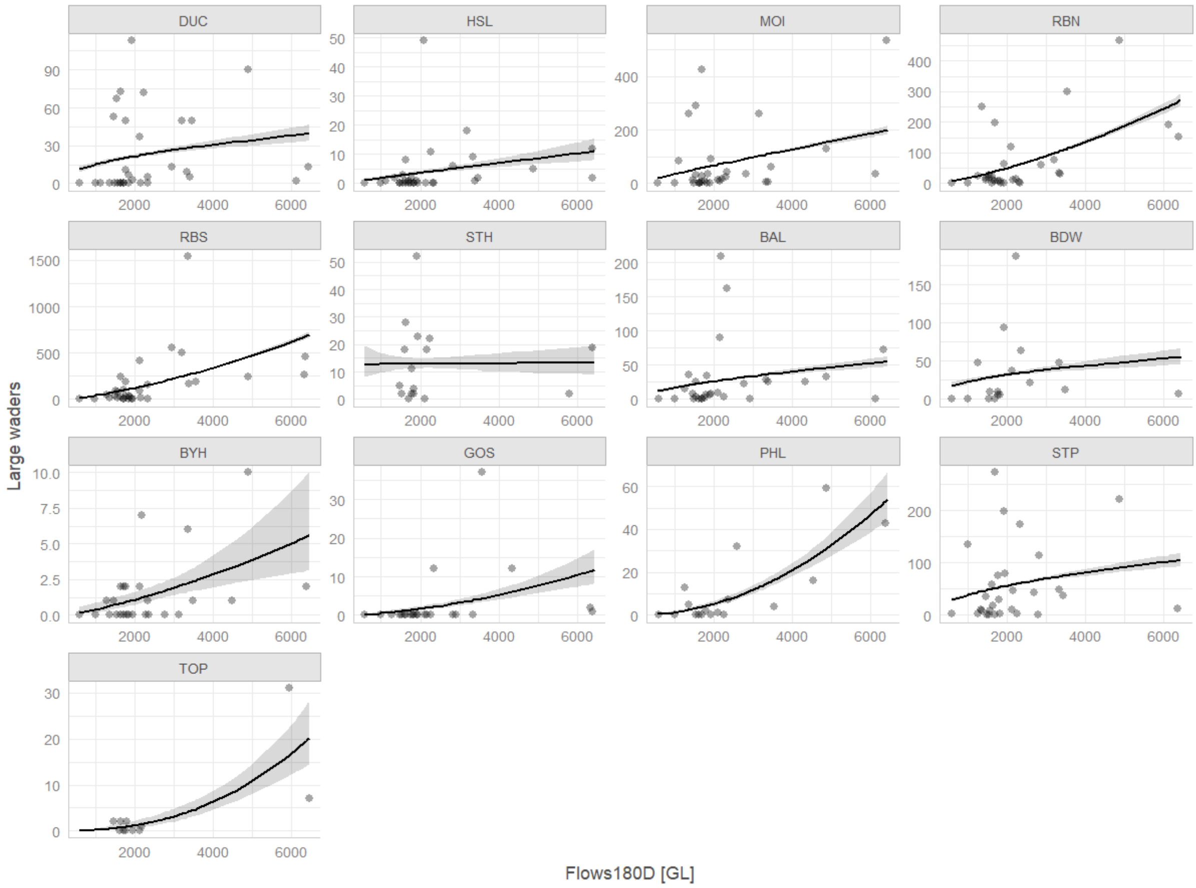
Large waders



Total numbers of large waders recorded in aerial surveys in the Barmah-Millewa forest each spring over the 2007-2020 period in relation to cumulative river flows 10, 30, 60, 90, 120 and 180 days preceding the surveys and maximum inundation extent over the entire water year (MaxInun) and the months of August – October (MaxInun3M).

