Technical information supporting the South Australian Basin Plan Environmental Outcome Evaluation

South Australian River Murray: Channel and Floodplain Priority Environmental Assets

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Department for Environment and Water

Government of South Australia

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81-95 Waymouth St, ADELAIDE SA 5000

Telephone +61 (8) 8463 6946

Facsimile +61 (8) 8463 6999

ABN 36702093234

www.environment.sa.gov.au

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Acknowledgement of Country

We acknowledge and respect the Traditional Custodians whose ancestral lands we live and work upon and we pay our respects to their Elders past and present.

We acknowledge and respect their deep spiritual connection and the relationship that Aboriginal and Torres Strait Islanders people have to Country.

We also pay our respects to the cultural authority of Aboriginal and Torres Strait Islander people and their nations in South Australia, as well as those across Australia.

Acknowledgements

This report is the result of extensive collaboration among numerous individuals and staff from South Australian government agencies, universities, and organisations, including the Murray–Darling Basin Authority (MDBA), Commonwealth Environmental Water Holder (CEWH), South Australian Research and Development Institute (SARDI), Commonwealth Scientific and Industrial Research Organisation (CSIRO), Flinders University and the University of Adelaide. These institutions provided data, information, expert insights, and reviews required to complete this work.

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Summary

South Australia has assessed the achievement of environmental outcomes relating to a subset of the South Australian River Murray (SA River Murray) Long-term Watering Plan (LTWP) targets for the Channel and Floodplain Priority Environmental Assets (PEA). By achieving these outcomes, the aim is to maintain or improve the health and ecological function of water-dependent ecosystems. The assessment of environmental outcomes presents the trend for each indicator, along with a detailed evaluation of the contribution of the Basin Plan and other influences on the achievement of these outcomes. A summary of the assessment is shown below.

Theme	Indicator	Trend	Information reliability	Key findings
Flow & Ecosystem Function	Flow velocity	↗ Trend Improved	★★★☆☆ Reliability Good	There has been improvement in the frequency of fast-flowing conditions, but this was largely driven by unregulated, high flows.
	Floodplain productivity: Microinvertebrates	NA Trend Not Applicable	★★★★☆ Reliability Very good	Microinvertebrate density and richness increased, particularly following high flow conditions.
Vegetation	River red gum	↗ Trend Improved	★☆☆☆☆ Reliability Poor	River red gum condition has increased across managed areas of Chowilla, Pike and Katarapko floodplains.
	Black box	↗ Trend Improved	★☆☆☆☆ Reliability Poor	Black box condition has improved, particularly in managed floodplain areas.
Fish	Murray cod	↗ Trend Improved	★★★☆☆ Reliability Good	Recruitment of Murray cod has continued to improve, with population structure characteristic of a more resilient population.
	Golden perch	↗ Trend Improved	★★★☆☆ Reliability Good	Golden perch recruitment has improved, with young-of-year detected in the population since 2021.

The following key messages have come from South Australia's assessment and evaluation of the achievement of environmental outcomes in the SA River Murray Channel PEA and Floodplain PEA.

- This includes through the delivery of water for the environment, which has:
    - supported managed floodplain inundations, improving the condition of river red gum and black box and their capacity to respond to future high (unregulated) flows

    - increased densities and diversity of microinvertebrates, critical for channel and floodplain productivity and food webs, particularly in conjunction with managed inundations and overbank flow conditions
    - provided spring-summer flows and more localised fast-flowing habitats, that likely facilitate recruitment and improved structure in Murray cod and golden perch populations
    - enabled targeted delivery of water, creating conditions for the breeding and recruitment of local frog species in the absence of sufficient natural flows.
- The delivery of water for the environment, in conjunction with weir pool manipulation and managed floodplain inundation, has been essential for improving environmental health and resilience across managed floodplains since the Millenium Drought.
- High (unregulated) flows are vital for reaching floodplain areas that cannot be supported through managed inundation. Some indicators are limited to sites with targeted delivery of water for the environment, where results may not reflect conditions across the broader channel and floodplain assets.
- Full implementation of the Basin Plan, including the recovery and delivery of the additional 450 GL and addressing current water delivery constraints, is critical to achieve more frequent, prolonged and significant overbank flows along the SA River Murray, further enhancing environmental outcomes in these assets.
- Ongoing effort and investment are necessary to continue to improve the health and resilience of the Channel and Floodplain, including the integrated and adaptive management of South Australia's supply measure projects.
- Continued engagement with local communities and First Nations to identify sustainable water management solutions and actions to identify and address key threats such as habitat loss and degradation are critical for the ongoing sustainability of some indicator species.

1 Introduction

1.1 Basin Plan Schedule 12

The reporting requirements outlined in Schedule 12 of the Basin Plan provide the Murray–Darling Basin Authority (MDBA) with the information necessary to evaluate the effectiveness of the Basin Plan against its objectives and outcomes (Chapter 4).

Matter 8 (achievement of environmental outcomes at an asset scale) is a state-based reporting obligation that is central to communicating the environmental outcomes achieved through the implementation of the Basin Plan. Basin states are required to report on Matter 8 on a 5-yearly basis, with the first round of reporting submitted in October 2020. The next round of reporting (of which this report contributes to) is to be submitted in October 2024. Technical reports for the 2025 Matter 8 Evaluation were prepared and submitted a year earlier (four years after the 2020 Evaluation) in order to support the MDBA's Basin-scale evaluation in 2025. The MDBA is required to undertake an evaluation of the Basin Plan against its objectives in 2025, which will draw on the reporting undertaken by the MDBA, and reporting submitted by the Basin states under Schedule 12.

1.2 South Australia's approach to 2025 Basin Plan Environmental Outcome Evaluation and Reporting (Matter 8)

South Australia has identified the following objectives for Matter 8 environmental outcome reporting:

- To meet Basin Plan reporting obligations (Schedule 12, Basin Plan)
- To inform South Australia's, the Australian Government's, and other States' environmental water delivery decision making and adaptive management capacity
- To make a meaningful contribution to MDBA's evaluation of the effectiveness of the Basin Plan (at Basin-scale) and our own evaluation of the effectiveness of the Basin Plan at a state-scale.

The South Australian Department for Environment and Water (DEW) has developed an approach to reporting on the achievement of environmental outcomes required for the Matter 8 reporting (Imgraben 2023). This approach recognises the linkages between the Basin Plan environmental objectives, environmental watering plans and strategies (state and Basin-wide) and asset-scale environmental outcome reporting (Matter 8). Four key evaluation questions guide South Australia's evaluation of environmental outcomes at an asset scale:

1. To what extent have outcomes been achieved?
2. If outcomes were not achieved, why not?
3. To what extent did the Basin Plan contribute to achieving outcomes?
4. Have there been any unanticipated outcomes?

Reporting for Matter 8 in South Australia is required for three Water Resource Plan (WRP) Areas:

- South Australian River Murray
- Eastern Mount Lofty Ranges
- Murray Region.

In line with the Basin Plan, South Australia has developed a Long-term Watering Plan (LTWP) for each of these WRP Areas. These plans identify Priority Environmental Assets (PEA) in each area together with environmental objectives, targets, and environmental water requirements (EWRs). The asset scale reporting of Matter 8 is therefore directly linked to the assets identified in the LTWPs and the objectives, targets, and EWRs for each.

The achievement of environmental outcomes over PEAs in the South Australian River Murray is assessed in relation to prioritised LTWP targets through the development of expected outcomes (see section 1.2.1). Prioritisation of LTWP targets was undertaken against the following criteria:

- Capability to track environmental trends at a range of spatial scales
- Environmental value
- Response to flow
- Consistency with the Basin-wide Environmental Watering Strategy
- Scientific credibility and reproducibility

1.2.1 South Australian River Murray expected outcomes

Targets in the South Australian River Murray LTWP are long-term and represent what is needed to support the PEAs in a 'healthy, functioning state'. The development of targets was not restricted to what is achievable under the Basin Plan, and the timeframes over which achievable targets are expected to be met vary based upon their response to water for the environment delivery and other management actions over time. To provide a more nuanced approach to the evaluation and reporting, quantitative expected environmental outcomes (expected outcomes) were developed that allows us to track the progression towards outcomes, targets, and objectives.

Expected outcomes quantify the extent to which LTWP targets are met over three time points post-Basin Plan adoption in 2012 (i.e. 2019, 2029 and 2042). These time points were chosen to align with key Basin Plan implementation activities and reporting. Expected outcomes were developed using a best-practice expert elicitation approach (Speirs-Bridge et al. 2010) and informed by Basin Plan hydrological modelling scenarios and best available data and information. The achievement of the short-term (2019) expected outcomes was assessed for 2020 Matter 8 reporting. For this round of reporting, progress towards intermediate outcomes (2029) will be assessed.

2 River Murray Channel and Floodplain Priority Environmental Assets

2.1 SA River Murray Channel Priority Environmental Asset

The South Australian River Murray (SA River Murray) Channel Priority Environmental Asset ('the Channel PEA') extends from Wellington to the South Australia border (~560 kms) (DEW 2020) (Figure 2-1 and Figure 2-2). The breadth of the Channel PEA extends to areas inundated at Flows to South Australia (QSA) of up to 40,000 ML day^{-1} under normal river operation (DEW 2020). There is a total of 28,800 ha that is within the Channel PEA and is divided into permanently and temporarily inundated areas (DEW 2020).

The Channel PEA is a system of both lentic (slow) and lotic (fast) flowing channels and anabranches, temporary wetlands, still backwaters, and saline swamps. Conditions in these waterways are invariably linked to the contemporary water regime throughout the Murray–Darling Basin (MDB), and respond directly to hydrological attributes including flow volumes, water velocity, and extent and frequency of inundation.

Permanent waters within the Channel PEA support a variety of organisms including fish, waterbirds, macroinvertebrates, microorganisms, and frogs. Temporary waters are typically more associated with frogs, fish, and understorey vegetation, but also support a variety of other organisms.

2.2 SA River Murray Floodplain Priority Environmental Asset

The SA River Murray Floodplain Priority Environmental Asset ('the Floodplain PEA') borders the Channel PEA, and therefore also extends from Wellington, South Australia to the South Australian border (Figure 2-1 and Figure 2-2). The Floodplain PEA is defined as the area of inundation between 40,000 and 80,000 ML day^{-1} under normal river operation (DEW 2020). There is no definition for areas that are inundated beyond 80,000 ML day^{-1}, as environmental water delivery to such areas is unfeasible under current schemes (DEW 2020).

The Floodplain PEA consists of a mosaic of ephemeral habitats and has a variable breadth along its extent. Areas upstream of Overland Corner have much wider expanses (up to 10 km), known as the Valley geomorphic zone, compared to areas downstream of Overland Corner, known as the Gorge geomorphic zone (Walker & Thoms 1993). Between Wellington and Overland Corner remains very little floodplain areas, most of which have been reclaimed (DEW 2020).

Floodplains have disproportionate biodiversity to the area they contain (Doody et al. 2015). Floodplains along the SA River Murray comprise two types. Shedding floodplains are areas where water recedes following a drop in inundating waters, defining these areas as ephemeral (Kilsby & Steggles 2015). Temporary wetlands are floodplain areas that exist within depressions of the land, and therefore retain lentic water for a certain period after a flood subsides (Kilsby & Steggles 2015).

The condition and extent of ecological communities on the floodplain are dynamic, responding to flow regime of the River Murray (Souter et al. 2012). Inundation of the Floodplain PEA provides a productive environment for Riverland flora and fauna that are dependent on wetlands. Specifically, floodplain inundation stimulates and supports breeding in many fish, frog, and waterbird species (Graham & Harris 2005; Hoffmann 2018; Humphries et al. 1999) and contributes to the establishment and persistence of flood-dependent and amphibious vegetation (Overton & Doody 2007). Overland flooding mediates nutrient transport throughout the Channel and Floodplain PEA, and structures primary productivity which benefits the whole food web (Ye et al. 2014).

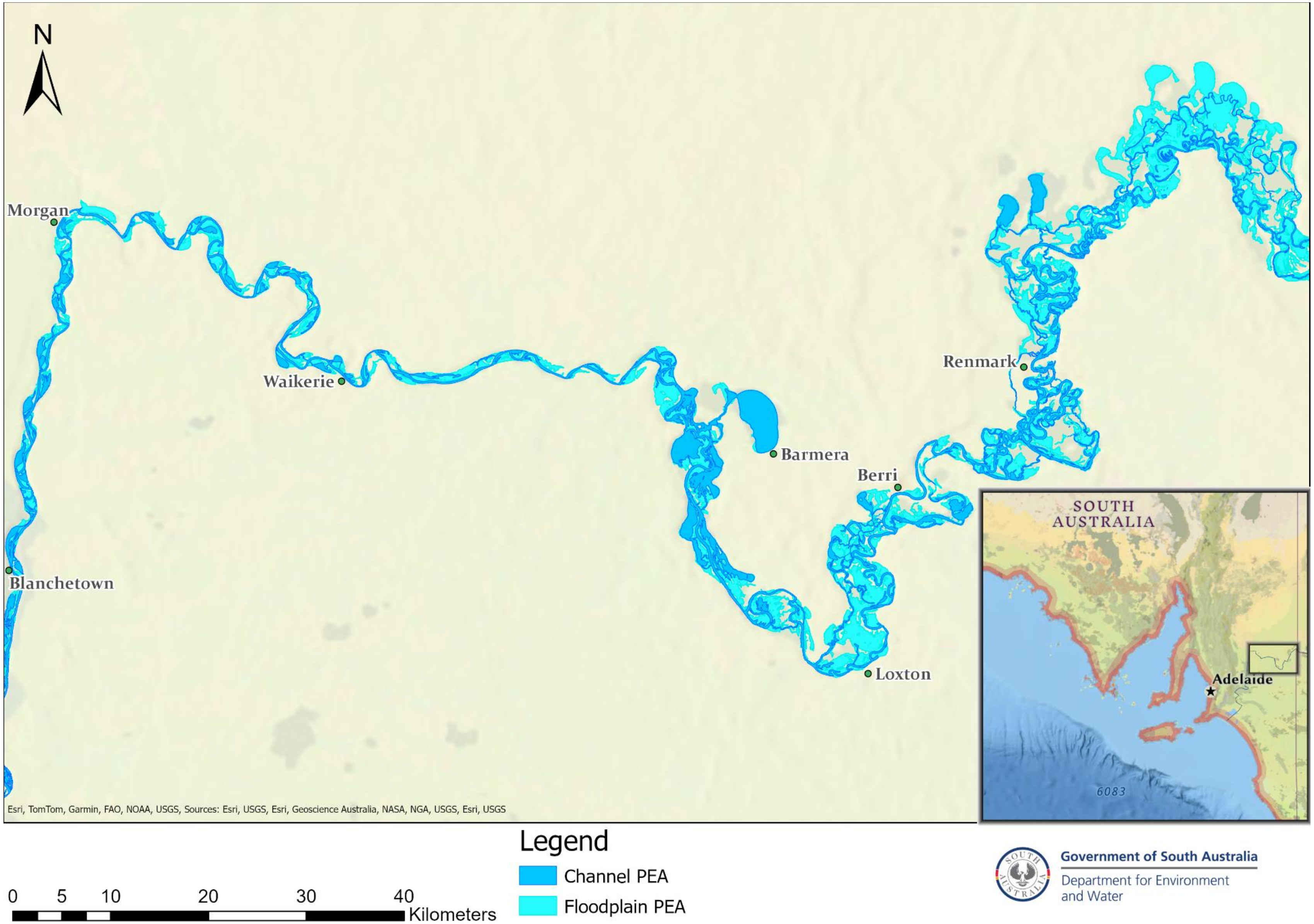


Figure 2-1. Map 1 of 2 showing the Channel PEA (dark blue) and Floodplain PEA (light blue) from Blanchetown to the South Australian Border.

Figure 2-2. Map 2 of 2 showing the Channel PEA (dark blue) and Floodplain PEA (light blue) from Wellington to Blanchetown.

2.3 Ramsar sites

The Channel and Floodplain PEAs overlap with the Banrock Station Wetland Complex and Riverland Ramsar listed wetlands of international importance. The area of overlap between the Channel and Floodplain PEAs with the 2 Ramsar wetlands is shown below in Table 2–1.

Table 2–1. Overlap of the Channel and Floodplain PEA with Ramsar-listed Wetlands.

PEA	Ramsar Wetland	Area of overlap (hectares)
The Channel PEA	Banrock Station	190
	Riverland	3,840
The Floodplain PEA	Banrock Station	710
	Riverland	13,250

The Banrock Station Wetland Complex is situated opposite Overland Corner in the South Australian Riverland. The wetland complex covers 1,375 ha of low-lying floodplain and upland mallee (Butcher et al. 2009). Banrock Station Wetland Complex meets the Ramsar criteria to be listed as a wetland of international importance because it supports nationally threatened species (e.g. Regent Parrot and southern bell frog).

The Riverland Ramsar wetland, which extends over an 80 km stretch of river and spans 30,615 ha with 27,213 ha dedicated to the preservation of biodiversity (Newall et al. 2009), encompasses a variety of aquatic environments. These include the River Murray, two significant anabranches (Chowilla and Ral Ral creeks), as well as lagoons, billabongs, swamps, and lakes (Newall et al. 2009). Recognised under the Ramsar Convention as a site of international importance, the wetland is vital for the support of species at risk in Australia, such as the Regent Parrot, southern bell frog, Murray cod, and Murray hardyhead. It also serves as a critical non-breeding refuge for nine species of migratory waterbirds recognised by global treaties, contributing to the conservation of waterbird populations that exceed 1% of their worldwide numbers, including the Freckled Duck, Red-Necked Avocet, and Red-Kneed Dotterel, alongside providing essential spawning grounds and migratory routes for significant native fish species.

3 Hydrology

3.1 Rainfall

3.1.1 Murray–Darling Basin

Rainfall is critical for the Murray–Darling Basin (MDB), and patterns vary significantly across the Basin's extent. Annual rainfall follows a general east-west gradient, with the areas bordering the highlands of the Great Dividing Range receiving approximately 1,000 mm per annum, while the arid west often receiving less than 300 mm (Gallant et al. 2012). Timing of rainfall in the Basin varies latitudinally. The southern Basin receives more consistent rainfall, mainly through regular precipitation during the cooler months (May–October), compared with the northern Basin that receives most of its rainfall during the warmer months (November–April), and is more variable due to interactions between multiple weather systems (Chiew et al. 2008; Dey et al. 2020; Gallant et al. 2012; MDBA 2019).

Rainfall deciles demonstrate prolonged dry periods broken by years of above-average to record rainfall (Figure 3-1). The end of the Millennium Drought (1996–2010) was marked by two consecutive years (2010–11 and 2011–12) of extensive rainfall across much of the Basin. From 2012–13 to 2015–16, rainfall across the Basin was mostly average to below average. Rainfall across the southern Basin, in particular the South Australian River Murray (SA River Murray), was well above average in 2016–17. Drought conditions commenced towards the end of the last decade. In 2019, rainfall was the lowest on record across the Basin, and areas in the north-east were most severely affected (BOM 2019). Rainfall has been higher than average over the last four years. In 2022–23, high rainfall was ubiquitous over the southern MDB and at or above average in the northern MDB, and resulted in a significant flooding event that impacted many sections of the northern and southern Basin.

Climate change has contributed to lower annual rainfall in the southern Basin and temporal shifts (MDBA 2019). In the southern Basin, winter and spring rainfall has declined, however, there is slightly more in autumn (MDBA 2019). Likewise, there has been a decline in winter and spring rainfall in the northern Basin and an increase in summer and autumn rainfall (MDBA 2019). Future projections suggest that a drier future is likely for the MDB, particularly in the southern basin and during winter, although these projections come with considerable uncertainty (Whetton & Chiew 2021). This projected decline in rainfall is expected to reduce runoff, with a median projected decrease in mean annual runoff of 14% in the southern Basin and 10% in the northern Basin by 2046–75 under the medium warming scenario (Whetton & Chiew 2021).

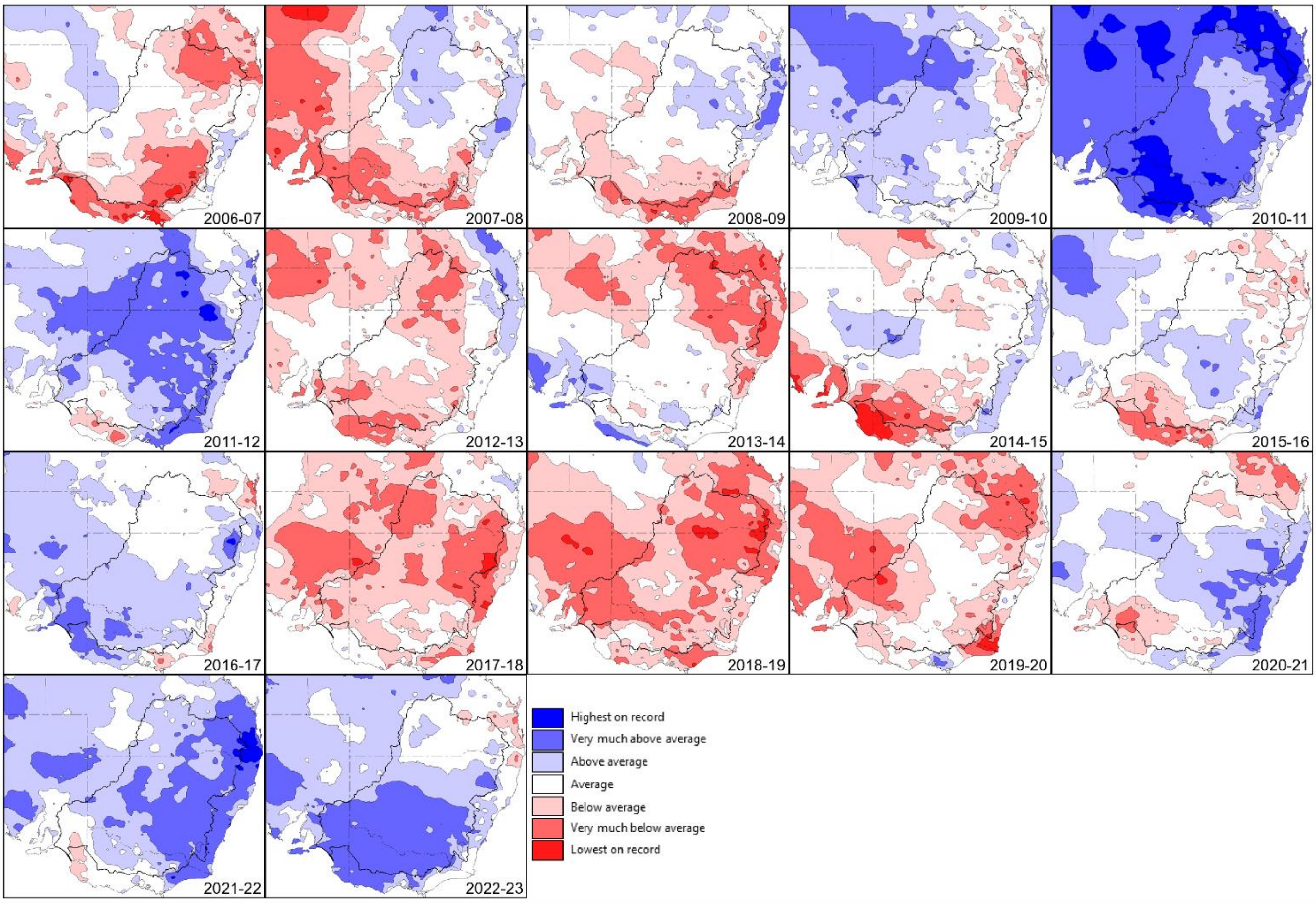


Figure 3-1. Rainfall deciles for the Murray–Darling Basin (black outline) in each water year (July – June) since July 2006. Data source: BOM 2023.

3.1.2 South Australian River Murray

Annual rainfall patterns at major towns located along the SA River Murray have been similar since the beginning of this century (Figure 3-2). Long-term annual rainfall was similar for the inland towns of Renmark, Waikerie, and Swan Reach, while Murray Bridge receives more rainfall due to its proximity to the Mount Lofty Ranges. Notably, periods of below average rainfall across all towns occurred during the Millennium Drought (1996–2010). All towns also experienced higher-than-average rainfall in 2010–11 and 2016–17. However, there was regionally variable rainfall in both 2021–22 and 2022–23, with Renmark, Waikerie and Murray Bridge exceeding their respective long-term averages, while below-average rainfall was recorded at Swan Reach.

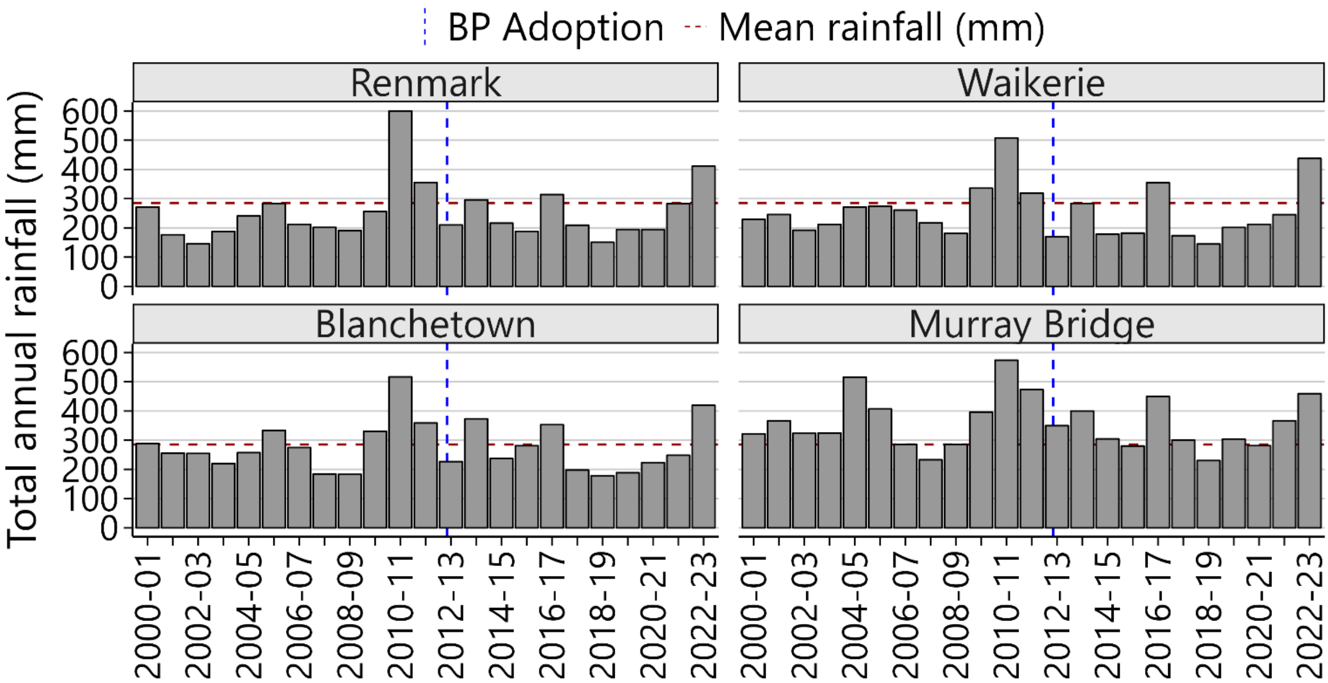


Figure 3-2. The total rainfall (mm) for each water year between July 2000 and June 2023 at major towns located along the SA River Murray. Data source: BOM 2023.

3.2 Flows to South Australia (QSA)

Flows to South Australia (QSA) quantifies the volume of water in the River Murray arriving at the South Australian border. Flow volumes (Figure 3-3) vary markedly with climatic conditions (e.g. rainfall, drought, temperature) and the diversion of water resources upstream, leading to annual and seasonal variability. Intra-annual patterns are relatively unpredictable, however, seasonal discharge patterns typically are at their peak in spring and at their lowest in late summer and early autumn (Maheshwari et al. 1995).

QSA has been highly variable over the last 22 years. The Millennium Drought occurred from 1996–2010 and included a period of prolonged low flow from 2001–02 to 2009–10 (average 1,717 GL year^{-1}). Widespread flooding occurred over the MDB in 2010–11, with QSA peaking at ~93,508 ML day^{-1} and an annual QSA totalling 15,137 GL. High flows continued in 2011–12 and 2012–13 with 10,248 GL and 6,970 GL of annual QSA, respectively. More moderate flows (3,570 GL) were recorded over 2013–14, before low flow conditions occurred over 2014–15 and 2015–16 (average 2,685 GL). In 2016–17, high flows were recorded with QSA peaking at ~94,381 ML day^{-1}. As there was a rapid recession in this high flow event, the annual volume (9,238 GL) was lower than 2010–11. Extreme dry conditions in the MDB (see Figure 3-1) between 2017–18 and 2019–20 greatly reduced QSA (average 2,508 GL year^{-1}) over this period. Three consecutive years of above-average rainfall in the Basin increased QSA between 2020–21 and 2022–23. Moderate flows were recorded in 2020–21 (3,078 GL year^{-1}), which were followed by high flows in 2021–22 (9,097 GL year^{-1}) and the third largest flooding event in the SA River Murray in 2022–23 (23,000 GL year^{-1}). The highest flow peaks in the last two water years were 42,976 ML day^{-1} (30/06/2022) and 185,746 ML day^{-1} (22/12/2022).

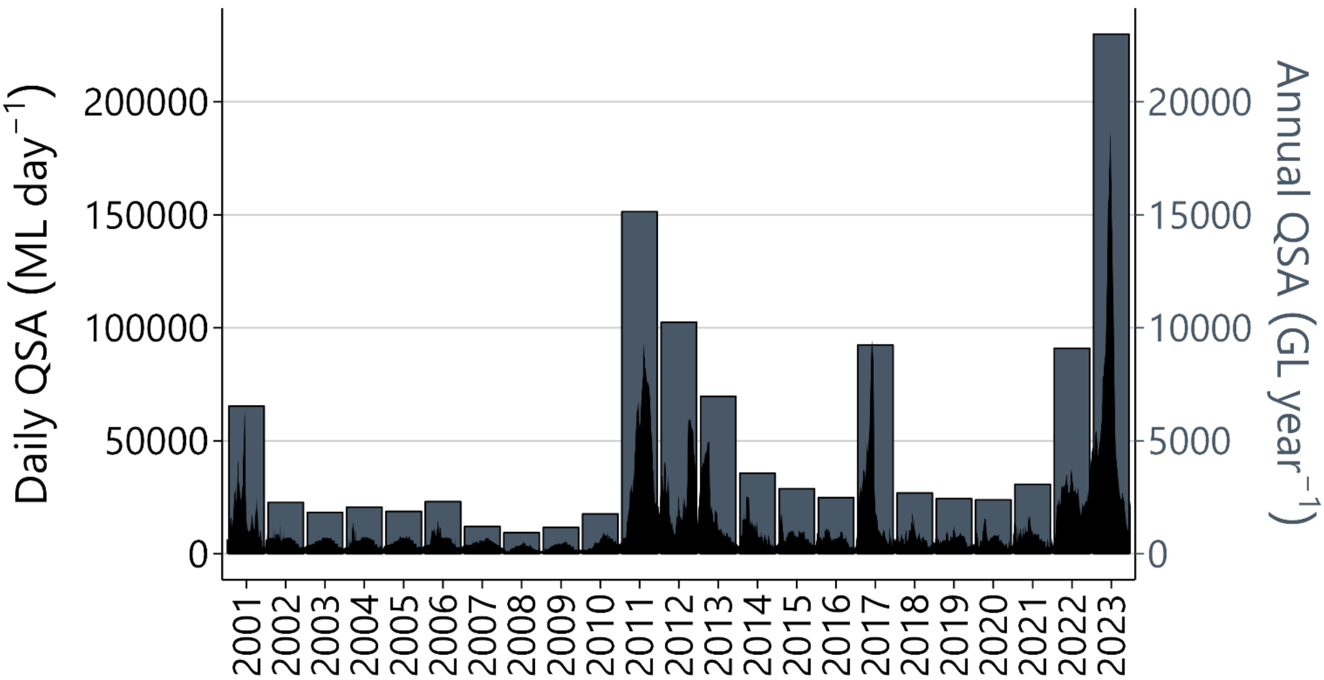


Figure 3-3. Flows to South Australia (QSA) between 2000-01 and 2022-23. The left axis and black area correspond to daily QSA (ML day^{-1}), while the right axis and grey bars correspond to annual QSA (GL year^{-1}) for each water year (1 July to 30 June).

3.2.1 Water for the environment

The Basin Plan provisions flow entitlements to South Australia within the total QSA (shown in Figure 3-4). Sources of QSA include SA entitlement flow, additional dilution flow (ADF), water for the environment and unregulated flows. In years with low QSA, the relative contribution of water for the environment to QSA is higher, while the total volume SA receives is lower. For example, in 2022 water for the environment comprised 4% of annual QSA, while in lower flow years such as 2019 it was 33% of annual QSA. The total volume of water for the environment between these two years also differed. Annual volumes of water for the environment provided to South Australia has ranged from 421 GL (2016) to 1,306 GL (2017) since the adoption of the Basin Plan.

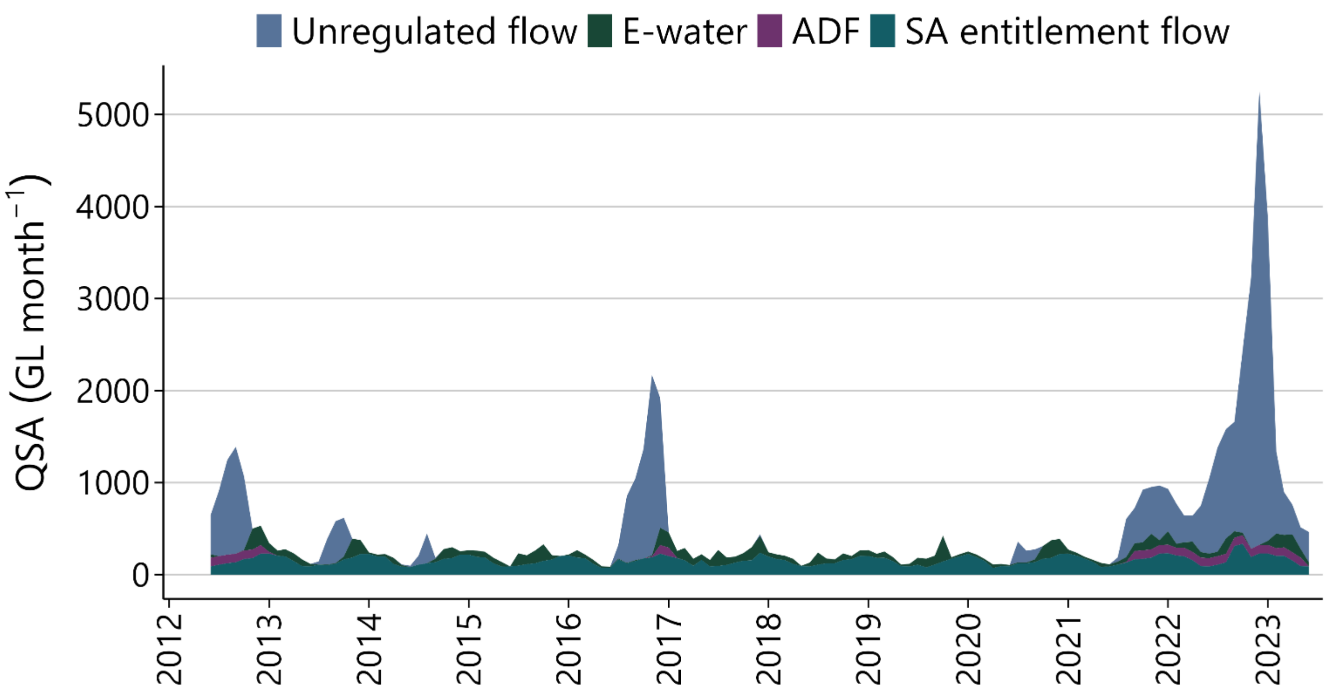


Figure 3-4. Contribution of unregulated flow, water for the environment (E-water), additional dilution flow (ADF) and SA entitlement flow to flow (GL month^{-1}) to the South Australian border (QSA) from June 2012 (Basin Plan adoption) to June 2023.

4 Objectives, targets and expected environmental outcomes

4.1 Ecological objectives and targets

The ecological objectives and targets outlined in the South Australian River Murray Long-Term Watering Plan (LTWP) represent what is required for each PEA to be in a healthy, functioning state (DEW 2020). As such, the objectives and targets within the LTWP were not constrained to those considered to be achievable under the Basin Plan. The ecological targets provide a means to assess and report on changes in condition over time, thereby tracking progress towards ecological objectives.

4.1.1 The Channel PEA

A total of 16 ecological objectives and 29 nested ecological targets are described for the Channel PEA within the SA River Murray LTWP (DEW 2020). These objectives and targets focus on abiotic processes, water quality, biofilms, vegetation, wetlands, groundwater, and fish. A total of six ecological targets were prioritised for the purpose of this assessment and evaluation of expected environmental outcomes for the Channel PEA (Table 4–1). This due to their importance for delivery of water for the environment and availability of monitoring data to track changes. In addition to the assessment and evaluation of expected outcomes, a case study of microinvertebrates is also provided.

Table 4–1. Ecological objectives and nested targets for the Channel PEA.

Indicator type	Ecological objective	Ecological target(s)
Flow	Provide diverse hydraulic conditions over the range of velocity classes in the lower third of weir pools, so that habitat and processes for dispersal of organic and inorganic material between reaches are maintained.	Habitat across the range of velocity classes is present in the lower third of weir pools for at least 60 consecutive days in Sep-Mar, at a maximum interval of 2 years.
Fish	Restore resilient populations of Murray cod.	Population age structure of Murray cod includes recent recruits, sub-adults and adults in 9 years in 10.
		Population structure of Murray cod indicates a large recruitment event one year in 5, demonstrated by a cohort representing >50% of the population.
	Restore resilient populations of golden perch.	Population age structure of golden perch includes young-of-year (YOY) with sub-adults and adults in 8 years in 10.
		Population age structure of golden perch indicates a large recruitment event 2 years in 5, demonstrated by separate cohorts representing >30% of the population.
Trees	Throughout the length of the Channel asset (i.e. SA border to Wellington), establish and maintain a diverse native flood-dependent plant community in areas inundated by flows of 10,000–40,000 ML day^{-1} QSA.	In standardised transects spanning the elevation gradient in the target zone, >70% of all river red gum trees have a Tree Condition Index (TCI) score ≥10.

4.1.2 The Floodplain PEA

There are a total of 21 ecological objectives and 40 nested ecological targets described for the Floodplain PEA within the South Australian River Murray LTWP (DEW 2020). These objectives and targets are based on the key components (Table 4–2), as well as existing objectives and targets for the Channel (Wallace et al. 2014a), Chowilla floodplain (Wallace et al. 2014), and Pike and Katarapko floodplains (Wallace, Denny, & Bice, 2017

Of these targets, a total of three prioritised ecological targets across three ecological objectives (Table 4–2) were used as the basis for this assessment and evaluation of expected outcomes for the Floodplain PEA. Targets were prioritised due information outlined above in section 4.1.1. In addition to the assessment and evaluation of expected outcomes, a case study of frogs and understorey vegetation are also provided.

Table 4–2. Ecological objectives and nested targets for the Floodplain PEA.

Indicator type	Ecological objective	Ecological target(s)
Microinvertebrates	Provide for mobilisation of carbon, nutrients and propagules from the floodplain to the river.	During inundation periods, record an increase in the abundance and diversity of invertebrate food resources, nutrients, and dissolved organic carbon (DOC) relative to those available during base flow.
Trees	Maintain a viable, functioning river red gum population within the managed floodplain.	In standardised transects that span the managed floodplain elevation gradient and existing spatial distribution, >70% of all trees have a TCI Score of ≥ 10.
	Maintain a viable, functioning black box population within the managed floodplain.	In standardised transects that span the managed floodplain elevation gradient and existing spatial distribution, >70% of all trees have a TCI Score of ≥ 10.

4.2 Methods

South Australia's key evaluation questions were designed to align with the MDBA's evaluation questions and their reporting guidelines. Answers to SA's key evaluation questions are intended to contribute to the MDBA's Basin-scale evaluation of the Basin Plan against its objectives.

4.2.1 Assessment

An evaluation methodology was developed to address each of SA's key evaluation questions, and is underpinned by the following assessments and evaluative processes:

- achievement of expected environmental outcomes
- trend (as described in section 4.2.2)
- information reliability (as described in section 4.2.3)
- evaluation of environmental outcomes using expert elicitation supported by available data and information including the identification of actions to achieve environmental outcomes in the future.

An overview of the method followed to address SA's key evaluation questions is shown in Table 4–3.

Table 4–3. The evaluation methodology followed to address SA's key evaluation questions.

SA key evaluation questions	Evaluation method
To what extent have outcomes been achieved at the asset scale?	Progress towards intermediate (2029) expected outcomes was quantitatively assessed and reported for each indicator at the asset scale. The data cut-off point for this assessment for all indicators was 30 June 2023. Trend and change will be assessed where possible. • All available data will be presented to provide a baseline for assessing and reporting trend. • Change since the 2020 evaluation will be assessed using data collected between July 2019 and June 2023.
If outcomes were not achieved, why not?	Qualitative evaluation of achievement of outcomes was undertaken using: • Contextual datasets and supplementary information • Expert judgement through a structured elicitation process • Assessment of documented assumptions, limitations and contributing factors for expected outcomes • Outcomes for 2020 Matter 8 reporting.
To what extent did the Basin Plan contribute to achieving outcomes?	Qualitative evaluation of achievement of outcomes was undertaken using: • Contextual datasets and supplementary information • Expert judgement through a structured elicitation process • Assessment of documented assumptions, limitations and contributing factors for expected outcomes • Outcomes for 2020 Matter 8 reporting. The evaluation will comment on the contribution of Basin Plan and will not attempt to provide an attribution of impact.
Have there been any unanticipated outcomes?	Qualitative evaluation of unanticipated outcomes at the asset scale will be undertaken using a structured expert elicitation process.

The cut-off date for data included in this evaluation was 30 June 2023. Any data collected after this date will be included in the next Basin Plan environmental outcome evaluation. This will take into consideration any environmental changes which have occurred since 30 June 2023.

4.2.2 Trend

A Bayesian modelling approach was used to assess trend in the time series data. Bayesian modelling calculates a probability distribution of coefficient values which estimate some relationship between a predictor (time step) and an outcome. The median coefficient summarises the slope (trend) describing the relationship, whilst the distribution around this estimate provides uncertainty about the true relationship that exists in the population. Bayesian trend analysis was performed in R Studio (R Core Team 2023), using generalised linear models and (if necessary) mixed models using the stan_glm and stan_glmer functions provided by the "rstanarm" package (Goodrich et al. 2020). All models used 4,000 iterations, four sampling chains, and the default (weakly-informative) priors. Specific details on variable specification are provided in the methods for each indicator. Trend direction was assessed using calculated probability (modified from Mastrandrea et al. 2010; as per McBride 2019) using a graduated scale to present results, and to align with trend categories used for the South Australian Trend and Condition Report Cards, presented in Table 4–4.

This trend outcome is summarised as the following:

- Improved: The indicator is improving over the period of assessment
- Stable: The indicator is neither improving nor declining over the period of assessment
- Declined: The indicator is declining over the period of assessment
- Unknown: Data are not sufficient to determine any trend in the status of this indicator.

Table 4–4. Alignment of trend outcomes based upon the probability of an increase or decrease (modified from Mastrandrea et al. 2010; as per McBride 2019) with the icons used for the evaluation.

Outcome	Probability (%)	Trend category
Virtually certain increase	>+99 to +100	Improved
Extremely likely increase	>+95 to +99	
Very likely increase	>+90 to +95	
Likely increase	>+66 to +90	
About as likely as not	-66 to +66	Stable
Likely decrease	<-66 to -90	Declined
Very likely decrease	<-90 to -95	
Extremely likely decrease	<-95 to -99	
Virtually certain decrease	<-99 to -100	

4.2.3 Information reliability

The reliability of data to assess the achievement of environmental outcomes and the progression towards the LTWP targets were scored based upon the method devised by Battisti et al. (2014) with modifications to improve its applicability to Matter 8 reporting. This scoring system assesses answers to questions relating to the method used for data collection, representativeness and repetition. A scoring system as shown in Table 4–5 was used to determine a final score for information reliability that ranges between 0 and 12. Final scores are then converted into an information reliability rating that ranges between poor and excellent using the matrix in Table 4–6.

Table 4–5. Scoring system for the reliability of data used to assess and analyse trend, condition and LTWP targets and expected outcomes for Matter 8 reporting.

Methods	Question	Scoring system		
		Yes	Partially	No
Methods used	Are the methods used appropriate to gather the information required for evaluation?	2	1	0
Standard methods	Has the same method been used over the sampling program?	2	1	0
Representativeness				
Space	Has sampling been conducted across the spatial extent of the PEA with equal effort?	2	1	0
Time	Has the duration of sampling been sufficient to represent change over the assessment period?	2	1	0
Repetition				
Space	Has sampling been conducted at the same sites over the assessment period?	2	1	0
Time	Has the frequency of sampling been sufficient to represent change over the assessment period?	2	1	0

Table 4–6. Conversion of the final score (0-12) of information reliability to an information reliability rating that ranges from poor to excellent for Matter 8 reporting.

Final score	Information reliability
12	Excellent
11	Very good
10	Good
9	Fair
≤8	Poor

4.2.4 Expert elicitation workshops

Relevant subject matter experts attended a half-day workshop for each respective indicator to evaluate and review the preliminary data and findings of the assessments as presented in a workshop paper. The process follows that outlined in Figure 4-1 to discuss and answer the questions described in Table 4–7. The feedback gathered within the expert elicitation workshops was then used to inform the evaluation section for each indicator.

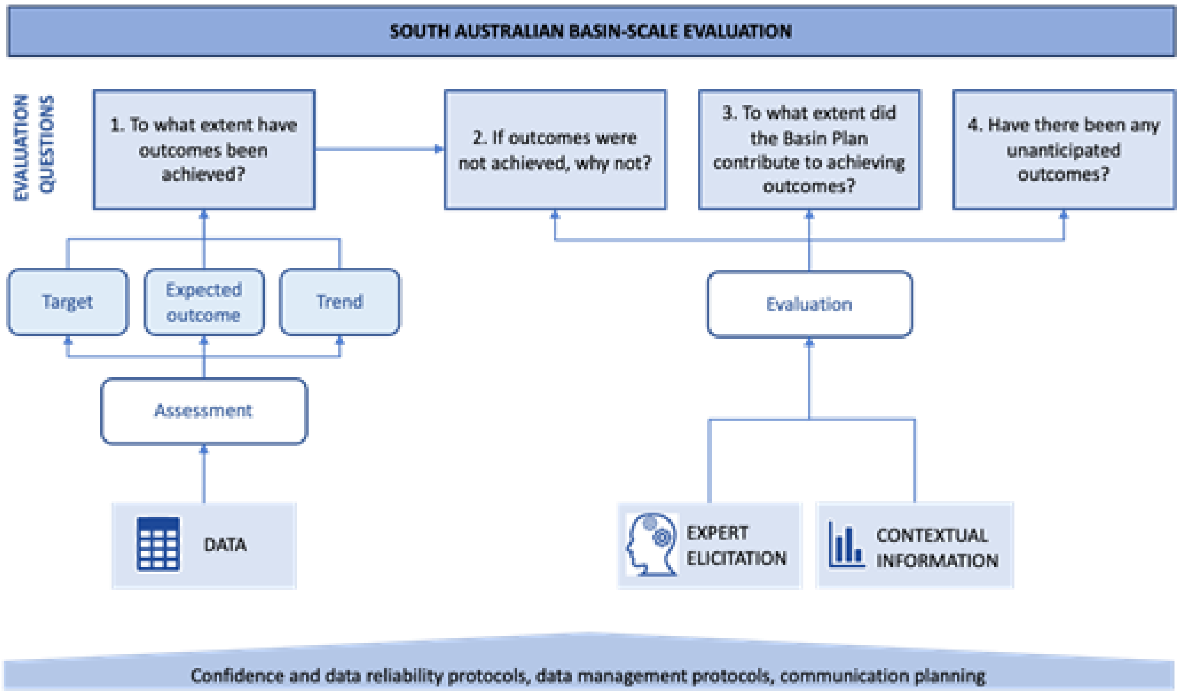


Figure 4-1. Schematic diagram showing how data driven and expert elicitation processes underpin the assessment and evaluation of environmental outcomes and enable South Australia's four evaluation questions to be addressed. The progress to the target will be considered through the assessment of expected outcomes.

Table 4–7. Evaluation questions asked under the expert elicitation process.

Matter 8 evaluation questions	Questions or information needed from experts for each indicator
To what extent have environmental outcomes been achieved at the asset scale?	• Is the data sourced for the analysis appropriate and have funding bodies been acknowledged? • Has information reliability been accurately assessed and justified? • Has the data been analysed and presented effectively? • Has the trend been represented correctly across the available dataset? • Has change between reporting periods been assessed adequately? *note: the information reliability-related questions above support discussion on each of the criteria within the information reliability scoring assessment
If environmental outcomes were not achieved, why not?	• What are the contributing factors influencing the observed outcome and do any factors have a stronger influence than others? • How have these factors influenced trend? • What evidence supports this (data, published information, observations, opinion)?
To what extent did the Basin Plan contribute to achieving environmental outcomes?	• Which Basin Plan activities or projects may have contributed to outcomes? • How have these Basin Plan activities contributed to the observed trend? • Are there any outcomes that may be expected but are yet to be observed due to a time lag in environmental response? • Are there any aspects of Basin Plan implementation that are expected to influence outcomes in the future?

Matter 8 evaluation questions	Questions or information needed from experts for each indicator
Have there been any unanticipated environmental outcomes?	• What evidence supports this (data, published information, observations, opinion)? • Have there been any unanticipated environmental outcomes (positive or negative) as a result of management actions or other Basin Plan implementation activities? • What evidence supports this (data, published information, observations, opinion)?

5 Flow Velocity

Trend **Improved**

★★★☆☆ Reliability **Good**

Key findings and messages:

- Improvement in the frequency of fast-flowing (lotic) conditions was largely driven by unregulated flow events.
- The construction and operation of weir infrastructure requires larger discharge volumes to achieve riverine velocities comparable to those once common (pre-regulation) in the SA River Murray.
- Weir pool management within normal operating ranges may allow for restoration of lotic conditions when used in conjunction with unregulated flows.
- Delivery of water for the environment has contributed to improvement of localised flow velocities for short periods (i.e. small flow pulses and weir pool operations).

5.1 Introduction

Flow velocity is a hydraulic characteristic of riverine systems, as is channel depth and river water level. Velocity is determined by a combination of discharge (hydrology) and channel morphology (e.g. shape, depth, debris) (Ye et al. 2023). Velocity is also affected by weirs and locks in the South Australian River Murray (SA River Murray), including their operation (Gibbs et al. 2023). For a given discharge, velocity decreases with greater cross–sectional area; therefore, flow is typically slowest in the lowest third of weir pools due to depth (Ye et al. 2023).

Hydrological characteristics (e.g. discharge) are often used to predict or infer changes in ecological components, yet it is often the hydraulics (e.g. velocity) which elicit these responses (Gibbs et al. 2023; Mallen-Cooper & Zampatti 2018). For example, an in–channel flow velocity of ≥0.1 $m\ s^{-1}$ limits stratification in the water column, suspending nutritious non–motile phytoplankton (e.g. planktic diatoms) and disadvantaging cyanobacteria (Furst et al. 2019; Gibbs et al. 2020). Velocity of ≥0.15 $m\ s^{-1}$ helps with the entrainment and drift of zooplankton (Gibbs et al. 2020), while ≥0.2 $m\ s^{-1}$ promotes Murray cod larvae drift and dispersal (Gibbs et al. 2023; Humphries 2005) and helps maintain desired concentrations of dissolved oxygen (Ye et al. 2020).

Velocities >0.3 $m\ s^{-1}$ are considered lotic conditions due to the dependence of riverine organisms such as Murray cod and golden perch on these flow ranges (Koehn & Nicol 2014). When the average cross-sectional velocity reaches the lotic range (>0.3 $m\ s^{-1}$), a greater range of overall velocities (here termed velocity classes) likely occur across a river reach (Bice et al. 2017). These conditions increase hydraulic diversity and complexity (Bice et al. 2017), which has benefits for riverine fish such as providing slackwater mesohabitats (Bice et al. 2017; Frederberg & Zampatti 2018; Koehn et al. 2020).

River regulation, water extraction and the removal of woody–debris have altered the natural hydraulics in the SA River Murray (Gibbs et al. 2023). Historical data demonstrate in–channel velocities were >0.3 $m\ s^{-1}$ during peak flow season (September–January) in a pre–regulation SA River Murray (Mallen-Cooper & Zampatti 2018), and modelled data estimate that there are large differences in the occurrence of these flows pre and post–regulation (Bice et al. 2017). Generally, there is a positive association between river discharge (Flows to South Australia; QSA) and median cross-sectional velocities, until approximately 60,000 $ML\ day^{-1}$ where velocity begins to plateau with increasing discharge (DEW unpublished data). However, this positive relationship (0-60,000 ML day^{-1}) is affected by the presence of weirs up until approximately bank-full QSA (i.e. <45,000 ML day^{-1}) based on modelled data between Lock 1 and Lock 3 (Bice et al. 2017), meaning that velocities would be greater for a given discharge without river regulation during river conditions below 45,000 ML day^{-1}. Indeed, more recent hydrodynamic modelling across weir pools 1–5 (with a range of water scenarios) indicates an impact of weirs and locks on in–channel velocities, and a QSA of >20,000 ML day^{-1} is required to transform weir pools from lentic to lotic flowing riverine habitats (Ye et al. 2023).

Considering the interactive effect between QSA and river regulation on riverine velocities, one feasible management action for restoring lotic hydraulics is weir pool lowering. Currently, small weir pool lowering events are undertaken from Lock 1 to 6 (Muller & Creeper 2021), and it is likely that improvements in lotic conditions increase with the magnitude of lowering events, when performed in tandem across multiple weir pools and during peak flow season (Ye et al. 2022; Ye et al. 2021; Ye et al. 2023).

5.2 Ecological objective, target and environmental outcomes

To improve the health of the SA River Murray and outcomes for flow–dependent biota, an ecological objective and target has been set for velocity, aiming to restore a range of velocity classes in the lower third of weir pools (Table 5–1). The ecological objective and targets are described in the South Australian River Murray Long-term Watering Plan (LTWP) (DEW 2020).

Table 5–1. Description of ecological objectives and targets related to flow velocity indicator, outlined in the LTWP (DEW 2020).

Ecological objective	Ecological target
Provide diverse hydraulic conditions over the range of velocity classes in the lower third of weir pools, so that habitat and processes for dispersal of organic and inorganic material between reaches are maintained.	Habitat across the range of velocity classes is present in the lower third of weir pools for at least 60 consecutive days in Sep–Mar, at a maximum interval of 2 years.

No expected outcomes have been devised for flow velocity. Therefore, the environmental outcome was evaluated based upon the ecological target from the LTWP at an annual scale, without the maximum return interval component (Table 5–2).

Table 5–2. Environmental outcome for flow velocity measured on an annual basis.

Environmental outcome
Habitat across the range of velocity classes is present in the lower third of weir pools for at least 60 consecutive days in Sep–Mar.

5.3 Method

To evaluate the environmental outcome for flow velocity, the length (km) of river with lotic conditions (>0.3 m s^{-1}) in each weir pool were compared to the channel length between locks (1–5). However, as estimates for specific locations in each weir pool (i.e. the lower third) are not available, a suitable percentage of weir pool was used to infer velocity in the lowest third. Therefore, 95% of each weir pool was required to have >0.3 m s^{-1} for 60 consecutive days between September and March to satisfy the environmental outcome.

5.3.1 Velocity models

Velocity conditions were assessed using the MIKE FLOOD hydrodynamic model (DEW 2021; DHI 2023) produced in part by DEW and for the CEWO MER program (Ye et al. 2023). This hydraulic model is based on bathymetric surveys of the SA River Murray, used to create digital networks of polygons (known as flexible mesh) that capture the response and variation in weir pool hydraulics with varying upstream (discharge) and downstream (weir pool water level) input conditions (DEW 2021; Gibbs et al. 2023).

Velocities were simulated using a steady–state modelling approach (Webb et al. 2017) over a range of discharges (2,000–100,000 ML day^{-1}) and weir pool water levels (Ye et al. 2023). As increases in QSA result in a greater inundated area (which differs between each weir pool), the cross-sectional area of the channel changes, thereby affecting velocity. Hydrodynamic model outputs in the main channel only were processed (defined by the area inundated at a discharge of 5,000 ML day^{-1}), to provide comparable velocity estimates between weir pools without the influence of slow flowing backwaters (Ye et al. 2023). For periods over 100,000 ML day^{-1} (i.e. the 2023 flood event), a dynamic modelling approach was used to represent the influence of the filling and draining of the broader floodplain of this large overbank event (Ye et al. 2024).

The distance (km) of each weir pool with >0.3 m s^{-1} was produced for weir pools 1 to 5 for each day since July 2014. The proportion of weir pools with lotic conditions (>0.3 m s^{-1}) was calculated using the distance between each lock, shown in Figure 5-1.

Only the "all water" CEWH model scenario is used in the outcome assessment, while the "no eWater" scenario was used as supporting information (see Ye et al. 2023).

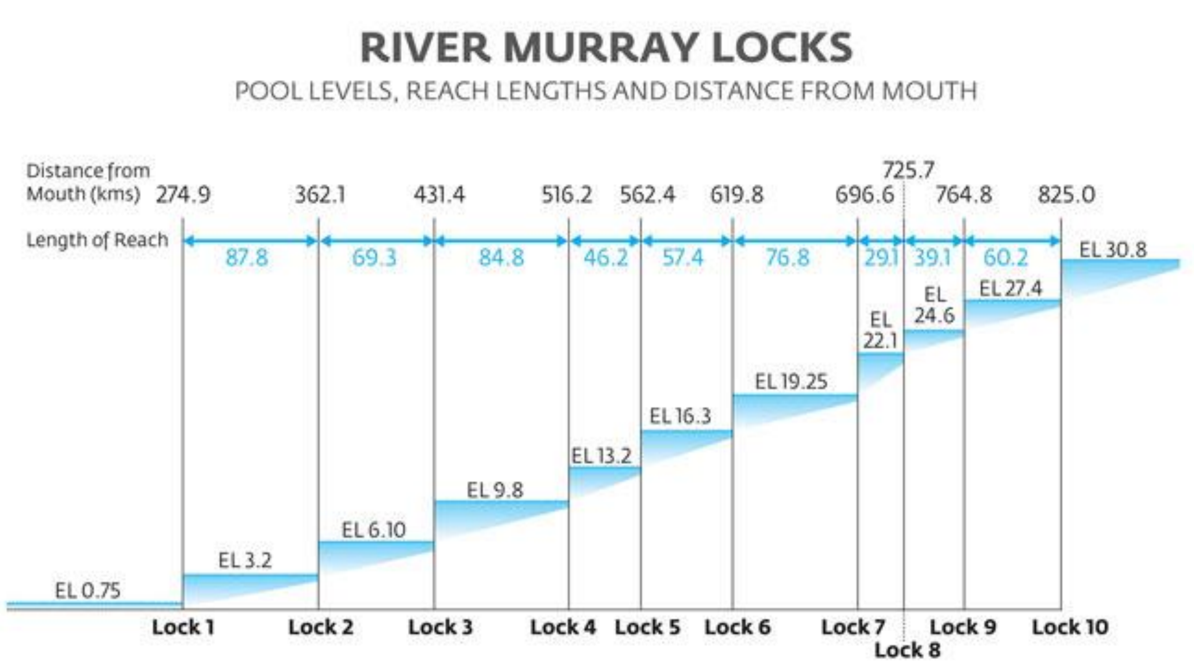


Figure 5-1. Schematic of the South Australian River Murray in relation to distance between locks, the distance and relative sea level gradient of each weir pool from the Murray Mouth. Source: SA Water.

5.3.2 Trend assessment

The approach used to assess trend with a Bayesian generalised linear model is discussed in section 4.2.2. Trend analysis for flow velocity was based on the annual occurrence of the environmental outcome between 2014–15 and 2022–23, using a binomial distribution (logit function). The binary response variable was based on when at least

95% of a weir pool had >0.3 m s^{-1} velocity, with a 1 given when this occurred, and 0 otherwise. Time step (years since the commencement of the assessment period) was included as a fixed effect, whilst weir pool was used as a random (intercept) factor. The model specification was:

Lotic proportion met ~ time step + (1 | weir pool)

5.3.3 Information reliability

The information reliability assessment for the flow velocity evaluation was conducted as per section 4.2.3.

5.3.4 Limitations and assumptions

As larger cross–sectional areas (typically upstream from a weir) will reduce in–channel velocity (Ye et al. 2023), assessing the environmental outcome for velocity assumes that the slowest flowing section of a weir pool is the lowest third, and that this section will experience lotic conditions last. It is also assumed that velocity estimates for 95% of a weir pool sufficiently represents velocity in the lowest third, and that when this condition occurs, habitats across the range of velocity classes are present in the lower third of weir pools.

5.4 Results

5.4.1 Environmental outcome assessment

The environmental outcome was not met in the last evaluation (2018–19), as there were zero days between September and March in any weir pool with modelled velocities >0.3 m s^{-1} in at least 95% of the weir pool (Table 5–3). Since 2018–19, the outcome has been met in 2021–22 in weir pools 1 to 2 and in all weir pools in 2022–23. Over the previous nine years, the outcome in specific weir pools was only met in three water years (2016–17, 2021–22, and 2022–23), but the requirement of 60 consecutive days in all weir pools collectively was only met in 2016–17 and 2022–23. Therefore, there has not been progression towards the LTWP target (including a two-year maximum return interval).

Table 5–3. The environmental outcome since 2014–15, based on the number of consecutive days between September and March with modelled velocities >0.3 m s^{-1} in the lower third of each weir pool.

Water year	WP1	WP2	WP3	WP4	WP5
2014–15	No	No	No	No	No
2015–16	No	No	No	No	No
2016–17	Yes	Yes	Yes	Yes	Yes
2017–18	No	No	No	No	No
2018–19	No	No	No	No	No
2019–20	No	No	No	No	No
2020–21	No	No	No	No	No
2021–22	Yes	Yes	No	No	No
2022–23	Yes	Yes	Yes	Yes	Yes

5.4.2 Spring-summer days with lotic conditions

The number of days with modelled lotic velocities (>0.3 m s^{-1}) were confined to the 2016–17, 2021–22, and 2022–23 water years (Table 5–4). However, the consecutive number of days was met in all weir pools only in 2016–17 and 2022–23. Since 2014–15, the highest average number of total and consecutive days across weir pools was in 2022–23.

Table 5–4. The total number of days in each water year where modelled velocities were >0.3 m s^{-1} in at least 95% of the weir pool. The numbers in brackets are the maximum consecutive days observed.

Water year	WP1	WP2	WP3	WP4	WP5
2014–15	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
2015–16	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
2016–17	125 (125)	125 (125)	99 (93)	113 (113)	87 (82)
2017–18	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
2018–19	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
2019–20	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
2020–21	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
2021–22	105 (65)	148 (73)	44 (30)	16 (13)	12 (12)
2022–23	202 (202)	179 (115)	113 (84)	124 (87)	141 (92)

5.4.3 Trend

The trend analysis suggests that the probability of the environmental outcome occurring was extremely likely (99% probability) to have **improved** over the assessment period (2014–15 to 2022–23), as shown by the majority of posterior slope values >0 (Figure 5-2).

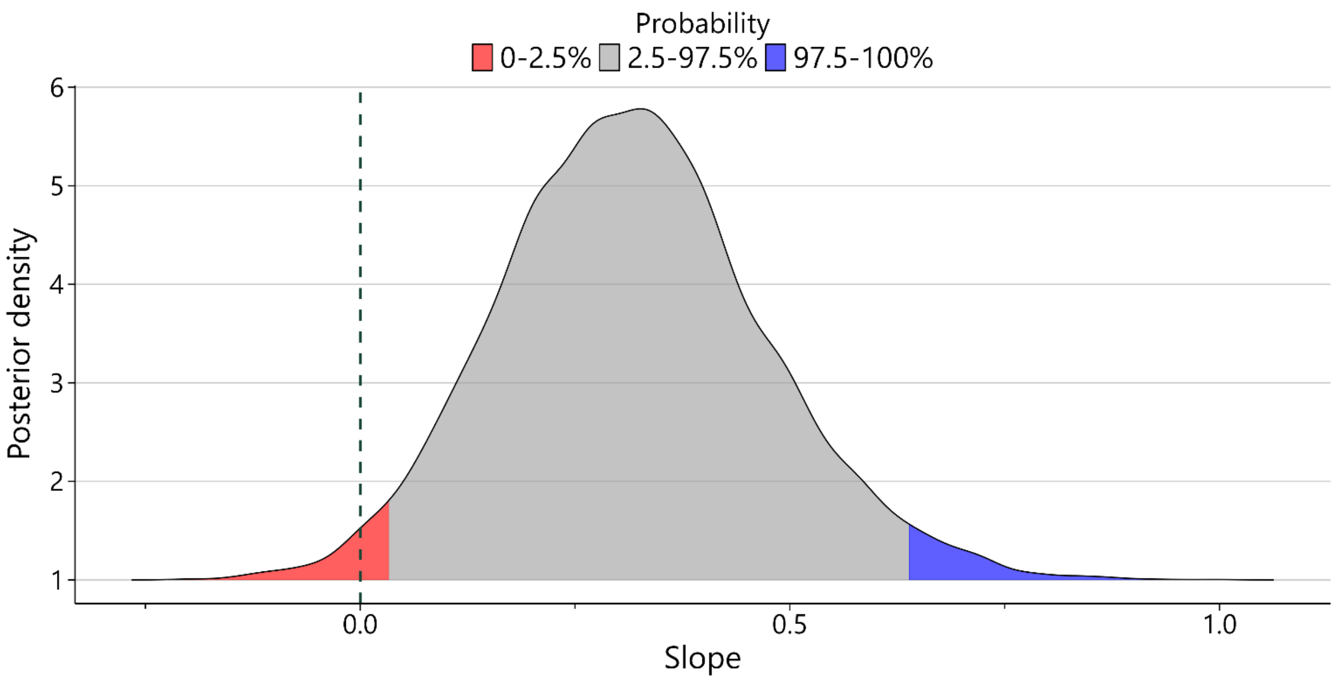


Figure 5-2. Estimated values for the slope generated from Bayesian modelling the success of the environmental outcome (95% of each weir pool having >0.3 m s^{-1} for at least 60 consecutive days between September and March). Posterior slope values >0 infer a positive trend (improved) and values <0 infer a negative trend (declined).

5.4.4 Supplementary Information

Flows to South Australia (QSA)

QSA has been highly variable since Basin Plan adoption (Figure 5-3). Following the Millennium Drought (1996–2010), widespread flooding occurred across the Murray–Darling Basin (MDB) in 2010–11, resulting in a moderate flood (total annual QSA 15,135 GL) and a peak QSA at ~94,000 ML day^{-1}. Minor flood conditions continued into 2011–12 with 10,248 GL of annual QSA. In 2012–13, 6,957 GL of annual QSA was observed. More moderate flows (3,570 GL) were recorded over 2013–14, before low flow conditions occurred in 2014–15 and 2015–16 (mean of 2,682 GL). In 2016–17, high flows were recorded with QSA peaking at ~94,600 ML day^{-1}, but there was a rapid recession of this high flow event, shown by the lower annual volume (9,238 GL) compared to 2010–11 (Figure 5-4). Extreme dry conditions in the MDB between 2017–18 and 2019–20 reduced QSA (2,508 GL year^{-1}) over this period. Three consecutive years of above-average rainfall in the Basin resulted in increased QSA between 2020–21 and 2022–23. Moderate flows were recorded in 2020-21 (3,078 GL) and were followed by high flows in 2021–22 (9,090 GL) and the third largest flooding event in the SA River Murray in 2022–23 (23,014 GL). The highest flow peaks in the last two water years were 43 GL day^{-1} (30/06/2022) and 186 GL day^{-1} (22/12/2022).

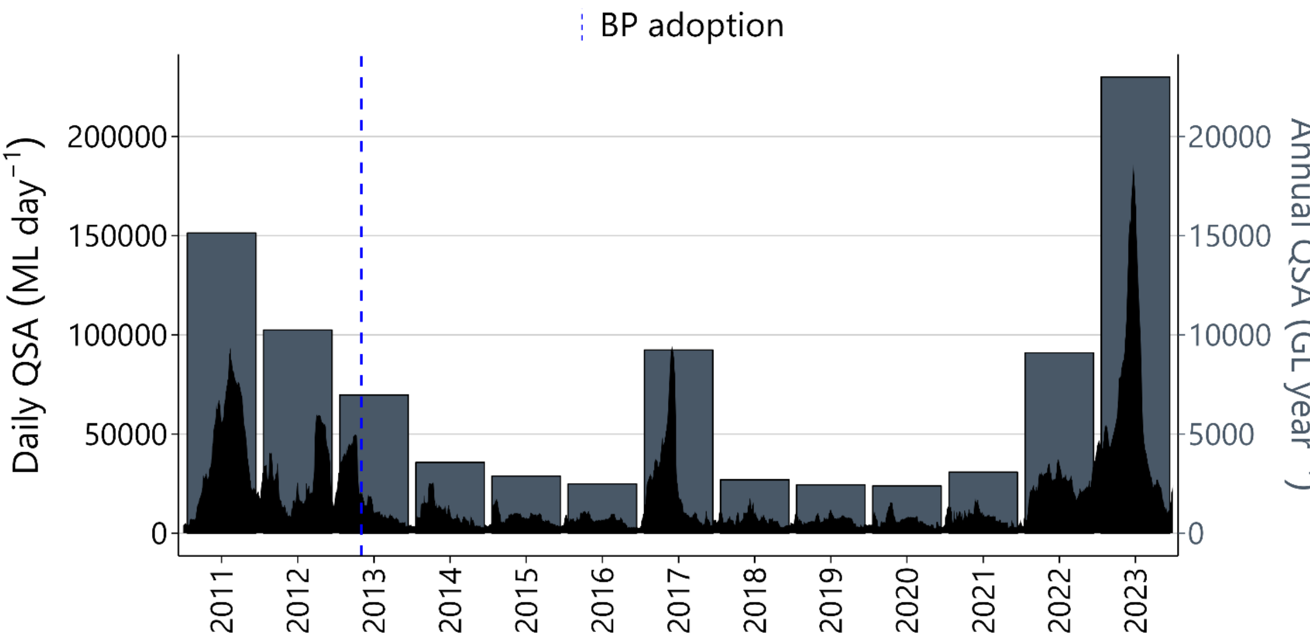


Figure 5-3. Flows to South Australia (QSA) between July 2010 and June 2023.

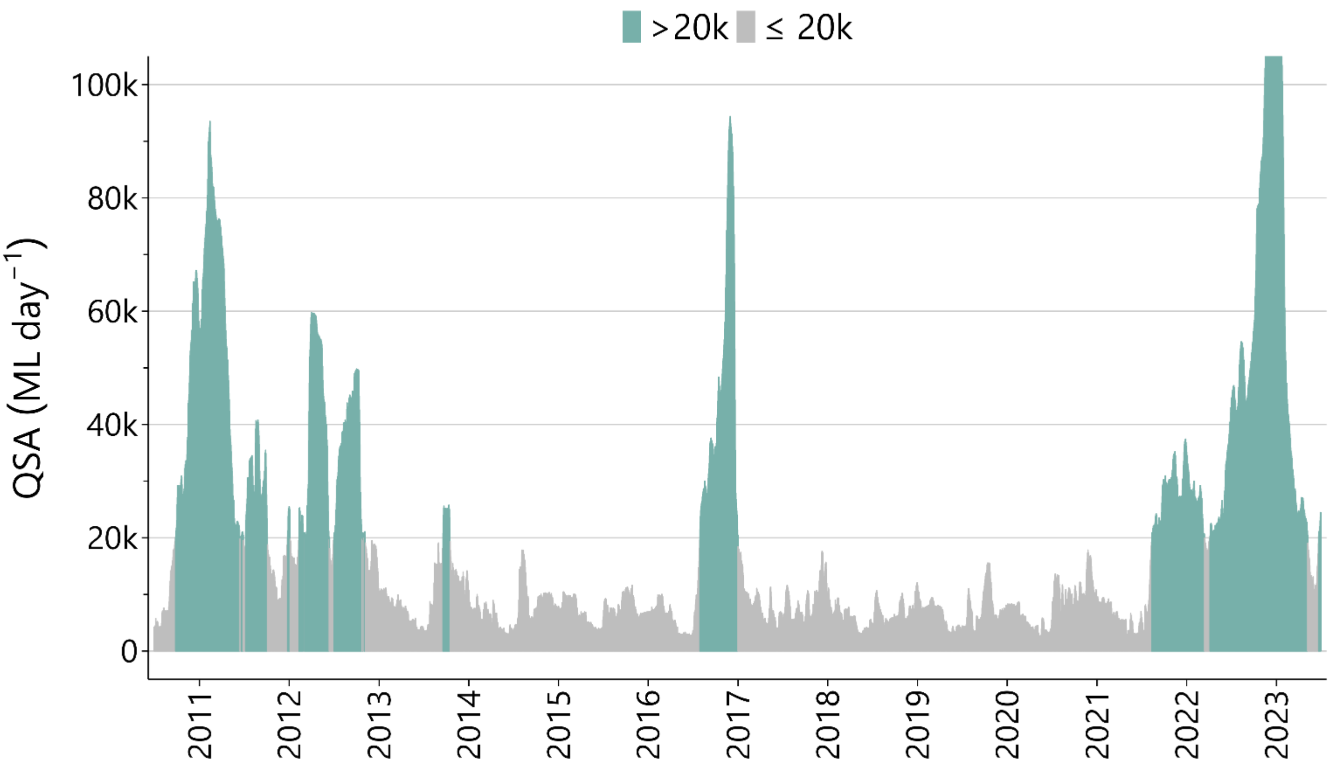


Figure 5-4. Flows to South Australia (QSA) between July 2010 and June 2023.

Spring-summer days with lotic conditions (no water for the environment scenario)

The number of days with lotic velocities for the scenario with no water for the environment is shown in Table 5–5. The number of days with modelled lotic velocities in 95% of the weir pool were confined to the same three years (2016–17, 2021–22 and 2022–23) as the outcome assessment (i.e. the all water scenario; Table 5–4). However, only 2016-17 had a similar number of consecutive days in the same weir pools as the "all water" scenario. In 2021–22, there was a substantially lower number of total and consecutive days with modelled lotic velocities in at least 95% of each weir pool in weir pools 1 to 4. This supports the difference in the proportion of each weir pool with modelled lotic velocity between the two CEWH scenarios (Figure 5-5).

Table 5–5. The total number of days in each water year where modelled velocities were >0.3 m s^{-1} in at least 95% of the weir pool for the "no water for the environment" CEWH scenario. The numbers in brackets are the maximum consecutive days observed.

Water year	WP1	WP2	WP3	WP4	WP5
2014–15	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
2015–16	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
2016–17	123 (123)	122 (122)	98 (94)	108 (106)	84 (81)
2017–18	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
2018–19	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
2019–20	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
2020–21	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
2021–22	62 (23)	83 (31)	12 (12)	0 (0)	0 (0)
2022–23	198 (198)	169 (115)	105 (84)	114 (55)	135 (92)

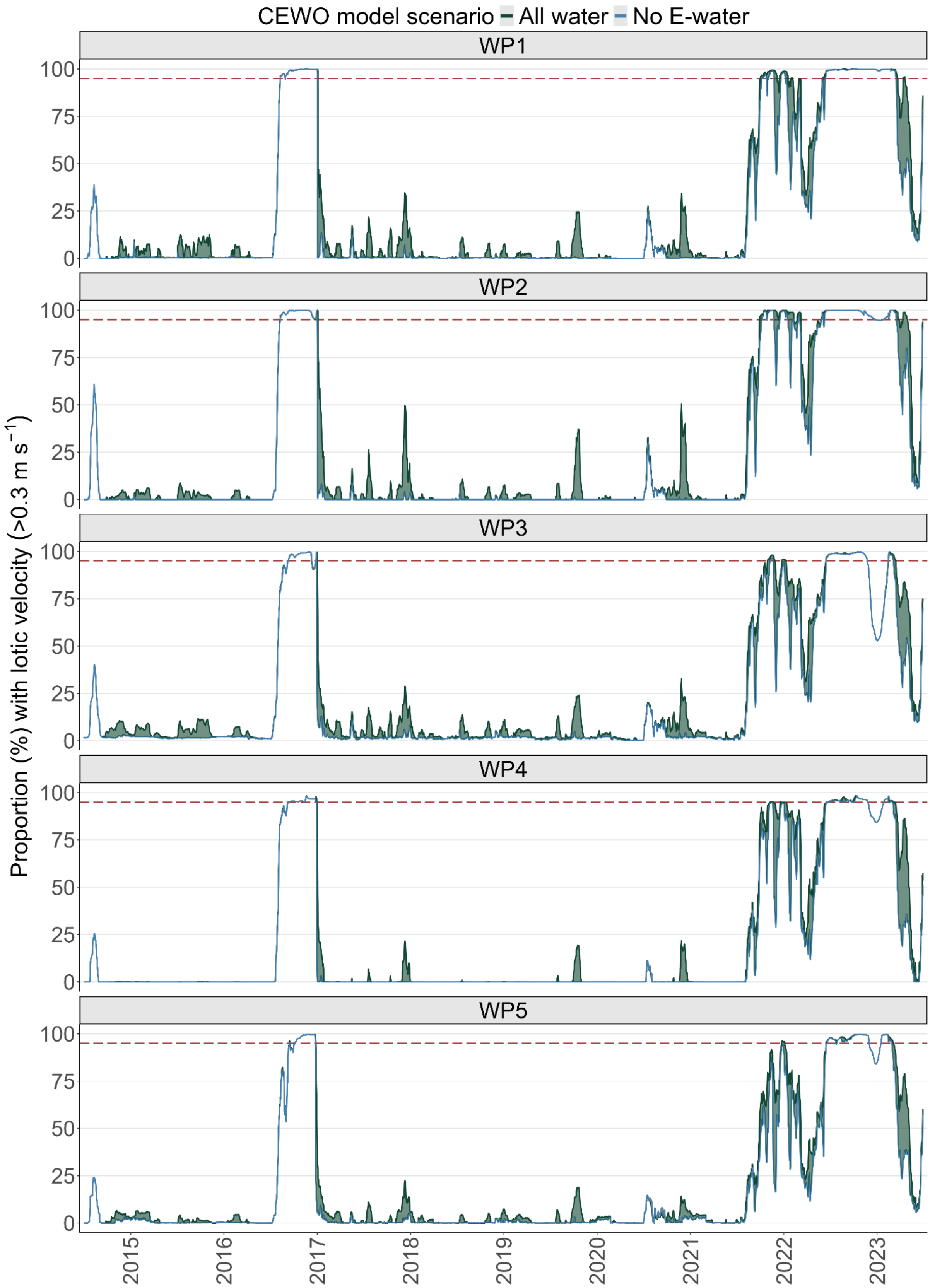


Figure 5-5. The percentage of weir pools 1–5 with modelled velocity of >0.3 m s^{-1} for the CEWH “all water” scenario (dark green; outcome assessment) and “no water for the environment” scenario (sky blue; supporting information) between July 2014 and June 2023. The filled (dark green) area represents the periods where velocity estimates for the “all water” scenario was higher than the “no water for the environment” scenario. The dark red dashed line represents the percentage (95%) of each weir pool determined as being representative of the lower third.

5.4.5 Information reliability

The information reliability rating for flow velocity was **good** (final score of 10). Justification for the scoring for flow velocity information reliability is provided in Table 5–6.

Table 5–6. Reliability of data used to assess outcomes of channel velocity. The methods used in data collection as well as the representativeness, repetition and sample independence of data were scored based upon the answers provided to questions related to each facet of data collection. Answers to questions regarding the methods, representativeness and repetition of data were scored 2 points – Yes, 1 point – Partially, 0 points – No.

Methods	Question	Answer and justification	Score
Methods used	Are the methods used appropriate to gather the information required for evaluation?	**Yes.** Model estimates were peer reviewed as part of CEWH reporting (Ye et al. 2022; Ye et al 2021; Ye et al. 2023; Ye et al. 2020).	**2**
Standard methods	Has the same method been used over the sampling program?	**Yes.** The model outputs provided are the same model conditions between 2014 and 2023. Note model consistency does imply that recent (and future) updates cause slightly different outputs when comparing published reports (e.g., Ye et al. 2022; Ye et al. 2023).	**2**
Representativeness			
Space	Has sampling been conducted across the spatial extent of the SA River Murray with equal effort?	**Partially**. Models are available for weir pools 1–5.	**1**
Time	Has the duration of sampling been sufficient to represent change over the assessment period?	**Partially**. Although model outputs are available for each day between 2014 and 2023, there is no data available before 2014.	**1**
Repetition			
Space	Has sampling been conducted at the same sites over the assessment period?	**Yes.**	**2**
Time	Has the frequency of sampling been sufficient to represent change over the assessment period?	**Yes**. Model outputs provided velocities and distance (km) with >0.3 m s^{-1} for every day between 2014 and 2023.	**2**
Final score			**10**
Information reliability			**Good**

5.5 Evaluation

In-channel velocities greater than 0.3 m s^{-1} likely occurred in the lower third of weir pools 1–5 for 60 consecutive days between September and March in 2016–17 and 2022–23. This average cross-sectional velocity implies that there was a greater range of velocity classes (Bice et al. 2017) during these periods. Moreover, these lotic conditions likely occurred in 2021–22, but only in weir pools 1 and 2. Outside of these key periods, lotic velocities were rarely experienced across 50% of weir pools 1–5 (see Figure 5-5).

There was an improvement in the probability of the environmental outcome being met, primarily due to high, unregulated flows that happened to occur at the end of the period in 2021–22 and 2022–23. Water for the environment was insufficient to achieve environmental outcomes, and progression towards the LTWP target has not occurred. However, some localised temporal and spatial extent of lotic habitats did occur in the main channel, of which, water for the environment contributed.

The lack of lotic velocities in the lower third of weir pools in the SA River Murray was primarily influenced by the frequency of interannual unregulated flow events. Coupled with these events is the effect of river regulation and management of weir infrastructure (i.e. to maintain stable weir levels). Overall, there were insufficient volumes of water for the environment to achieve the environmental outcome.

5.6 Key factors contributing to environmental outcomes

5.6.1 Unregulated flows and climate

One of the strongest influences on flow velocity has been periods of unregulated flow. In years where high river flows occur over the spring–summer months (Figure 5-3), in-channel lotic velocities have occurred in the lower third of SA River Murray weir pools (Figure 5-5; Table 5–4). In these instances, such as 2021–22 and 2022–23, lotic conditions have largely been due to climatic conditions in the MDB, with higher-than-average rainfall across the Basin (Figure 5-6; Figure 5-7). For example, there were lotic velocities and overbank flows (>45,000 ML day^{-1}) for the first eight months of the 2022–23, following a year (2021–22) with above-average rainfall in the MDB (Ye et al. 2024). An ecological outcome from these lotic velocities was fish assemblages in the SA River Murray that are more characteristic of a flowing riverine environment, with greater abundances of larger-bodied and flow-cued species such as golden perch (Ye et al. 2023).

Whilst there is a strong influence of unregulated flow events on channel velocity, water delivery including delivery of water for the environment, have contributed to discrete events of flow velocity (see Figure 5-5). For example, unregulated flows occurred in 2016–17 with a high magnitude but generally short duration; however, modelled flow estimates demonstrate that water for the environment lengthened the duration of lotic velocities across a greater proportion of weir pools. During this period (20/12/2016 – 10/02/2017), the average difference in proportion of weir pool with lotic velocity between model scenarios of with and without water for the environment was greatest for weir pool 2 (23%) and lowest for weir pool 5 (13%).

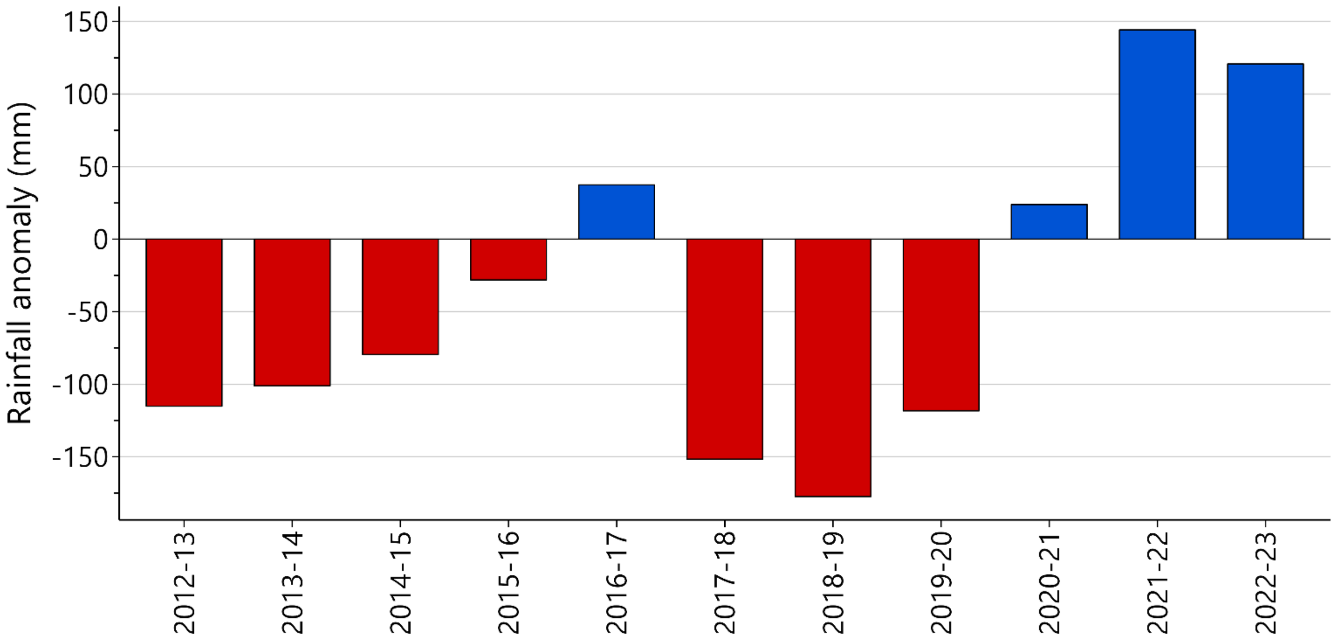


Figure 5-6. Differences between annual rainfall and the long-term rainfall average (1966–1990) in the Murray–Darling Basin. Source: BOM 2023.