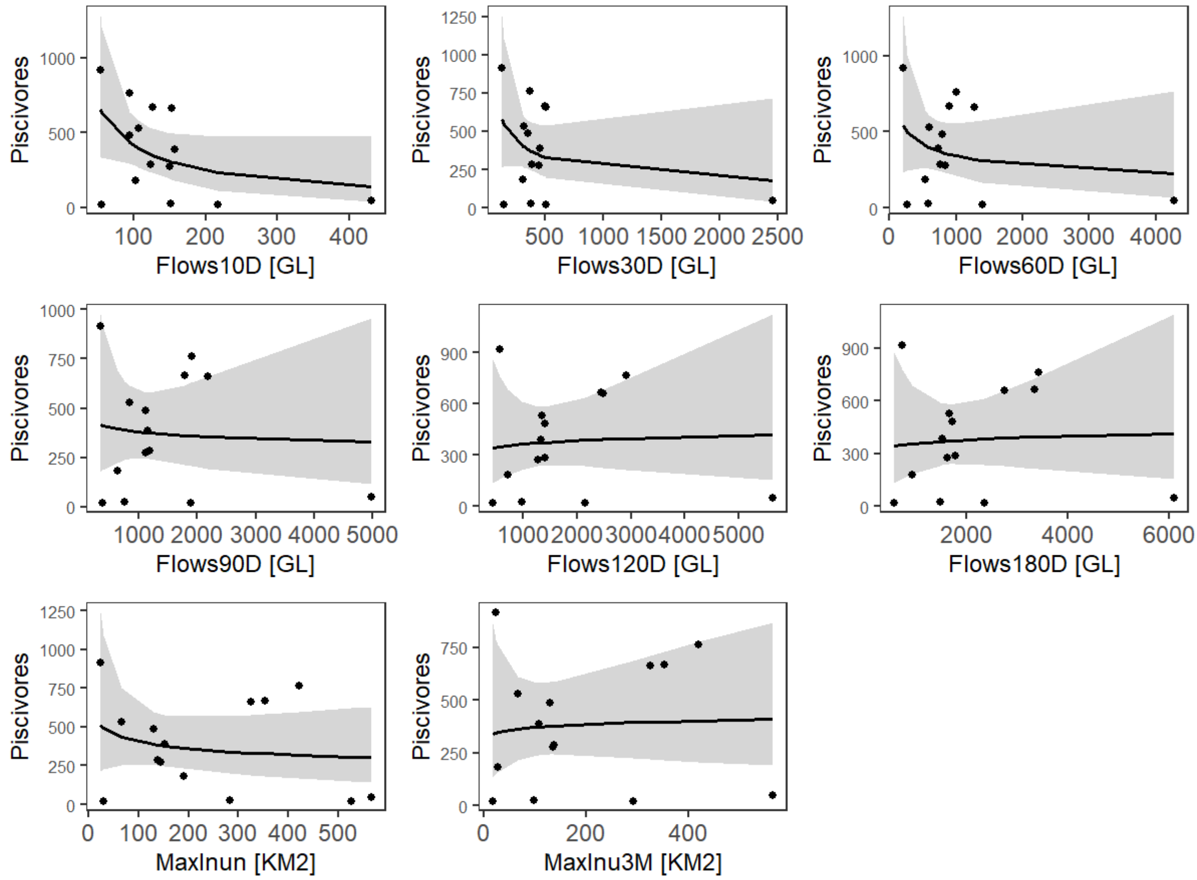


Average (across wetlands) large wader density recorded in ground surveys in the Barmah-Millewa Forest (1999-2021) in relation to cumulative river flows preceding to ground surveys and maximum inundation over the entire water year (MaxInun) and the months of August – October (MaxInun3M).