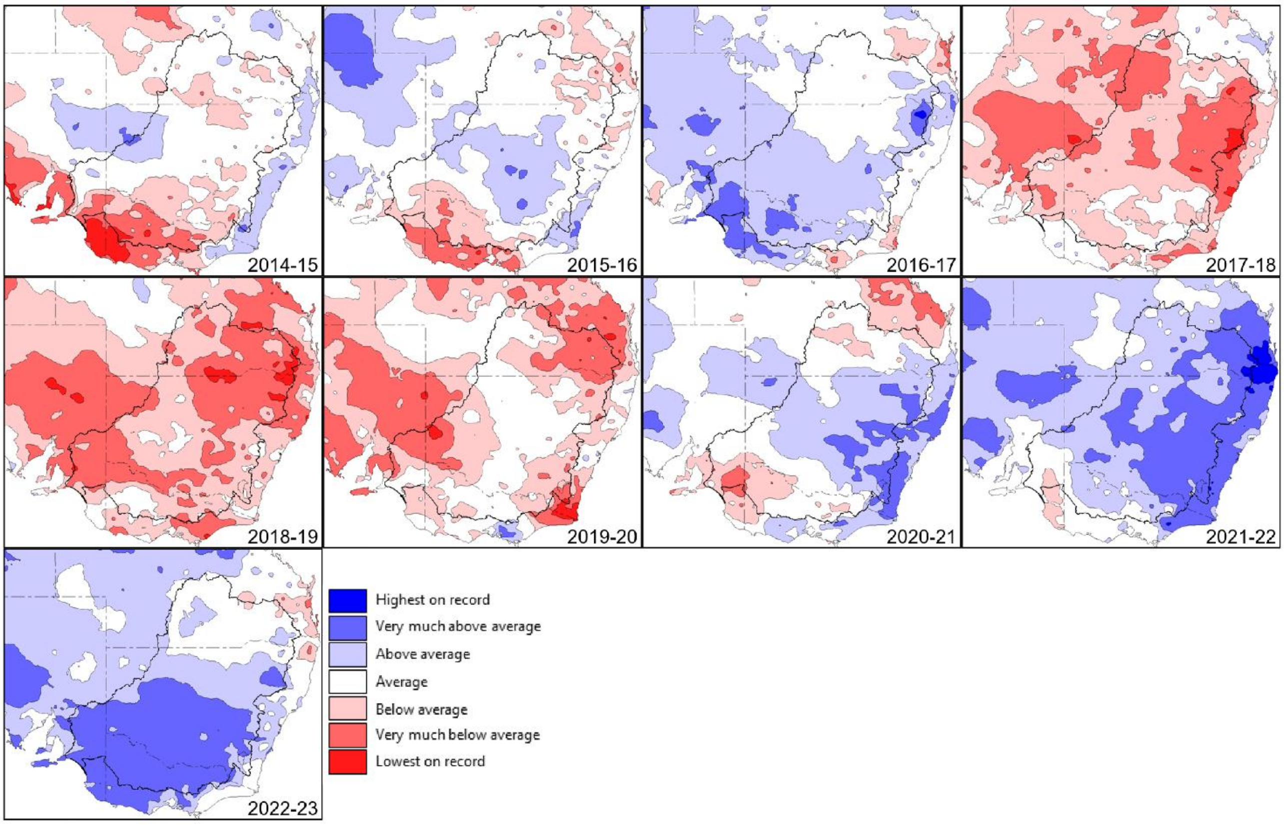


Figure 5-7. Murray–Darling Basin rainfall deciles between the 1 of July and the 30 of June each year since 2014-15. Source: BOM 2023.

5.6.2 River regulation

The presence and operation of weir infrastructure in the SA River Murray defines it as a regulated river. River regulation, water extraction and the removal of woody–debris have altered the natural hydraulics (Gibbs et al. 2023), and historical data shows that lotic velocities occurred regularly during peak flow season (September–January) in a pre–regulation SA River Murray (Mallen-Cooper & Zampatti 2018). River regulation has affected the positive relationship between river discharge and velocity up to bank-full flows (<45,000 ML day^{-1}), after which the relationship reconverges (Bice et al. 2017). Therefore, higher river flows are now required to produce lotic conditions, which would otherwise occur at lower flows in the absence of weirs and locks. This necessitates a strong dependence of velocity outcomes on interannual and interdecadal climatic conditions in the Basin to produce adequate flows.

Rainfall deficits, in combination with the operation of weirs, have contributed to a lack of high (unregulated) flow events that are required to meet the environmental outcome. In the absence of a high (unregulated) flow event, volumes of water for the environment coupled with South Australia's Entitlement flows and additional dilution flows were insufficient to achieve 60 consecutive days of lotic flow in the lower third of each weir pool.

5.6.3 Water for the environment

Since July 2014, there have been some discrete periods whereby water for the environment has contributed to lotic velocities in the SA River Murray. For example, between July 2018 and June 2019 (a period of no unregulated flows) portions of weir pools 1, 2 and 3 were estimated to have velocities >0.3 m s^{-1}, which would have likely not occurred without water for the environment (see Figure 5-5). Despite this, there was likely a limited spatial influence of these flow conditions, and there is no evidence suggesting these velocities reached the lower third of weir pools.

South Australia's Entitlement is insufficient alone to achieve fast-flowing conditions within the SA River Murray. Under current constraints to water delivery, volumes of water for the environment and regulated river conditions, it is unfeasible for water for the environment to meet the environmental outcome for flow velocity in the absence of unregulated river flow events. Timing and coordination of water releases between water holders across the whole River Murray are critical to increase the efficiency of limited volumes of water for the environment and induce lotic velocities in the lower third of weir pools for 60 consecutive days. Increased availability and quantity of water for the environment would also assist in increasing the frequency of lotic conditions.

Unregulated flows (water exceeding amounts required to meet delivery and storage capacity) are protected as Planned Environmental Water. Therefore, these types of flows are indirect contributions from the Basin Plan for velocities in the SA River Murray, since they result in substantial portions of the river with fast-flowing conditions.

5.6.4 Weir lowering operations

Weir pool operations (i.e. raising and lowering of weirs) did not affect the achievement of velocity outcomes, as determined by outputs from the hydrodynamic model scenarios representing these management actions (Ye et al. 2023). However, with limited volumes of water for the environment, weir pool lowering operations can result in hydraulic restoration, especially when coinciding with annual peaks in QSA (e.g. December) and performed across multiple weirs (Muller & Creeper 2021; Ye et al. 2022; Ye et al. 2023). For example, modelled outputs suggest that a lowering of 1 m at 10,000 ML day^{-1} QSA could triple the length of weir pool 1 with lotic conditions (Bice et al. 2017). Recently, there have been minor lowering operations of weirs 1–6 (expect 5) of between 0.03 and 0.11 m, which was indirectly contributed to by water for the environment (to refill the weir pools) (Ye et al. 2023).

5.7 Actions to achieve environmental outcomes

To improve the likelihood of achieving environmental outcomes for flow velocity in the SA River Murray, a restoration of riverine habitats conducive to lotic flows is required. This is only likely to occur with full implementation of the Basin Plan.

Restoration of lotic habitats may be enhanced under current constraints and volumes of water for the environment through the following:

- **Coordinated water delivery:** restoring lotic habitats to large reaches of the SA River Murray can be enhanced by coordinated delivery of water for the environment from all upstream tributaries (Darling, Murrumbidgee and Goulburn), and increased releases from Lake Victoria. Timing of delivery is critical for flow velocity and increased coordination between water managers to improve the efficiency and timing (likely between September and March) of water delivery to improve flow outcomes.
- **Weir pool lowering:** Lowering weir pools by 1 m at discharge of ≥10,000 ML day^{-1} would increase the length of lotic habitat at least three–fold in the Lock 1–2 and 2–3 weir pools, while a minor increase would occur in the Lock 3–4 weir pool (Bice et al. 2017). Weir pool lowering performed in tandem across multiple weir pools can enhance restoration of lotic habitats (Ye et al. 2023).
- **Water for the environment** could be delivered in synergy with weir pool lowering to further enhance hydraulic diversity (Bice et al. 2017). The use of weir pool management to support flow velocities in the SA River Murray channel needs further investigation, particularly any potential impacts on sites (such as Chowilla) that already provide fast-flowing habitats.

5.8 Conclusion

Implementation of the Basin Plan thus far is yet to have a significant impact on flow velocities across the extent of the SA River Murray Channel. As a result, there has been limited achievement of the environmental outcome and no progression towards the LTWP target for flow velocity in the River Murray Channel PEA. Weir pool operations such as lowering events could continue to enhance fast-flowing habitats, albeit at a limited spatial extent.

6 Floodplain productivity: Microinvertebrates

NA Trend Not Applicable

★★★★☆ Reliability Very good

Key findings and messages:

- Since the adoption of the Basin Plan, the density and species richness of microinvertebrates has increased, particularly following overbank flows in the SA River Murray.
- The greatest differences in density and species richness were between 2019–20 and 2022–23 which were years of low and high flows respectively.
- Managed floodplain inundations in the SA River Murray likely enhance abundance and diversity in localised areas, facilitated by water for the environment; however, the greatest impact will likely be during dry years.
- Further monitoring is required to increase our knowledge of, and how to evaluate the response of microinvertebrates to different flow and management scenarios.

6.1 Introduction

Microinvertebrates are planktic (zooplankton) organisms encompassing rotifers and microcrustaceans (cladocerans, copepods, and ostracods), which are an important link between primary producers and higher-order consumers in the riverine-floodplain trophic system (Furst et al. 2014). Microinvertebrates are an important conduit for riverine-floodplain ecosystem functioning; microinvertebrates consume bacteria, phytoplankton and detritus material (Boon & Shiel 1990), but are subsequently prey for higher trophic organisms such as fish (Arumugam & Geddes 1996; Gibbs et al. 2020; Tonkin et al. 2006).

Microinvertebrates respond rapidly to increasing flows (Ye et al. 2024). When overbank flooding occurs, large amounts of dissolved and particulate organic matter and nutrients (Hein et al. 2003), as well as phytoplankton (Tockner et al. 1999) and microinvertebrates, are transferred from floodplain habitats into the river channel (Furst et al. 2014; Gibbs et al. 2020; Ye et al. 2023). Microinvertebrate emergence is triggered by the inundation of egg banks (diapausing embryos) within sediments, and access to still or slow-flowing habitats following this increases their survival, feeding and reproduction (Gibbs et al. 2020; Ye et al. 2023). Receding waters entrain microinvertebrate communities in flow and direct them back towards the channel, allowing for the assimilation of biomass into the riverine ecosystem, contributing to riverine productivity.

The timing, duration and frequency of floodplain inundation significantly influences the density, species composition and biomass of microinvertebrates (Bice et al. 2014). Floodplain inundation is most beneficial to microinvertebrates during their peak growing season in spring and summer (Bice et al. 2014), when water temperatures increase (~25°C) (Ye et al. 2018). The duration of inundation and water residence time on the floodplain is also positively associated with the biomass and density of microinvertebrates (Bice et al. 2014). Frequency of inundation events also impacts the density and biomass of microinvertebrates, as flooding events replenish the egg bank while extended dry periods can reduce the diversity and abundance of microinvertebrate emergence (Boulton & Lloyd 1992; Wilson et al. 2014; Ye et al. 2023).

The quality of microinvertebrates as food resources for higher order consumers is likely to be influenced by their diet. Microinvertebrates have a limited ability to synthesise long-chain polyunsaturated fatty acids and therefore, must obtain them from their food (Guo et al. 2017). As such, microinvertebrates that consume more nutritious foods are potentially a high-quality food resource for higher order consumers (Gibbs et al. 2020). The nutritional value of phytoplankton food resources is influenced by hydrology, with nutritious diatoms dominant under high flows, and nutritionally poor Cyanophyta dominant under low flows (Aldridge 2012; Ye et al. 2014). Consequently, the quality of microinvertebrate food resources for higher order consumers may also be influenced by hydrological conditions.

6.2 Ecological objective, targets, and environmental outcomes

The ecological objective and targets for floodplain productivity from the [South Australian River Murray Long-term Watering Plan] (LTWP) (DEW 2020) are presented in (Table 6–1). An expected outcome was not elicited for floodplain productivity. However, based on the conceptual understanding of microinvertebrate response to flows (i.e. expect to see an increase in microinvertebrates during overbank flooding and managed floodplain inundation), the environmental outcome was assessed based on these discrete events. Water quality parameters (i.e. nutrients and dissolved organic carbon; DOC) were not included as part of the environmental outcome or assessed in Matter 8 reporting, as the Matter 12 reporting assessed these water quality events.

Table 6–1. Ecological objective, target and environmental outcome for floodplain productivity (microinvertebrates).

Characteristic	Description
Ecological objective	Provide for mobilisation of carbon, nutrients and propagules from the floodplain to the river.
Ecological target	During inundation periods, record an increase in the abundance and diversity of invertebrate food resources, nutrients, and DOC relative to those available during base flow.
Environmental outcome	During inundation periods, record an increase in the abundance and diversity of invertebrate food resources, relative to those available during base flow.

6.3 Method

To assess the environmental outcome for floodplain productivity (Table 6–1), the abundance (defined as density of individuals L^{-1}) and taxonomic richness of microinvertebrates were compared between water years from 2019–20 to 2022–23. The differences in response of these ecological metrics between baseflow (3,000–7,000 ML day^{-1}) and overbank flow (>45,000 ML day^{-1}) was qualitatively described.

6.3.1 Sampling design

Microinvertebrate data were sourced from the CEWH monitoring, evaluation and reporting (MER) program (Ye et al. 2024). The method used to sample microinvertebrates is described in Ye et al. (2024). Samples were collected between October and January in 2019–20, 2020–21, 2021–22 and 2022–23 at one site downstream from Lock 1 (distance: 5 km), Lock 4 (distance: 15 km), and Lock 6 (distance: 5 km). Samples were grouped into sampling trips based on the date of collection (within 3 days; see Table 6–2). Two Perspex Haney plankton traps (4.5 L) were used to sample microinvertebrates from the surface, middle and bottom of the water column at the mid-point of the river channel. Three replicate samples with a total volume of 27 L (9 L each from the surface, middle and bottom) were collected and preserved (in ethanol) in the field and returned to the laboratory for processing.

Table 6–2. Summary of CEWH MER microinvertebrate sampling dates between 2019 and 2023.

Trip	2019–20	2020–21	2021–22	2022–23
1	10/10	12–14/10	11–13/10	
2	21/10	27–29/10	25–27/10	24–26/10
3	4–6/11	9–11/11	8–10/11	7–9/11
4	18–19/11	24–26/11	22–24/11	21–23/11
5	2–4/12	7–9/12	6–8/12	5–7/12
6	16–18/12	21–23/12	20–22/12	19–21/12
7	7–9/01	6–7/01	5–7/01	4–6/01
8				18–19/01

6.3.2 Analysis

The effect of sampling year (water year) and trip on microinvertebrate densities and taxonomic richness were analysed using univariate permutational multivariate analysis of variance (PERMANOVA; Anderson 2001). To ensure a balanced model design between water years, only samples from trips two to seven were used. A two-way interaction between water year and sampling location (Lock) was included, whilst sampling trip was used as a blocking factor (i.e. assessing the statistical significance for water year, sampling trip, and their interaction, controlling for site location). Post-hoc testing (pairwise comparisons) was performed when a statistically significant (considered ≤ 0.05) term was found, using the False Discovery Rate (FDR) to adjust for multiple comparisons.

6.3.3 Information reliability

The information reliability assessment for the microinvertebrates evaluation was conducted as per section 4.2.3.

6.4 Results

6.4.1 Environmental outcome assessment

The environmental outcome was met for microinvertebrates, considering there were clear differences in densities between periods of overbank inundation (>45,000 ML day^{-1} in 2022-23) relative to baseflow (3,000–7,000 ML day^{-1} in 2019-20). This difference was also observed for taxonomic richness but was much less pronounced (Figure 6-1).

There was statistical evidence for differences in densities between water years (Pseudo-F_3 = 25.286, P < 0.001). There was no evidence for differences in densities between Locks, and no interaction between water year and Lock was evident (Figure 6-1). The average microinvertebrate density was significantly greater in 2022–23 compared to all other water years (Table 6–3; Figure 6-1), and the largest t-statistic values belonged to these pairwise differences (Table 6–3).

For taxonomic richness, there was evidence for differences in mean richness between water years (Pseudo-F_3 = 13.484, P < 0.001). Moreover, there was a significant main effect of Lock on mean richness (Pseudo-F_2 = 4.163, P = 0.006), but no interaction between water year and Lock (Figure 6-1). Pairwise comparisons suggest significant differences between 2021–22 and 2022–23, and the comparisons between these years and all other water years (Table 6–3; Figure 6-1). Taxonomic richness was not significantly different between 2019–20 and 2020–21. The largest t-statistic values belonged to the pairwise comparisons between 2022–23 and all other water years (Table 6–3). There was a significant difference in taxonomic richness between Lock 1 and Lock 4 (Table 6–3; Figure 6-1), but not Lock 1 and Lock 6 (Figure 6-1; Table 6–3).

Table 6–3. Pairwise PERMANOVA results for the comparisons of microinvertebrate density data between water years. Sampling trip was used as a blocking factor when permuting significance.

Densities			Richness		
Comparison	*t*-statistic	Adjusted *P*	Comparison	*t*-statistic	Adjusted *P*
2019–20, 2020–21	0.955	0.375	2019–20, 2020–21	0.941	0.255
2019–20, 2021–22	0.697	0.433	2019–20, 2021–22	2.72	**< 0.001**
2019–20, 2022–23	6.304	**< 0.001**	2019–20, 2022–23	4.247	**< 0.001**
2020–21, 2021–22	1.725	0.094	2020–21, 2021–22	1.674	**0.022**
2020–21, 2022–23	7.377	**< 0.001**	2020–21, 2022–23	4.566	**< 0.001**
2021–22, 2022–23	5.894	**< 0.001**	2021–22, 2022–23	6.144	**< 0.001**
			Lock 1 vs Lock 4	2.726	**0.008**
			Lock 1 vs Lock 6	1.649	0.099
			Lock 4 vs Lock 6	0.959	0.255

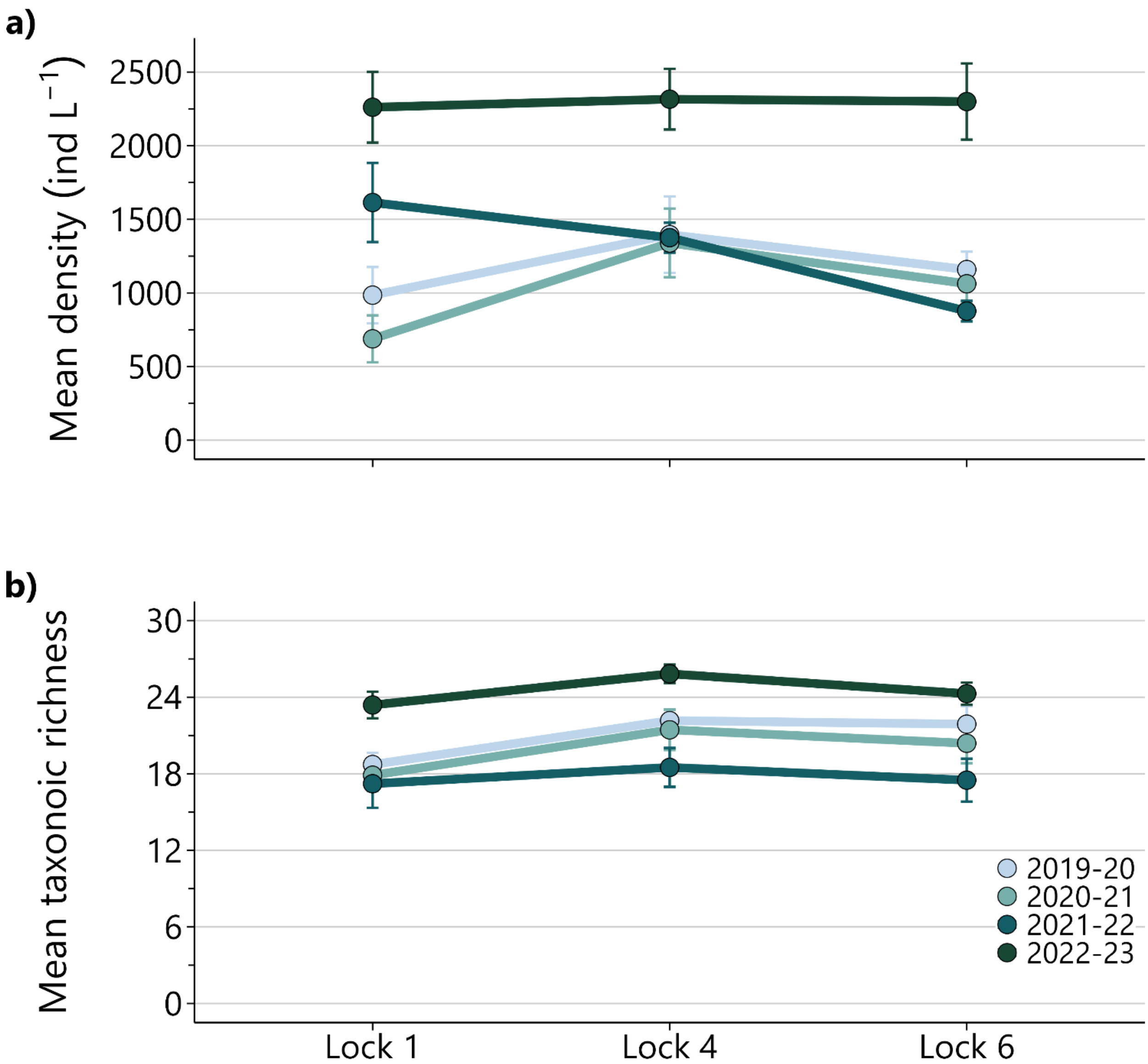


Figure 6-1. The difference in mean estimates for microinvertebrate a) densities (individuals L^{-1}) and b) taxonomic richness, between water years and sampling Lock. The error bars are the standard deviations.

It was evident that microinvertebrate densities varied substantially over sampling trips within each water year, with density generally (i.e. majority of years) peaking in December (Figure 6-2). There were clear increases in microinvertebrate densities during periods of overbank flows (2022–23) relative to baseflows (2019–20). However, densities observed at Lock 4 (Figure 6-2 b.) and Lock 6 (Figure 6-2 c.) were comparable between 2020–21 and 2021–22, with the latter having substantially more QSA.

The taxonomic richness did vary across sampling trips, and in most water years became higher throughout the sampling period (Figure 6-3). However, the relationship between taxonomic richness in years with overbank flows relative to base flows was much less pronounced compared to densities (Figure 6-2).

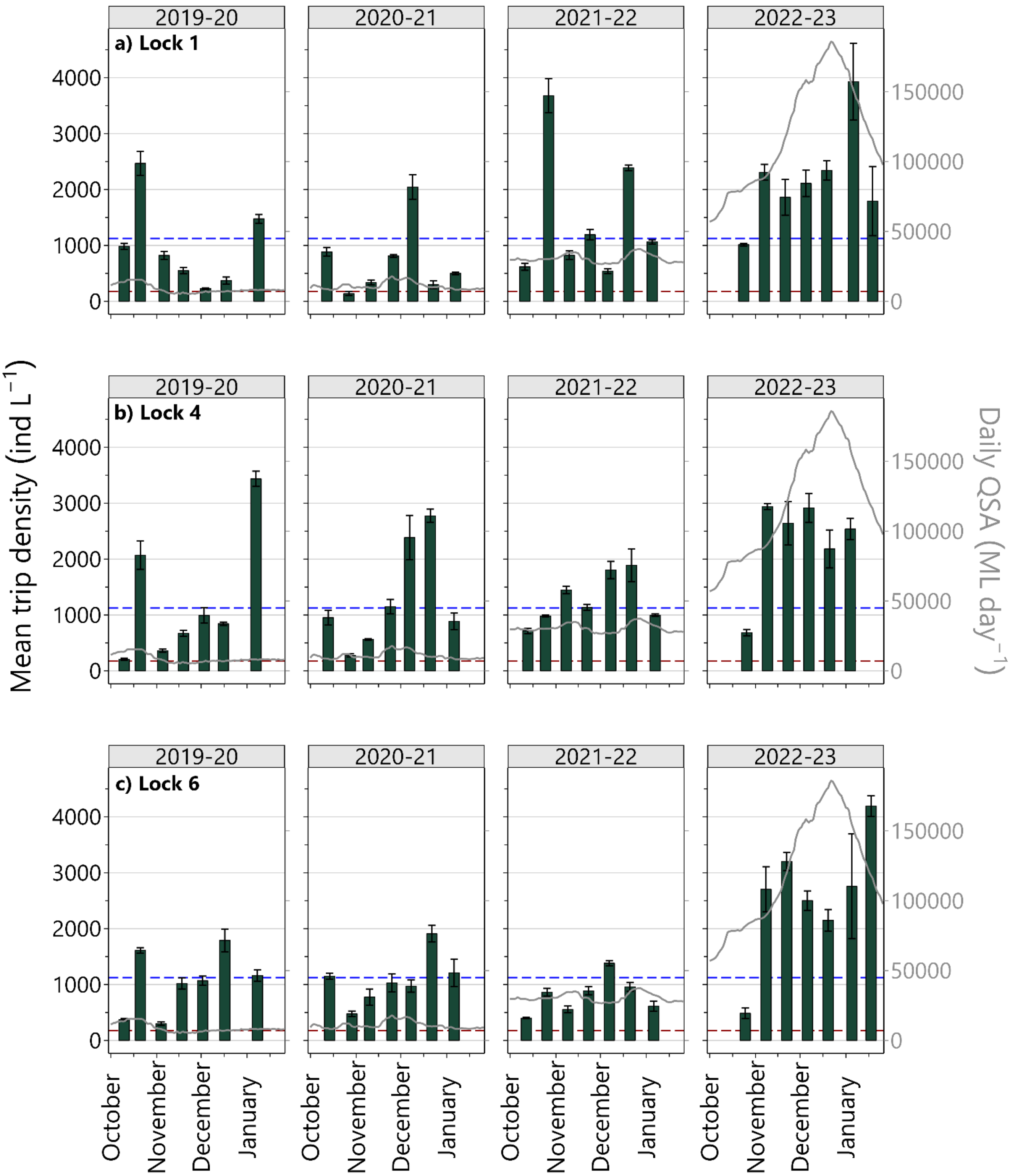


Figure 6-2. The average and standard error of microinvertebrate densities for each sampling trip across the four water years for a) Lock 1, b) Lock 4, and c) Lock 6. The grey line and right-hand axis shows the flows to South Australia (QSA). The blue horizontal line indicates the threshold for bankfull flows (45,000 ML day^{-1}); the red horizontal line indicates the threshold for base flow (7,000 ML day^{-1}).

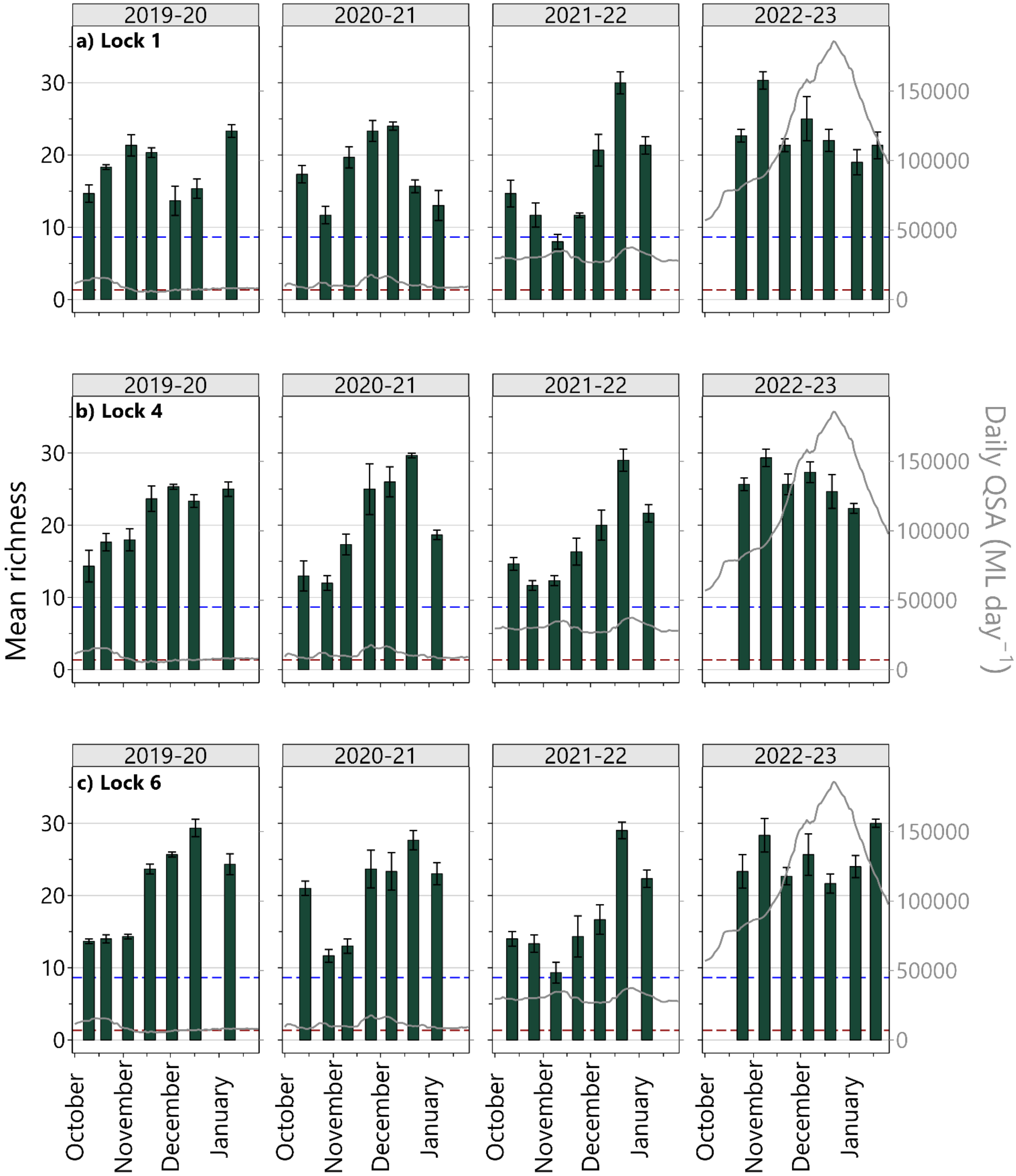


Figure 6-3. The average and standard error of microinvertebrate taxonomic richness for each sampling trip across the four water years for a) Lock 1, b) Lock 4, and c) Lock 6. The grey line and right-hand axis show the flows to South Australia (QSA). The blue horizontal line indicates the threshold for bankfull flows (45,000 ML day^{-1}); the red horizontal line indicates the threshold for base flow (7,000 ML day^{-1}).

6.4.2 Information reliability

The information reliability rating was classed as **very good** for microinvertebrates (final score of 11). Justification for the information reliability rating for microinvertebrates is provided in Table 6–4.

Table 6–4. Reliability of information to assess outcomes of microinvertebrates. The methods used in data collection as well as the representativeness, repetition and sample independence of data were scored based upon the answers provided to questions related to each facet of data collection. Answers to questions regarding the methods, representativeness and repetition of data were scored 2 points – Yes, 1 point – Partially, 0. points – No.

Methods	**Question**	**Answer and justification**	**Score**
Methods used	Are the methods used appropriate to gather the information required for evaluation?	**Yes.** A standardised methodology has been used throughout the monitoring program that has determined the densities and species richness of microinvertebrates in relation to flow and floodplain inundation.	**2**
Standard methods	Has the same method been used over the sampling program?	**Yes.** The same method for microinvertebrate sampling, analysis and identification was used throughout the monitoring program.	**2**
Representativeness			
Space	Has sampling been conducted across the spatial extent of the SA River Murray with equal effort?	**Partially.** Sampling was conducted at 3 core MER sites in the floodplain (Lock 6) and gorge (Lock 1) geomorphic zones of the lower Murray River.	**1**
Time	Has the duration of sampling been sufficient to represent change over the assessment period?	**Yes.** Sampling was conducted approximately fortnightly each year during the spring-summer months. Samples therefore occurred before, during and after floods and flow pulses.	**2**
Repetition			
Space	Has sampling been conducted at the same sites over the assessment period?	**Yes.** Samples were collected at the same sites over the monitoring program.	**2**
Time	Has the frequency of sampling been sufficient to represent change over the assessment period?	**Yes.** Sampling has been conducted annually, typically from October to January.	**2**
Final score			**11**
Information reliability			**Very Good**

6.5 Evaluation

The environmental outcome (Table 6–1) was considered met as the density and taxonomic richness of microinvertebrates have increased during periods of overbank flows (2022–23) relative to baseflows (2019–20). Microinvertebrate densities and richness were the highest in 2022–23 compared to all other water years (Figure 6-1), and these were the highest observed since (longer-term) monitoring began in 2014–15 (Ye et al. 2024). Only taxonomic richness was found to be marginally higher in Lock 4 compared to Lock 1, but this difference was not observed between Lock 1 compared to Lock 6 (Table 6–3; Figure 6-1). Therefore, whilst water for the environment has contributed to the reduction in flow-rate recession during overbank inundation (Ye et al. 2024), the environmental outcome for microinvertebrates were largely driven by high (unregulated) flows.

6.5.1 Key factors contributing to environmental outcomes

Lateral connectivity

River regulation in the SA River Murray has altered the natural variability in flooding magnitude, duration and frequency (Maheshwari et al. 1995; Walker & Thoms 1993; Ye et al. 2023), affecting the lateral (outwards to floodplain margin) connectivity. Microinvertebrate densities and richness during the spring-summer months of 2022–23 were the highest observed since monitoring began in 2014–15 (Ye et al. 2024). This was supported by extensive hydrological mixing between in-channel and floodplain habitats across the sampling season, and replenishment of plant and microorganism propagules contributed to enhanced productivity (Ye et al. 2024). Despite this, microinvertebrate taxa that are typically associated with lateral connectivity were in low abundance in 2022–23 (Ye et al. 2024), and the contribution of water for the environment to these patterns were limited during 2022–23, simply due to the magnitude of the flood (Ye et al. 2024).

Longitudinal connectivity

The longitudinal connectivity is important for the dispersal of microinvertebrates diversities. Intra-annual comparisons of microinvertebrate taxonomic richness (see columns in Figure 6-3) suggest there were similarities across the sampling locks during the assessment period in most sampling years, which perhaps indicates longitudinal connectivity of flows along the SA River Murray. Upstream connectivity is vital for flow-cued riverine fish (Bice et al., 2021; Zampatti et al., 2015), and Murray cod larvae have been found to consume species from the Trichocerca genera (Bice et al., 2023). These microinvertebrates are typically littoral but at times dominate planktic communities when entrained (Furst et al., 2019). There is a relationship between their abundance and in-channel velocities ranging from 0.15–0.2 m s^{-1} (over 4 km to 5 km), although this may vary over sampling months across spring and summer (Gibbs et al. 2023). There was an observed increase in densities of Trichocerca over the assessment period (2019–20, 121 ind L^{-1}; 2020–21, 134 ind L^{-1}; 2021–22, 256 ind L^{-1}; 198 ind L^{-1}), and densities observed in 2021–22 and 2022–23 coincided with two consecutive years of >0.3 m s^{-1} in substantial proportions of each SA weir pool (see section 5 Velocity). Ye et al. (2024) found evidence during the 2022–23 flood that further supports the flow-responsive nature of littoral rotifers (facultatively pelagic) and facilitating spring-flow pulses with water for the environment achieved increases in the abundance of this functional group. Therefore, the protection and restoration of spring flow pulses are likely to have a positive effect on the aquatic food-web.

Managed floodplain inundations

There is clear importance maintaining overbank flows and inundation of floodplain environments in the absence of natural inundation events. In 2021–22, a managed inundation event on the Chowilla floodplain was performed in conjunction with operation of the Chowilla environmental regulator and raises of Lock 6 (+0.42 m), beginning in early August and a drawdown beginning in early November to early December (Ye et al. 2023). The operation resulted in a total of 5,500 ha of floodplain and temporary wetlands being inundated (Hodder & Vial 2022). Although the taxonomic richness of microinvertebrates was higher in Lock 4 compared to Lock 1 across most water years (Figure 6-1; Table 6–3), these differences were not consistent between Lock 6 and Lock 1, also considered within the floodplain geomorphic zone of the SA River Murray, implying location largely did not influence taxonomic richness.

6.6 Actions to achieve environmental outcomes

Measures to enhance microinvertebrate densities and taxonomic richness in the SA River Murray may include the continued provision of water for the environment combined with managed floodplain inundations which are performed for other environmental outcomes (e.g. floodplain vegetation and amphibians).

6.6.1 Managed floodplain inundations

The continued operation of environmental regulators at Chowilla, Pike and Katarapko floodplains should enable greater expanses of each floodplain to be inundated in future years, likely having the greatest impact during dry years with low flow. Floodplain inundation events should occur during the warmer months (spring and early summer) as water temperature is positively associated with microinvertebrate biomass (Ye et al. 2024). At least three weeks of floodplain inundation is required to allow for diapause egg production and egg bank replenishment, helping to develop microinvertebrate communities (D Furst, personal communication, April 2020). This should contribute to an increase in channel and floodplain productivity in the SA River Murray.

It is important that managed floodplain inundations do not compromise within-channel spring flow pulses, which are important for the downstream transport of microinvertebrates, including rotifers from the genus Trichocerca (see section 6.5.1 Longitudinal connectivity).

6.6.2 Future assessment of environmental outcome

Further monitoring and research are required to fill knowledge gaps, particularly around how microinvertebrates respond to different flow and management scenarios. This is a current priority of South Australia's Integrated Operations Program and is also included as part of the Commonwealth Environmental Water Holder Monitoring, Evaluation and Research Program. Future assessment of the achievement of the floodplain productivity (microinvertebrate) environmental outcome, including evaluation of the contribution of water for the environment, in the SA River Murray should be done irrespective of whether the floodplain was inundated, and include aspects of the community that involve longitudinal connectivity.

6.7 Conclusion

The density and species richness of microinvertebrates has increased following overbank flows since the adoption of the Basin Plan. Managed floodplain inundations in the SA River Murray likely enhance their abundance and diversity in localised areas, which can be facilitated by water for the environment; however, there is likely little effect of water for the environment above 30,000 ML day^{-1} QSA, and further monitoring is required to increase our knowledge of, and how to evaluate, the response of microinvertebrates to different flow and management scenarios (Ye et al. 2024).

7 River red gum

Trend
Improved

★☆☆ Reliability
☆☆ **Poor**

Key findings and messages:

- Overall, the percentage of river red gum with a Tree Condition Index (TCI) score of ≥10 across managed areas of the Channel and Floodplain PEAs (Chowilla, Pike, Katarapko) has improved between 2008–09 and 2022–23.
- Since 2019, both Channel and Floodplain PEA river red gum condition has improved but with variability across years, and is considered on-track towards the 2029 expected outcome.
- High (unregulated) flow events and increased average rainfall following the Millenium Drought have been the key drivers of improved condition in river red gum within the SA River Murray. These events are needed more frequently to support the resilience of the river red gum population, particularly those outside of management influence.
- Delivery of water for the environment has been important in maintaining river red gum condition, particularly during dry phases between higher flow years. These areas support the maintenance of tree condition, increased resilience of trees and improved future responses to flood events.
- Full implementation of the Basin Plan, including addressing current water delivery constraints, is required to achieve greater frequency, duration and magnitude of overbank flows along the SA River Murray, which may lead to improvements in river red gum condition across the Channel and Floodplain PEAs.

7.1 Introduction

River red gum (*Eucalyptus camaldulensis ssp. camaldulensis*) is a long-lived (500–1,000 years), medium–large (up to 42 m high), single-stemmed eucalyptus tree that inhabits watercourses, floodplains, and grassy woodlands across mainland Australia (see Rogers & Ralph 2010). River red gum dominate riparian and lower floodplain habitats along the South Australian River Murray (SA River Murray) (George et al. 2005; Kilsby & Steggles 2015; Wallace et al. 2020b). River red gum is the most widely distributed eucalypt in Australia (Doody et al. 2015; Keatley et al. 2021), and is considered an iconic species due to their ecological, cultural, recreational, and economic (e.g. silviculture) value (Keatley et al. 2021; Rogers & Ralph 2010).

River red gum perform essential hydrological and biogeochemical functions that support ecological conditions in the SA River Murray and provide habitat for a multitude of riparian dwelling species. Deep-rooted floodplain vegetation, such as river red gum, can perform hydraulic redistribution through the passive absorption and movement of soil water between tree roots in wetter soils, to areas with drier moisture content (Caldwell et al. 1998; Holland et al. 2006). The leaf litter produced by river red gum communities contributes a substantial proportion to the total organic material within floodplains soils in Chowilla and Katarapko (Gibbs et al. 2022).

River red gum have evolved for a flooding regime with wetting and drying cycles (Doody et al. 2015). Floodplain trees rely on plant available water to perform photosynthesis (to produce energy) and transpiration (internal movement of water and nutrients). Water stress leads to a decrease in canopy foliage (crown extent and crown density) as a response to regulate water loss, affecting photosynthetic potential (Doody et al. 2015) and impacting flowering, distribution, and recruitment (Keatley et al. 2021; Kilsby & Steggles 2015). Trees suffering from physiological stress can respond to improved environmental conditions with epicormic growth (bud sprouting from the primary trunk rather than periphery branches) (Souter et al. 2010).

Trees access water from the unsaturated soil zone (i.e., between the top of the water table and the ground surface). The biological availability of soil moisture is influenced by soil type, salinity, and water content (Holland et al. 2011; Holland et al. 2006). Main contributors to soil moisture include:

- vertical infiltration during local rainfall (Baldwin 2011);
- lateral infiltration during elevated channel flow, sometimes termed bank recharge (Gehrig et al. 2016); and
- vertical infiltration during inundation, resulting from overbank flow (Wallace et al. 2020b).

Floodplain trees rely on recurring inundation events to recharge floodplain soil moisture to support active growth and must maintain their viability between inundation events by accessing soil water replenished by rainfall or fresh groundwater.

River regulation has decreased the floodplain inundation extent and reduced the frequency of inundation (Maheshwari et al. 1995). Declining water availability during the Millennium Drought (1996–2010) contributed to significant regional decline in river red gum condition (Doody et al. 2015; George et al. 2005; Souter et al. 2010). Supporting river red gum is a key objective of delivery of water for the environment.