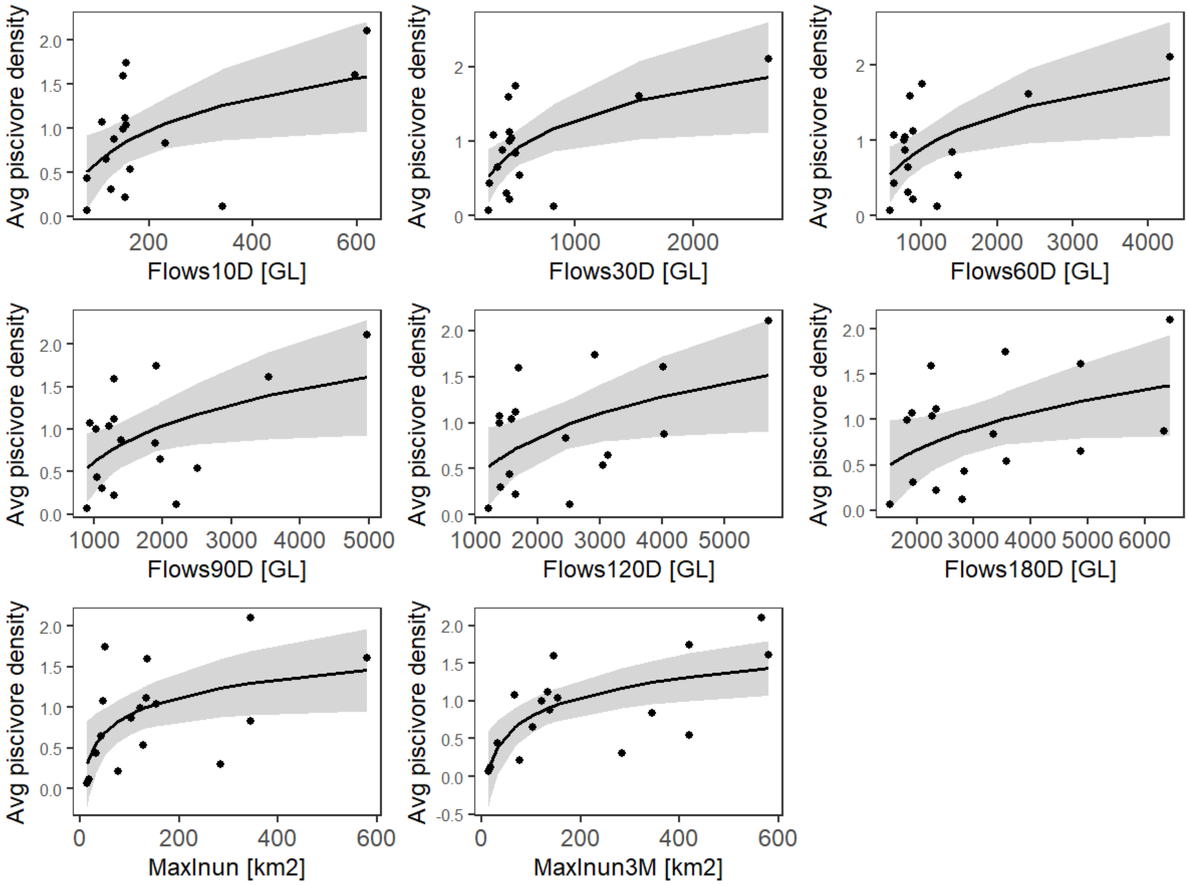


Total large wader abundance recorded in ground surveys in the Barmah-Millewa Forest (1999-2021) in relation to cumulative river flows 180 days preceding the surveys. Millewa Forest ground survey sites included Duck Lagoon (DUC), Horseshoe Lagoon (HSL), Moira Lake (MOI), Reed Beds North (RBN), Reed Beds South (RBS), and St Helena Swamp (STH). Barmah Forest ground survey sites included Barmah Lake (BAL), Boals Deadwood (BDW), Bunyip Hole (BYH), Goose Swamp (GOS), Pig Hole (PHL), Steamer Plain (STP) and Top Island (TOP).