7.2 Ecological objective, target and environments outcomes

The ecological objectives and targets from the South Australian River Murray Long-term Watering Plan (LTWP) (DEW 2020) for river red gum in the SA River Murray Channel and Floodplain PEA are described in Table 7–1.

Table 7–1. Description of ecological objectives and targets related to the river red gum indicator, outlined in the LTWP (DEW 2020).

Ecological objective	Ecological target
Channel PEA: Throughout the length of the Channel asset (i.e. SA border to Wellington), establish and maintain a diverse native flood-dependent plant community in areas inundated by flows of 10,000–40,000 ML day^{-1} QSA.	In standardised transects spanning the elevation gradient in the target zone, 70% of river red gum have a Tree Condition Index (TCI) score ≥10.
Floodplain PEA: Maintain a viable, functioning river red gum population within the Floodplain PEA.	In standardised transects that span the Floodplain PEA elevation gradient and existing spatial distribution, >70% of all trees have a TCI ≥10.

The expected outcomes (Table 7–2) represent the percentage of river red gum expected to be in good or excellent condition (i.e. have a TCI score equal or exceeding 10) under Basin Plan implementation at several time intervals (2019, 2029 and 2042). An elicitation process was undertaken to develop the expected outcomes for the 2019 and 2025 Matter 8 reporting.

Table 7–2. The expected environmental outcomes for river red gum in the Channel and Floodplain PEAs in 2019, 2029 and 2042.

Expected outcome	Year 2019	Year 2029	Year 2042
Channel PEA	**52%** (80% confidence range of 27–62%) of river red gum in the Channel PEA will have a TCI of ≥10.	**53%** (80% confidence range of 23–69%) of river red gum in the Channel PEA will have a TCI of ≥10.	**58%** (80% confidence range of 22–77%) of river red gum in the Channel PEA will have a TCI of ≥10.
Floodplain PEA	**46%** (80% confidence range of 26–61%) of river red gum in the Floodplain PEA will have a TCI of ≥10.	**47%** (80% confidence range of 14–67%) of river red gum in the Floodplain PEA will have a TCI of ≥10.	**48%** (80% confidence range of 12–67%) of river red gum in the Floodplain PEA will have a TCI of ≥10.

Over time, the total percentage of river red gum trees with Tree Condition Index (TCI) scores ≥10 are expected to increase slightly between 2019 and 2029 and again between 2029 and 2042 (Figure 7-1). Confidence in expected outcomes decreases somewhat over time.

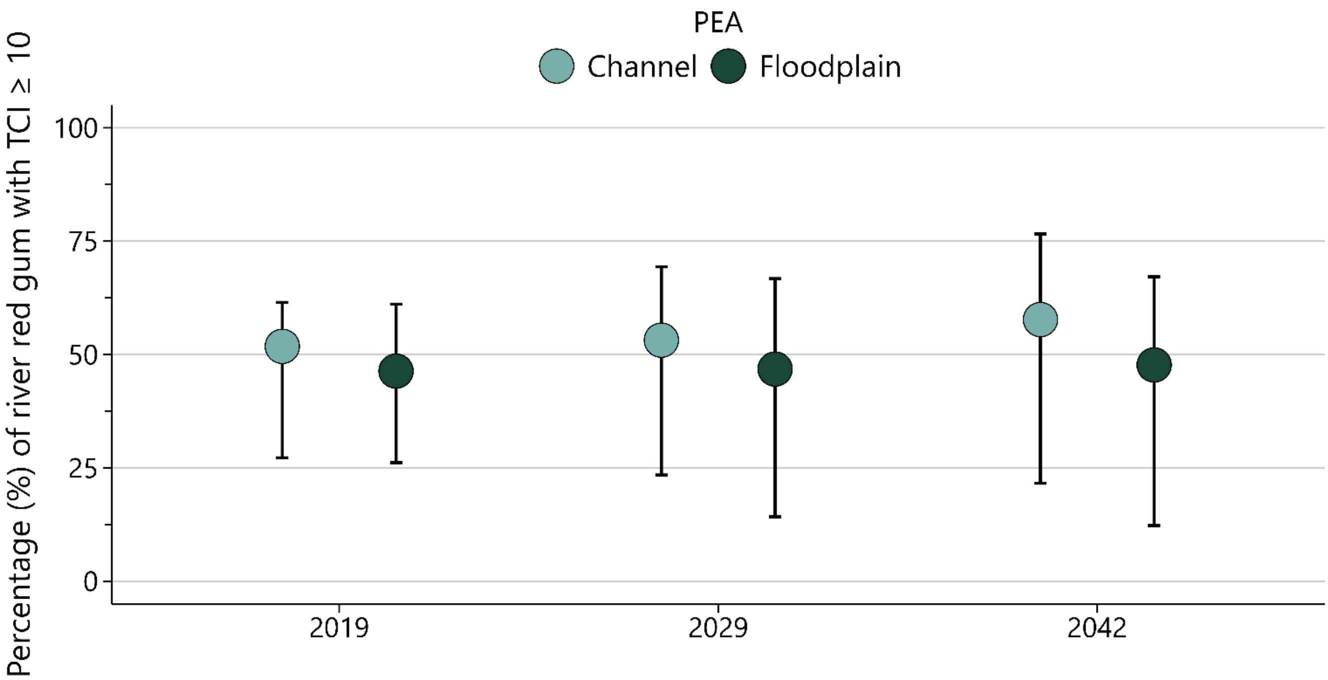


Figure 7-1. Expected environmental outcomes for river red gum in the Channel and Floodplain PEAs in 2019, 2029 and 2042.

7.3 Method

7.3.1 Data sources

Tree condition data has been collected on the Chowilla floodplain as part of TLM program. Recent data for the Pike and Katarapko floodplains were collected by DEW as part of its ongoing responsibilities for effective use and management of water for the environment in South Australia, with data collected prior to 2021 partially funded through the South Australian Riverland Floodplain Integrated Infrastructure Program (SARFIIP) and the Riverine Recovery Project (RRP).

Two River Murray inundation models were used to assign each river red gum tree to the Channel or Floodplain PEA, or outside of the PEAs. The MIKE FLOOD hydrodynamic model was used to partition tree data from the Pike and Katarapko floodplains (DEW 2021; DHI 2023). However, this hydrodynamic model does not have inundation estimates for weir pool 6; therefore, tree data from Chowilla was partitioned using the River Murray Floodplain Inundation Model (RiM-FiM; Overton et al. 2006).

7.3.2 Data collection

Tree condition data were collected using the standardised TLM tree condition method (Souter et al. 2010). Transects of 30 trees with a diameter at chest height of ≥10 cm visually assessed to determine their condition. The crown extent and crown density of each tree is recorded to the nearest 5% and allocated a score from 0 to 7 (Table 7–3). The TCI is the sum of the crown extent and crown density scores, ranging from 0 to 14. A TCI of 0 is interpreted as a non-viable tree and a score of 14 is reflective of a tree in excellent condition with a high degree of resilience (Table 7–4) (Wallace et al. 2020a).

Table 7–3. The categories for reporting crown extent (CE) and crown density (CD) (adapted from Souter et al. 2010).

Score	Description	Percentage of CE/CD
0	None	0%
1	Minimal	1-10%
2	Sparse	11-20%
3	Sparse-Medium	21-40%
4	Medium	41-60%
5	Medium-Major	61-80%
6	Major	81-90%
7	Maximum	91-100%

Table 7–4. Score system for TCI and corresponding condition description (Wallace et al. 2020b).

TCI	Condition	Description
0	Non-viable	Tree may be dead or very near to the critical point of loss. A small proportion of trees may respond to delivery of water but are likely to be in a precarious position i.e., response may not be sustained, and tree may not recover.
2-4	Very poor	Tree viable but in very poor condition and in a precarious position i.e., continuation of dry conditions is likely to lead to death. Trees with low TCIs have a slow response. A single watering may stabilise condition. Multiple, back-to-back watering will be required to achieve good condition.
5-7	Poor	Most trees would be expected to respond positively to watering. Inundation may stabilise condition or result in an improvement. Trees may be at the edge of the resilience period, i.e., continuation of dry conditions is likely to lead to a marked loss

TCI	Condition	Description
		of condition. Multiple, back-to-back watering is likely to be required to achieve good condition
8-9	Moderate	Most trees with TCIs ≥8 would be expected to respond positively to watering and increase to the next condition class.
10-12	Good	Trees are expected to have a moderate degree of resilience and should be able to withstand a short dry period with minimal loss of condition.
13-14	Excellent	Trees are expected to have a high degree of resilience and should be able to withstand a short period with minimal loss of condition.

The number of assessments undertaken on individual river red gum over each floodplain (Chowilla, Pike and Katarapko) in the Channel and Floodplain PEAs for each water year are shown in Table 7–5.

Table 7–5. The number of assessments undertaken on river red gum each year over Chowilla, Pike and Katarapko floodplains in the Channel and Floodplain PEAs from 2007–08 to 2022–23.

	Chowilla		Pike		Katarapko	
Year	**Channel**	**Floodplain**	**Channel**	**Floodplain**	**Channel**	**Floodplain**
2007–08	63	729	81	112	NA	NA
2008–09	267	1453	NA	NA	NA	NA
2009–10	82	1117	81	112	NA	NA
2010–11	63	447	NA	NA	NA	NA
2011–12	111	713	58	106	NA	NA
2012–13	124	860	NA	NA	NA	NA
2013–14	139	1095	NA	NA	NA	NA
2014–15	120	1018	92	108	126	69
2015–16	121	1043	NA	NA	NA	NA
2016–17	126	1011	30	41	126	69
2017–18	128	1027	30	41	263	229
2018–19	142	918	30	41	278	235
2019–20	142	1047	79	44	394	318
2020–21	178	1194	125	210	378	306
2021–22	226	1777	133	255	316	336
2022–23	174	1295	116	253	339	310
Total	**2206**	**16744**	**855**	**1323**	**2220**	**1872**

7.4 Trend assessment

The approach used to assess trend with a Bayesian generalised linear model is discussed in section 4.2.2. Trend analysis for river red gum was based on the proportion of trees in each transect with a good or higher TCI (≥10), using a beta distribution (logit link). Years were treated as independent data points for the analysis. Time step (years since 2007–08) was included as a fixed effect, while tree transect code was used as a random (both intercept and slope) factor.

7.5 Information reliability

The information reliability assessment for the river red gum evaluation was conducted as per section 4.2.3.

7.6 Limitations and assumptions

7.6.1 Spatial representativeness

To date, there is limited ability to assess the overall change in condition of floodplain trees for the whole of the Channel and Floodplains in the PEAs due to a lack of spatially representative monitoring data. Tree condition data utilised in this assessment were collected from the Chowilla, Pike and Katarapko floodplains and thus, will reflect those managed floodplains rather than the whole of PEA.

Trees that have been inundated by operation of the floodplain environmental regulators on Chowilla, Pike and Katarapko floodplains may be in better condition than trees that have only been inundated by high flow events (Denny et al. 2019a; Wallace et al. 2020b). The direct influence of weir pool raising events may also be difficult to quantify due to a lack of ability to delineate from other influences.

The proportion of trees that are either sampled inside, or outside, of the managed inundation extents within each of the three managed floodplains also varies spatially and temporally. Approximately 94%, 39%, and 64% of all surveyed river red gum in the Channel and Floodplain PEAs for Chowilla, Pike and Katarapko, respectively, are within the current maximum managed inundation extents (watering that has occurred thus far).

Furthermore, the Chowilla, Pike and Katarapko floodplains are located within the Valley section of the SA River Murray, from the SA border to Overland Corner. The Valley section of the SA River Murray receives lower rainfall and is subject to different groundwater conditions compared with the Gorge section, from Overland corner to Mannum. No tree data were analysed from the gorge section of the SA River Murray; therefore, the results of this assessment cannot be used to infer the condition of river red gum throughout the entirety of the Channel and Floodplain PEAs within the SA River Murray.

Spatial representativeness of the data gradually improved over time, with fewer transects and low spatial representativeness in the first 5 years of sampling, but incremental improvements with the later addition of sites at Katarapko and Pike. Additionally, more transects were added to better span the floodplain elevation gradient at Chowilla. The Pike and Katarapko regulators became operational in 2020, while the Chowilla regulator has been operational since 2014, thus water for the environment has been delivered for a shorter period at Pike and Katarapko floodplains.

7.6.2 Method limitations

This report evaluates progress against expected outcomes rather than the LTWP targets. Under the LTWP targets, tree condition is assessed at the transect level, and requires 70% or more of the trees in each transect to have a TCI score of ≥10. By contrast, in this expected outcome assessment, all river red gum were evaluated at the PEA scale.

Differences in inundation models (RiM-FiM and MIKE FLOOD) and spatial layers used for assigning the trees between the two PEAs in 2023 and 2019 may have caused some differences in the PEA's to which trees were assigned, and/or which trees may have been excluded/included in analysis, compared to the 2019 assessment. As a result, some values, such as the number of surveyed trees in the Channel and Floodplain PEA, have changed since the last assessment. This may have affected the results, although the trend remains similar to that observed in the 2019 expected environmental outcome assessment.

There were significant additions to the volume of assessments undertaken over the second half of the time series. Additional monitoring sites aimed to increase representativeness of different landform elements, management treatments, and hydrological units within the floodplains. Furthermore, earlier years of data are skewed towards

Chowilla and Pike floodplains which are more heavily impacted by shallow saline groundwater in comparison to the Katarapko floodplain (which contributes more data in the second half of the time series).

Both inundation models (RiM-FiM and MIKE FLOOD) utilised in this assessment have varying degrees of resolution but are considered the most consistent and accurate currently available in each of the two locations where they have been used.

7.7 Results

7.7.1 Environmental outcome assessment: Channel PEA

The expected outcome for river red gum in good or excellent condition in the Channel PEA was exceeded in 2018–19 with 73% of trees with a TCI ≥10 (Figure 7-2). Since 2018–19, the percentage of river red gum with a TCI ≥10 declined (less than 10%) in 2019–20 and 2020–21, before peaking in 2022–23 at 75%. Based on current trends, the 2029 expected outcome for river red gum (53%) is currently on-track, as the percentage of trees with a TCI ≥10 has been above 60% since 2017–18.

7.7.2 Tree condition: Channel PEA

The overall percentage of river red gum in the Channel PEA with a TCI ≥10 increased from 9% in 2007–08 (noting the relatively small sample size) to 75% in 2022–23 (Figure 7-2). Change in TCIs was variable over the entire assessment period, however the general trend showed consistent and gradual improvements. The number of river red gum in good or excellent condition was low between 2007–08 and 2008–09 (mean = 6%), improving in 2009–10 and 2011–12. The percentage of trees with good or excellent condition was relatively stable between 2012–13 and 2014–15, increasing to 51% in 2016–17. Since 2017–18, the number of river red gum in good or excellent condition have exceeded the 2019 expected outcome and remained relatively stable.

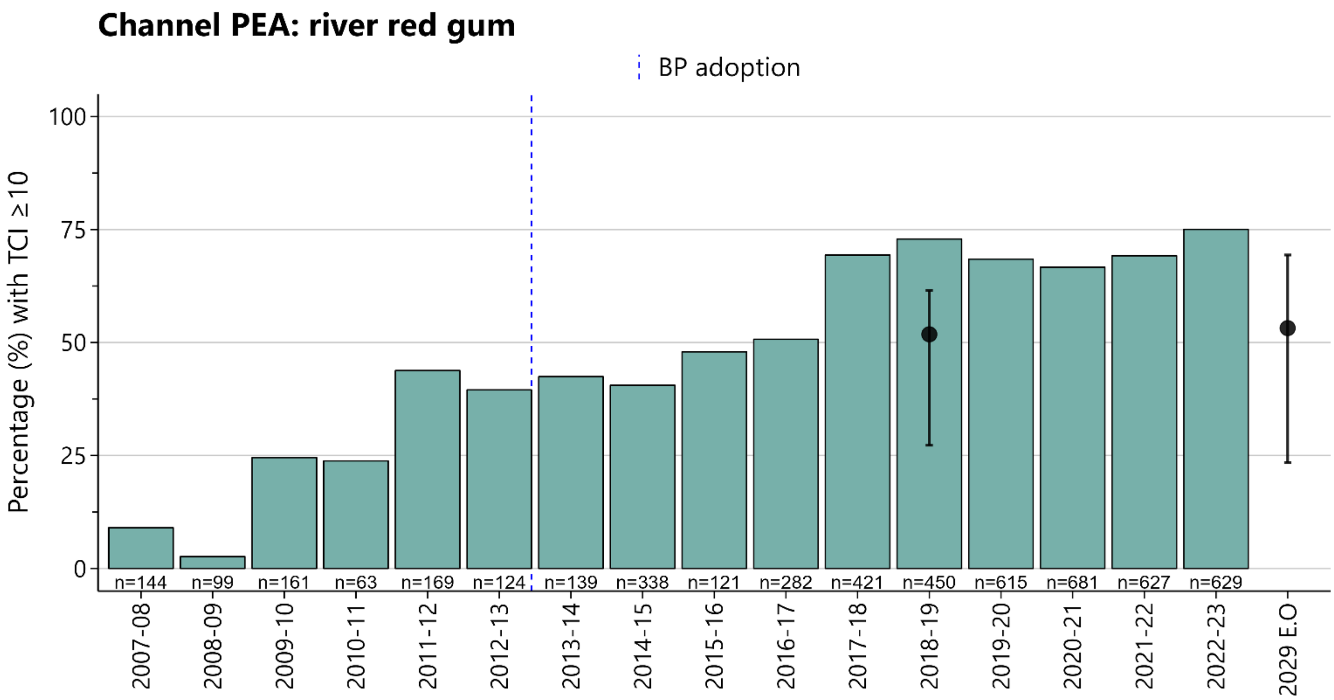


Figure 7-2. The percentage (%) of river red gum with a TCI ≥10 in the Channel PEA extent of the Chowilla, Pike and Katarapko floodplains between 2007–08 and 2022–23. Sample size (n) is provided above the x-axis for the corresponding water year. The 2019 and 2029 expected outcomes (±80% confidence interval) are referenced by the black point and associated error bars.

7.7.3 Trend: Channel PEA

It is virtually certain (100% probability) that the proportion of river red gum with a TCI ≥10 in the Channel PEA increased (median, 0.19) between 2007–08 and 2022–23. This indicates that the proportion of river red gum in good or excellent condition has **improved** over the assessment period, as shown by all posterior slope values >0 (Figure 7-3).

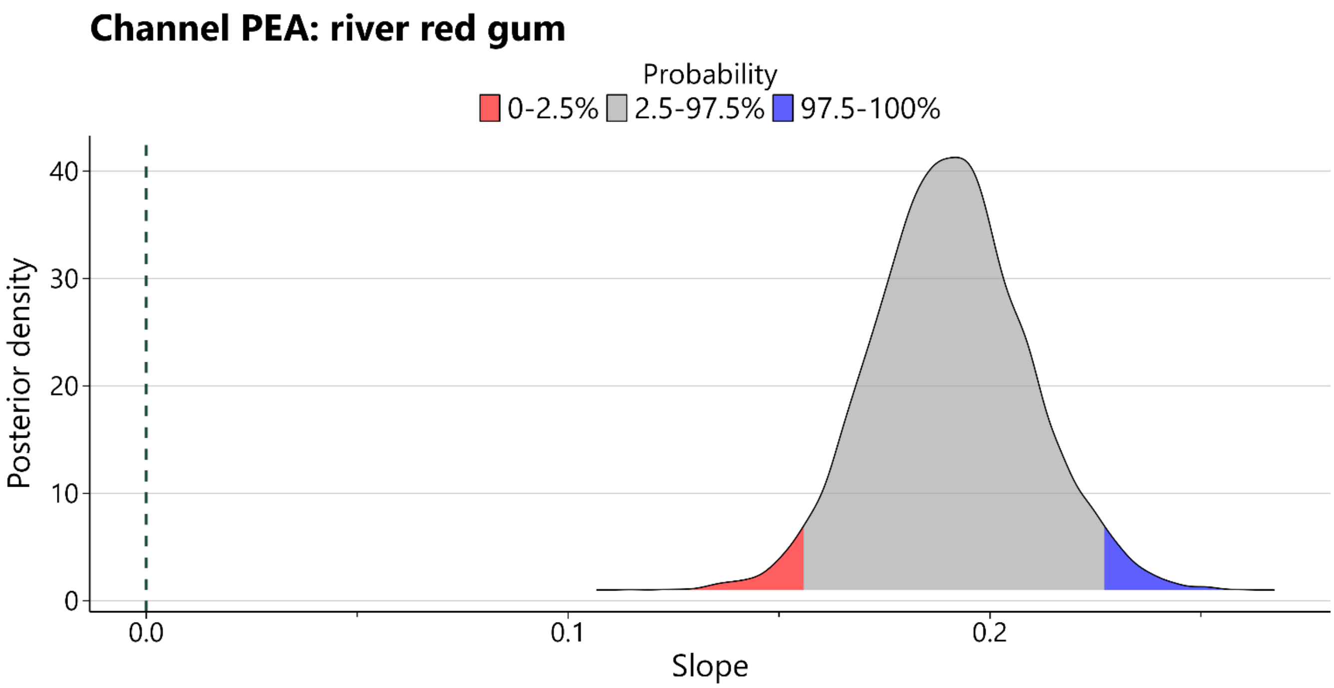


Figure 7-3. Estimated values for the slope generated from Bayesian modelling for the probability of river red gum in good or excellent condition (TCI ≥10) in the Channel PEA extent of the Chowilla, Pike and Katarapko floodplains from 2007–08 to 2022–23. Posterior slope values >0 infer a positive trend (improvement) and values <0 infer a negative trend (decline).

7.7.4 Environmental outcome assessment: Floodplain PEA

The expected outcomes for river red gum in good or excellent condition in the Floodplain PEA was exceeded in the previous evaluation (2018–19), with 63% of river red gum with a TCI ≥10 (Figure 7-4). The percentage of river red gum with a TCI ≥10 declined to 53% in 2020–21 but remained above the 2019 expected outcome. In 2022-23, the percentage of river red gum with a TCI ≥10 in the Floodplain PEA increased to 72%; therefore, the 2029 expected outcome (47%) is currently considered on-track.

7.7.5 Tree condition: Floodplain PEA

The percentage of river red gum in the Floodplain PEA with a TCI ≥10 increased from 12% in 2007–08 to 72% in 2022–23 (Figure 7-4). The observed increase was non-linear and variable over the assessment period. This was driven by an increase in 2010–11 and 2013–14. River red gum with a TCI ≥10 decreased gradually between 2014 and 2017, until increasing substantially to 65% in 2017–18, exceeding the 2019 expected outcome of 46%. Condition decreased slightly each year thereafter until 2020–21, before increasing again to 72% in 2022–23.

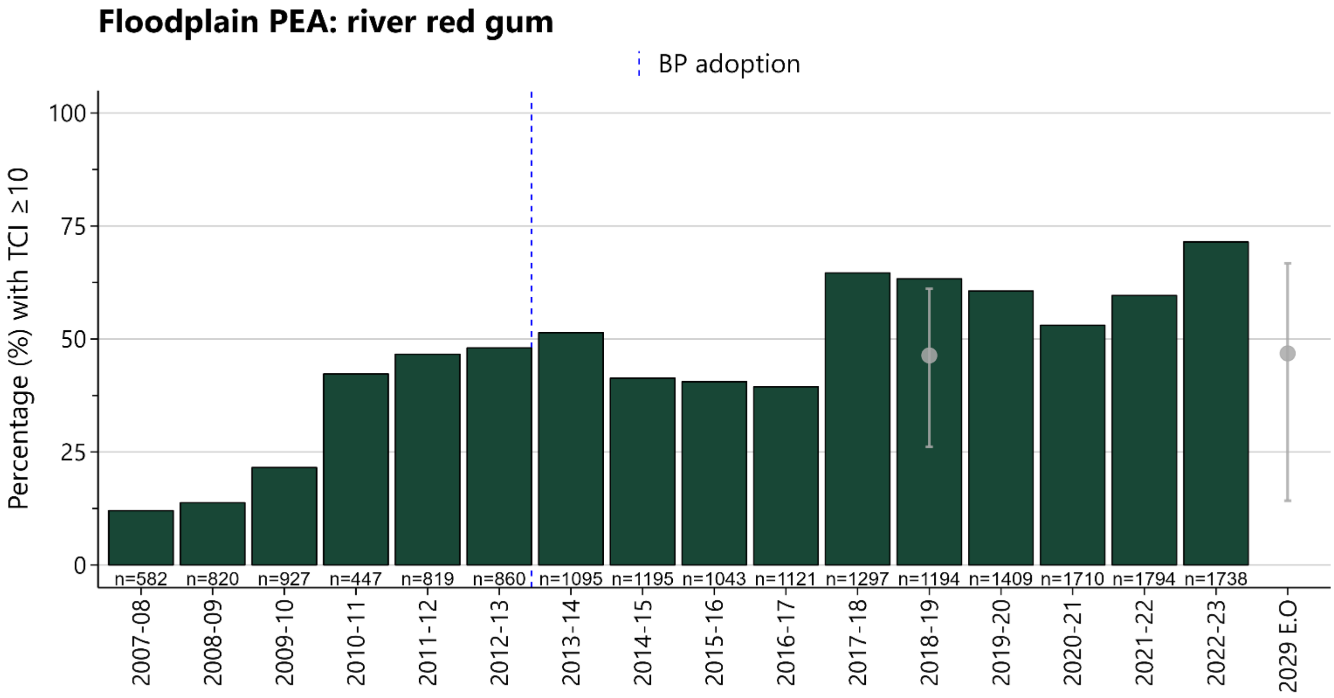


Figure 7-4. The percentage (%) of river red gum with TCI ≥10 in the Floodplain PEA extent of the Chowilla, Pike and Katarapko floodplains between 2007–08 and 2022–23. Sample size (n) is provided above the x-axis for the corresponding water year. The 2019 and 2029 expected outcomes (±80% confidence interval) are referenced by the grey point and associated error bars.

7.7.6 Trend: Floodplain PEA

It is virtually certain (100% probability) that the proportion of river red gum with TCI ≥10 in the Floodplain PEA increased (median, 0.143) from 2007–08 to 2022–23. This indicates that the proportion of river red gum in good or excellent condition has **improved**, as shown by all posterior slope values >0 (Figure 7-5).

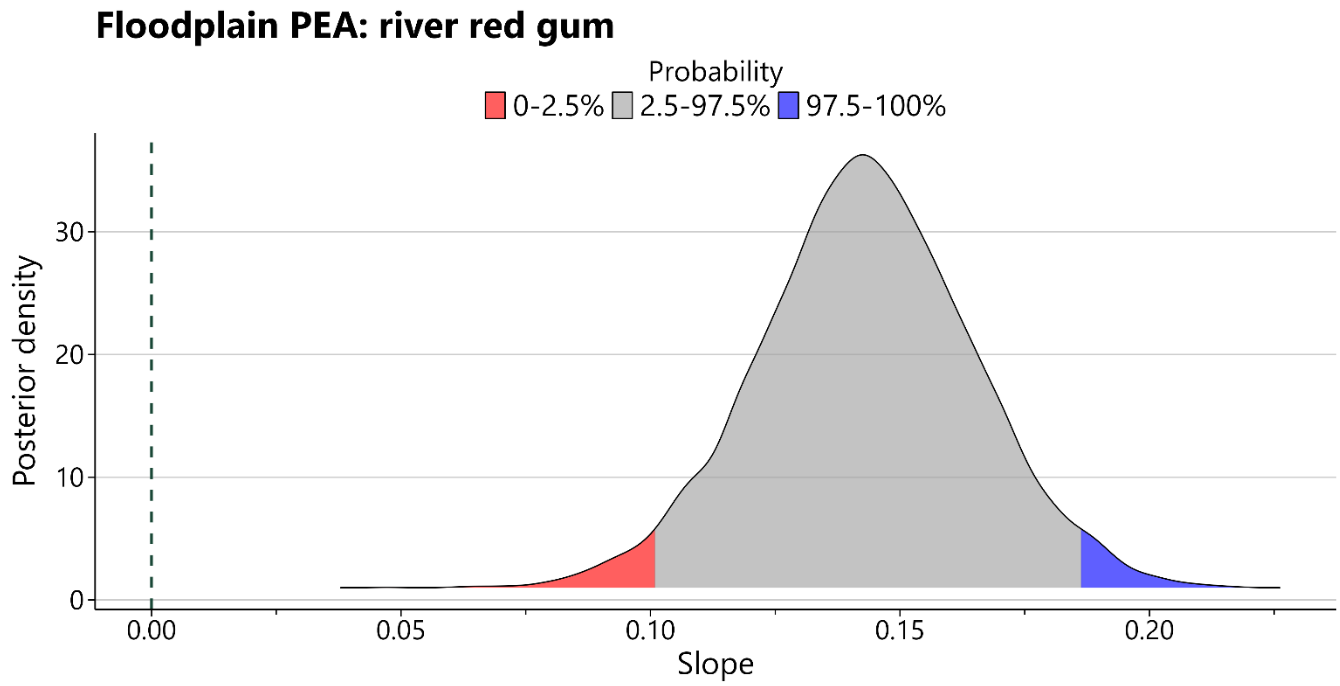


Figure 7-5. Estimated values for the slope generated from Bayesian modelling for the probability of river red gum in good or excellent condition (TCI ≥10) in the Floodplain PEA extent of the Chowilla, Pike and Katarapko floodplains from 2007-08 to 2022-23. Posterior slope values >0 infer a positive trend (improvement) and values <0 infer a negative trend (decline).

7.7.7 Contextual data: dead trees

All analyses undertaken as a part of this assessment included dead trees, which are recorded as having a TCI of 0. Figure 7-6 shows that the percentage of dead trees recorded throughout the assessment was similar over time between PEAs. A general reduction in dead trees over the assessment period appears likely due to sampling methodology and increased sampling effort.

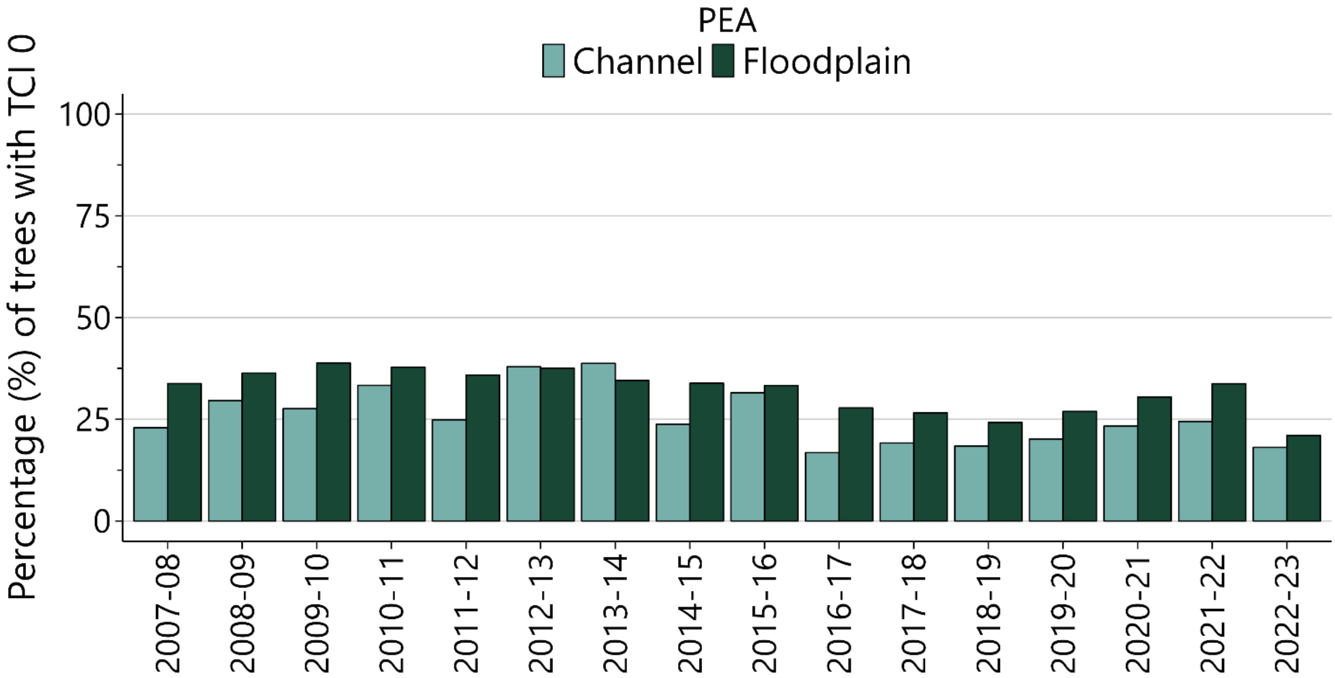


Figure 7-6. The percentage of sampled river red gum with a TCI of 0 (dead) in the Channel and Floodplain PEA.

7.7.8 Information reliability

The information reliability rating for river red gum was **poor** (final score of 8). Justification for the scoring of river red gum information reliability is provided in (Table 7–6).

Table 7–6. The reliability of river red gum data used in the assessment of environmental outcomes. The methods used in data collection including repetition and sample independence, as well as the representativeness of data were scored based upon the answers provided to questions related to each facet of data collection. Answers to questions regarding the methods, representativeness and repetition of data were scored 2 points – Yes, 1 point – Partially, 0 points – No.

Information Reliability			
Methods	**Question**	**Answer and justification**	**Score**
Methods used	Are the methods used appropriate to gather the information required for evaluation?	**Yes.** The LTWP target and expected outcomes were established upon data collected using the TCI method.	**2**
Standard methods	Has the same method been used over the sampling program?	**Yes.** Tree condition data were collected using the standardised 'The Living Murray' tree condition method (Souter et al. 2010).	**2**
Repetition			
Space	Has sampling been conducted at the same sites over the assessment period?	**Partially**. There are differences in the inaugural year of monitoring between trees sampled on the Pike, Katarapko and Chowilla floodplains. Additional sites were allocated to monitoring programs as they progressed.	**1**

Information Reliability			
Methods	**Question**	**Answer and justification**	**Score**
		Sites were re-visited annually for each monitoring program.	
Time	Has the frequency of sampling been sufficient to represent change over the assessment period?	**Yes.** Tree condition data were generally recorded annually since Basin Plan adoption and baseline data exists.	**2**
Representativeness			
Space	Has sampling been conducted across the spatial extent of the PEAs with equal effort?	**No.** Only data from Chowilla, Pike and Katarapko floodplains were analysed. The protocol for establishing transects at other managed wetlands excluded dead (defoliated) trees from inclusion within transects. Consequently, these non-standardized transects were not compared to standardised transects which include defoliated trees at the time of transect establishment.	**0**
Time	Has the duration of sampling been sufficient to represent change over the assessment period?	**Partially.** Tree condition data were recorded annually since Basin Plan adoption and baseline data exists. However, there were fluctuations in sample size between years, with four-fold fluctuations in the Channel PEA and twofold in the Floodplain PEA. Sample sizes were relatively comparable in the Channel PEA from 2015–16 to 2018–19 and in the Floodplain PEA from 2012–13 to 2018–19.	**1**
Final Score			**8**
Information Reliability			**Poor**

7.8 Evaluation

The assessment of trends indicated the number of river red gum in good or excellent condition has increased across the managed areas of Chowilla, Pike and Katarapko floodplains from 2007–08 to 2022–23. However, it is difficult to interpret these environmental outcomes due to potential confounding factors such as changes in the sampling effort and additional sampling locations. The condition of river red gum observed within this assessment cannot be inferred across the whole Channel and Floodplain PEA because most trees sampled are located on managed floodplains, and the portion of trees influenced by delivery of water for the environment is unlikely to be matched over the entire Channel and Floodplain PEA.

Over the assessment period, the condition of river red gum exhibited similar trends in both PEAs. Poor condition was observed between 2007–08 and 2008–09, while consistent improvement occurred between 2009–10 and 2018–19. Condition stabilised at ~70% from 2018–19 onwards with some minor variance, including a small decrease in 2020–21. Substantial improvements in river red gum condition were observed shortly after periods of high flow, such as 2010–12, 2016–17 and 2022–23. Recently, river red gum in good or excellent condition, have largely stabilised in the parts of the Channel and Floodplain PEAs where trees are monitored.

The improvement in river red gum condition in selected floodplain locations across the assessment period appears largely attributable to unregulated high flow events, with additional influences from delivery of water for the environment, and seasonally of higher rainfall. However, analysis of the relative contribution of these factors was not quantified for this assessment.

7.8.1 Key factors contributing to environmental outcomes

High (unregulated) flow events

The duration and frequency of unregulated high flow events have a significant influence on the condition of river red gum (Denny et al. 2019b; Doody et al. 2014; Wallace et al. 2020b). The greatest improvements in river red gum condition in Chowilla, Pike and Katarapko (e.g. 2017–18) occurred following water years with unregulated high flows (e.g. 2016–17 and 2022-23). Following high flows, a greater percentage of trees were in good or excellent condition, and less in poor condition. Floodplain trees respond positively to high flow events due to enhanced availability of soil water, when inundation increases vertical and lateral bank recharge (Doody et al. 2014).

Floodplain trees in good or better condition may be more resilient to short dry periods compared to trees in lower condition classes (Wallace et al. 2020b). Trees that receive inundation are expected to increase condition classes within 1–2 years (Wallace et al. 2020b), although there is likely a lag phase between soil saturation and improvement in tree condition (Wallace et al. 2020a).

Rainfall

Rainfall is an important source of available soil water for river red gum (Gehrig & Frahn 2015). Rainfall may be sufficient for some floodplain trees to maintain stable-but-poor condition (Wallace et al. 2020b), supporting persistence between inundation events. During 2010–11, 2016–17, 2021–22 and 2022–23, the Basin experienced higher-than-average rainfall (see Figure 3-1; Figure 3-2), resulting in substantial high flow events during those years (see Figure 3-3). Rainfall likely contributed to increased condition in river red gum.

Delivery of water for the environment

River regulation in the SA River Murray has adversely impacted connectivity between the river and floodplain. Increased water scarcity and reduced flows during the Millennium Drought (1996–2010) contributed to a significant regional decline in river red gum populations (Doody et al. 2015; George et al. 2005; Souter et al. 2010). The operation of floodplain environmental regulators, weir pool raising and pumping of water aims to maintain soil moisture in floodplains and wetlands along the SA River Murray (Doody et al. 2015; Wallace et al. 2020b).

Improved within-channel flows since the break of the Millennium Drought and subsequent adoption of the Basin Plan (see section 0), driven by widespread rainfall and run-off in the upper catchments, may have helped limit the decline in river gum condition. Elevated river water levels deliver water to riparian trees through lateral bank recharge (Gehrig et al. 2016; Wallace et al. 2020b), which may have maintained river red gum condition during drier years and between floods, where some minor condition declines were observed. River red gum condition has been supported elsewhere by elevated in-channel water levels up to 120 m from the river channel due to lateral recharge contributing to soil water (Doody et al. 2014).

Denny et al. (2019b) found river red gum at watered sites maintained higher condition classes during dry years, compared to river red gum at unwatered sites. Thus, trees at watered sites may have improved capacity to respond with a stronger growth response when high (unregulated) flows are next experienced (Wallace et al. 2020b). Whilst this analysis has not been undertaken based on watering history, delivery of water for the environment likely contributed to an increase in tree condition given the history of delivering water for the environment at the three floodplains.

Weir pool raising, supported by delivery of water for the environment, has likely positively contributed short-term, spatially constrained benefits to river red gum condition over the assessment period.

Average return intervals (ARI)

Regulation in the SA River Murray has impacted river-floodplain connectivity and reduced the frequency of inundation. Tree condition data assessed in this report are restricted to the Chowilla, Pike and Katarapko floodplains, and hence limits the ability to infer tree condition across the whole Floodplain PEA. Analysis of average return intervals (ARI) against system-scale EWRs (DEW 2020) can provide some indication of water stress and condition outside the managed floodplain areas.

The water regime preference to support river red gum are a minimum inundation duration of 1–4 months, occurring on an average return interval of 1–4 years, with a maximum interval of 5–7 years (DEW 2020). This seeks to prevent decline in river red gum condition in the SA River Murray. Table 7–7 shows the average return interval for flows at or above a specific discharge for a given duration observed in South Australia (i.e., QSA) since July 2000. These estimates suggest river red gum located in Channel PEA areas inundated up to 25,000 ML day^{-1} remain inundated for an average duration of 1 month at an average frequency of 3.3 years (Table 7–7), in line with the suggested water regime preference. Whereas for trees located at inundation extents at or above 30,000 ML day^{-1}, the average frequency of inundation is 4.6 years, exceeding the optimal water regime. Furthermore, river red gum on the floodplain (≥50,000 ML day^{-1}) are averaging an inundation duration of 1 month every 7.7 years, which is above the maximum suggested return interval of 7 years.

Table 7–7. The average return interval (in years) for various flow bands and durations of Flows to South Australia (QSA) observed between September and March each year (2000–2023). N/A implies a flow band for that duration has not occurred during spring-summer months since 2000.

PEA	Flow bands (ML day^{-1})	30 days	60 days	90 days	120 days
Channel	10,000	2.1	2.9	2.9	3.3
	15,000	2.9	3.3	4.6	4.6
	20,000	3.3	4.6	4.6	5.8
	25,000	3.3	5.8	5.8	7.7
	30,000	4.6	7.7	7.7	11.5
	35,000	5.8	7.7	11.5	11.5
	40,000	5.8	7.7	11.5	11.5
Floodplain	50,000	7.7	11.5	11.5	11.5
	60,000	7.7	11.5	23	23
	70,000	7.7	11.5	23	N/A
	80,000	23	23	23	N/A

7.9 Unanticipated Outcomes

River red gum condition remained somewhat similar between the Channel and Floodplain PEAs from 2007–08 to 2022–23. This could be because a significant proportion of trees from the Chowilla floodplain are within managed wetlands and temporary creeks, with the Floodplain PEA having almost four times more samples than the Channel PEA.

7.10 Action to achieve environmental outcomes

Delivery of water for the environment is an important management tool to improve and support the condition and resilience of floodplain tree populations (Wallace et al. 2020a). The conceptual model of stress recovery for floodplain eucalypts (see Wallace et al. 2020b) describes how floodplain tree condition changes with the duration and frequency of dry phases and inundation or watering events. This model highlights the importance of delivery of water for the environment during dry phases to reduce the number of trees declining to poor or very poor condition. The use of water for the environment supports floodplain trees in managed areas (94% Chowilla; 39% Pike; 64% Katarapko). This helps during drier periods when river-floodplain connectivity is reduced (Wallace et al. 2020b).

Full delivery of the Basin Plan, including the recovery and delivery of the 450 GL of water for the environment and addressing current water delivery constraints is critical, together with the further optimisation of water delivery for improved tree condition.

None of the environmental regulators at Chowilla, Pike and Katarapko floodplains have yet been operated to full theoretical extent of inundation and therefore the influence of delivery of environmental water may increase in these locations in future and the condition of trees may diverge further from the condition of trees on the unmanaged floodplain. Hence the addition of monitoring in other unmanaged locations is a high priority. In-channel pulses, weir pool raising, with additional measures such as groundwater management would also further increase tree resilience and condition.