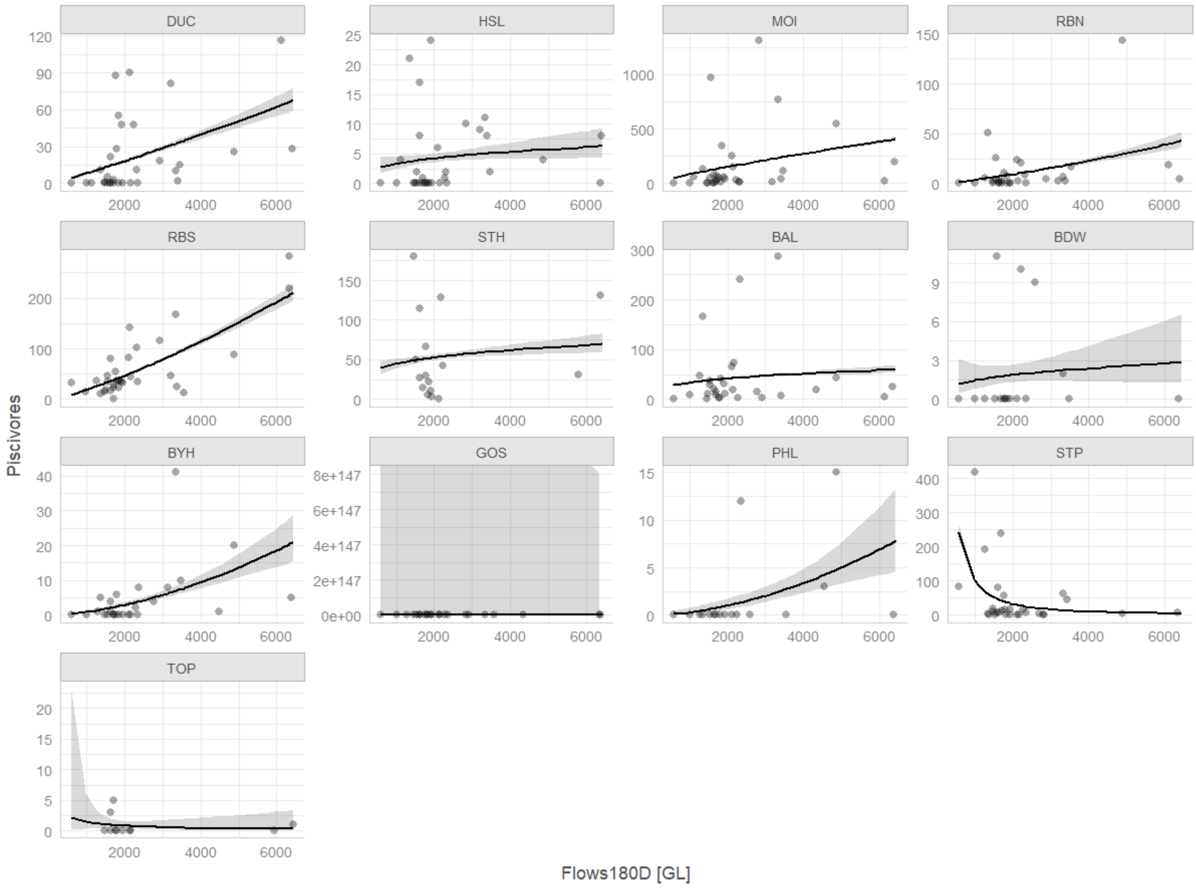
Piscivores



Total numbers of piscivores recorded in aerial surveys in the Barmah-Millewa forest each spring over the 2007-2020 period in relation to cumulative river flows 10, 30, 60, 90, 120 and 180 days preceding the surveys and maximum inundation extent over the entire water year (MaxInun) and the months of August – October (MaxInun3M).