7.11 Conclusion

The proportion of trees in good or excellent condition across the managed Chowilla, Pike and Katarapko floodplains, within Channel and Floodplain PEAs, have increased between 2007–08 and 2022–23. River red gum TCI at the three managed floodplains in the Channel and Floodplain PEA has improved overall to 2022–23, though some minor reductions were observed since the 2019 assessment. Improvements in tree condition post-Millennium Drought provide an indication that water for the environment delivered under the Basin Plan has contributed to positive outcomes, particularly in managed floodplain areas. Overall improvements in hydroclimatic conditions across the MDB have likely substantially affected tree condition.

8 Black box

Trend **Improved**

★☆☆☆☆ Reliability **Poor**

Key findings and messages:

- Overall, the percentage of black box with a Tree Condition Index (TCI) score of ≥10 across managed areas of the Floodplain PEA (Chowilla, Pike, Katarapko) has increased between 2008–09 and 2022–23.
- Since 2019, black box condition has improved, and is considered on-track towards the 2029 expected outcome.
- High (unregulated) flow events and increased rainfall following the Millenium Drought have likely been key drivers of improved black box condition within the SA River Murray. These events are needed more frequently to support the resilience of the black box populations, particularly those outside of management influence.
- Delivery of water for the environment has been important in supporting black box condition, particularly during dry phases between higher flow years. These areas support the maintenance of tree condition, increased resilience of trees and improved future responses to flood events.
- Full implementation of the Basin Plan, including addressing current water delivery constraints, is required to achieve greater frequency, duration and magnitude of overbank flows along the SA River Murray, which may lead to improvements in black box condition across the Floodplain PEA.

8.1 Introduction

Black box (*Eucalyptus largiflorens*) is a long-lived, medium sized (up to 20 m high) and usually single-stemmed tree, commonly distributed over much of the southern Murray–Darling Basin (MDB) floodplain (Overton et al. 2018; Rogers & Ralph 2010). Black box woodlands have the second largest coverage of any floodplain vegetation in the South Australian River Murray (SA River Murray) (Kilsby & Steggles 2015), and grow on the high elevation floodplain, which is less frequently inundated (Overton et al. 2018). Black box communities are of high conservation value and serve as a key indicator for upper floodplain condition (Doody et al. 2021; Wallace et al. 2020a).

Black box woodlands contribute a range of ecosystem services. Floodwater is infiltrated more rapidly into floodplain soils in areas with established black box communities, compared with grazing impacted bare habitats (Bramley et al. 2003; Roberts & Marston 2011). Black box trees play a role in the sequestration and cycling of carbon and nutrients (Francis & Sheldon 2002; Gibbs et al. 2023), and they provide habitat for a suite of flora and fauna (McGinness et al. 2018; Moxham et al. 2017).

Black box trees rely on plant available water to perform photosynthesis (to produce energy), and transpiration (internal movement of water and nutrients). Black box is more salt-tolerant, and has a lower transpiration rate (and therefore slower growth), compared with river red gum (Roberts & Marston 2011). The species uses rainfall and groundwater to persist outside of high flow events (Gehrig & Frahn 2015; Overton et al. 2018).

On SA floodplains, Black box commonly grow at higher elevations than lignum and river red gum communities, and lower elevation than mallee which is situated on the highland (never inundated) (Kilsby & Steggles 2015; Rogers & Paton 2008).

The availability of water for floodplain trees, and thus their resilience between flooding events, relies on the moisture content in the unsaturated soil zone (i.e., between the top of the water table and the ground surface). The availability of soil moisture is influenced by soil type, salinity, and water content (Holland et al. 2011; Holland et al. 2006). Main contributors to soil moisture include:

- vertical infiltration during local rainfall (Baldwin 2011);
- lateral infiltration during elevated channel flow termed bank recharge (Gehrig et al. 2016); and
- vertical infiltration during inundation, termed overbank (Wallace et al. 2020b).

Therefore, floodplain trees rely on recurring inundation events to recharge the moisture content in floodplain soils and maintain their viability between such events.

The condition of river red gum and black box have been in long-term decline across the MDB (Doody et al. 2014; Overton et al. 2018), associated with increased groundwater level, soil salinity, reduced floodplain connectivity and frequency of flood events (Overton et al. 2006; Wen et al. 2009). Drought, river regulation and abstraction, irrigation, grazing and land clearance all adversely impact black box woodlands (Doody et al. 2014; Doody et al. 2015; Doody et al. 2021; Overton et al. 2006; Overton et al. 2018).

8.2 Ecological objective, target and environmental outcomes

The ecological objective and targets from the South Australian River Murray Long-term Watering Plan (LTWP) (DEW 2020) for black box in the SA River Murray Floodplain PEA are described in Table 8–1.

Table 8–1. Description of ecological objective and targets related to the black box indicator, outlined in the LTWP (DEW 2020).

Ecological objective	Ecological target
Maintain a viable, functioning black box population within the Floodplain Priority Environmental Asset (PEA).	In standardised transects that span the Floodplain PEA elevation gradient and existing spatial distribution, >70% of all trees have a TCI ≥10.

The process to develop expected outcomes was undertaken in 2019 and are based on the percentage of trees with a TCI ≥10. The expected outcomes present the percentage of black box expected to be in good or excellent condition (i.e., have a TCI score equal or exceeding 10) under Basin Plan implementation at given time intervals (2019, 2029, 2042). The expected outcomes for black box in 2019, 2029 and 2042 are presented in Table 8–2 and Figure 8-1. The total percentage of black box with TCI ≥10 is expected to increase slightly between 2019 and 2029 and increase again between 2029 and 2042. The confidence range of the expected outcomes decreases somewhat over time.

Table 8–2. Expected outcomes for black box in the Floodplain Priority Environmental Asset (PEA) in 2019, 2029, and 2042.

Expected outcome	Year		
	2019	2029	2042
Floodplain PEA	**35%** (80% confidence range of 23-45%) of black box will have a TCI of ≥10.	**46%** (80% confidence range of 16-68%) of black box will have a TCI of ≥10.	**52%** (80% confidence range of 24-73%) of black box will have a TCI of ≥10.

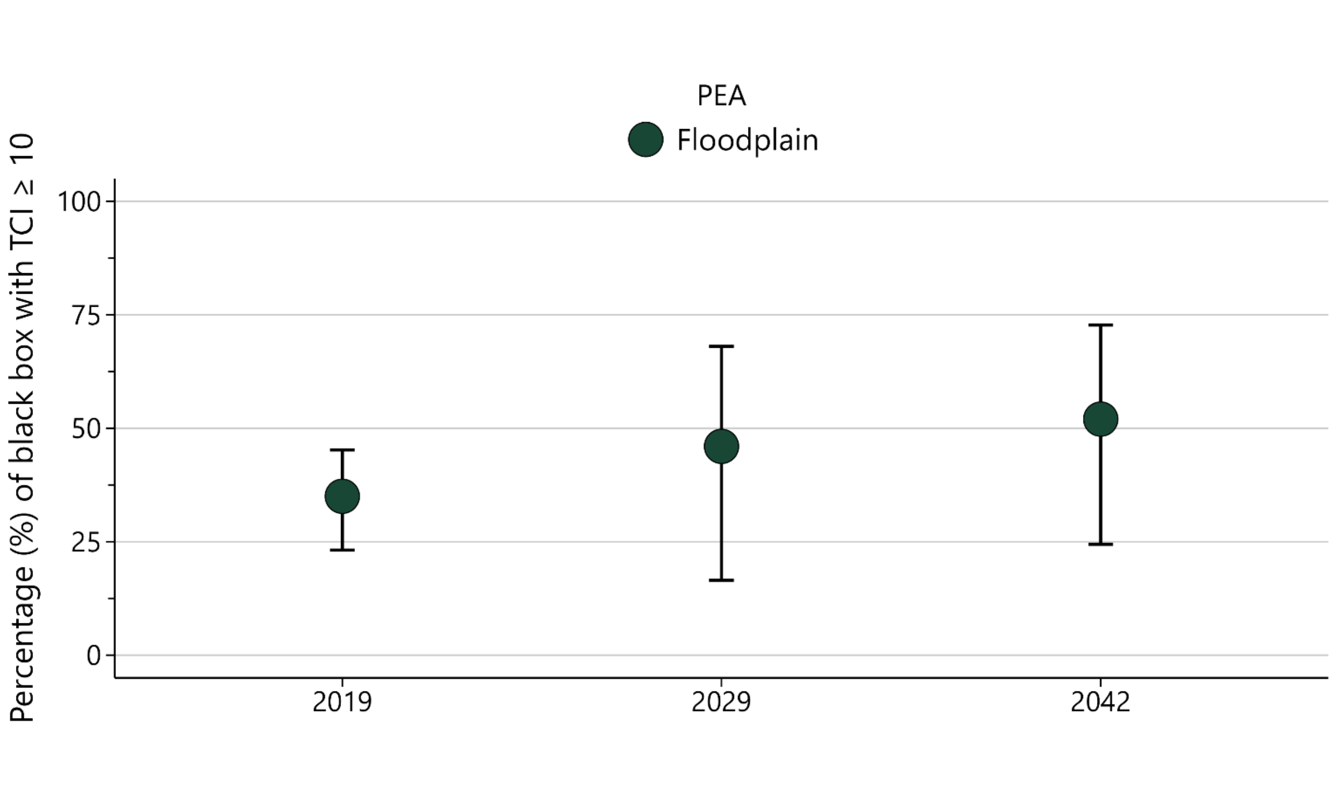


Figure 8-1. Expected outcomes for the percentage of black box in good or excellent condition (TCI ≥10) in 2019, 2029 and 2042.

8.3 Method

8.3.1 Data sources

Tree condition data from Chowilla floodplain were collected as part of TLM program. Recent data for the Pike and Katarapko floodplains were collected by DEW as part of its ongoing responsibilities for effective use and management of water for the environment in South Australia. Data collected prior to 2021 was partially funded through the South Australian Riverland Floodplain Integrated Infrastructure Program (SARFIIP) and the Riverine Recovery Project (RRP).

The spatial coordinates of each surveyed tree were used to assign them to the Floodplain PEA, Channel PEA, or outside of the PEAs. For this purpose, two River Murray inundation models were used. Tree data from Pike and Katarapko floodplains were partitioned using the MIKE FLOOD hydrodynamic model (DEW 2021; DHI 2023). However, this hydrodynamic model does not have inundation estimates for weir pool 6; therefore, tree data from

Chowilla was partitioned using the River Murray Floodplain Inundation Model (RiM FiM), developed by Overton et al. (2006).

8.3.2 Data collection

Tree condition data were collected using the standardised TLM tree condition method (Souter et al. 2010). Trees assessed using the TLM method are arranged in transects. At each transect, the condition of 30 trees with a diameter at breast height of ≥10 cm is visually assessed. The crown extent and crown density of each tree is scored to the nearest 5% and allocated a score from 0 to 7 based on the categories in Table 8–3. The tree condition index (TCI) is the sum of the crown extent and crown density scores, and therefore range from 0 to 14. A TCI of 0 is interpreted as a non-viable tree and a score of 14 is reflective of a tree in excellent condition with a high degree of resilience (Table 8–4) (Wallace et al. 2020b).

Table 8–3. Categories for reporting crown extent (CE) and crown density (CD) (adapted from Souter et al. 2010).

Score	Description	Percentage of CE/CD
0	None	0%
1	Minimal	1-10%
2	Sparse	11-20%
3	Sparse-Medium	21-40%
4	Medium	41-60%
5	Medium-Major	61-80%
6	Major	81-90%
7	Maximum	91-100%

Table 8–4. Scoring system for TCI and corresponding condition description (Wallace et al. 2020).

TCI	Condition	Description
0	Non-viable	Tree may be dead or very near to the critical point of loss. A small proportion of trees may respond to delivery of water but are likely to be in a precarious position i.e., response may not be sustained, and tree may not recover.
2-4	Very poor	Tree viable but in very poor condition and in a precarious position i.e., continuation of dry conditions is likely to lead to death. Trees with low TCI have a slow response. A single watering may stabilise condition. Multiple, back-to-back watering will be required to achieve good condition.
5-7	Poor	Most trees would be expected to respond positively to watering. Inundation may stabilise condition or result in an improvement. Trees may be at the edge of the resilience period, i.e., continuation of dry conditions is likely to lead to a marked loss of condition. Multiple, back-to-back watering is likely to be required to achieve good condition
8-9	Moderate	Most trees with TCI ≥8 would be expected to respond positively to watering and increase to the next condition class.
10-12	Good	Trees are expected to have a moderate degree of resilience and should be able to withstand a short dry period with minimal loss of condition.
13-14	Excellent	Trees are expected to have a high degree of resilience and should be able to withstand a short period with minimal loss of condition.

The number of assessments undertaken on black box over each floodplain (Chowilla, Pike and Katarapko) in the Floodplain PEA for each water year are shown in Table 8–5.

Table 8–5. The number of black box assessed each year over Chowilla, Pike and Katarapko floodplains in the Floodplain PEA from 2007–08 to 2022–23.

Year	Chowilla Floodplain	Pike Floodplain	Katarapko Floodplain
2007–08	30	44	NA
2008–09	242	NA	NA
2009–10	238	62	NA
2011–12	35	38	NA
2012–13	200	NA	NA
2013–14	395	NA	NA
2014–15	495	17	284
2015–16	472	NA	NA
2016–17	307	108	284
2017–18	276	108	618
2018–19	321	108	636
2019–20	349	108	666
2020–21	712	112	673
2021–22	1,324	119	699
2022–23	979	87	740
Total	**6,375**	**911**	**4,600**

8.4 Trend assessment

The approach used to assess trend with a Bayesian generalised linear model is discussed in section 4.2.2. Trend analysis for black box was based on the proportion of trees in each transect with a good or higher TCI (≥10), using a beta distribution (logit link). Years were treated as independent data points for the analysis. Time step (years since 2007–08) was included as a fixed effect, while tree transect code was used as a random (both intercept and slope) factor.

8.5 Information reliability

The information reliability assessment for the black box evaluation was conducted as per section 4.2.3.

8.6 Limitations and assumptions

8.6.1 Spatial representativeness

To date, there is limited ability to assess the overall change in condition of floodplain trees for the whole of channel and floodplain PEAs due to a lack of spatially diverse monitoring data. Tree condition data utilised in this assessment were collected from the Chowilla, Pike and Katarapko floodplains and thus, will reflect managed floodplains rather than the whole of the PEA.

Trees that have been inundated by operation of the floodplain environmental regulators on Chowilla, Pike and Katarapko floodplains may be in better condition than trees that have only been inundated by high flow events (Denny et al. 2019a; Wallace et al. 2020b). The direct influence of weir pool raising events may also be difficult to quantify due to a lack of ability to delineate from other influences.

The proportion of trees that are either sampled inside, or outside, of the managed inundation extents within each of the three managed floodplains also varies. Under the current maximum extent that managed inundations have reached (no regulators have been operated to their full extents yet), 81% of black box in the Floodplain PEA on the Pike Floodplain are within the managed inundation extent. Comparatively, 64% of black box are within areas that can be inundated by infrastructure on the Katarapko floodplain. At Chowilla, 79% of trees across the managed Floodplain PEA were within the current maximum management footprint.

Furthermore, the Chowilla, Pike and Katarapko floodplains are located within the valley section of the SA River Murray, from the SA border to Overland Corner. The Valley section of the SA River Murray receives lower rainfall and is subject to different groundwater conditions compared with the Gorge section, from Overland corner to Mannum. The results of this assessment cannot be used to infer the condition of black box throughout the entirety of the Floodplain PEA within the SA River Murray.

Spatial representativeness of the data gradually improved over time, with fewer transects and low spatial representativeness in the first five years of sampling, but incremental improvements with the later addition of sites from Katarapko and Pike. Additionally, more transects were added to better span the floodplain elevation gradient at Chowilla. The Pike and Katarapko regulators were commissioned in 2020, while the Chowilla regulator was operated for the first time in 2014, and hence Pike and Katarapko floodplains have had water for the environment delivered for a shorter period.

8.6.2 Method limitations

This report evaluates progress against expected outcomes rather than LTWP targets. Under the LTWP targets, tree condition is assessed at the transect level, and requires 70% or more of the trees in each transect to have a TCI score of ≥10. By contrast, for this expected outcome assessment, all black box were evaluated at the PEA scale.

Differences in inundation models (RiM-FiM and MIKE FLOOD) and spatial layers used for assigning the trees between the two PEAs in 2023 and 2019 may have caused some differences in the number of trees assigned to a PEA and/or which trees may have been excluded/included in analysis, compared to the 2019 assessment. As a result, some values, such as the number of surveyed trees in each Floodplain, have changed since the last assessment. This may have affected the results, although the trend remains similar to that observed in the 2019 assessment.

There were significant additions to the volume of assessments undertaken over the second half of the time series. Additional monitoring sites aimed to increase representativeness of different landform elements, management treatments, and hydrological units within the floodplains. Furthermore, earlier years of data are skewed towards Chowilla and Pike floodplains which are more heavily impacted by shallow saline groundwater in comparison to the Katarapko floodplain (which contributes more data in the second half of the time series).

Both inundation models (RiM-FiM and MIKE FLOOD) utilised in this assessment have varying degrees of resolution but are considered the most consistent and accurate currently available in each of the two locations where they have been used.

8.7 Results

8.7.1 Environmental outcome assessment

The expected outcome for black box in good or excellent condition in the Floodplain PEA was 35% for 2019 and was exceeded in the last evaluation (2018–19), with 68% of trees scoring a TCI ≥10 (Figure 8-2). Since 2018–19, the percentage of black box with a TCI ≥10 declined slightly to 60% in 2021–22, before increasing to 69% in 2022–23. Based on current trends, the black box 2029 expected outcome (46%) is on-track.

8.7.2 Tree condition

The percentage of black box in the Floodplain PEA with a TCI ≥10 increased from 16% in 2007–08 to 68% in 2022–23 (Figure 8-2), noting that substantial changes in sample sizes occurred during this period. The observed increase was non-linear and variable across the assessment period. There were more trees with TCI ≥ 10 in 2011–12, post-Millennium Drought (1996–2010) (no data collected in 2010–11). Black box TCI declined from 2013–14 to 2014–15 from 51% to 23%, before remaining around 30% between 2015–16 and 2016–17. Following this, the percentage of black box in good or excellent condition increased substantially from 32% to 64% in 2017–18. Over the next four water years (2018–19 to 2021–22), the number of black box with TCI ≥10 did not fall below 60% in the Floodplain PEA. The highest percentage of black box in good or excellent condition (69%) was recorded in 2022–23.

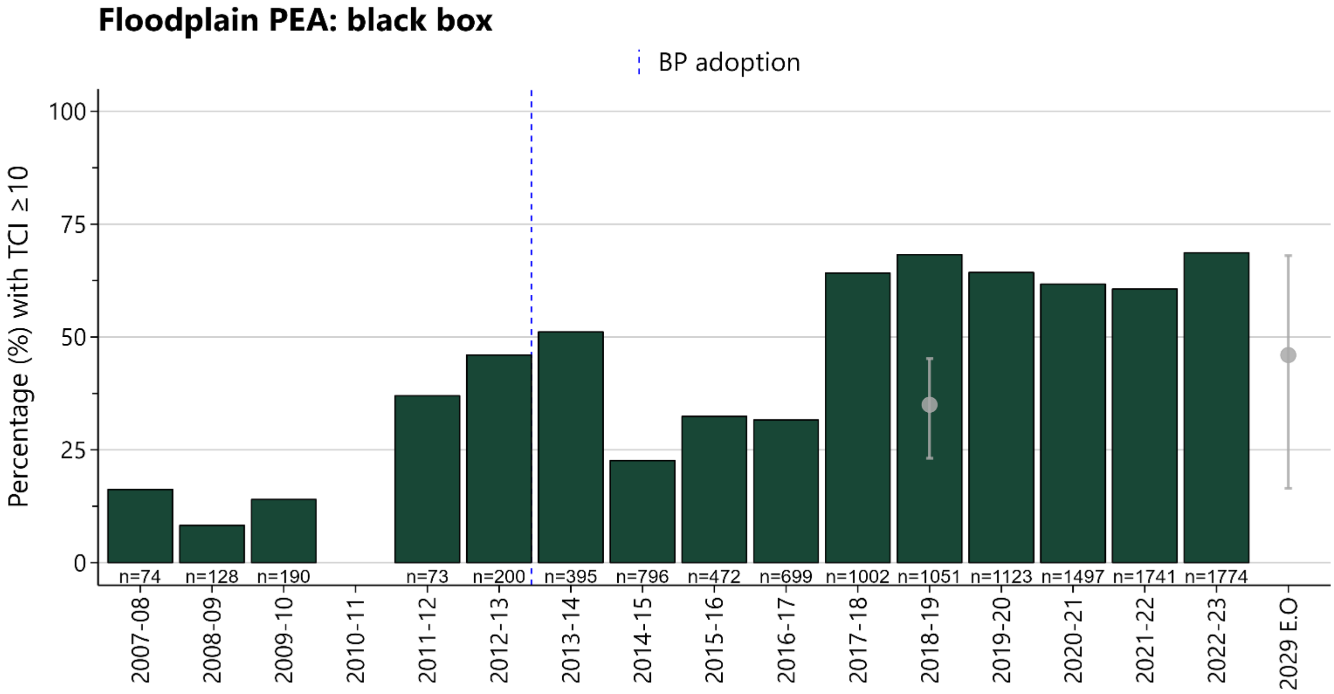


Figure 8-2. Percentage of black box with TCI ≥10 in the Floodplain PEA extent of the Chowilla, Pike and Katarapko floodplains between 2007–08 and 2022–23. Sample size (n) is provided above the x-axis for the corresponding water year. The 2019 and 2029 expected outcomes (±80% confidence interval) are referenced by the grey point and associated error bars.

8.7.3 Trend assessment

It is virtually certain (100% probability) that the proportion of black box with a TCI ≥10, in the Floodplain PEA, increased (median, 0.158) from 2007–08 to 2022–23. This indicates that the proportion of black box in good or excellent condition has **improved**, as shown by all posterior slope values >0 (Figure 8-3).

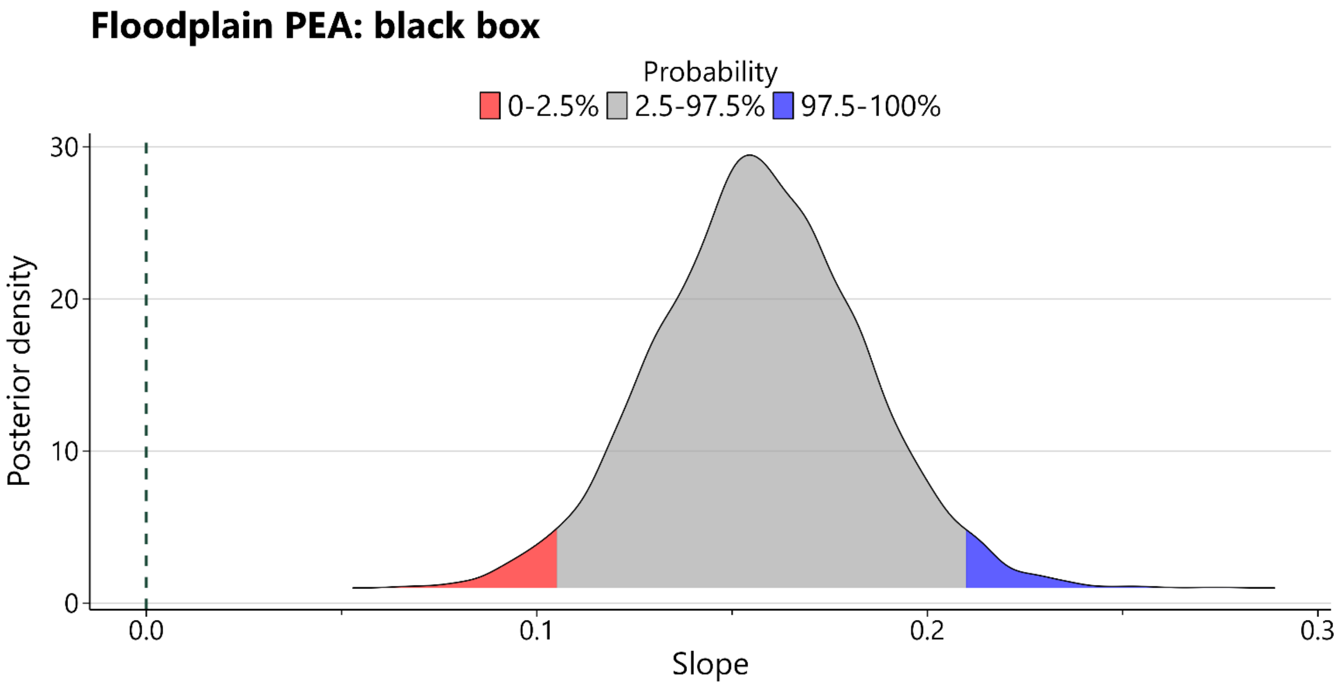


Figure 8-3. Estimated values for the slope generated from Bayesian modelling for the probability of black box in good or excellent condition (TCI ≥10) in the Floodplain PEA extent of the Chowilla, Pike and Katarapko floodplains from 2007–08 to 2022–23. Posterior slope values >0 infer a positive trend (improvement) and values <0 infer a negative trend (decline).

8.7.4 Contextual data: dead trees

All analyses undertaken as a part of this assessment included dead trees, which are recorded as having a TCI of 0. Figure 8-4 shows the percentage of dead trees recorded throughout the assessment was similar, aside from 2011–12. This shows a slight reduction in dead trees over the assessment period, likely due to increased sampling effort.

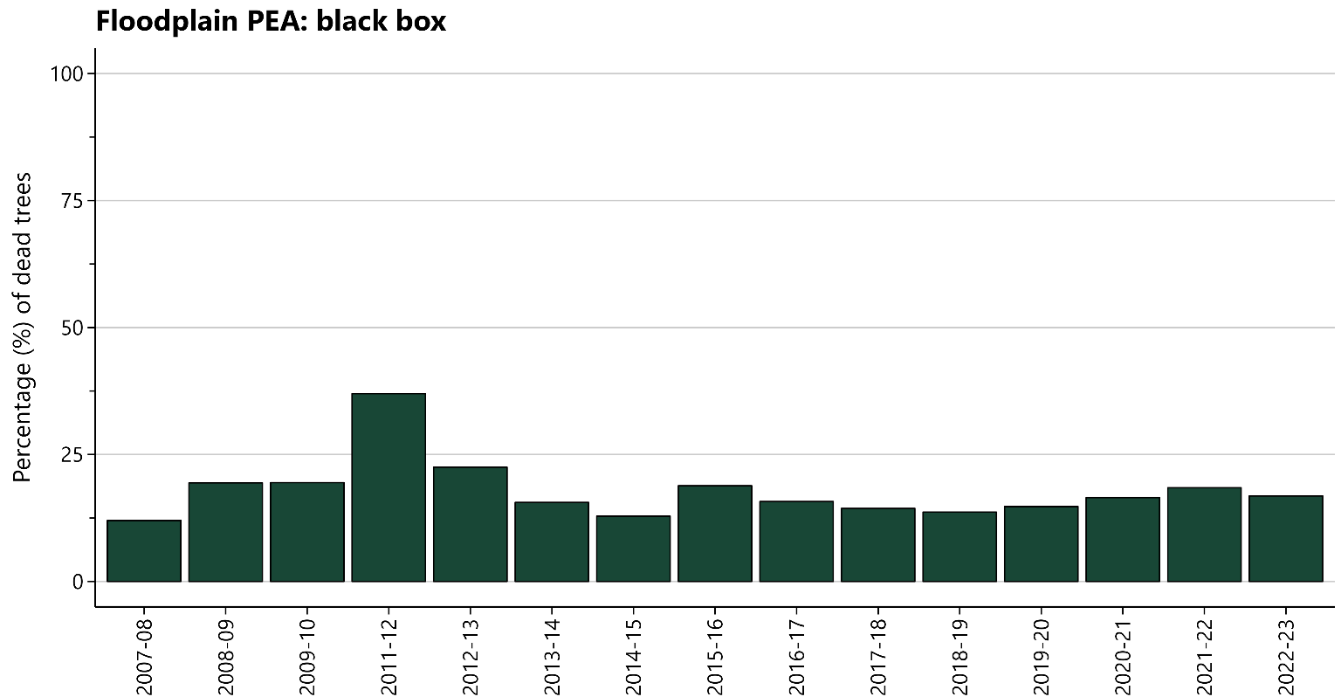


Figure 8-4. The percentage of sampled black box with a TCI of 0 (dead) in the Channel and Floodplain PEA.

8.7.5 Information reliability

The information reliability rating for black box was **poor** (final score of 8). Justification for the scoring of black box information reliability is provided in Table 8–6. The data utilised in this report were assessed and underwent quality assurance and control (QA/QC) processes.

Table 8–6. Reliability of data to assess outcomes of floodplain trees. The methods used in data collection including repetition and sample independence, as well as the representativeness of data were scored based upon the answers provided to questions related to each facet of data collection. Answers to questions regarding the methods, representativeness and repetition of data were scored 2 points – Yes, 1 point – Partially, 0 points – No.

Methods	Question	Answer and justification	Score
Methods used	Are the methods used appropriate to gather the information required for evaluation?	**Yes.** The LTWP target and expected outcomes were established upon data collected using the TCI method.	**2**
Standard methods	Has the same method been used over the sampling program?	**Yes.** Tree condition data were collected using the standardised 'The Living Murray' tree condition method (Souter et al. 2010).	**2**
Repetition			
Space	Has sampling been conducted at the same sites over the assessment period?	**Partially**. There are differences in the inaugural year of monitoring between trees sampled on the Pike, Katarapko and Chowilla floodplains. Furthermore, additional transects were allocated to monitoring programs as they progressed. The majority of transects were re-visited annually following their establishment.	**1**

Methods	Question	Answer and justification	Score
Time	Has the frequency of sampling been sufficient to represent change over the assessment period?	**Yes.** Tree condition data were recorded annually since Basin Plan adoption and baseline data exists.	**2**
Representativeness			
Space	Has sampling been conducted across the spatial extent of the SA River Murray with equal effort?	**No.** Only data from Chowilla, Pike and Katarapko floodplains were analysed. The protocol for establishing transects at other managed wetlands excluded dead (defoliated) trees from inclusion within transects. Consequently, these non-standardized transects were not compared to standardised transects which include defoliated trees at the time of transect establishment.	**0**
Time	Has the duration of sampling been sufficient to represent change over the assessment period?	**Yes.** Tree condition data was available for each year following Basin Plan adoption (2012–13 to 2018–19) and for years prior to Basin Plan adoption (2008–09 to 2011–12).	**1**
Final Score			**8**
Information Reliability			**Poor**

8.8 Evaluation

The assessment of trends indicated an increase in the number of black box in good or excellent condition across the Chowilla, Pike, and Katarapko floodplains from 2007–08 to 2022–23 (Figure 8-2). However, it is difficult to interpret these environmental outcomes for the entirety of the Floodplain PEA due to potential confounding factors, such as changes in the sample size and sampling locations, in addition to the proportion of trees influenced by delivery of water for the environment.

Over the assessment period, the percentage of black box with TCI ≥10 was low between 2007–08 and 2009–10 (during the Millennium Drought 1996–2010), with consistent improvement between 2011–12 and 2013–14, however there was also a sustained increase in the number of trees sampled during this period which likely affects the interpretation of this data (Figure 8-2). The percentage of trees with TCI ≥10 reduced substantially in 2014–15, which corresponded with an increase in the number of trees studied across the Pike and Katarapko floodplains. The number of black box with a TCI ≥10 remained below 50% until an increase in 2017–18, which was associated with a substantial increase in the number of trees sampled and followed a high flow event (Figure 8-2).

Improvements in black box condition in selected floodplain locations were largely observed shortly after periods of higher flow, such as the 2010–2012, 2016–17 and 2021–2023 (see Figure 3-3). Improvements in condition were likely influenced by factors including high rainfall and floodplain inundation. The observed improvement in black box condition over the assessment period appears largely attributed to unregulated high flow events, with additional influences from delivery of water for the environment, and seasonal of increased rainfall. Attribution of these specific factors was outside of the scope of this evaluation.

8.8.1 High (unregulated) flow events

High flows are critical for improving the condition of black box, with trees that experience more recent and frequent inundation showing improved condition (Denny et al. 2019b; Gehrig & Frahn 2015; Moxham et al. 2017; Overton et al. 2018; Wallace et al. 2020a). This assessment did not differentiate between trees affected by unregulated floods and those that also received water for the environment. However, significant improvements in the condition of black box across managed areas of Chowilla, Pike, and Katarapko floodplains were observed following unregulated, high flow events, particularly the 2010–11, 2016–17 and 2022–23 high flows (Figure 8-2). These results align with previous findings (Denny et al. 2019b; Doody et al. 2014; Doody et al. 2021; Wallace 2022a; b; c), which documented significant improvement in the condition of floodplain trees on the Chowilla, Pike, and Katarapko floodplains after high, unregulated flows.

8.8.2 Rainfall

Rainfall is a primary water source for floodplain trees, with high rainfall linked to improvements in condition (Jensen 2017). Black box are particularly dependent on rainfall, as they are typically found at higher elevations on the floodplain than river red gum, resulting in longer durations between inundation and longer periods of low soil water availability (Kilsby & Steggles 2015). During 2010–12, 2016–17 and 2021–23, the Basin experienced higher-than-average rainfall (see Figure 3-1; Figure 3-2), which aligned with associated unregulated high flow events (see Figure 3-3). The specific effects of black box condition could not be conclusively assessed due to overlapping factors such as variations in sampling effort and frequency, along with high unregulated water flows. Other research has observed improvements in floodplain tree conditions after significant rainfall events (Doody et al. 2014).

8.8.3 Delivery of water for the environment

Managed floodplain inundation (i.e. operation of the Chowilla, Pike and Katarapko environmental regulators), pumping, and weir pool raising have delivered water to black box within managed areas of the floodplain, enhancing condition during dry periods. These actions, while limited in scale compared to unregulated high flows or floods, are critical to improve and maintain tree condition (Wallace et al. 2020a).

8.8.4 Average return intervals (ARI)

Regulation in the SA River Murray has impacted river-floodplain connectivity and reduced the frequency of inundation. Tree condition data assessed in this report are restricted to the Chowilla, Pike and Katarapko floodplains, and hence limits the ability to infer tree condition across the whole Floodplain PEA. Analysis of average return intervals (ARI) against system-scale EWRs (DEW 2020) can provide some indication of water stress and condition outside the managed floodplain areas.

The water regime preference to support black box is a minimum inundation duration of 1–6 months, occurring on an ARI of 3–7 years, with a maximum interval of 8 years (DEW 2020). This seeks to prevent decline in black box condition in the SA River Murray. Table 8–7 shows the ARI for flows at or above a specific discharge for a given duration observed in South Australia (i.e, QSA) since July 2000. These estimates suggest black box located in floodplain areas up to 70,000 ML day^{-1} remain inundated for a duration of 1 month, at an average frequency of every 7.7 years, close to the maximum allowable interval of 8 years.

Table 8–7. The average return interval (ARI; in years) for various flow bands and durations of Flows to South Australia (QSA) observed between September and March each year (2000-2023). N/A implies a flow band for that duration has not occurred during spring-summer months since 2000.

PEA	Flow bands (ML day^{-1})	30 days	60 days	90 days	120 days	150 days
Channel	10,000	2.1	2.9	2.9	3.3	4.6
	15,000	2.9	3.3	4.6	4.6	7.7
	20,000	3.3	4.6	4.6	5.8	7.7
	25,000	3.3	5.8	5.8	7.7	7.7
	30,000	4.6	7.7	7.7	11.5	11.5
	35,000	5.8	7.7	11.5	11.5	23
	40,000	5.8	7.7	11.5	11.5	23

PEA	Flow bands (ML day^{-1})	30 days	60 days	90 days	120 days	150 days
Floodplain	50,000	7.7	11.5	11.5	11.5	N/A
	60,000	7.7	11.5	23	23	N/A
	70,000	7.7	11.5	23	N/A	N/A
	80,000	23	23	23	N/A	N/A

8.8.5 Unanticipated Outcomes

No unanticipated outcomes were highlighted through this assessment.

8.8.6 Action to achieve environmental outcomes

Water for the environment is an important management tool to improve the condition and resilience of floodplain trees (Wallace et al. 2020a). The conceptual model of stress recovery for floodplain eucalypts (see Wallace et al. 2020b) describes how floodplain tree condition transitions due to the duration and frequency of dry phases and inundation or watering events. This model describes the value of the delivery of water for the environment during dry phases between floods to reduce trees declining towards very poor condition. Efficient use of water for the environment, in adequate volumes, is expected to support floodplain trees in managed areas to better recover from a decline in condition when dry periods occur and river-floodplain connectivity is reduced (Wallace et al. 2020b).

Further optimisation of the delivery of water for the environment along with addressing current water delivery constraints could support improved tree condition. Floodplain environmental regulators have not yet been operated to full inundation and therefore the delivery of water for the environment may increase at these sites in the future. Further weir pool raising, with additional measures such as groundwater management, would also further increase tree condition and resilience. Long-term efforts will need to focus on adaptive management strategies to respond to changing environmental conditions, particularly an increased frequency and duration of drought resulting from the impacts of climate change.

None of the environmental watering regulators at Chowilla, Pike and Katarapko floodplains have yet been operated to full extent of possible inundation and therefore, the influence of delivery of environmental water may increase in these locations and diverge further from the condition of trees in the unmanaged floodplain. Hence, the addition of monitoring programs in other locations of the PEA is a high priority.

8.9 Conclusion

Outcomes for black box have improved since adoption of the Basin Plan. Though it is difficult to separate climate drivers and management actions, there are some indications that water for the environment delivered under the Basin Plan has contributed to these outcomes, particularly at managed floodplain areas. Since the 2019 assessment, the number of black box with a TCI ≥10 has increased, with some minor reductions in interim years. Enhanced management of water for the environment to South Australia is expected to further improve outcomes for black box across the Floodplain PEA in future years.

9 Case study: Understorey vegetation responses to managed floodplain inundations

9.1 Introduction

Floodplains and wetlands in the MDB support a high diversity of plant species, including communities of understorey vegetation. These habitats range over an elevation gradient, extending from the river littoral zone to the floodplain margins. Contained within the elevation gradient is one type of habitat, shedding-floodplains, where a drop in river levels correspond to a reduction in inundation extent (Kilsby & Steggles 2015). As the extent and composition of understorey vegetation varies with changes in water regime (e.g. water level) (Walker et al. 1994), monitoring the condition of understorey vegetation provides insight into the condition of floodplain assets.

Longitudinal (upstream and downstream) connectivity in riverine ecosystems provide important ecological functions, such as facilitating the migration and dispersal of fish (Bice et al. 2021; Zampatti et al. 2015). However, the lateral (outwards to floodplain margin) connectivity of rivers is also vital for such ecosystems, connecting the river channel to surrounding floodplains. River regulation in the South Australian River Murray (SA River Murray) has altered the variability in flooding magnitude, duration and frequency (Maheshwari et al. 1995b; Walker & Thoms 1993; Ye et al. 2023), and changed former lotic environments to pool habitats (Walker et al. 1992). This has resulted in a permanent change to the prevailing water regime, often defined as the frequency, duration, depth, timing and variability of flooding waters (Blanch & Walker 1998; Blanch et al. 1999; Nicol & Ganf 2017; Nicol et al. 2003). Overbank flows (>45,000 ML day^{-1}) can be extended in magnitude and duration through delivery of water for the environment, supporting an integral part of natural flow regime in floodplain rivers (Ye et al. 2024).

9.1.1 Understorey vegetation functional types

A diverse community of understorey vegetation is important for floodplains and wetlands in the SA River Murray as it provides important ecosystem functions. These include primary production and nutrient cycling (Zhang et al. 2022), carbon sequestration (Whitaker et al. 2015), protecting floodplain soils from erosion, and provision of habitat and food resources for waterbirds, terrestrial birds, amphibians, reptiles and insects. The establishment and persistence of riverine plant species is largely influenced by recent and historical water regimes (Blanch et al. 1999; Nicol & Ganf 2017), often expressed in semi-arid floodplains through wetting and drying phases (Mason et al. 2022).

Understorey species in the SA River Murray are adapted to regular disturbance through variable flow regimes (Nicol et al. 2023). As species differ in their tolerance to changes in water regimes, taxa have been grouped into functional types (Brock & Casanova 1997; Casanova 2011). A simplified classification is used for monitoring and reporting understorey vegetation condition for the SA River Murray (Bice et al. 2014; Nicol et al. 2010). This classification includes:

- Amphibious species, which tolerate or respond to fluctuating water levels, including wetting and drying phases as adult and juvenile plants;
- The flood-dependent group, intolerant of extended inundation and will germinate on soils during flood recession, but not germinate in response to rainfall; and
- Terrestrial species, which mostly tolerate low soil moisture for extended periods, but still require high soil moisture at times throughout their lifecycle.

The prevalence of these three functional types on floodplains reflects the recent and historical water regime. In the absence of floodplain inundation, terrestrial species typically dominate, with a reduction in amphibious and flood-dependent species. Amphibious and flood-dependent species can persist in situ during dry phases as a seed bank or other underground organs such as tubers, or their propagules can be reintroduced to a site via floodwaters. The long-term water regime can influence how well plants regenerate in response to inundation (Nielsen & Brock 2009). A floodplain in good condition will respond with a diverse assemblage of understorey plants in both dry and wet phases.

9.2 Understorey vegetation monitoring

9.2.1 Data sources

The aim of this case study was to evaluate functional plant group data collected through monitoring programs in the three managed SA River Murray floodplains (Chowilla, Pike and Katarapko). This data has been collected on Chowilla floodplain as part of TLM program since 2006, while data from Pike (since 2017) and Katarapko (since 2015) has been collected as part of DEW's ongoing responsibilities for effective use and management of water for the environment in South Australia.

To support the ecological restoration of the floodplain environments at Chowilla, Pike and Katarapko, water for the environment is delivered across parts of these floodplains via infrastructure operations. These operations involve operation of environmental regulators to increase the water level upstream and through the anabranch, inducing overbank flows and supporting lateral connectivity with the floodplain. In conjunction with the operation of the floodplain environmental regulators on Chowilla, Pike and Katarapko floodplains, the River Murray weirs at Lock 6, Lock 5 and Lock 4 are concurrently raised above normal operating levels to facilitate suitable anabranch flows. Water can also be pumped to discrete wetlands and their immediate floodplains. As such, it should be stressed that understorey vegetation data collected from these managed floodplain environments are not representative of conditions across the broader channel and floodplain assets for the SA River Murray where such management intervention cannot occur.

9.2.1 Ecological objectives and targets

The individual monitoring programs report against ecological objectives and targets. Ecological objectives are statements that specify what management actions (including the delivery of environmental water) are intended to achieve (Kilsby & Steggles 2015). Ecological targets provide a quantitative means to evaluate progress towards achieving the objectives, and monitoring outcomes are also critical to inform adaptive management of water for the environment (DEWNR 2017a; b). For this purpose, annual floodplain survey reports are produced evaluating changes in understorey condition relative to the targets. Ecological targets for understorey vegetation are purposeful interval targets, which require the presence and quasi-abundance (i.e. distribution) of species belonging to particular functional groups over interannual periods (see section 9.1.1). The ecological targets for shedding-floodplain sites in the three managed floodplains are provided in Appendix A.

9.2.2 Shedding-floodplain monitoring

To monitor the condition of understorey vegetation, data were collected across numerous shedding-floodplain sites in Chowilla, Pike and Katarapko generally between mid-February to the end of March. Methodologies for collecting these data are described in the annual floodplain reports (DEW 2023a; b; Nicol et al. 2023), but were largely consistent across the three managed floodplains. At each site, three 15 x 1 m quadrants, divided into 1 x 1 m cells, were arranged in straight lines parallel to the elevation contours and separated from each other by a 50 m gap (Figure 9-1). The presence-absence of live plants that were rooted in each cell were recorded and identified to the lowest taxonomic resolution possible. Cells that were not inundated and contained no live plants were recorded as bare soil, and inundated cells that contained no live rooted plants were recorded as open water.

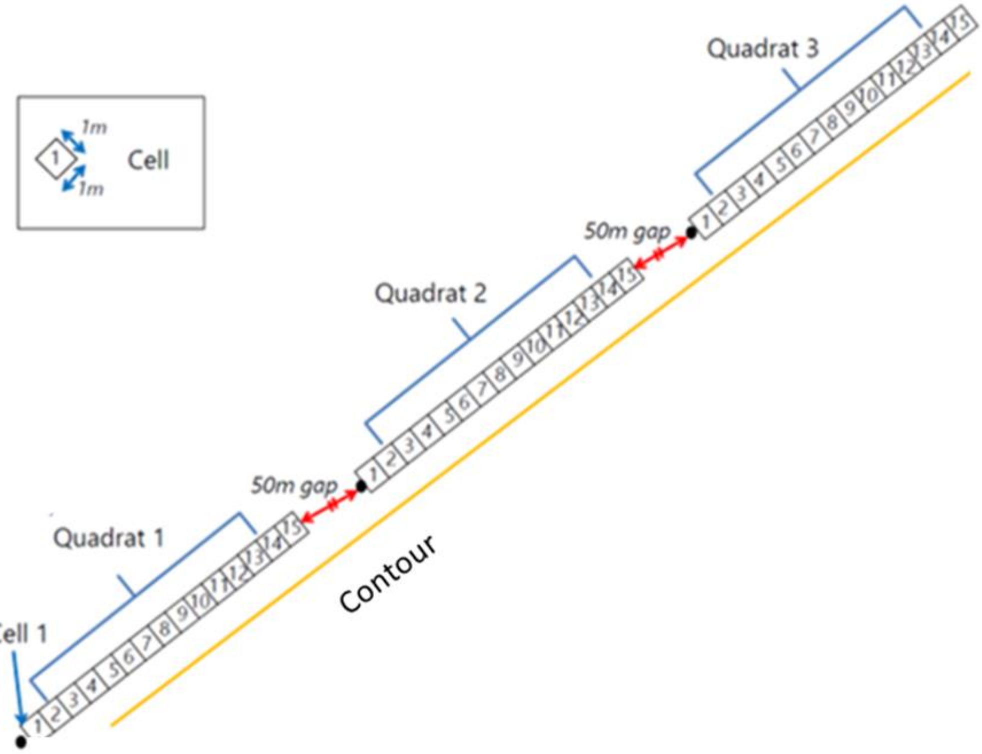


Figure 9-1. Schematic showing layout of the understorey vegetation monitoring in shedding-floodplain sites.

The two metrics used to monitor condition of understorey vegetation in shedding-floodplain sites were:

1. Distribution (quasi-abundance), defined as the percentage of sampled cells containing flood-dependent and/or amphibious taxa.
2. Species richness, which was the number of flood-dependent and/or amphibious species present in sampled quadrant cells.

9.3 Riverine conditions

Flows to South Australia (QSA) have been highly variable over the last 18 years (Figure 9-2). The Millennium Drought occurred from 1996–2010 and included a period of prolonged low flow from 2001–02 to 2009–10 (average 1,717 GL year^{-1}). Widespread flooding occurred across the MDB in 2010–11, with QSA peaking at ~93,508 ML day^{-1} and an annual QSA totalling 15,137 GL. High flows continued in 2011–12 and 2012–13 with annual QSA 10,248 GL and 6,970 GL, respectively. More moderate flows (3,570 GL) were recorded over 2013–14, before low flow conditions occurred over 2014–15 and 2015–16 (average 2,685 GL). In 2016–17, high flows were recorded with QSA peaking at ~94,381 ML day^{-1}. As there was a rapid recession in this high flow event, the annual volume (9,238 GL) was lower than 2010–11. Extreme dry conditions in the MDB between 2017–18 and 2019–20 (see section 3) greatly reduced QSA (average 2,508 GL year^{-1}) over this period. Three consecutive years of above-average rainfall occurred in the MDB resulted in increased QSA between 2020–21 and 2022–23. Moderate flows were recorded in 2020–21 (3,078 GL year^{-1}), which were followed by high flows in 2021–22 (9,097 GL year^{-1}) and the third largest recorded flooding event in the SA River Murray in 2022–23 (23,000 GL year^{-1}). The highest flow peaks in these two water years were 42,976 ML day^{-1} (30/06/2022) and 185,746 ML day^{-1} (22/12/2022).

9.4 Response of flood-dependent and/or amphibious taxa

Annual monitoring data from the three managed Riverland region floodplains (Chowilla, Pike, and Katarapko) indicate that the percentage of cells containing flood-dependent and/or amphibious taxa was highest in 2011 (Chowilla), 2017 and 2023 (Figure 9-2 a). In 2011, two interval targets were exceeded for Chowilla following elevated riverine flows (Figure 9-2). The 2017 data suggest that all interval targets were exceeded in Chowilla following a floodplain operation in the preceding spring (inundating 7,650 ha) that was taken over by a large natural flood event (Figure 9-2), whilst Pike and Katarapko exceeded two and three interval targets, respectively, due to the natural flood event during which QSA peaked at over 94,000 ML day^{-1}. In 2023, all three floodplains exceeded the 1 in 7 years target (65%; Figure 9-2 a). This followed operation of the environmental regulators at Chowilla and Pike in winter to early spring 2022 and the subsequent extended period of elevated riverine flows associated with the 2022–23 River Murray flood (Figure 9-2).

Monitoring data from Chowilla in 2007 (22%) and 2010 (21%) indicate an influence of some site-specific pumping operations (see section 9.5), despite an extended period of low riverine flows (Figure 9-2). In the year following the initial operation of the Chowilla Creek regulator (inundating 2,300 ha), understorey vegetation distribution achieved greater percentage of cells than the 1 in 3 years target (20%) in conjunction with low riverine flows (Figure 9-2). The 1 in 3 years target was achieved in Chowilla floodplain sites in 2018, which may indicate the effect of retained soil moisture on understorey vegetation following the 2017 flood, while a similar response in 2019 might be related to the 2018 floodplain operation and wetland pumping that resulted in inundation over 2,250 ha. Floodplain operations in 2021 and 2022, combined with high local rainfall and increased QSA (Figure 9-2) and particularly the 2022–23 River Murray flood which inundated almost the entire floodplain, contributed to vegetation responses in 2022 and 2023 for all three floodplains. Generally, maximum return interval targets are met (see section 9.2) for functional distribution in all three of the managed floodplains (Appendix B; Appendix C).

The number of flood-dependent and/or amphibious taxa in shedding-floodplain sites for each floodplain (Figure 9-2 b) has generally trended similar to patterns in distribution (Figure 9-2 a). For example, species richness in Chowilla exceeded the target (≥15 species) in: 2007 and 2010, following pumped delivery of water for the environment to discrete sites in 2006 and 2009, respectively (see section 9.5); 2015 following the initial operation of the Chowilla Creek regulator the previous year (inundating 2,300 ha); and in 2019 following the 2018 regulator event (inundating 2,250 ha) (Figure 9-2 b). For the Pike floodplain, species richness was close to the 1 in 3 years target (>15 species) in 2017 (14 species) and 2022 (15 species). This was achieved in 2023 following contributions of riverine flows and three consecutive floodplain operations in 2020 (1,528 ha), 2021 (2,023 ha) and 2022 (2,899 ha) and the subsequent major natural flood of 2022. Katarapko floodplain has seen a diverse set of species present in almost all years that monitoring has occurred, with the lowest species richness occurring in 2020 (21 species), which still exceeded the 1 in 3 years target (>15 species). Two consecutive years of floodplain operations in 2020 (800 ha), 2021 (1,116 ha) and targeted additional watering of one wetland site in 2022 through operation of an ancillary regulator (2 to 33 ha) contributed to the response in 2022 (39 species) and 2023 (46 species) with substantial species richness near the 1 in 7 years target (>40 species), noting the 2023 result followed the major natural flood of 2022.

There is a correlation between the percentage of floodplain cells with flood-dependent and/or amphibious taxa and the number of species in shedding-floodplain sites across Chowilla, Pike, and Katarapko (Figure 9-3).

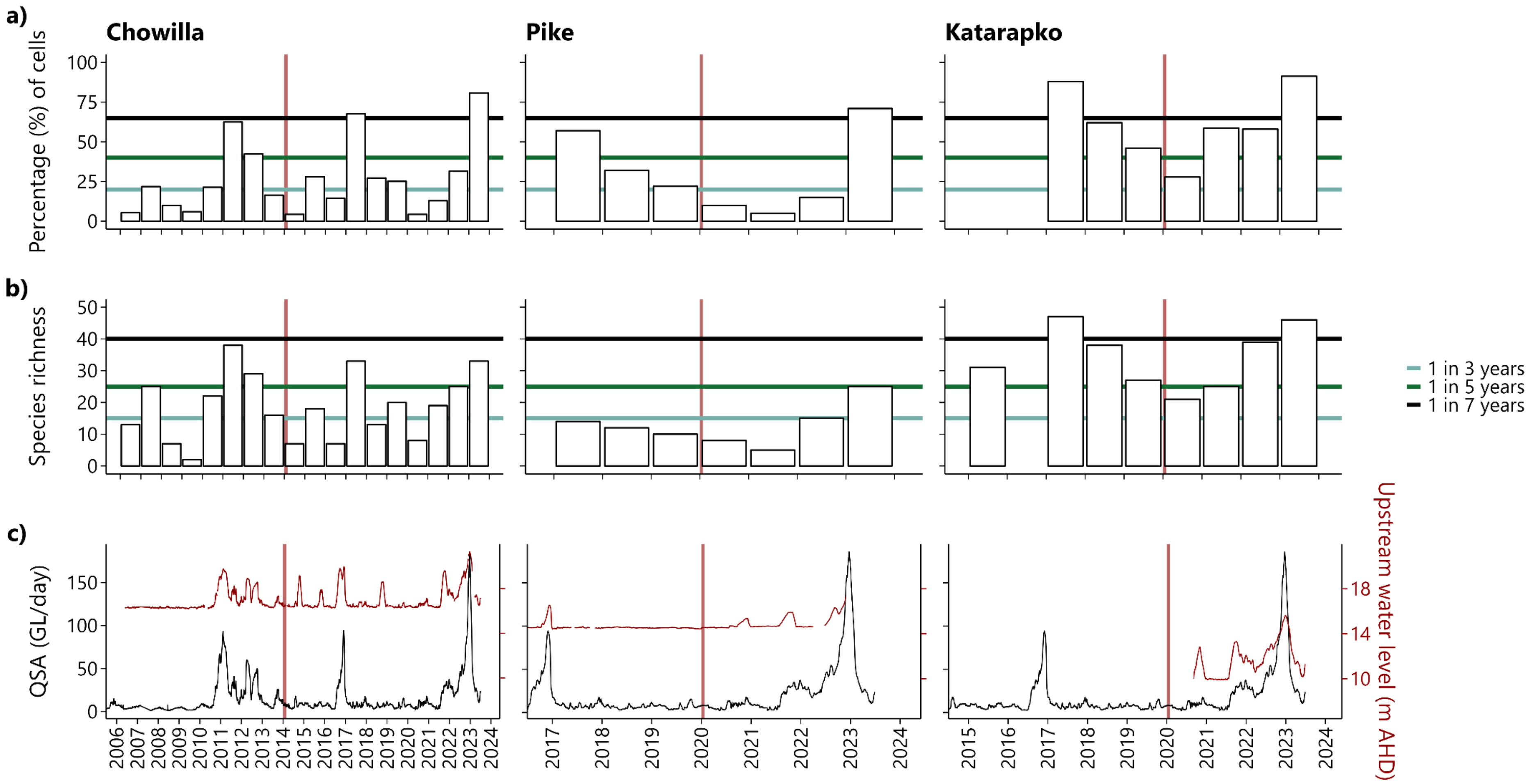


Figure 9-2. **a) the percentage of cells containing flood-dependent or amphibious taxa in sites; b) the number of species of flood-dependent or amphibious taxa in sites; and c) the Flows to South Australia (QSA; black line; GL day^{-1}) and the water level (m AHD) upstream of each environmental regulator in Chowilla (A4261091), Pike (A4261053) and Katarapko (A4261790). Note: understorey vegetation monitoring generally occurs between mid-February and the end of March each year; observed percentage of cells can either equal or exceed the floodplain targets.**

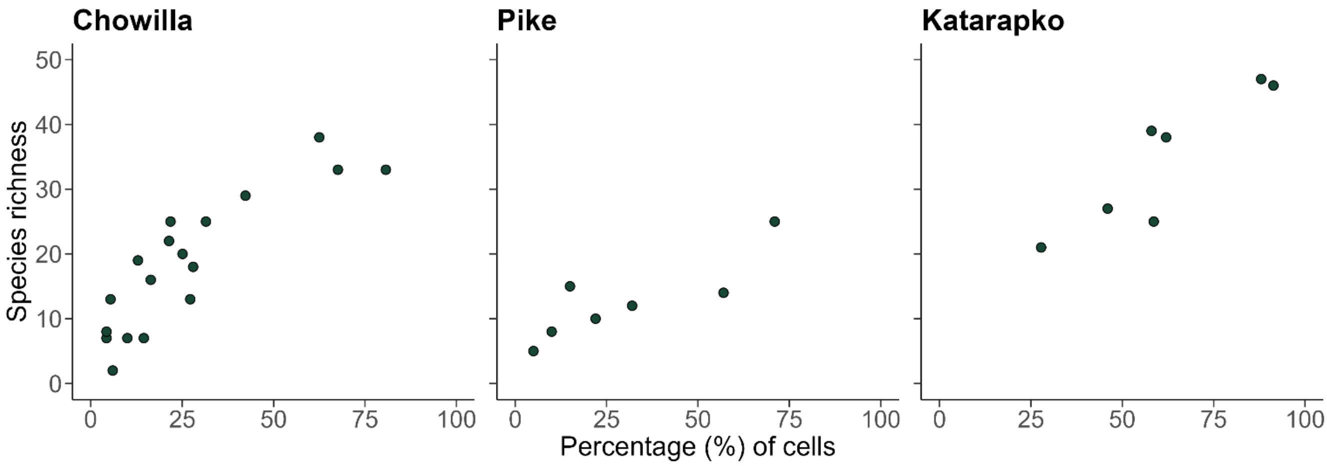


Figure 9-3. Scatterplot of the percentage of sampled site cells with flood-dependent and/or amphibious taxa (distribution), and the number of those taxa (species richness), observed in shedding-floodplains.

9.5 Environmental regulator operations and pumping management interventions

The operation of the environmental regulator at Chowilla has occurred on six occasions since construction was completed in 2014. Since 2020, the Pike environmental regulator has been operated on 3 occasions and at Katarapko on 2 occasions. The record of these operations in each of the three managed floodplains is provided in Appendix D.

Water for the environment has been delivered to 29 different wetland sites at Chowilla via pumping since 2004. This included large sites such as the Coppermine Complex and Gum Flat wetlands pumped in 2006 and 2009, after extended periods without water (Mokany et al. 2024). The pumped delivery of water for the environment to wetlands at Chowilla has contributed to supporting understorey vegetation, and remains an important option for site management in drier years either through discrete delivery or in conjunction with lower-level regulator operations. Pumped delivery has also been undertaken to a lesser extent at Pike and Katarapko and continues to be an option for watering under some conditions.

9.6 Evaluation

Monitoring on the Chowilla, Pike and Katarapko managed floodplains indicated that the response of flood-dependent and/or amphibious understorey vegetation appears correlated with extent of inundation (either natural or through delivery of water for the environment). Generally, a larger proportion of the floodplain is inundated following larger peaks in flow and therefore the percentage of cells that support flood-dependent and/or amphibious vegetation likely increases following these periods. The largest peaks in QSA (i.e. 2010–11, 2016–17, and 2022–23) often resulted in meeting or exceeding the floodplain targets with the greatest return interval requirement (e.g. 1 in 7 years) for both the distribution and species richness of understorey plant assemblages. Achievement of shorter return interval targets has occurred in all three managed floodplains in between natural flood events in the SA River Murray, with some having occurred after delivery of water for the environment over the previous spring-summer period. The relationship between the richness of flood-dependent and/or amphibious species and their distribution suggests that when floodplain inundation occurs, the plant communities are not dominated by a few, opportunistic species, rather a more diverse composition of species (Figure 9-3).

9.6.1 Water regime

Water regime (frequency, duration, depth, timing and variability) is one of the most important drivers in the structure of understorey floodplain vegetation communities (Blanch et al. 1999; Nicol & Ganf 2017), and overbank flows (>45,000 ML day^{-1}) are an integral part of the natural water regime for maintaining ecological integrity in floodplain rivers (Ye et al. 2024). Observations from the three managed Riverland floodplains demonstrate that suitable riverine flows leading to overbank inundation events are expected to increase the extent and diversity of flood dependent and amphibious understorey vegetation along the elevation gradient. Floristic composition is expected to shift back toward one dominated by terrestrial species, in dry periods (Nicol & Frahn 2019; Nicol et al. 2023), an important (and natural) aspect of extant vegetation in semi-arid floodplains (Mason et al. 2022). This implies that floodplains (and temporary wetlands) undergo constant state transitions, generated by the antecedent flow conditions.

Analysis of monitoring data demonstrates that both large natural floods and delivery of water for the environment, either immediately preceding natural flooding, or in intervening drier years, can contribute to substantial responses in flood-dependent and/or amphibious understorey vegetation.

Floodplain environmental regulators at Chowilla, Pike and Katarapko floodplains are yet to be operated to the full extent to achieve maximum possible inundation. It is expected that with future and larger environmental watering events when circumstances permit, will result in an increase in the presence and diversity of amphibious and floodplain species in the area of influence from the watering actions across the three managed floodplains. Even with a maximum extent achieved with operation of the floodplain regulators, the inundation extent across the three managed floodplains cannot match that achieved under the natural flooding events in 2010–11, 2016–17 and 2022–23. However, delivery of water for the environment helps to maintain the diversity of seed banks within managed floodplain soils, by contributing to the responses in flood-dependent and/or amphibious vegetation both during, and in intervening years of natural overbank flooding.

Frequency of inundation for the Channel and Floodplain PEAs

River regulation and water extraction in the SA River Murray has reduced the frequency, extent and duration of naturally occurring floodplain inundations (Maheshwari et al. 1995a; Walker & Thoms 1993; Ye et al. 2023). As such, delivery of water for the environment is used to reinstate some elements of a more natural water regime, and support ecological processes, including understorey vegetation, within the managed SA River Murray floodplains Chowilla, Pike and Katarapko. However, South Australia's River Murray Channel and Floodplain PEAs cover areas which are outside the influence of these management actions, and thus the condition of understorey vegetation represented by the data presented here from the three managed floodplains cannot be used to reflect the conditions across the whole Channel and Floodplain PEAs.

Recurrence intervals provide summary information on the frequency of a flow event of a particular magnitude (Table 9–1). The EWRs set for the River Murray WRP Area describe the frequency and duration for certain magnitudes of QSA flows, and how they link to ecological outcomes (DEW 2020; Kilsby & Steggles 2015; Wallace et al. 2014). For example, the recommended duration for floodplain inundation of lignum (*Duma florulenta*; an amphibious species) is between 30 and 210 days, with a frequency between 1 and 7 years (maximum interval 7–10 years) (Kilsby & Steggles 2015). However, the return intervals of various flow bands (QSA) observed since July 2000 (Table 9–1) suggests that only habitats in the Channel PEA are inundated for the minimum duration (30 days) within the prescribed frequency for this water-dependent species (1–7 years). Comparatively, the average return interval for higher flow bands suggests that habitats in the Floodplain PEA are only inundated for the minimum duration (30 days) over the timeframe in the prescribed maximum interval (7–10 years), on average. Therefore, there might be many habitats outside of the managed floodplains of Chowilla, Pike and Katarapko that are not supported by sufficient river flow to support water-dependent understorey vegetation within the Floodplain PEA.

Table 9–1. The average return interval (ARI; in years) for various flow bands and durations of Flows to South Australia (QSA) observed between September and March each year (2000-2023). N/A implies a flow band for that duration has not occurred during spring-summer months since 2000.

PEA	QSA bands (ML day^{-1})	30 days	60 days	90 days	120 days	150 days	210 days
Channel	10,000	2.1	2.9	2.9	3.3	4.6	7.7
	15,000	2.9	3.3	4.6	4.6	7.7	11.5
	20,000	3.3	4.6	4.6	5.8	7.7	23
	25,000	3.3	5.8	5.8	7.7	7.7	N/A
	30,000	4.6	7.7	7.7	11.5	11.5	N/A
	35,000	5.8	7.7	11.5	11.5	23	N/A
	40,000	5.8	7.7	11.5	11.5	23	N/A
Floodplain	50,000	7.7	11.5	11.5	11.5	N/A	N/A
	60,000	7.7	11.5	23	23	N/A	N/A
	70,000	7.7	11.5	23	N/A	N/A	N/A
	80,000	23	23	23	N/A	N/A	N/A

9.6.1 Other factors

There are a range of other factors that affect the ability of diverse understorey vegetation to persist in good condition. These include grazing pressure, condition of overstorey species (e.g. river red gum; see section 7), groundwater, soil condition and fire regime.

9.7 Conclusion

This case study highlights the importance of floodplain inundation events (natural flooding and managed inundation) to amphibious and flood-dependent understorey plant species. The large-scale inundation in the SA River Murray from the 2022-23 River Murray flood event likely had the greatest influence on the structure of floodplain vegetation in the latest results (data from 2023), resulting in increased prevalence of water-dependent species. However, the effects of delivery of water for the environment at the three managed floodplain sites were also evident and contributed to outcomes for understorey vegetation in the years preceding the 2022–23 River Murray flood event.

The smaller-scale managed floodplain watering events, contributed through the delivery of water, have helped to maintain soil seed banks and extant vegetation at locations between periods of larger and natural inundation events, supporting the long-term viability of understorey vegetation in those locations where water for the environment can be delivered. Re-colonisation of floodplains following extended dry periods and genetic diversity of plant populations throughout the assets will continue to rely on connected river flow of sufficient magnitudes to generate significant overbank inundation.

10 Murray cod

Trend
Improved

Reliability
Good

Key findings and messages:

- Since the adoption of the Basin Plan, Murray cod recruitment has improved, with all age classes (recent recruits, sub-adults and adults) detected annually since 2012.
- The presence of all age classes of Murray cod every year since the adoption of the Basin Plan indicates that Murray cod recruitment is on track toward the expected outcome in 2029.
- Targeted delivery of flow pulses over spring-summer, augmented by water for the environment, have likely contributed to improvements in Murray cod populations.
- Improvements to connectivity, increased extent of good flowing habitats under normal operation conditions, along with delivery of water for the environment have contributed to improvements in Murray cod populations.
- Good recruitment of Murray cod was detected in 2023, with the highest body condition of fish in all sampling years and high growth rates of adult and young-of-year detected, likely due to increased resource availability in response to the flood event.
- Continued targeted delivery of water for the environment along with other management actions (e.g. weir pool management, physical habitat restoration) will support continued improvement of Murray cod populations in the SA River Murray.

10.1 Introduction

Murray cod (*Maccullochella peelii*) is the largest (commonly >1,200 mm) freshwater fish in the Murray–Darling Basin (MDB) where it is an apex predator inhabiting river channels in low to mid-altitude reaches (Lintermans 2023) (Anderson et al. 1992; Koehn et al. 2020a; Lintermans 2009; Zampatti et al. 2014). It is an iconic species, having high cultural, ecological and recreational value (Ebner et al. 2016), and once supported a substantial commercial fishing industry (National Murray Cod Recovery Team 2010). In the South Australian reaches of the South Australian River Murray (SA River Murray), populations of Murray cod are classified as depleted, with abundances substantially lower than historical levels prior to the 1960s (FRDC 2020). Key threats across the range of Murray cod include habitat loss and degradation, changes to natural flow regimes, reduced connectivity (i.e. instream barriers to movement), coldwater pollution and overharvest, and associated declines have resulted in the species listing as Vulnerable under the *Environment Protection and Biodiversity Conservation Act 1999*.

Murray cod is a river channel specialist and prefers lotic (flowing, velocity >0.3 m s^{-1}) reaches of the river channel and anabranches (Koehn & Nicol 2014), even during flood when ephemeral habitats are available (Leigh & Zampatti 2013). Within these lotic environments, the species is associated with structural habitat (e.g. woody debris, cliff) and deep, slower flowing water closer to the river bank (Koehn & Nicol 2014). Murray cod are sensitive to low water temperatures (Ryan et al. 2003; Todd et al. 2005) and low dissolved oxygen (King et al. 2012; Leigh & Zampatti 2013). Cold water pollution (e.g. release of water deep below the surface of dams that disrupts downstream water temperatures) and hypoxic (dissolved oxygen <2 mg L^{-1}) can limit recruitment success (Ye et al. 2018), and hypoxic blackwater events can cause mass adult mortality (Leigh & Zampatti 2013).

The life history of Murray cod is characterised by longevity (up to 48 years), slow sexual maturity (four to six years) and growth rates, and high fecundity (3,300 eggs per kilo of body weight) (Anderson et al. 1992; Koehn et al. 2020b). In South Australia, Murray cod appear to be generally sedentary with limited movement (<10 km) in the vicinity of a home location (Fredberg et al. 2019; Leigh & Zampatti 2013). In the Chowilla system, regular movements occur among lotic anabranch and adjacent main channel habitats, particularly in late winter-spring. Long-distance upstream movements (>100 km) are irregular and appear associated with natural flooding. Spawning occurs annually between October and December and is cued mostly by temperature increases (Ingram et al. 2022). Murray cod are nest-spawners, meaning they adhere their eggs to hard substrates, such as logs, rocks and clay surfaces (Koehn et al. 2020b). Once eggs hatch, larvae drift downstream (Humphries 2005), and in some regions of the MDB, their survival appears to be directly associated with prey abundance and influenced by flow and riverine productivity (Tonkin et al. 2017). In the SA River Murray, Murray cod spawn annually, but recruitment is variable (Zampatti et al. 2014).

River regulation, water abstraction and the removal of woody-debris have degraded habitat quality for Murray cod. In the SA River Murray, river regulation has transitioned the river from a lotic to lentic (still or very slow flowing) environment (Bice et al. 2017), and woody debris has been removed for navigation and water conveyance (Nicol et al. 2002). Lotic habitats with structural complexity provide favourable juvenile and adult habitat, and support key life processes, including spawning and recruitment (Ye et al. 2023). It is hypothesised that lotic reaches of river, even at mesohabitat scales (1–10 km), are beneficial to Murray cod recruitment by facilitating the drift of larvae to slack waters (area of still water that is unaffected by river flow) (Koehn et al. 2020a) where food resources are likely to concentrate. The importance of lotic river reaches with hydraulic complexity is highlighted by the regular recruitment of Murray cod in the lotic Chowilla anabranch during the Millennium Drought (1996–2010), when recruitment in the lentic main channel of the SA River Murray was negligible (Zampatti et al. 2014).

10.2 Ecological objective, target and environmental outcomes

The ecological objective for Murray cod is outlined in the South Australian River Murray Long-term Watering Plan (LTWP) (DEW 2020) and in Table 10–1. The objective is underpinned by three targets relating to population age structure, large recruitment events and overall abundance catch-per-unit-effort (CPUE) (Kilsby & Steggles 2015); however, only the population age structure target has been used as the basis for the assessment of Murray cod environmental outcomes (Table 10–1).

Table 10–1. Description of ecological objectives and targets related to the Murray cod indicator, outlined in the LTWP (DEW 2020).

Ecological objective	Ecological targets
Restore resilient populations of Murray cod.	Population age structure of Murray cod includes recent recruits, sub-adults and adults in **9 of 10 years (90%).**

The expected environmental outcomes for Murray cod population age structure for 2019 (achieved), 2029 and 2042 were determined by elicitation with key experts (Table 10–2). These form the basis of the assessment of Murray cod environmental outcomes in the SA River Murray Channel PEA.

Table 10–2. Expected environmental outcomes for Murray cod population age structure in 2019, 2029, and 2042.

Expected outcome	Year 2019	2029	2042
Age structure			
Population of Murray cod will include recent recruits, sub-adults and adults in:	**5 of 7 (71%)** years since Basin Plan adoption (80% confidence range of 48–86%).	**10 of 17 (59%)** years since Basin Plan adoption (80% confidence range of 45–76%).	**18 of 30 (60%)** years since Basin Plan adoption (80% confidence range of 36–71%).

It was expected that the total percentage of years that the Murray cod population age structure will include all life stages (recent recruits, sub-adults and adults) will decline between 2019 and 2029, but will remain fairly stable between 2029 and 2042 (Figure 10-1). Confidence in expected outcomes remains relatively stable over the three time points.

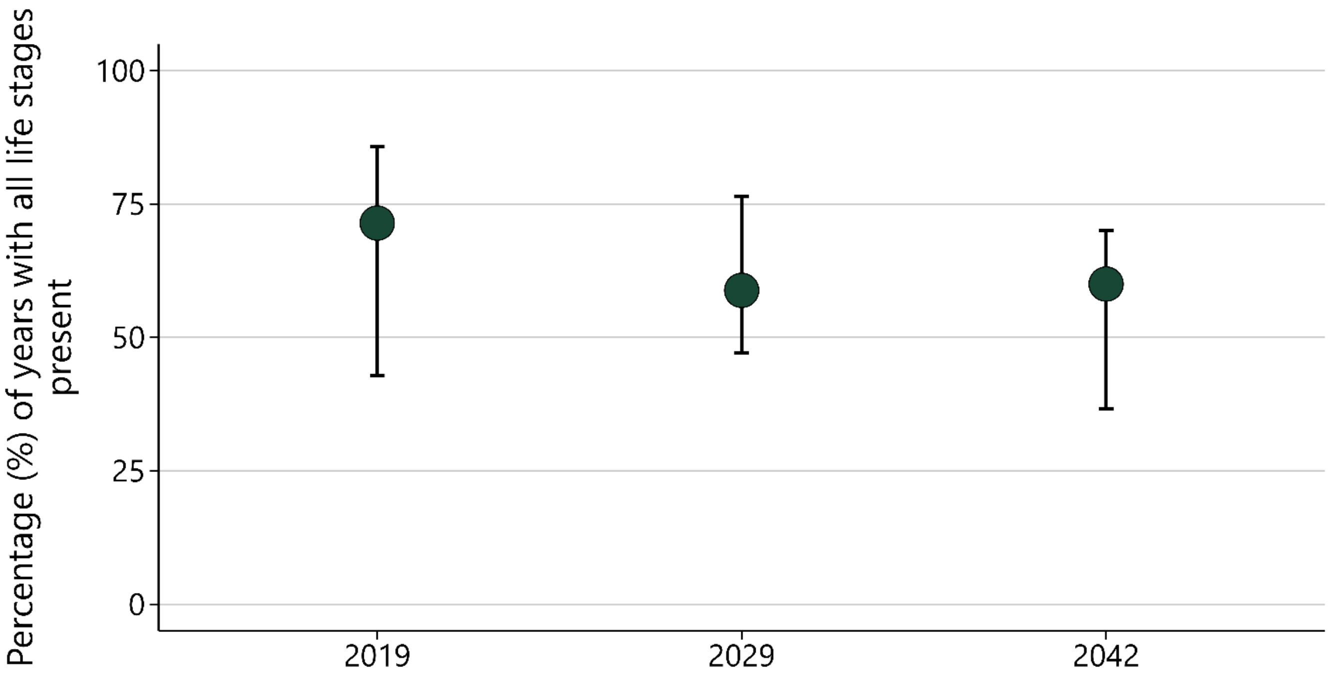


Figure 10-1. The percentage of years since Basin Plan adoption (2012) that are expected to have Murray cod population age structure including recent recruits, sub-adults and adults in 2019, 2029, and 2042.

10.3 Method

10.3.1 Data sources

Assessments of the environmental outcomes for Murray cod used length-frequency data collated from the following sources:

- **Murray Fishway Assessment -** Murray–Darling Basin Authority (MDBA) Murray River Fishway Assessment Program Lock 1-3
- **Native Fish Monitoring** - Department of Primary Industries and Regions South Australia (PIRSA) Fisheries and Aquaculture and South Australian Research and Development Institute (SARDI) Aquatic Sciences Native Fish Monitoring Program
- **The Living Murray (TLM) Chowilla Condition Monitoring** & **TLM Chowilla Targeted Monitoring Program** - The Living Murray (TLM) Chowilla Condition Monitoring Program
- **CEWH LTIM MER Cat 1**- Commonwealth Environment Water Holder (CEWH) Lower River Murray Long Term Intervention Monitoring (LTIM)/Monitoring, Evaluation and Research (MER) Category 1 (mandatory indicators with standard protocols)
- **CEWH LTIM MER Cat 3 Targeted YOY** - CEWH Lower River Murray LTIM/MER Category 3 (targeted young-of-year (YOY) monitoring)
- **CEWH LTIM MER Cat 3 Juvenile Recruitment -** CEWH Lower River Murray MER Category 3 (juvenile recruitment monitoring).
- **Other Programs -**
  - Commonwealth Environmental Water Holder (CEWH) Short Term Intervention Monitoring (STIM) Program
  - SA Riverland Floodplain Integrated Infrastructure Program (SARFIIP) Pike Condition Monitoring Program
  - South Australian Riverland Floodplains Integrated Infrastructure Program (SARFIIP) Katarapko Condition Monitoring Program
  - MDBA Murray–Darling Basin Fish Survey
  - Fisheries Research Development Corporation Murray cod angler surveys.

10.3.2 Data collection

From 2002–03 to 2022–23, a total of 2,024 Murray cod were captured throughout the SA River Murray. Murray cod were captured in the SA River Murray or within 5 km of the SA border in New South Wales. Murray cod were primarily captured in the floodplain geomorphic zone (*n* = 1,422, see section 2.2), and secondarily, across the gorge geomorphic zone (*n* = 602, see section 2.2). Fish were caught in the main channel and associated anabranches of the SA River Murray, using electrofishing, gill nets and drum nets (not used since 2013). The representation of catch through years from the top seven programs is given in Table 10–3.

The methods used to capture Murray cod across the seven monitoring programs that contributed >30 individuals to the collated dataset are described for the Murray Fishway Assessment and Native Fish Monitoring programs in Zampatti et al. (2014), the Chowilla Condition Monitoring and Targeted Monitoring in Fredberg et al. (2023), and CEWH LTIM and MER Category 1 and 3 (targeted YOY and juvenile recruitment) in Ye et al. (2023). The total effort applied across these programs varies from year to year and has an influence on total catch and detectability (presence/absence) of age classes. Total electrofishing effort is shown in Figure 10-2. The Native Fish Monitoring program, not presented in Figure 10-2 due to non-comparable sampling methods, included an additional 587 drum nets and 140 gill nets over 9 years (2004–05 to 2012–13).

Table 10–3. The number of Murray cod caught in each monitoring program. Monitoring programs contributing >30 captures are explicitly mentioned and programs with <30 captures are aggregated in 'Other Programs'. The duration of sampling for each program is shown in green. Fish were sampled in the gorge (G) and floodplain (FP) geomorphic zones. *na* = no sampling undertaken.

Year	Murray Fishway Assessment (G)	Native Fish Monitoring (FP & G)	TLM Chowilla Condition Monitoring (FP)	TLM Chowilla Targeted Monitoring (FP)	CEWH LTIM/MER CAT 1 (G)	CEWH LTIM/MER CAT 3 Targeted YOY (FP & G)	CEWH MER CAT 3 Juvenile Recruitment (FP & G)	Other Programs (FP & G)
Program catch	152	147	254	309	202	278	565	117
2002–03	10							
2003–04	13							
2004–05	9	11	6					
2005–06	*na*	83	10					
2006–07	12	12	10					
2007–08	8	2	11					
2008–09	8	*0*	16					
2009–10	7	4	9					
2010–11	68	28	6					
2011–12	7	4	8					
2012–13	10	3	6					4
2013–14			29	32				12
2014–15			9	*na*	11	20		3
2015–16			12	50	16	28		8
2016–17			3	15	8	*na*		13
2017–18			17	33	14	21		8
2018–19			13	27	18	17		
2019–20			24	36	59	48	103	8
2020–21			32	41	25	64	160	17
2021–22			25	52	38	51	271	25
2022–23			8	23	13	29	31	19

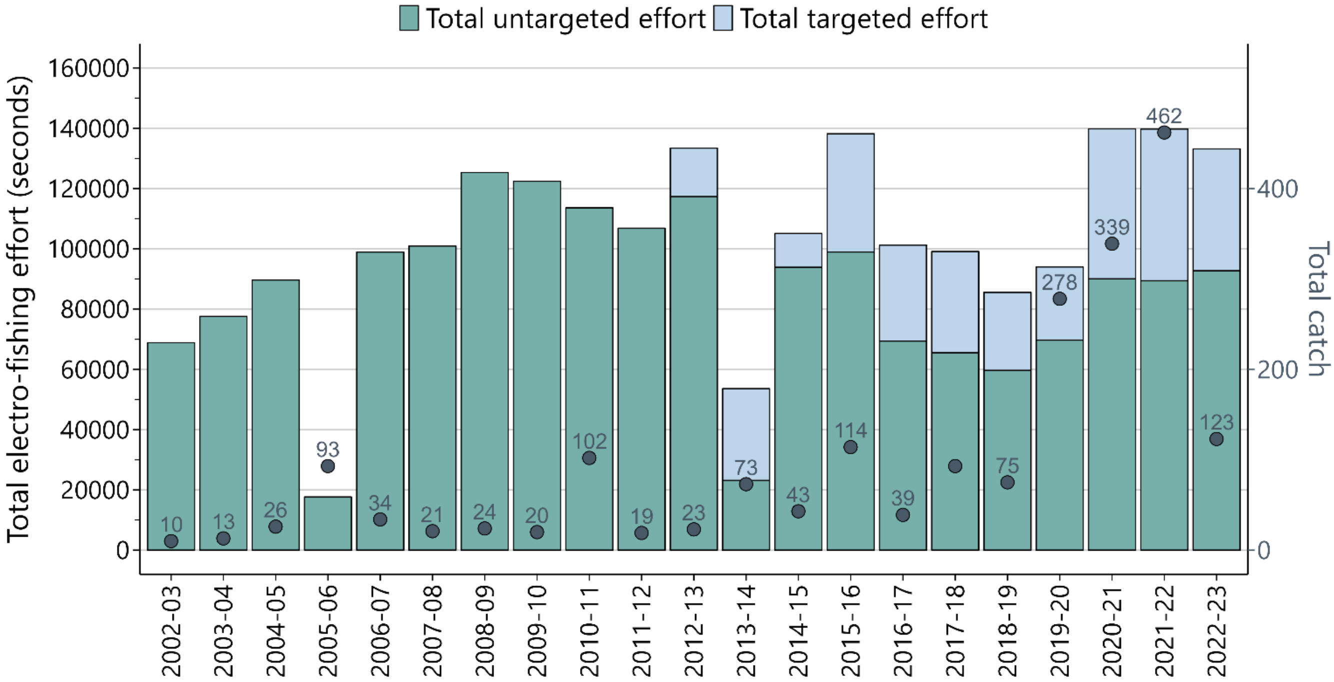


Figure 10-2. Murray cod electrofishing effort across all programs between 2002 and 2023, as compared with total catches for those years. Linear trendline and R^2 indicates change in total catch over time (not assessed against sample effort). Note that this does not include additional sample effort and catch associated with netting for Native Fish Monitoring Program between 2004–2013. Due to equipment failure, sampling effort in 2019–20 is lower than it actually was.

10.3.3 Trend assessment

The approach to assess trend using a Bayesian Generalised Linear Mixed Model is discussed in section 4.2.2. From 2002–03 to 2022–23, trends in relation to expected outcomes for Murray cod were assessed based upon the presence of the three life stages of recent recruits, sub-adults, and adults in the annual population age structure of Murray cod. Years were treated as independent data points for the analysis, with a 1 allocated to years with all life stages detected and a 0 allocated otherwise. Time step (years since the commencement of the assessment period) was included as a fixed effect. A binomial family was fitted to the Bayesian Generalised Linear Mixed Model.

10.3.4 Information reliability

The information reliability assessment for the Murray cod evaluation was conducted as per section 4.2.3.

10.3.5 Limitations and assumptions

General **assumptions** relating to the Murray cod expected environmental outcome assessment were identified by experts, these included:

- Higher morphological growth rates would have occurred over 2022–23 (George Giatas, personal communication, February 2024) likely due to increases in productivity and food resources associated with widespread flooding. Therefore, the age structure of Murray cod (inferred from length) in 2022–23 may misrepresent the true age profile of this species based on length data.

A number of general **limitations** relating to the expected environmental outcomes for Murray cod population age structure were also identified by experts, and included:

- Caution needs to be taken when interpreting the results of Murray cod population age structures due to discrepancies in sampling effort, timing and location between years.
- In high flow years, there may be considerable delay (1-2 years) before Murray cod recruits are detectable in the population (Zampatti et al. 2014).
- The conceptual understanding of how Murray cod responds to flow, including delivery of water for the environment, has changed since the previous evaluation; they can be influenced at a local scale and the similarity between populations in anabranches (Chowilla) and in the main channel will change based on prevailing flow conditions (i.e., during drought and low flow periods).

10.4 Results

10.4.1 Environmental outcome assessment

The last assessment and evaluation in 2019 found that Murray cod age population structure featured recent recruits, sub-adults and adults in all seven years following the adoption of the Basin Plan (2012) (Table 10–4; Figure 10-3: Figure 10-4) as was expected. Since 2019, the Murray cod population has continued to have recent recruits, sub-adults and adults in the population age structure in all years (Table 10–4; Figure 10-3; Figure 10-4). With the annual population age structure of Murray cod featuring all age classes in all 11 years since Basin Plan adoption, the results are on track towards the 2029 expected outcome.

Table 10–4. The presence/absence of recent Murray cod recruits (<200 mm, includes YOY and age 1+ fish), sub-adults (200–600 mm) and adults (>600 mm) in the population structure of Murray cod from 2002–03 to 2022–23.