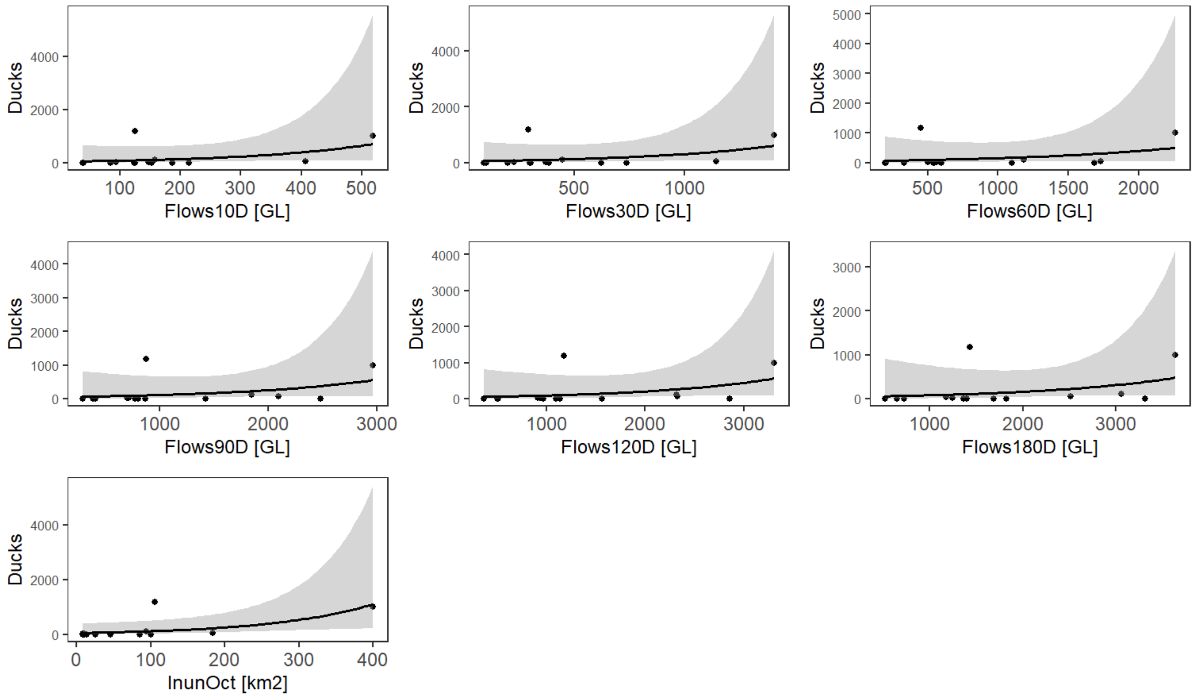
Average (across wetlands) large wader density recorded in ground surveys in the Barmah-Millewa Forest (1999-2021) in relation to cumulative river flows preceding to ground surveys and maximum inundation extent over the entire water year (MaxInun) and the months of August – October (MaxInun3M).



Total piscivore abundance recorded in ground surveys in the Barmah-Millewa Forest (1999-2021) in relation to cumulative river flows 180 days preceding the surveys. Millewa Forest ground survey sites included Duck Lagoon (DUC), Horseshoe Lagoon (HSL), Moira Lake (MOI), Reed Beds North (RBN), Reed Beds South (RBS), and St Helena Swamp (STH). Barmah Forest ground survey sites included Barmah Lake (BAL), Boals Deadwood (BDW), Bunyip Hole (BYH), Goose Swamp (GOS), Pig Hole (PHL), Steamer Plain (STP) and Top Island (TOP).

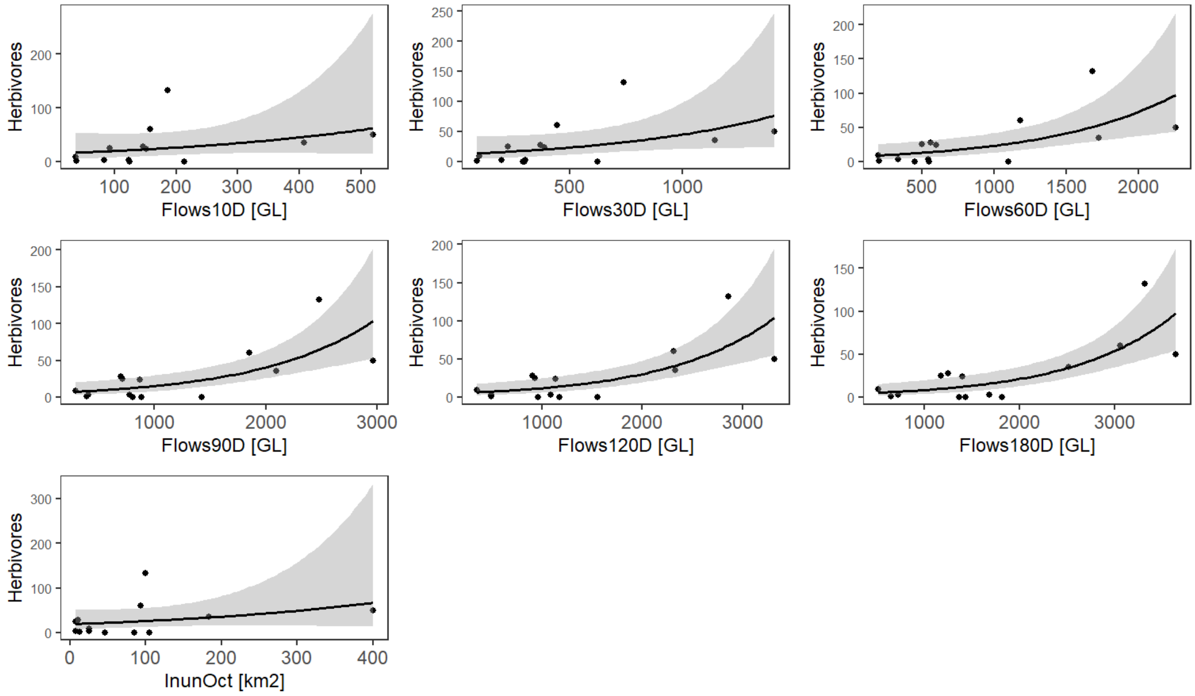
Appendix 5b Model results – Koondrook-Perricoota Forest