Year	Total catch	Recent recruits	Sub-adults	Adults
2002–03	10	Absent	Absent	Present
2003–04	13	Absent	Absent	Present
2004–05	26	Absent	Present	Present
2005–06	93	Absent	Present	Present
2006–07	34	Absent	Present	Present
2007–08	21	Absent	Present	Present
2008–09	24	Present	Present	Present
2009–10	20	Present	Present	Present
2010–11	102	Absent	Present	Present
2011–12	19	Absent	Present	Present
2012–13	23	Present	Present	Present
2013–14	73	Present	Present	Present
2014–15	43	Present	Present	Present
2015–16	114	Present	Present	Present
2016–17	39	Present	Present	Present
2017–18	93	Present	Present	Present
2018–19	75	Present	Present	Present
2019–20	278	Present	Present	Present
2020–21	339	Present	Present	Present
2021–22	462	Present	Present	Present
2022–23	123	Present	Present	Present

10.4.2 Trend

The presence of recent recruits, sub-adults and adults within the annual population age structure of Murray cod from 2002–03 to 2022–23 was virtually certain (100% probability) to be **improved**, as shown by all posterior slope values >0 (Figure 10-3).

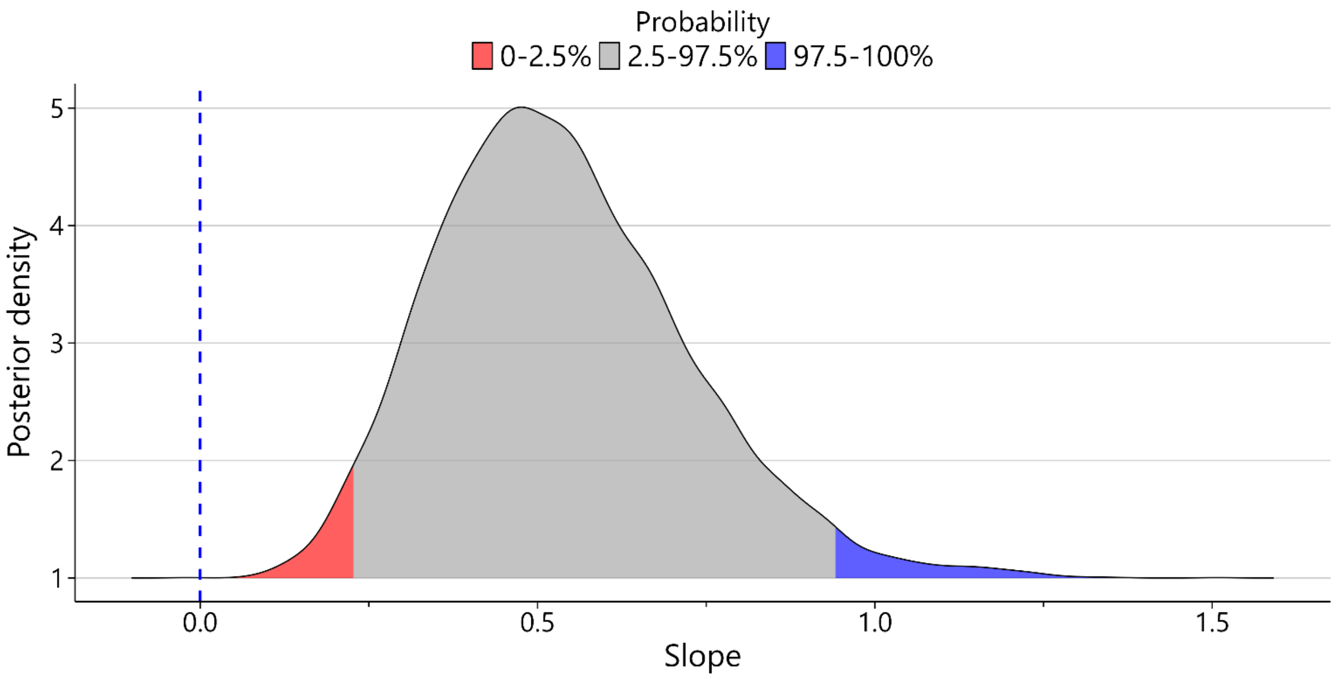


Figure 10-3. Estimated values for the slope generated from Bayesian modelling for the frequency of years all life stages of Murray cod were present in the population. Posterior slope values >0 infer a positive trend (improved) and values <0 infer a negative trend (declined).

10.4.3 Murray cod age structure: length-frequencies

Since 2002–03, there have been clear changes in the frequency of Murray cod lengths, indicating a population characterised by a greater proportion of larger/older fish during the Millennium Drought (1996–2010) (Figure 10-4). Greater proportional frequencies of YOY fish in the Murray cod population during the last decade has continued since 2014–15, with the highest proportion of YOY fish occurring in 2019-20 (30% of sampled fish; see Figure 10-5). Since then, a greater proportion of fish within the sub-adult category have been captured, and in 2022–23 a small increase in the proportion of adult fish was recorded.

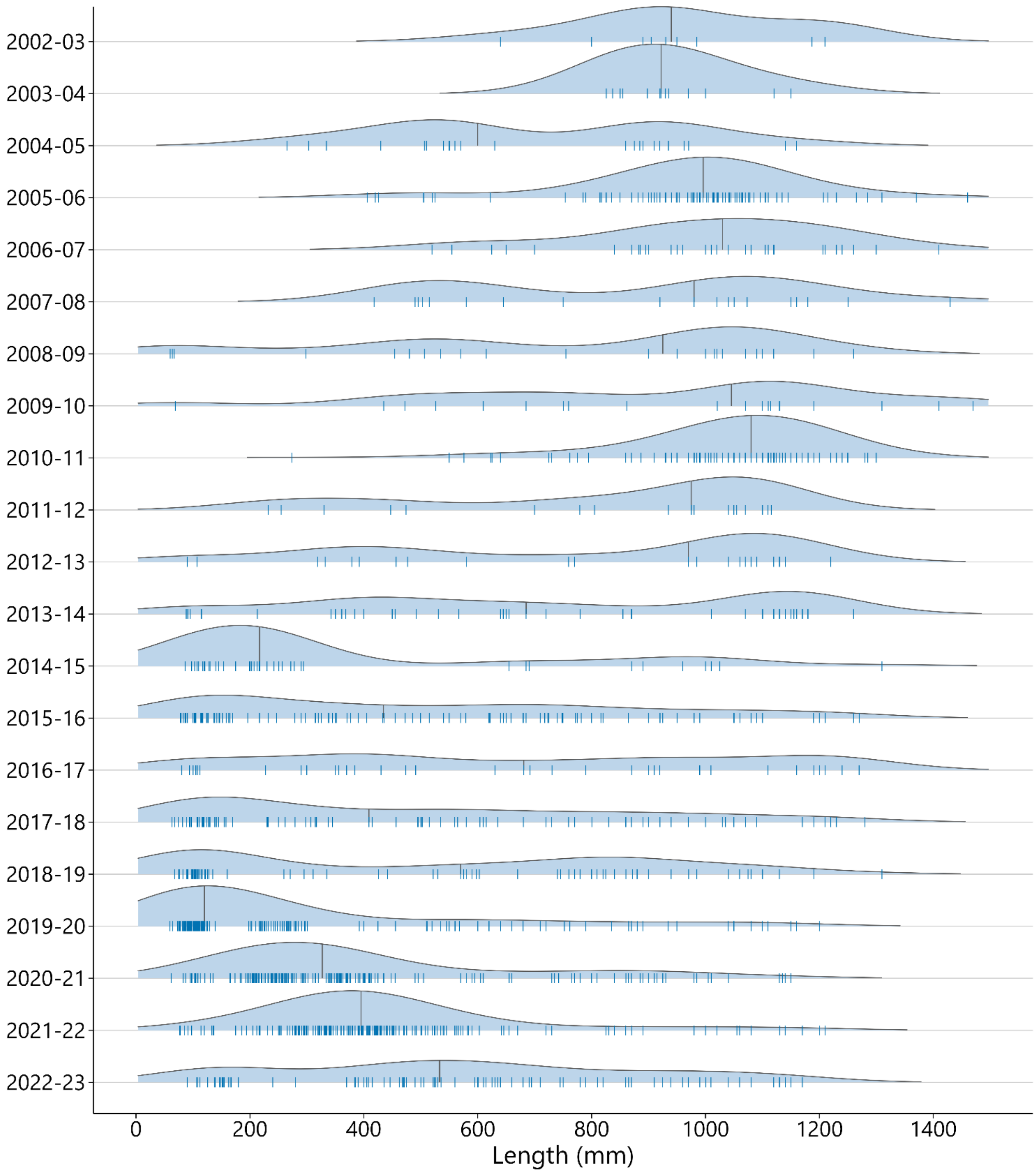


Figure 10-4. Density plot of Murray cod length (mm) sampling between 2002–03 and 2022–23 watering years. Each vertical dash in each water year represents the length of individual fish, while the black line is the median length of sampled Murray cod for that water year.

Figure 10-5. Proportional frequencies of Murray cod life stages in each water year between 2002–03 and 2022–23. Colours denote divisions between Murray cod length and the inferred age: light blue = recent recruits; dark blue =sub-adults; and grey = adults. n = the total number of fish measured across all appropriate monitoring programs. Data from the CEWH MER Cat 3 - early juveniles monitoring and the Pike fishway sampling has not been included, as sampling is biased towards fish of a particular age.

10.4.4 Information reliability

The information reliability rating was classed as **good** for Murray cod (final score of 10). Justification for the information reliability rating for Murray cod is provided in Table 10–5.

Table 10–5. Reliability of data to assess outcomes of Murray Cod. The methods used in data collection as well as the representativeness, repetition and sample independence of data were scored based upon the answers provided to questions related to each facet of data collection. Answers to questions regarding the methods, representativeness and repetition of data were scored 2 points – Yes, 1 point – Partially, 0 points – No.

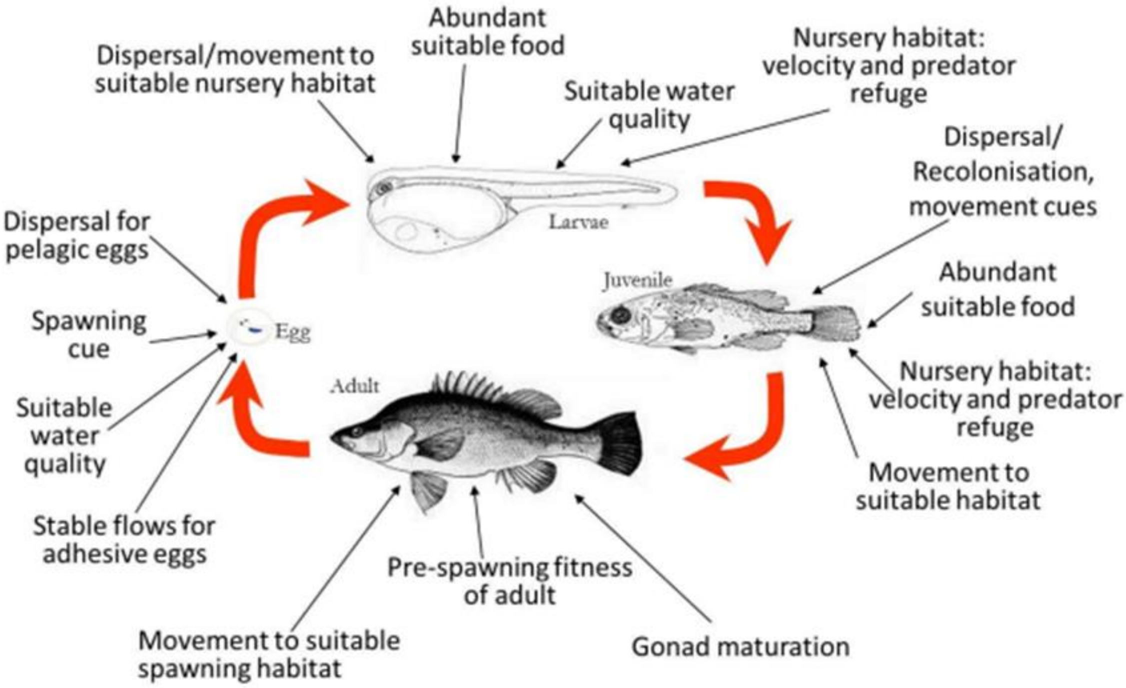
Methods	**Question**	**Answer and justification**	**Score**
Methods used	Are the methods used appropriate to gather the information required for evaluation?	**Yes.** Data collection is appropriate in determining the presence of YOY, sub-adults and adults in the annual population age structure.	**2**
Standard methods	Has the same method been used over the sampling program?	**Yes.** Murray cod were captured primarily using electrofishing over the course of the program.	**2**
Representativeness			
Space	Has sampling been conducted across the spatial extent of the SA River Murray with equal effort?	**Partially.** The sampling effort over the gorge and floodplain geomorphic zones of the SA River Murray has been relatively equitable. However, captures from the floodplain geomorphic zones are largely from the Chowilla anabranch.	**1**
Time	Has the duration of sampling been sufficient to represent change over the assessment period?	**Yes.** Sampling has been conducted from 2004-05 to 2020-21, and therefore, includes years of monitoring over a wide range of hydrological conditions.	**2**
Repetition			
Space	Has sampling been conducted at the same sites over the assessment period?	**Partially**. Differences in the commencement and duration of monitoring programs and accessibility issues from flood and high flow events has led to inconsistency in the sites sampled each year. Despite this, regular sites are visited annually within monitoring programs.	**1**
Time	Has the frequency of sampling been sufficient to represent change over the assessment period?	**Yes.** Annual data regarding the population age structure of Murray cod was acquired to assess trend and condition.	**2**
Final score			**10**
Information reliability			**Good**

10.5 Evaluation

From 2002–03 to 2022–23, the trend for the presence of all age classes (recent recruits, sub-adults and adults) in the annual population structure of Murray cod in the SA River Murray has improved (Figure 10-5). Recent recruits and sub-adults were present in all years following the adoption of the Basin Plan in 2012, and this result has exceeded expected outcomes. In addition to activities associated with Basin Plan implementation other complementary actions, may have also influenced these outcomes.

Koehn et al. (2020a) outline several key life history processes (Figure 10-6) which influence successful recruitment and survival of Murray cod. Each of these life history processes are influenced by both natural and environmental flows. Improved flow regimes to South Australia aim to address four key criteria required for successful recruitment of Murray cod, these include:

- The total number of breeding age adults (>600mm) available to seed a population of new recruits (Koehn et al. 2020a)
- Adult body condition, which can influence gonad development, fecundity and larval condition of freshwater fish (Balcombe et al. 2012; Koehn et al. 2020a)
- Dispersal of larvae, which is critical to the survivability of Murray cod recruits (Koehn et al. 2020a)
- Carrying capacity, which is associated with habitat and resource availability (Zampatti et al. 2014)



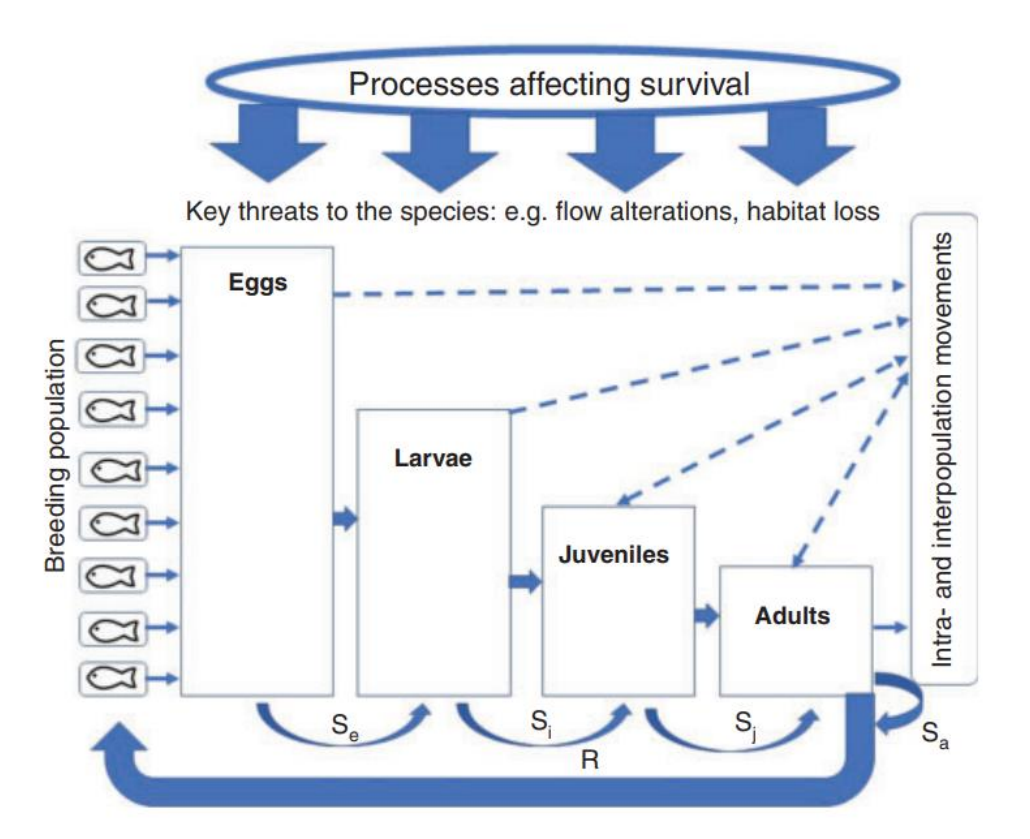


Figure 10-6. Conceptual models showing the life cycle for Murray cod (egg, larvae, juveniles, adults) and indicating threats and population processes affecting survival rates for each life stage (Se, eggs; Sl, larvae; Sj, juveniles; Sa, adults) and subsequent recruitment (R) into the adult (breeding) population. Potential movements within or among populations are shown by dashed arrows. From Koehn et al. (2017) and Koehn et al. (2020a).

The primary environmental factors that influence these criteria include:

- flow (discharge) and lateral/longitudinal connectivity
- hypoxic blackwater events
- productivity and resource availability
- hydraulic diversity and lotic habitat extent
- physical habitat (snag and woody debris) extent.

Flows to South Australia (QSA)

One of the current management mechanisms to support Murray cod in South Australia is QSA. This includes:

- overbank flows (QSA >45,000 ML day^{-1}), which occurred in the 2012–13, 2016–17, 2022–23 water years
- in-channel flow pulses (QSA 12,000–45,000 ML day^{-1}), which occurred to some extent in most years, but at a greater magnitude in 2013–14 and 2021–22
- base flows (QSA <12,000 ML day^{-1}), which occurred in all years since 2012.

During the Millennium Drought (1996–2010), recruitment of Murray cod in the SA River Murray channel and anabranches was negligible as indicated by the lack of small fish (Figure 10-4). Following increased flows after the drought break, Murray cod recruits have been recorded every year since 2012–13.

Positive trends in Murray cod outcomes since adoption of the Basin Plan in 2012 have been influenced by comparatively wetter climate over the past decade and associated high flow periods (in particular, 2010-2013, 2016-17 and 2021-2023), and increased in-channel spring flow pulses supported by water for the environment (Brenton Zampatti and Chris Bice, personal communication, September 2023).

Outcomes of the expert elicitation workshop reinforced the current understanding that adult Murray cod spawn each year, though the strength of recruitment is dependent on a number of factors, including:

- environmental conditions preceding spawning and the number and condition of reproductively mature adults
- effective dispersal and survival of larvae
- availability of suitable habitats and resources to support Murray cod populations of all age classes.

Flows to South Australia (QSA) is often augmented with water for the environment to optimise environmental outcomes. Spring flow pulses can be delivered to help support Murray cod populations, informed by the current conceptual understanding of Murray cod life history requirements (King et al. 2009).

Hypoxic blackwater

Hypoxic blackwater poses a substantial risk to Murray cod populations, contributing to mass fish kills during intermittent high flow events (CEWH 2017; King et al. 2012; Zampatti et al. 2014). Hypoxic blackwater events are characterised by persistent low dissolved oxygen concentrations (<2 ppm), caused by high (overbank) flows mobilising organic matter and dissolved organic carbon (DOC) into aquatic systems, which decompose and create anaerobic conditions. These events often occur after prolonged periods of lower in-channel flows that allow organic matter and detritus to accumulate on the floodplain. High flow events that peak then subside quickly can amplify the impacts of hypoxic blackwater, whereas extended flow periods provide for additional flushing and dilution (CEWH 2017).

Hypoxic blackwater events impact the survival of recent recruits, sub-adult and adult Murray cod. This was demonstrated in the SA River Murray by the significant reductions in Murray cod abundance following a blackwater event in 2010–11 (following high flows) (Zampatti et al. 2014). A further hypoxic event occurred in 2016–17; the utilisation of environmental flows to prolong the high flow event may have reduced the overall impact of hypoxic blackwater, limiting fish mortalities in the southern regions of the MDB (CEWH 2017).

Another hypoxic blackwater event occurred upstream of South Australia, notably within Broken Creek, the Goulburn River and some upper portions of the 'mid-Murray', during the 2022–23 high flow event; however, there was minimal impact in South Australia (DEW 2023b). It is assumed that the 2022–23 high flow event provided favourable conditions for Murray cod recruitment in South Australia due to favorable antecedent conditions in 2021–22 and minimal hypoxic blackwater impacts to adult Murray cod in South Australia.

Productivity

Productivity and the availability and quality of food resources in aquatic ecosystems, is influenced by flow-dependent processes, such as nutrient and matter transport and water level variability (CEWH 2020; Wallace et al. 2014). Gross primary production within aquatic systems influences stream metabolism and food webs, which are important factors in determining fish body condition (Balcombe et al. 2014; Balcombe et al. 2012; Koehn et al. 2020b), which can influence fish reproductive potential, growth rates and survival (Balcombe et al. 2012; Koehn et al. 2020a; Marshall et al. 1998; Roff 2002).

Environmental flows have been used to improve lotic habitat within sections of the MDB, including South Australia (MDBA 2020). Trophic productivity can be enhanced through augmented flows that increase matter transport and vary water levels at specific times of the year (Wallace & Furst 2016). However, overbank flows are typically required to boost adult Murray cod body condition ahead of spawning (Brenton Zampatti, personal communication, April 2024).

Assessments of environmental flows on stream metabolism indicated that at short time scales (daily-weekly) water for the environment provided substantial improvements on metabolic rates, though these impacts were minor when assessed at a seasonal scale (Ye et al. 2023). The cumulative impact of these small seasonal improvements is difficult to assess collectively and has not been quantified. Thus, the extent to which water for the environment has supported Murray cod via improvements to productivity is largely unknown.

Hydraulic Diversity and Lotic Habitat Extent

Hydraulically diverse, flowing (lotic) habitats (mean cross-sectional velocity >0.3 m s^{-1}) are preferred by both juvenile and adult Murray cod, and support key life history processes, including spawning and recruitment (Ye et al. 2023). Murray cod are capable of recruitment over mesohabitat scales (1–10 km) (Leigh & Zampatti 2011), and therefore, improvement in the temporal and spatial extent of hydraulically diverse habitat is likely to have been a factor in the recent successful recruitment of Murray cod (Ye et al. 2023).

An improvement in the extent of lotic habitats within the Channel and Floodplain PEA can be attributed to the proportional increases in flows, which have occurred since the adoption of the Basin Plan. Despite much of this increase being a result of increased natural flows across the Basin, water for the environment has, at times, played a crucial role in sustaining velocities when they might have otherwise fallen below key levels (Ye et al. 2023).

Monitoring and evaluation of water for the environment delivery in 2022 has shown that water supplied in the months of September, October, November, and January can help maintain velocities, more than 0.3 m s^{-1} for an extended period across larger areas of the river channel (Ye et al. 2023). Notwithstanding, the direct contribution of water for the environment on the overall recruitment and survivability of Murray cod is unknown, and can only be assessed together with unmanaged natural flow events.

Physical habitat extent

Snags are in-stream woody habitat found in rivers, composed of tree roots, trunks, or branches. Snags are a preferred habitat of Murray cod, providing shelter, resources and breeding sites (Crook & Robertson 1999; Lyon et al. 2019; Nicol et al. 2002). Snags create dynamic and diverse hydraulics within these reaches, promoting eddies, vortices and constrictions, which create the hydraulic diversity required to maintain viable Murray cod habitat (Abbe & Montgomery 1996; Crook & Robertson 1999; Nicol et al. 2002). Snags also provide surfaces for Murray cod to attach their eggs and shelter for YOY and juveniles (Cadwallader 1978). Snags are also vital for supporting the growth of biofilms (Baldwin et al. 2014; Cummings et al. 2015), and serve as a habitat for the small invertebrates and shellfish that feed on them, which in-turn serve as food resources for Murray cod (DEW 2023a).

In the past, snags were removed from the SA River Murray to facilitate the navigation of river vessels, mitigate flood risks, and enhance the river's appearance (DEW 2023a). The historical extraction of snags is believed to have significantly contributed to the dwindling numbers of native fish (Koehn et al. 2020a). This has resulted in the reduction of Murray cod habitat, which, due to intraspecific competition, may reduce spawning extent or the overall carrying capacity of Murray cod in the Lower Murray.

The DEW is currently undertaking small-scale re-snagging projects under the Sustaining Riverland Environments program to improve physical habitat extent within the river and support Murray cod populations (DEW 2023a). Though the current extent of re-snagging has occurred at a relatively small-scale, this on-going process will continue to improve and expand available physical habitat for Murray cod and support increased structural diversity within lotic environments.

10.6 Unanticipated Outcomes

The outcomes resulting from delivery of water for the environment to support Murray cod populations were generally predictable, with the exception of lower than anticipated recruitment in 2021–22. In general, expected recruitment outcomes are difficult to predict and often diverge from researchers expectations (George Giatas, personal communication, February 2024), further research is required to understand the mechanisms that cause these discrepancies.

10.7 Action to achieve environmental outcomes

10.7.1 Lotic habitat Extent

Water for the environment should continue to be used to boost and prolong spring flow pulses to support lotic environments during Murray cod spawning season (Brenton Zampatti, personal communication, September 2023). This will improve dispersal of Murray cod larvae and increase the extent of suitable spawning habitats for adult fish. In the SA River Murray, increased lotic conditions can be generated through water level management (i.e. weir lowering/removal) and increasing the magnitude and duration of flow pulses. Risks associated with changes in velocities in established Murray cod habitats, such as anabranches (Chowilla), should be managed to avoid compromising one established lotic environment to improve another; this is in reference to management actions such as weir pool lowering or floodplain regulator management (Chris Bice, personal communication, March 2024).

Continued restoration of suitable physical habitat via re-snagging projects will help improve the carrying capacity of the system for Murray cod.

10.7.2 Water quality and flow management.

Water for the environment can also be used to improve and prime the Channel and Floodplain PEA at appropriate times of the year to improve productivity in the system, and antecedent conditions for Murray cod spawning season (Brenton Zampatti, personal communication, September 2023). Increased intensity and frequency of flows will improve transport of organic matter and water level variability, promoting productivity.

Increased frequency and magnitude of flows can reduce the risk of hypoxic blackwater by regularly flushing organic matter from the river and floodplain (CEWH 2017). Augmented flows after high flow events can increase dilution and mixing of blackwater to reduce its impacts, particularly through a prolonged extension of flows using water for the environment, as occurred in 2016–17 (CEWH 2017).

Removal of constraints to flow will increase the ability of water managers to increase the volume and magnitude of flows throughout the SA River Murray. In addition, improved infrastructure upstream can help to further augment the intensity of QSA.

10.8 Conclusion

Outcomes for Murray cod have improved since the adoption of the Basin Plan. Though it is difficult to separate improved natural hydroclimatic conditions post-Millennium Drought (1996–2010), there are indications that water for the environment delivered under the Basin Plan has contributed to these outcomes.

Increased magnitude and duration of spring flow pulses are likely to have a benefit for Murray cod spawning and recruitment (Ye et al. 2023). Augmented flows post-flood in 2016–17 likely reduced the impact of the hypoxic blackwater event (CEWH 2017). The delivery of water for the environment to South Australia may have also improved ecosystem productivity (Ye et al. 2023).

Full delivery of the Basin Plan, including the recovery and delivery of the 450 GL for the environment and addressing current water delivery constraints, are also important to ensure the volume, timing and duration of flows create conditions to support Murray cod populations in the SA River Murray.

More research and monitoring are required on a long-term scale to account for temporal variability in hydro-climatic conditions and during periods of drought and reduced rainfall. Targeted monitoring programs associated with delivery of water for the environment are key in determining whether the Basin Plan is measurably improving Murray cod populations and overall ecological health.

11 Golden perch

Trend **Improved**

★★★☆☆ Reliability **Good**

Key findings and messages:

- Population age structure of golden perch has improved since the Millennium Drought, with young-of-year fish detected more frequently (in 46% of years).
- Overall improvement in the presence of all life stages (recent recruits, sub-adults and adults) is largely due to the high (unregulated) flow conditions between 2011–2014 and 2021–2023.
- Despite overall improvement in the population age structure of golden perch, the presence of young individuals indicates that the number of years with all age classes and occurrence of significant recruitment, will likely be lower than expected in 2029.
- Recruitment of golden perch was detected in 2023, with excellent fish condition, high growth rates of adult and young-of-year detected, likely due to an increase in resources available from the 2022–23 River Murray flood event.
- Despite overall improvements in the population age structure of golden perch, responses in populations since the adoption of the Basin Plan have been variable, with lower-than-expected outcomes, due to minimal recruitment and declining abundances between 2015 and 2020.
- Improvements in water delivery (e.g. coordination of spring-summer flow pulses, addressing current water delivery constraints) and other management actions (e.g., weir pool management, physical habitat restoration) are needed for further improvements in golden perch populations in the SA River Murray.

11.1 Introduction

Golden perch (*Macquaria ambigua*) is a medium to large freshwater native fish (commonly growing to 400–500 mm total length) that is found in inland river systems over large parts of central and eastern Australia, including the Murray–Darling, Lake Eyre, Bulloo and Dawson-Fitzroy drainage systems (Kailola et al. 1993). The species is widespread across the MDB and is found throughout the SA River Murray and Lakes (Lintermans 2023), and is of ecological, cultural and commercial significance.

Golden perch is a top-level predator that favours structural aquatic habitats such as snags, rocky ledges and undercut banks (Allen et al. 2002; Battaglene & Prokop 1987; Koehn & Nicol 2014). In the SA River Murray, the species favours the main river channel and anabranches, but can be found across almost all macrohabitats, including lakes, floodplains, wetlands and backwaters.

The life history of golden perch is characterised by high growth rate (K = 0.45–0.56) (Anderson et al. 1992a), high longevity (maximum lifespan of 28 years) (Koehn et al. 2020; Mallen-Cooper & Stuart 2003), intermediate age at reproductive maturity (four years for females and 2 years for males) (Mallen-Cooper & Stuart 2003) and high fecundity (up to 500,000 eggs) (Lintermans 2007). In the southern MDB, spawning occurs in response to warming water temperatures (≥20 °C) (King et al. 2016; Ye et al. 2020) and elevated within-channel or overbank flows (Zampatti & Leigh 2013a; b). Golden perch seek lotic river reaches to spawn pelagically (Zampatti & Leigh 2013b;

Zampatti et al. 2021) as river drift is crucial for the dispersal of eggs and larvae, and ultimately recruitment (Zampatti et al. 2021).

In the southern MDB, golden perch life histories and population dynamics operate over large spatial scales (100s to 1,000 km). Adults, while often largely sedentary, can migrate 1,000 km in the Murray and Darling rivers (Bice et al. 2021; Reynolds 1983; Zampatti et al. 2018a). Furthermore, elevated flow and flooding that occurs at the catchment scale (100–1,000 km), rather than site scale (tens of km), is associated with spawning and recruitment (Zampatti et al. 2021). System connectivity is important for the bi-directional movements of adults and juveniles, and downstream dispersal of eggs and larvae. Drifting eggs and larvae can travel substantial distances (potentially up to 100 km) downstream (Zampatti et al. 2015), while juveniles (1+ years of age) can travel extensive distances downstream or upstream, typically during high flows (Thiem et al. 2023; Zampatti et al. 2021). The large distances of dispersal of early life stages and juveniles means that population demographics in the SA River Murray can be driven by spawning events in distant upstream reaches, including the lower Darling River and mid-River Murray, as well as locally within the SA Murray River (Zampatti et al. 2021).

River regulation in the SA River Murray has impacted golden perch populations (Koehn et al. 2020). The ecology of golden perch renders the species susceptible to the impacts of altered flow regimes and barriers to movement (e.g. weir pool environments may impact drift of eggs/larvae) (Zampatti et al. 2018a; Zampatti et al. 2018b). In particular, golden perch requires river flows and connectivity to meet life history requirements for long-distance migration (Zampatti et al. 2018a), flow-cued spawning (Zampatti & Leigh 2013a), obligate drifting phases for eggs and larvae (Koster et al. 2014), and inter-regional meta-population dynamics (Zampatti et al. 2018b; Zampatti et al. 2015).

The SA River Murray is regulated through weir infrastructure, which affects longitudinal and lateral connectivity, impacting golden perch recruitment, movement, dispersal and migration, especially during times of low flows (Bice et al. 2021; Koehn et al. 2020). To promote a resilient population age structure of golden perch in the SA River Murray, spring-early summer flow pulses of >20,000 ML day^{-1} flow at the South Australian border (QSA) are required for strong recruitment and dispersal from upstream (Ye et al. 2023).

11.2 Ecological objective, target and environmental outcomes

The ecological objective for golden perch in the Channel and Floodplain PEA is outlined in the South Australian River Murray Long-term Watering plan (LTWP) (DEW 2020). The objective is underpinned by three targets relating to population age structure, large recruitment events and catch-per-unit-effort (CPUE) of the golden perch population (Kilsby & Steggles 2015); however, expected outcomes were only derived for the population age structure and recruitment events (Table 11–1).

Table 11–1. Description of ecological objective and targets related to the golden perch indicator, outlined in the LTWP (DEW 2020).

Ecological objective	Ecological targets
Restore resilient populations of golden perch.	Population age structure of golden perch includes young-of-year (YOY) with sub-adults and adults in 8 years in 10.
	Population age structure of golden perch indicates a large recruitment event 2 years in 5, demonstrated by separate cohorts representing >30% of the population.

The expected environmental outcomes for golden perch population age structure for 2019, 2029 and 2042 were determined by elicitation with key experts. These form the basis of the assessment of golden perch environmental outcomes in the SA River Murray Channel PEA (Table 11–2; Figure 11-1).

Table 11–2. The expected environmental outcomes for age structure, and recruitment, characteristics of the golden perch population in 2019, 2029, and 2042.

	Year		
Expected outcome	**2019**	**2029**	**2042**
Age structure			
Populations of golden perch will include YOY, sub-adults and adults in:	**5 of 7 (71%)** years since Basin Plan adoption (80% confidence range of 53–92% of years).	**11 of 17 (65%)** years since Basin Plan adoption (80% confidence range of 51–78% of years).	**21 of 30 (70%)** years since Basin Plan adoption (80% confidence range of 49–81% of years).
Recruitment			
Populations of golden perch will indicate a large recruitment event in 2 of 5 years, demonstrated by separate cohorts representing >30% of the population in:	**3 of 7 (43%)** years since Basin Plan adoption (80% confidence range of 33–62% of years).	**8 of 17 (47%)** years since Basin Plan adoption (80% confidence range of 29–65% of years).	**13 of 30 (43%)** years since Basin Plan adoption (80% confidence range of 49–81% of years).

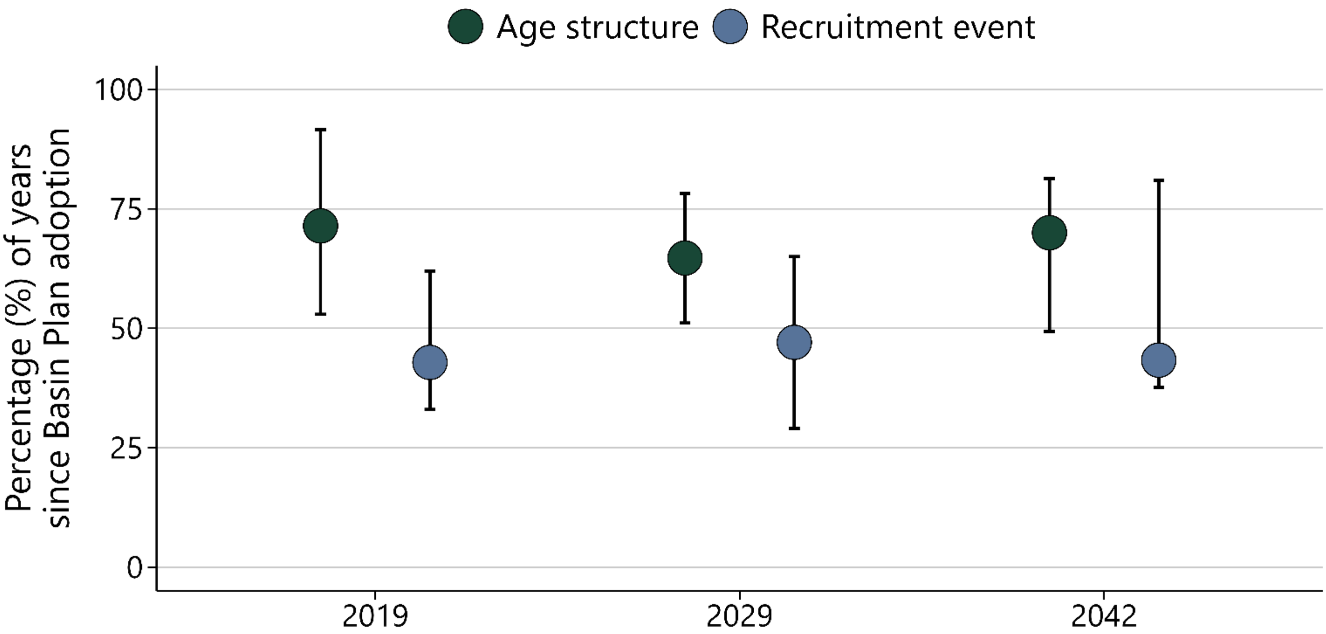


Figure 11-1. The percentage of years expected outcomes are expected to be met for golden perch populations for 1) age structure (green) and 2) recruitment (grey) in 2019, 2029, and 2042, since Basin Plan adoption (2012).

11.3 Method

11.3.1 Data sources

Assessments of the expected outcomes for golden perch used ageing data collated from the following sources:

- Commonwealth Environmental Water Holder (CEWH) Short Term Intervention Monitoring (STIM) program

- CEWH Lower Murray River Long Term Intervention Monitoring (LTIM) and Monitoring, Evaluation and Research (MER) Category 1 programs (mandatory indicators with standard protocols)
- CEWH Lower Murray River LTIM and MER Category 3 programs (targeted hypothesis-driven monitoring)
- The Living Murray (TLM) Chowilla Condition Monitoring program
- Murray-Darling Basin Authority (MDBA)/Native Fish Strategy Intervention Monitoring at Katarapko.

11.3.2 Data collection

A total of 2,454 golden perch were captured across the SA River Murray from 2005 to 2023. Golden perch were captured in the SA River Murray or within 5 km of the SA border in New South Wales. Golden perch were primarily captured in the floodplain geomorphic zone (*n* = 1,605), and secondarily across the gorge geomorphic zone (*n* = 848) of the SA River Murray. The representation of catch through years from the top seven programs is given in Table 11–3. Electrofishing was used across all programs to capture fish (Fredberg et al. 2019; Wilson et al. 2014; Ye et al. 2020), aside from Katarapko Intervention Monitoring which used fyke nets (Wilson et al. 2014). Captured golden perch were aged using otoliths (ear stones), described in (Zampatti et al. 2015), as body length does not accurately reflect the age of individuals in the MDB (Anderson et al. 1992b).

Table 11–3. The number of golden perch caught across all monitoring programs. The duration of sampling for each program is shown in green. Fish were sampled in the gorge (G), floodplain (FP), and swamp (S) geomorphic zones.

	Chowilla Condition Monitoring (FP)	Katarapko Condition Monitoring (FP)	CEWH STIM (FP, G, & S)	CEWH LTIM/MER CAT 3 – Targeted YOY (FP & G)	CEWH LTIM/MER CAT 1 (G)	Pike Condition Monitoring (FP)
Program catch	**969**	**123**	**331**	**499**	**511**	**21**
2005	78					
2006	57					
2007	31					
2008	49					
2009	48					
2010	50	48				
2011	62	50				
2012	70		83			
2013	65		140			
2014	67		108			
2015	33			60	77	
2016	59			76	55	
2017	58			68	44	
2018	20			60	47	
2019	48			63	50	
2020	32			39	81	
2021	35	25		39	52	21
2022	47			44	62	
2023	60			50	43	

11.4 Trend assessment

The approach to assess trend using a Bayesian Generalised Linear Model is discussed in section 4.2.2. Trend for golden perch was assessed based upon the presence all life stages (recent recruits, sub-adults, and adults) in the annual population age structure from 2005 to 2023. Years were treated as independent data points for the analysis, with a 1 allocated to years with all life stages detected and a 0 allocated otherwise. Time step (years since the commencement of the assessment period) was included as a fixed effect. A binomial family was fitted to the Bayesian Generalised Linear Model.

11.5 Information reliability

The information reliability assessment for the golden perch evaluation was conducted as per section 4.2.3.

11.6 Limitations and assumptions

The detection of YOY golden perch can be affected by high-flow events, and there is also an upstream influence on the potential sources of golden perch recruits in the SA River Murray.

There are several limitations in assessing recruitment events for golden perch, i.e. 'a large recruitment event two years in five, demonstrated by separate cohorts represented by >30% of the population', and needs to be treated with caution. This target does not necessarily reflect a "strong" recruitment event, as it is still possible for resilient populations to fail to meet this target if several years of recruitment were to occur within a five-year period. This is because each recruitment event contributes a significant number of juvenile fish to the total population, compounding over multiple years, which can make smaller cohorts less prominent in the population age structure. Notwithstanding, even small recruitment events are still important for building resilience in the population (Ye et al. 2023).

11.7 Results

11.7.1 Environmental outcome assessment: Age structure

The last expected outcome assessment and evaluation (in 2019) found that golden perch age structure did not include younger life stages as frequently as had been expected at that stage of Basin Plan adoption (Table 11–4). It was expected that all golden perch life stages would be present in the annual population in five of seven (71%) years since 2012 but was instead only observed in 29% of years (Figure 11-2).

Since 2019, this frequency has increased from 29% (autumn 2019) to 46% (autumn 2023) of years, indicating improved recruitment of YOY, which were detected in 2021, 2022, and 2023. In 2029, we expect this frequency of detection to increase further to 65% of years; however, the data currently suggest that we are not on track to meet this expected outcome.

Table 11–4. The presence/absence of YOY (<1 years), sub-adults (1-3 years), and adults (>3 years) in the annual population of golden perch in the SA River Murray from 2005 to 2023.