Ducks



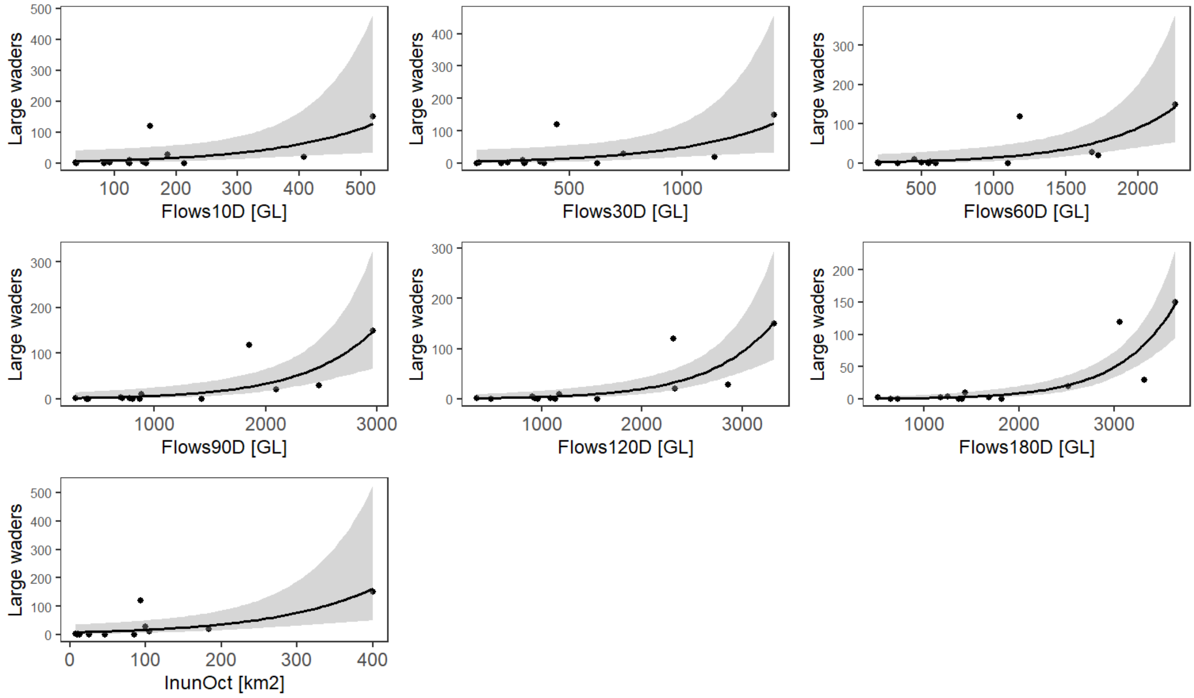
Total numbers of ducks recorded in aerial surveys in the Koondrook-Perricoota Forest each spring over the 2007-2020 period in relation to cumulative river flows 10, 30, 60, 90, 120 and 180 days preceding the spring surveys and minimum inundation extent over the month of October (InunOct).

Herbivores



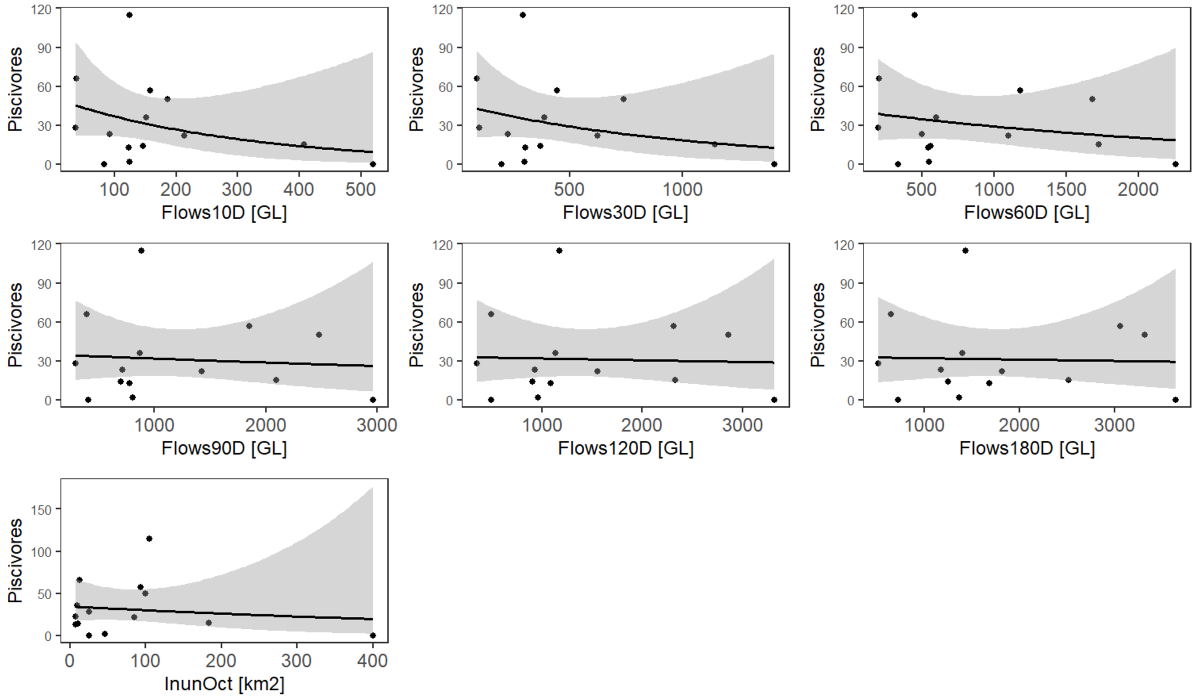
Total numbers of herbivores recorded in aerial surveys in the Koondrook-Perricoota Forest each spring over the 2007-2020 period in relation to cumulative river flows 10, 30, 60, 90, 120 and 180 days preceding the spring surveys and minimum inundation extent over the month of October (InunOct)

Large waders



Total numbers of large waders recorded in aerial surveys in the Koondrook-Perricoota Forest each spring over the 2007-2020 period in relation to cumulative river flows 10, 30, 60, 90, 120 and 180 days preceding the spring surveys and minimum inundation extent over the month of October (InunOct).

Piscivores



Total numbers of piscivores recorded in aerial surveys in the Koondrook-Perricoota Forest each spring over the 2007-2020 period in relation to cumulative river flows 10, 30, 60, 90, 120 and 180 days preceding the spring surveys and minimum inundation extent over the month of October (InunOct)

Appendix 6a Frequency and Duration analyses – d/s Yarrawonga Weir

All Flow Options – January to December

Flow range (Murray DS Yarrawonga Weir)	Event Duration	Average number of events per decade that flows occur in flow range				
		Y15D25 Base case	Y25D25	Y30D30	Y40D40	Y45D40
10,000 + ML/day	<= 10 days	29	29	30	29	31
	11 - 30 days	9	10	9	10	9
	31 - 45 days	3	1	2	2	2
	> 45 days	10	9	8	8	8
15,000 + ML/day	<= 10 days	30	25	24	24	24
	11 - 30 days	7	7	7	6	7
	31 - 45 days	2	2	2	2	2
	> 45 days	4	7	7	7	7
25,000 + ML/day	<= 10 days	13	16	11	10	11
	11 - 30 days	5	5	6	6	7
	31 - 45 days	0	1	2	2	2
	> 45 days	3	3	3	3	3
30,000 + ML/day	<= 10 days	11	13	14	11	11
	11 - 30 days	3	3	3	4	4
	31 - 45 days	1	1	1	3	3
	> 45 days	2	2	2	2	2
40,000 + ML/day	<= 10 days	8	8	8	11	9
	11 - 30 days	4	4	3	4	6
	31 - 45 days	1	1	1	1	1
	> 45 days	1	1	1	1	1
45,000 + ML/day	<= 10 days	7	7	7	8	8
	11 - 30 days	3	3	3	3	2
	31 - 45 days	1	1	0	0	0
	> 45 days	1	1	1	1	1

All Flow Options – August to October

Flow range (Murray DS Yarrawonga Weir)	Event Duration	Average number of events per decade that flows occur in flow range				
		Y15D25 Base case	Y25D25	Y30D30	Y40D40	Y45D40
10,000 + ML/day	<= 10 days	5	4	4	4	4
	11 - 30 days	2	2	1	2	1
	31 - 45 days	1	0	0	0	0
	> 45 days	4	2	2	2	2
15,000 + ML/day	<= 10 days	12	7	7	7	7
	11 - 30 days	3	2	2	1	1
	31 - 45 days	1	2	1	1	1
	> 45 days	1	4	4	4	4
25,000 + ML/day	<= 10 days	7	10	5	4	4
	11 - 30 days	2	3	4	3	4
	31 - 45 days	0	0	2	2	2
	> 45 days	1	1	2	2	2
30,000 + ML/day	<= 10 days	5	8	10	6	6
	11 - 30 days	2	1	2	2	3
	31 - 45 days	1	1	1	2	2
	> 45 days	1	1	1	1	1
40,000 + ML/day	<= 10 days	4	4	5	8	6
	11 - 30 days	3	3	2	3	5
	31 - 45 days	1	1	1	0	0
	> 45 days	0	0	0	0	0
45,000 + ML/day	<= 10 days	4	4	4	5	5
	11 - 30 days	2	2	2	2	2
	31 - 45 days	1	1	0	0	0
	> 45 days	0	0	0	0	0

Appendix 6b Frequency and Duration analyses – d/s Torrumbarry Weir

All Flow Options – January to December

Flow range (Murray DS Torrumbarry Weir)	Event Duration	Average number of events per decade that flows occur in flow range				
		Y15D25 Base case	Y25D25	Y30D30	Y40D40	Y45D40
10,000 + ML/day	<= 10 days	5	6	6	6	6
	11 - 30 days	3	3	4	4	4
	31 - 45 days	0	1	1	1	1
	> 45 days	4	4	4	4	4
15,000 + ML/day	<= 10 days	4	5	5	5	5
	11 - 30 days	2	4	4	4	4
	31 - 45 days	1	1	1	1	1
	> 45 days	3	3	3	4	4
25,000 + ML/day	<= 10 days	4	3	4	4	4
	11 - 30 days	2	3	3	3	3
	31 - 45 days	1	1	1	1	1
	> 45 days	2	2	2	2	2

All Flow Options – August to October

Flow range (Murray DS Torrumbarry Weir)	Event Duration	Average number of events per decade that flows occur in flow range				
		Y15D25 Base case	Y25D25	Y30D30	Y40D40	Y45D40
10,000 + ML/day	<= 10 days	2	4	3	3	4
	11 - 30 days	2	2	2	2	2
	31 - 45 days	0	0	0	1	1
	> 45 days	1	2	2	2	2
15,000 + ML/day	<= 10 days	2	3	3	3	3
	11 - 30 days	1	2	2	2	2
	31 - 45 days	1	1	1	0	0
	> 45 days	1	2	2	2	2
25,000 + ML/day	<= 10 days	2	2	2	3	3
	11 - 30 days	1	2	2	2	2
	31 - 45 days	0	0	0	0	0
	> 45 days	1	1	1	1	1