		Life stages		
	Total catch	YOY	Sub-adults	Adults
2005	78	Absent	Absent	Present
2006	57	Absent	Absent	Present
2007	31	Absent	Present	Present
2008	49	Absent	Present	Present

		Life stages		
	Total catch	YOY	Sub-adults	Adults
2009	48	Absent	Present	Present
2010	98	Present	Absent	Present
2011	112	Present	Present	Present
2012	153	Present	Present	Present
2013	205	Present	Present	Present
2014	173	Present	Present	Present
2015	170	Absent	Present	Present
2016	187	Absent	Present	Present
2017	169	Absent	Present	Present
2018	125	Absent	Present	Present
2019	161	Absent	Present	Present
2020	151	Absent	Present	Present
2021	171	Present	Present	Present
2022	153	Present	Present	Present
2023	152	Present	Present	Present

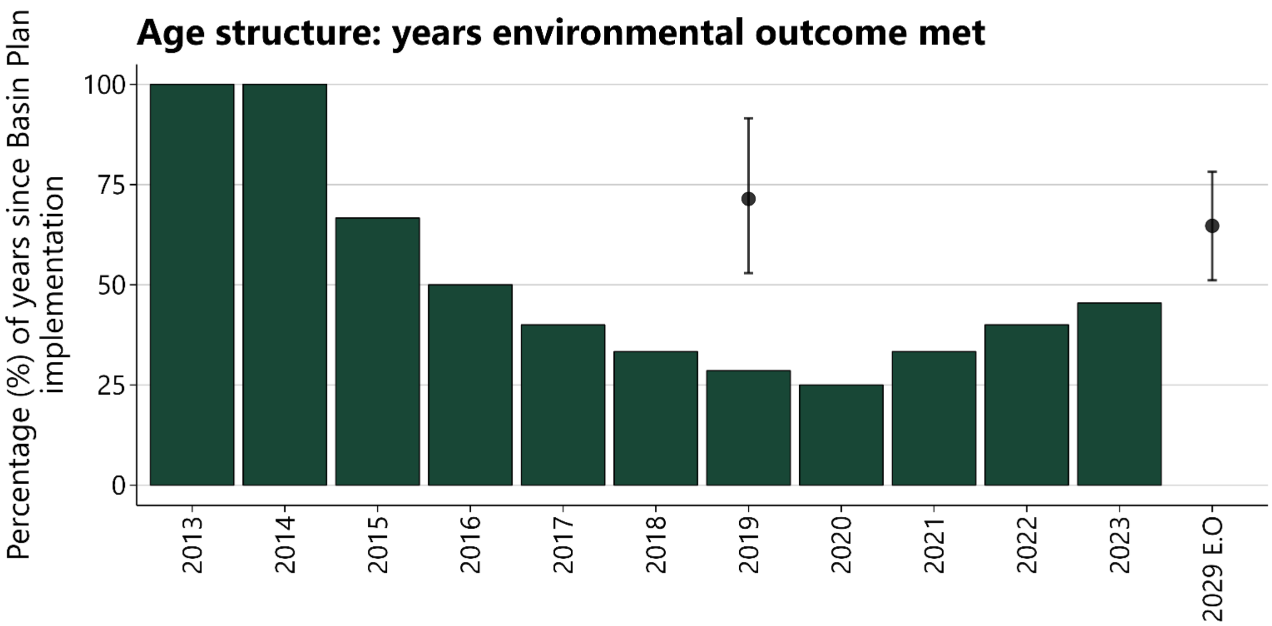


Figure 11-2. Cumulative percentage of years, since Basin Plan adoption (2012), where the targeted age structure of golden perch was achieved. The 2019 and 2029 expected outcomes (±80% confidence interval) are referenced by the black point and associated error bars. Data source: SARDI.

11.7.2 Environmental outcome assessment: Recruitment events

In 2019, the last expected outcome assessment and evaluation found that the frequency of golden perch recruitment events since Basin Plan adoption (2012) was lower than expected (Table 11–5). It was expected that at least two young cohorts (i.e., aged YOY to 5 years) would be observed in three of seven (43%) years, representing >30% of the sampled population each, but this occurred in only 14% of years in autumn 2019 (Figure 11-3).

Since 2019, the frequency of large golden perch recruitment events, where YOY make up >30% of total population, has continued to decrease from 14% (autumn 2019) to 9% (autumn 2023) (Table 11–5), indicating a decline in large recruitment events. In 2029, we expected this frequency of recruitment to increase to 47% of years; however, the data currently suggests that we are not on track to meet the outcome expected in 2029.

Table 11–5. The annual relative contribution (%) of young cohorts (aged YOY to 5) compared to the overall sampled golden perch population from 2005 to 2023. Note: total catch only reflects captures from non-targeted programs.

		Age (years)					
	Total catch	**YOY**	**1**	**2**	**3**	**4**	**5**
2005	78	0	0	0	0	33	8
2006	57	0	0	0	0	0	44
2007	31	0	39	0	0	0	0
2008	49	0	0	65	0	0	0
2009	48	0	0	0	69	0	0
2010	98	10	0	0	0	58	0
2011	112	38	45	0	0	0	11
2012	153	18	46	27	0	0	0
2013	205	1	11	17	56	0	0
2014	175	2	0	7	21	54	1
2015	170	0	0	2	8	32	35
2016	190	0	0	1	2	13	28
2017	170	0	1	0	2	4	22
2018	127	0	0	0	1	7	3
2019	161	0	1	2	1	1	8
2020	113	0	2	1	4	0	0
2021	133	2	0	6	4	6	2
2022	109	35	6	2	6	5	9
2023	103	9	63	3	0	3	1

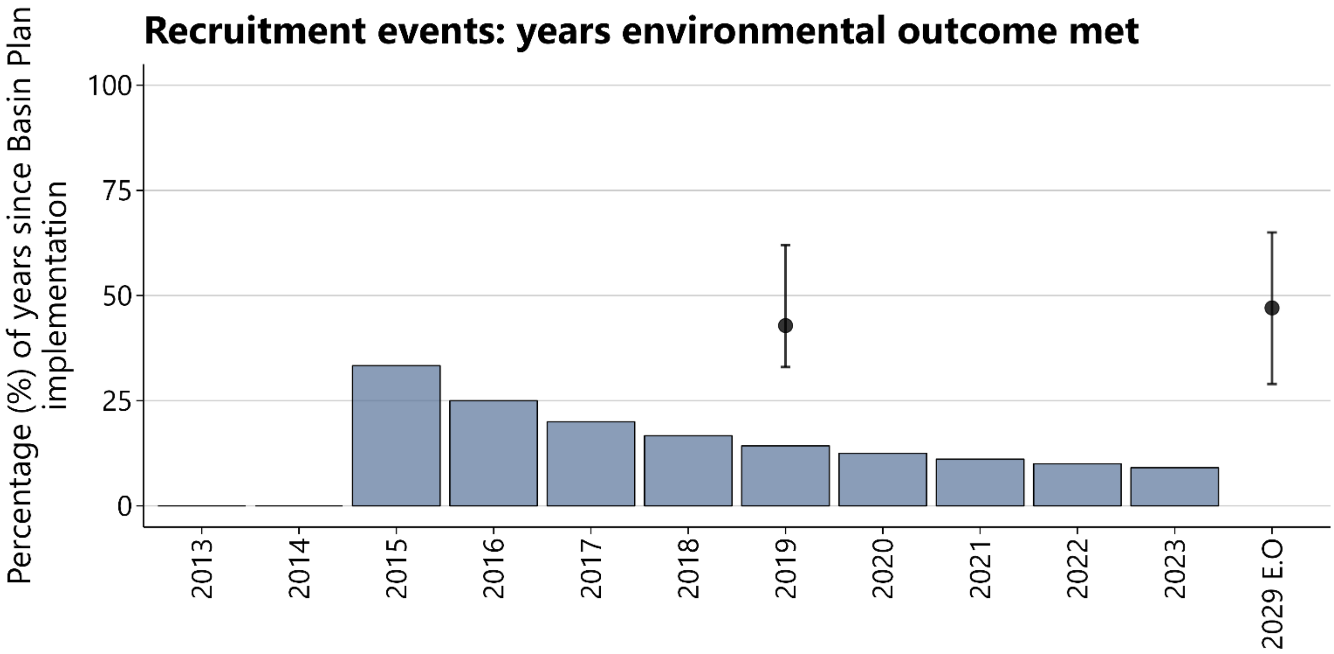


Figure 11-3. The annual percentage of years since Basin Plan adoption where the long-term target for recruitment event of golden perch was achieved. The 2019 and 2029 expected outcomes (±80% confidence interval) are referenced by the point and associated error bars. Data source: SARDI.

11.7.3 Trend

From 2005 to 2023, the presence of recent recruits, sub-adults and adults within the annual population age structure of golden perch was extremely likely (95% probability) to have **improved** (Figure 11-4).

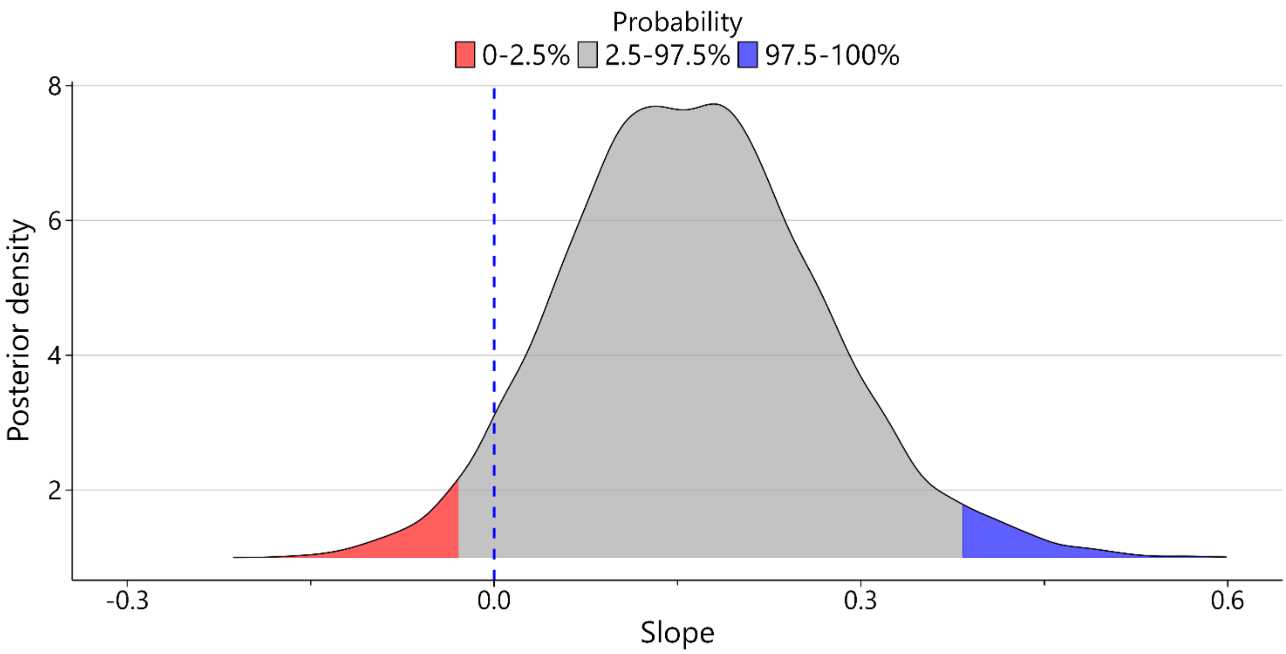


Figure 11-4. Estimated values for the slope generated from Bayesian modelling for the frequency of years all life stages of golden perch were present in the population. Posterior slope values >0 infer a positive trend (improved) and values <0 infer a negative trend (declined).

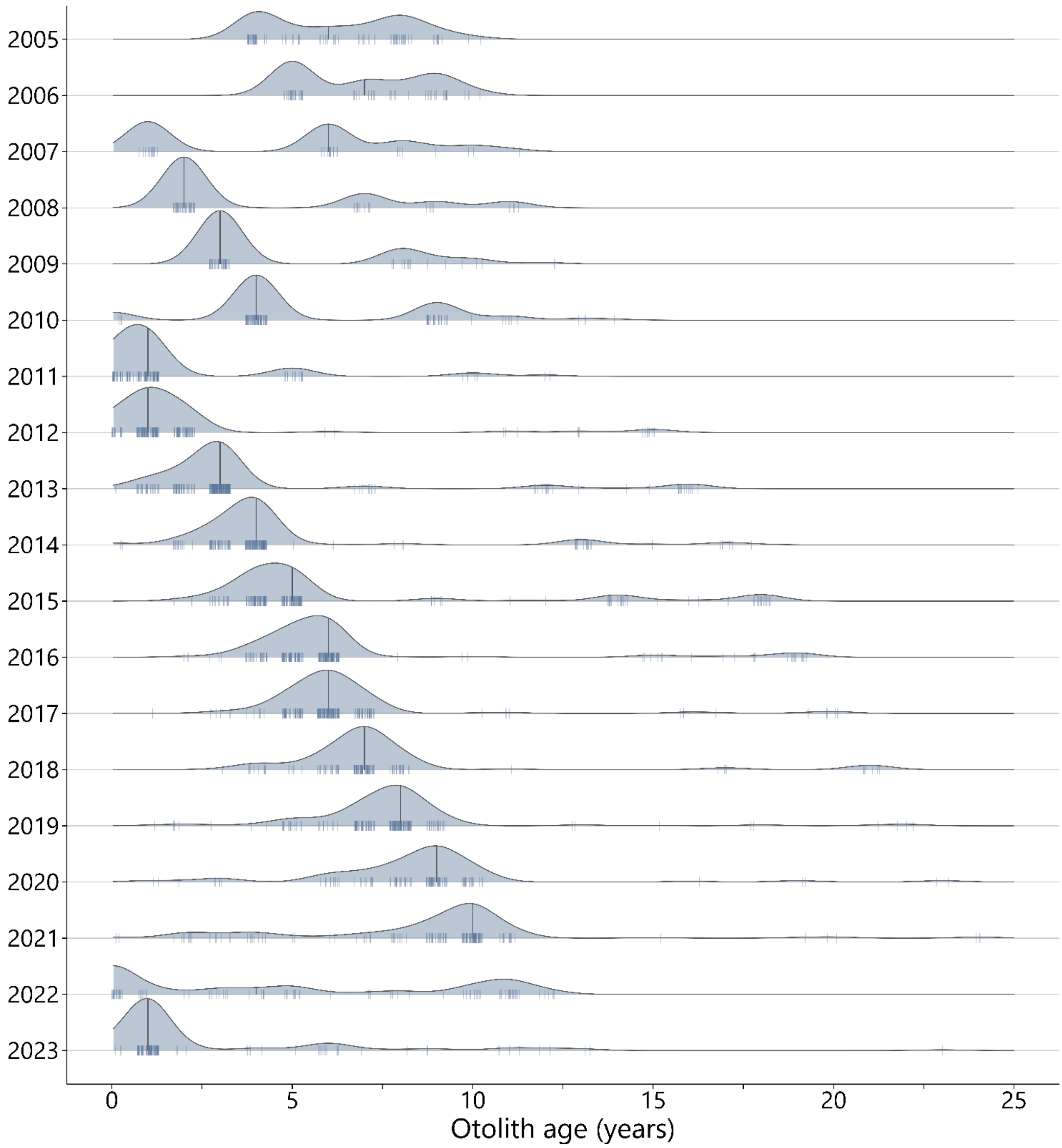


Figure 11-5. Density plot of golden perch age structure between 2005 and 2023. Each vertical dash represents the age of an individual fish, while the black line is the median age of sample golden perch for that year. Data from the CEWH MER Cat 3 - Targeted YOY has not been included, as this sampling is biased towards fish of a particular age. Data source: SARDI.

11.7.4 Information reliability

The information reliability rating was classed as **good** for golden perch (final score of 10). Justification for the information reliability rating for golden perch is provided in Table 11–6.

Table 11–6. Reliability of data to assess outcomes of golden perch. The methods used in data collection as well as the representativeness, repetition and sample independence of data were scored based upon the answers provided to questions related to each facet of data collection. Answers to questions regarding the methods, representativeness and repetition of data were scored 2 points – Yes, 1 point – Partially, 0 points – No.

Methods	**Question**	**Answer and justification**	**Score**
Methods used	Are the methods used appropriate to gather the information required for evaluation?	**Yes.** Data collection is appropriate in determining the annual population age structure and recruitment events.	**2**
Standard methods	Has the same method been used over the sampling program?	**Yes.** Golden perch were captured using electrofishing. A standard method exists for aging golden perch from their otoliths.	**2**
Representativeness			
Space	Has sampling been conducted across the spatial extent of the SA River Murray with equal effort?	**Partially.** The sampling effort over the SA River Murray channel has been more intensive over the floodplain geomorphic zone than the gorge geomorphic zone, with almost twice the number of captures.	**1**
Time	Has the duration of sampling been sufficient to represent change over the assessment period?	**Yes.** Sampling has been conducted from 2005 to 2023, and therefore, includes years of monitoring over a wide range of hydrological conditions.	**2**
Repetition			
Space	Has sampling been conducted at the same sites over the assessment period?	**Partially**. Differences in the commencement and duration of monitoring programs and accessibility issues from flood and high flow events has led to inconsistency in the sites sampled each year. Despite this, regular sites are visited annually within monitoring programs.	**1**
Time	Has the frequency of sampling been sufficient to represent change over the assessment period?	**Yes.** Golden perch have been aged annually to ascertain the species population.	**2**
Final score			**10**
Information reliability			**Good**

11.8 Evaluation

The trend for presence of all life stages (recent recruits, sub-adults and adults) in the annual population structure of golden perch in the SA River Murray has improved since 2005, mainly due to high flows between 2011 to 2014 and 2021 to 2023 and the resulting ecosystem benefits. Despite this, there has been a variable response in golden perch populations since Basin Plan adoption in 2012, with environmental outcomes currently lower than expected, and minimal recruitment and declining abundance between 2015 and 2020 (Ye et al. 2023), despite an overall increase in the volume of water for the environment. Since 2019, there has been some recruitment (i.e., the presence of YOY) particularly occurring after 2020 (Ye et al. 2023), coinciding with a period of unregulated QSA.

The main influences on population age structure and recruitment events appear to be high in-channel flows or overbank flows, and Basin-scale connectivity. Water for the environment appears to have supported low-level recruitment of golden perch in the SA River Murray since the Basin Plan was adopted (Ye et al. 2023).

11.8.1 Key factors contributing to environmental outcomes

High in-channel spring-summer flows

Flow pulses during spring-summer influence spawning, recruitment and movement of golden perch (Koehn et al. 2014). Within-channel flows >20,000 ML day^{-1} or overbank flows >40,000 ML day^{-1} appear to promote spawning and recruitment, and population resilience (King et al. 2016; Ye et al. 2023; Zampatti & Leigh 2013b). Sufficient within-channel flow has been shown to contribute to notable spikes in YOY cohort abundance and establishment of prominent cohorts of golden perch (Zampatti & Leigh 2013b), and these cohorts can remain as a significant proportion of populations in future years (Zampatti & Leigh 2013a; Zampatti et al. 2021). Key periods of high flow since Basin Plan adoption have occurred in 2012 (~50,000 ML day^{-1}), 2013 (~25,000 ML day^{-1}), 2016 (>93,000 ML day^{-1}), 2021 (~37,000 ML day^{-1}), and 2022 (>180,000 ML day^{-1}) (Figure 11-6). These conditions likely stimulated spawning and facilitated the drift of eggs and larvae and subsequent recruitment (Figure 11-5), apart from 2016 when a significant blackwater event occurred that potentially impacted survival of golden perch eggs and larvae (Ye et al. 2020).

Recent unregulated flows (2021–22 and 2022–23) have led to fish assemblages that are characteristic of a flowing riverine environment (Ye et al. 2023). Historically, in an unregulated MDB, there was greater annual frequency and prevalence of flowing riverine conditions (Mallen-Cooper & Zampatti 2018). Whilst delivery of water for the environment has contributed to spring-summer flow pulses since Basin Plan, these have typically been below the flow magnitudes (i.e. <20,000 ML day^{-1}) considered necessary to elicit a strong recruitment response from golden perch. Constraints on the delivery of water for environment have impacted the capacity to deliver high flow volumes to the SA River Murray (Ye et al. 2023).

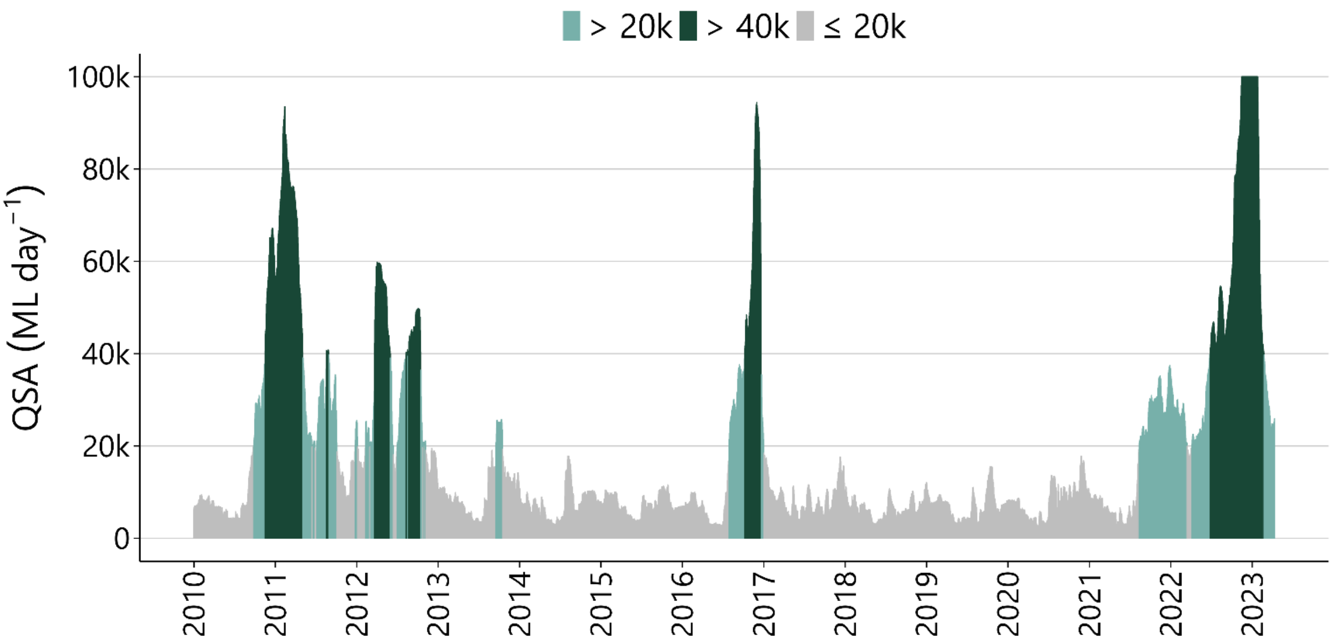


Figure 11-6. Daily Flows to South Australia (QSA) between 2010 and 2023, with the three flow bands highlighted which are indicative of golden perch in the Channel and Floodplain PEA. Note that the peak (>185,000 ML day^{-1}) of the 2022-23 flood event has been truncated on the y-axis.

Within-channel flows and local spawning and recruitment

Despite the strong influence of high within-channel flow pulses or overbank flows on golden perch recruitment, lower flows that are influenced by the management of water for the environment remain important for golden perch populations up to 18,000 ML day^{-1} (Ye et al. 2023). Smaller flows have supported low-level recruitment in the population between 2014–2021, which has increased the overall resilience of this population, especially following consecutive years with sufficient flows during spring-summer time (Ye et al. 2022; Ye et al. 2023). Furthermore, golden perch in the SA River Murray can exhibit a strong upstream movement response during subtle increases in flow during spring-summer (Mallen-Cooper & Brand 2007). This reinforces the interdependence between, and effect of, periodic high-flow events, smaller flows, and Basin-scale connectivity for golden perch populations, some of which can be managed using water for the environment.

Basin-scale connectivity

Considering the long-distance dispersal and migration strategies of GP, river regulation across the MDB impacts their population dynamics (Koehn et al. 2020; Zampatti & Leigh 2013a; Zampatti et al. 2021). Recruitment and population age structure in the SA River Murray are influenced by both localised spawning and recruitment as well as by upstream regions, such as in the lower Darling and mid-Murray Rivers (Zampatti et al. 2019; Zampatti et al. 2021). Furthermore, golden perch recruitment is often variable and episodic (Koehn et al. 2020; Zampatti et al. 2019). Critical to population resilience is maintenance of connectivity at local scales (e.g. between reaches, anabranches, and floodplains) and at regional scales (Stuart & Sharpe 2020), necessitating broader management strategies for flow-cued spawning fish species related to delivery of water for the environment.

11.8.2 Knowledge gaps

The exact influence of cues such as hydraulic diversity on spawning of golden perch is a current knowledge gap that requires further study. There is also some difficulty in the detection of YOY golden perch, especially during relatively low-level recruitment, after which recently spawned individuals appear as juveniles in succeeding years (Ye et al. 2023). While exact causal mechanisms are unclear, current evidence suggests that spawning rates are influenced by interacting factors including water temperature, flow events, and some prevailing antecedent conditions (King et al. 2016; Koehn et al. 2020). Therefore, improvement in the timing of spring-summer flows with water for the environment can contribute to golden perch environmental outcomes.

Observations appear to indicate that detectability of YOY is somewhat unreliable, particularly during the peak of high flow events. This is evidenced by a lack of YOY cohorts detected where subsequent 1 year old cohorts are detected in following years.

In other regions of the MDB, large lake environments have been posited as critical nursery habitats for golden perch (Stuart and Sharpe 2020). In the SA River Murray, juvenile golden perch are commonly found in floodplain lakes following overbank flooding, but also in more permanent habitats including the Lakes, which may facilitate more regular recruitment. Indeed, at times, age structures of golden perch from the Lakes have differed from fish sampled from the main channel, suggesting localised recruitment had occurred. While hypothesised, the influence of processes occurring in the Lakes on broader population dynamics is poorly understood and warrants further investigation. Furthermore, golden perch are the target of a commercial fishery within the Lakes; the influence of this fishery on the broader population also warrants further investigation.

11.8.3 Unanticipated outcomes

Observed outcomes for golden perch age structure were not as expected at this stage of Basin Plan implementation, in-part due to life history processes that align with factors outside of current management mechanisms. While more water for the environment was expected to allow golden perch age structures to improve, with respect to the expected outcomes, this has not been the case, highlighting the importance of high within-channel flows and overbank high flow events in the life history of the species.

11.8.4 Actions to achieve environmental outcomes

The condition and resilience of golden perch populations can be improved through promoting spring–summer within-channel flows >20,000 ML day^{-1}. Furthermore, maintaining suitable within-channel flows will contribute to the overall resilience of golden perch populations. Encouraging limited or low-level recruitment for maintaining the presence of juvenile fish in the population, while also simultaneously contributing to connectivity throughout the Basin.

In between periodic high-flow events, the continued delivery of smaller volumes of water for the environment to support recruitment and contribute to the overall resilience of the population. Weir pool manipulation, including lowering, which can increase the length of fast-flowing habitat and may further improve recruitment in golden perch. Maintaining connectivity at local and regional scales to support spawning and recruitment is also critical.

Full implementation of the Basin Plan, including recovery and delivery of the 450 GL of additional water for the environment and addressing current water delivery constraints, may help further improve these mechanisms for flow-cued fish species such as golden perch.

11.8.5 Conclusion

The current age structure of golden perch includes fewer young and juvenile individuals than expected, however the overall trend for golden perch population age structure has improved since the Millennium Drought (1996–2010). The improved trend is likely due to an overall improvement in hydroclimatic conditions post-Millennium Drought, including several high flow events. There are some indications that water for the environment delivered under the Basin Plan has contributed to these outcomes by supporting low-level recruitment associated with spring–summer freshes.

12 Case Study: Frogs at Chowilla Floodplain

12.1 Introduction

Water regime has a strong influence on frogs in the MDB (Wassens 2010). The inundation of temporary wetlands and floodplains (compared to permanent habitats) provides favourable conditions for tadpole development, as they generate complex habitats often with lower predator densities and nutrition from littoral, floodplain and terrestrial vegetation and organic matter (Hoffmann 2018; McGinness et al. 2014; Sarker et al. 2022; Wassens & Maher 2011). The hydroperiod (length of water residency) of seasonal inundations has a strong influence on the lifecycle of frogs, and the reproduction and recruitment of many species depends on the duration and timing of seasonal flows (Mathwin et al. 2021; Wassens 2010).

River regulation and water extraction has dramatically altered the natural water regime in the SA River Murray. Historically, interannual flows were highly variable, leading to fluctuations in water levels of temporary wetlands. However, river regulation, focused on maintaining stable water levels in weir pools, has resulted in the permanent and stabilised inundation of once-temporary wetlands near the channel (Walker & Thoms 1993). A reduction in duration, frequency and magnitude of overbank flow events that inundate temporary wetlands and floodplains (Maheshwari et al. 1995; Ye et al. 2023) has reduced the extent and frequency of frog breeding events and may contribute to a decline in species that are unlikely to survive prolonged dry periods (Mathwin et al. 2023; McGinness et al. 2014; Wassens 2010).

In the SA Riverland region, there are a total of eight frog species: eastern sign-bearing froglet (*Crinia parinsignifera*), eastern banjo frog (*Limnodynastes dumerilii*), long-thumbed frog (*Limnodynastes fletcheri*), spotted marsh frog (*Limnodynastes tasmaniensis*), Peron's tree frog (*Litoria peronii*), southern bell frog (*Litoria raniformis*), painted burrowing frog (*Neobatrachus pictus*), and Sudell's burrowing frog (*Neobatrachus sudellae*). The southern bell frog is a Vulnerable-listed species under the *Environment Protection and Biodiversity Conservation Act 1999*, as the species has experienced a regional decline throughout south–eastern Australia (Clemann & Gillespie 2012; Mathwin et al. 2023), leading to a fragmented and disjunct distribution in the SA River Murray (Mathwin & Whiterod 2021).

Water for the environment is a key management tool for stimulating frog breeding and mitigating the effects of river regulation. Targeted delivery to temporary wetlands can simulate conditions that are conducive to wetting and drying phases, benefiting tadpole abundance in the absence of natural inundation events (Hoffmann 2018). Maintaining a minimum water level within these wetlands can also promote amphibian outcomes in the SA River Murray (Robinson et al. 2021), whilst the frequency aspect of delivery may reduce the probability of extinction in amphibian populations (Mathwin et al. 2023). Similar frog breeding outcomes from delivery of water for the environment have also been observed at wetlands in other Basin States (McGinness et al. 2014; Sarker et al. 2022).

To better understand the effect of water for the environment on frog populations, in particular the southern bell frog in the SA Riverland region, we present a case study from Chowilla, a managed floodplain of the SA River Murray. Investigated are frog breeding activities and adult recruitment on the Chowilla floodplain, in response to a managed floodplain inundation in 2021–22, and a further managed floodplain inundation overtaken by the large natural flood event in 2022–23. Data from the Chowilla floodplain were collected by the DEW under TLM Chowilla Condition Monitoring program, as part of its ongoing responsibilities for effective use and management of water for the environment in South Australia.

12.2 Method

12.2.1 Regulator operations

Frog breeding and recruitment were monitored on the Chowilla floodplain during two successive floodplain operations in 2021–22 and 2022–23. Full operational details and methodologies are described in Hodder & Vial (2022) and Hodder & Vial (2024). In 2021–22, the Chowilla environmental regulator was operated in conjunction with a weir pool raising at Lock 6 beginning in early August, successfully raising water levels in Chowilla Creek by 3.29 m (19.59 m AHD) by early October. This was sustained for four weeks until November when the regulator began to decrease water levels and the operation was completed by December 2021, successfully inundating ~5,500 ha (Figure 12-1). The Chowilla environmental regulator was again operated during winter and spring in 2022 commencing in late July, successfully raising water levels in Chowilla Creek by 3.25 m (19.55 m AHD) by mid-September. Following an increase QSA >50,000 ML day^{-1}, the floodplain operation was ceased in October 2022, and by late December the natural flood had peaked at >185,000 ML day^{-1}, inundating the vast majority of the Chowilla floodplain (Figure 12-1). QSA had receded below 35,000 ML day^{-1} by the end of February 2023.

12.2.2 Frog call surveys

Frog calling was surveyed at sites for five minutes each after sunset in 2021–22 and 2022–23. Species presence and abundance was determined via call recognition, with abundances recorded using an ordinal scale: 0 individuals, 1 male calling, 2-9 males calling, 10-50 males calling, and >50 males calling. In 2021–22, call surveys were conducted at six wetlands (Gum Flat, Werta Wert, Coppermine Complex, Lake Limbra, Lake Littra, and Brandy Bottle) over four (approximately) monthly sampling rounds between September and December. In 2022–23, surveys were conducted at four temporary wetlands (Brandy Bottle, Coombool Swamp, Gum Flat, and Monoman Depression), and one pool-connected creek (Pilby Creek), over two to three six-weekly sampling rounds between late August and mid-November to early-December. For each sampling round, two to three sites were surveyed at each wetland.

12.2.3 Tadpole surveys

Tadpole abundance was surveyed at 33 sites across seven wetlands (Lake Littra, Gum Flat, Lake Limbra, Brandy Bottle, Werta Wert, Lock 6 Road Floodplain, Coppermine Complex) in 2021–22. Four sampling rounds were undertaken corresponding to the filling (September), peak (October), and recession (November and December) stages of the managed inundation. At each site, two fyke nets (one standard and one double-winged) (Hodder & Vial 2022) were placed in shallow water (~30–60 cm deep) within fringing frog habitats (e.g. lignum vegetation). In 2022–23, tadpoles were sampled from 18 sites in four large wetlands (Lake Limbra, Lake Littra, Lock 6 Road Floodplain, and Werta Wert), with sampling rounds aligning with those in 2021–22, except for the last round (February) due to peak flooding. At each site, three single-winged fyke nets were deployed to lessen the sample dilution due to increased inundation extent.

Fyke nets were set during the evening and collected the next morning, with tadpoles in each net transferred to water tubs where they were identified to species level (where possible), counted, measured (tail-snout length) and development stage determined (as per Gosner 1960). Due to difficulties differentiating between tadpoles from several species; the eastern banjo frog, long-thumbed frog and spotted marsh frog were grouped together; and the painted burrowing frog and Sudell's burrowing frog were also grouped together (Anstis 2017; Bino et al. 2018). Development stages were only recorded from a subset of net samples; the first 25 individuals of each net were staged in 2021–22, and the first 30 individuals were staged in 2022–23, with the remainder identified and counted.

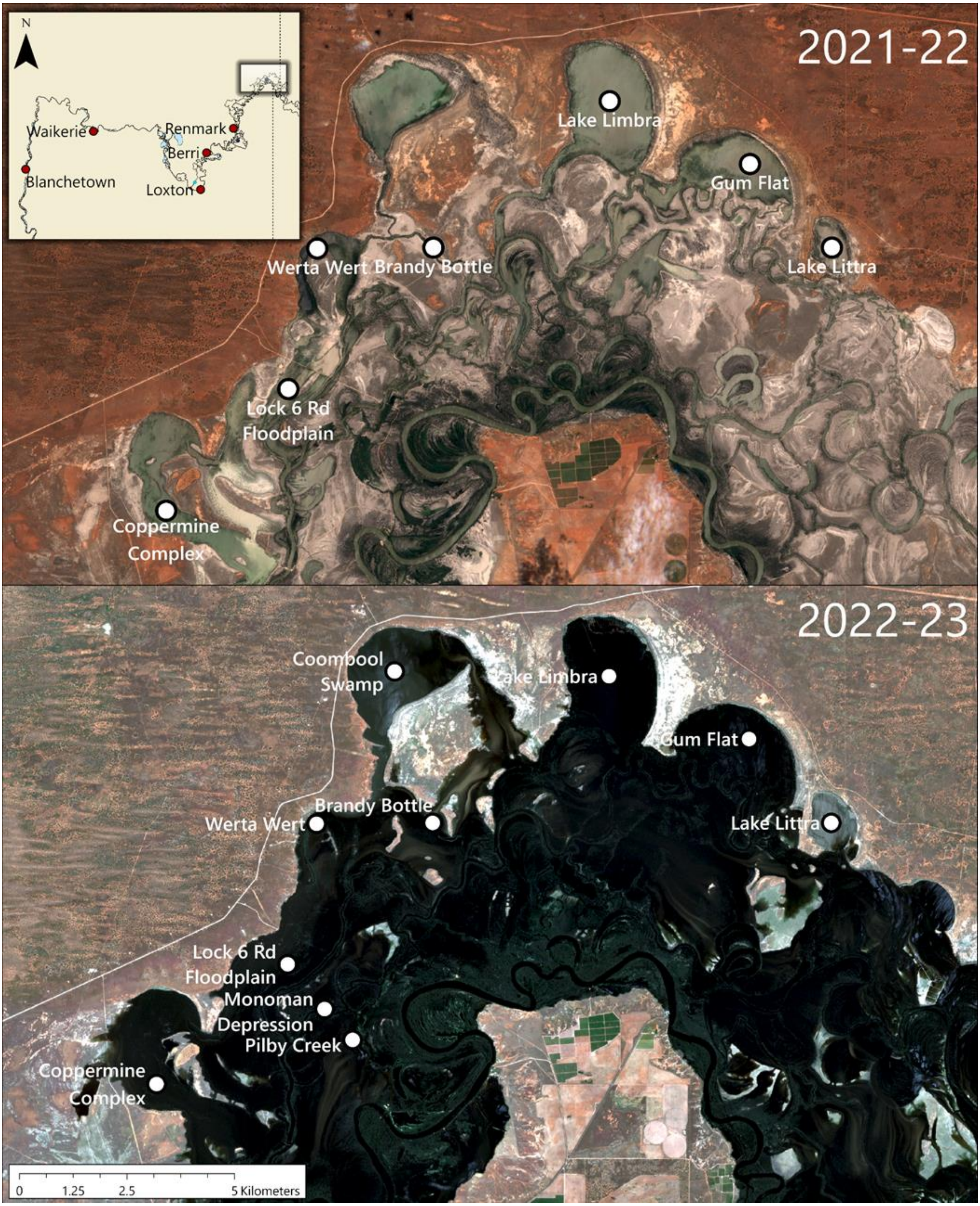


Figure 12-1. The location of wetlands sampled surveyed for frog calls and tadpoles, and extent of inundation on the Chowilla floodplain during 2021–22 (top; image dated 28 October 2021) and the 2022–23 flood (bottom; image dated 2 December 2022).

12.2.4 Limitations and assumptions

Sampling during the Chowilla regulator operation in 2021–22, compared to 2022–23, aimed to maximise the spatial distribution of sites across the floodplain, rather than focusing on replication across sampling rounds. Also, access to certain sites was restricted during different sampling rounds between the two years. Difficulty in identifying *Neobatrachus* and *Limnodynastes* tadpoles may have led to the misidentification of *Neobatrachus* individuals when they were in fact *Limnodynastes* tadpoles. We believe this is a relatively small proportion of overall captures, and unlikely to significantly influence the results. However, the ratio of *Neobatrachus* to *Limnodynastes* individuals may have been over-estimated in these results, and direct comparisons between these two genera should be interpreted with caution.

The focus on the managed floodplains of Chowilla (with extensive infrastructure to enable managed floodplain inundation) is presented as a case study, and does not reflect the responses or challenges faced in other areas of the SA River Murray. As such, these results cannot infer population dynamics throughout the lower catchment.

12.3 Results

12.3.1 Adult male calling

All eight frog species expected to be present on the Chowilla floodplain were heard during surveys in 2021–22, and seven of the eight species were heard at all surveyed wetlands (Table 12–1). Peron's tree frog was the most abundant calling species, and each of the eight species were heard in abundances of 10–50 individuals at a minimum of one wetland, except for the painted burrowing frog. Adult males of the southern bell frog were most abundant in two of the largest Chowilla wetlands (Gum Flat and Lake Limbra).

Table 12–1. Maximum abundances (in categories) of frog species based on male calls heard during surveys of inundated wetlands during the operation of the Chowilla regulator in 2021–22.

Species	Brandy Bottle	Coppermine	Gum Flat	Lake Limbra	Lake Littra	Werta Wert
Eastern sign-bearing froglet (*Crinia parinsignifera*)	2–9	2–9	10–50	2–9	2–9	10–50
Eastern banjo frog (*Limnodynastes dumerilii*)	2–9	2–9	2–9	2–9	2–9	10–50
Long-thumbed frog (*Limnodynastes fletcheri*)	2–9	2–9	10–50	2–9	2–9	2–9
Spotted marsh frog (*Limnodynastes tasmaniensis*)	2–9	10–50	10–50	10–50	10–50	10–50
Peron's tree frog (*Litoria peronii*)	10–50	10–50	10–50	10–50	10–50	10–50
Southern bell frog (*Litoria raniformis*)	2–9	2–9	10–50	10–50	2–9	2–9
Painted burrowing frog (*Neobatrachus pictus*)	0	2–9	1	2–9	2–9	2–9
Sudell's burrowing frog (*Neobatrachus sudellae*)	1	10–50	2–9	2–9	10–50	2–9

During the 2022–23 flood, seven of the eight expected frog species were recorded (Table 12–2). The painted burrowing frog was not recorded during call surveys, although an adult was captured during the tadpole surveys. All six wetland dependent frog species (eastern banjo frog, long-thumbed frog, eastern sign-bearing froglet, Peron's tree frog, and southern bell frog) were recorded during the surveys. Each of these wetland dependent frog species were recorded in abundances of 10–50 calling individuals at a minimum of one wetland, except for the eastern banjo frog which had a maximum calling abundance of 2–9 individuals. Peron's tree frog was the most abundant species, while the southern bell frog was the equal-second highest male calling species present, along with the spotted marsh frog and the eastern sign-bearing froglet.

Table 12–2. Maximum abundances (in categories) of frog species based on male call surveys of inundated wetlands during the flood in 2022–23.

Species	Brandy Bottle	Coppermine	Gum Flat	Lake Limbra	Lake Littra
Eastern sign-bearing froglet (*Crinia parinsignifera*)	10–50	2–9	10–50	10–50	10–50
Eastern banjo frog (*Limnodynastes dumerilii*)	2–9	2–9	2–9	2–9	2–9
Long-thumbed frog (*Limnodynastes fletcheri*)	2–9	2–9	10–50	2–9	2–9
Spotted marsh frog (*Limnodynastes tasmaniensis*)	10–50	2–9	10–50	10-50	10–50
Peron's tree frog (*Litoria peronii*)	10–50	10–50	10–50	10–50	10–50
Southern bell frog (*Litoria raniformis*)	2–9	10–50	10–50	10-50	10–50
Painted burrowing frog (*Neobatrachus pictus*)	0	0	0	0	0
Sudell's burrowing frog (*Neobatrachus sudellae*)	2–9	0	2–9	2-9	0

12.3.2 Tadpole abundance

All five expected tadpole taxa (comprising three species and two genera; see section 12.2.3) were captured in both 2021–22 and 2022–23, although the eastern sign-bearing froglet was recorded just once during the flood (Table 12–3). The eastern banjo frog, long-thumbed frog, spotted marsh frog, Peron's tree frog, and the southern bell frog had the highest mean abundance among all species during the regulator event, and these abundances were substantially higher compared with observations during the 2022–23 River Murray flood. The eastern banjo frog, long-thumbed frog, and spotted marsh frog had the highest mean tadpole abundance among all frog species during the 2022–23 River Murray flood.

Table 12–3. Mean and standard error (S.E.) of tadpoles captured per fyke net across all sites from sampling during the 2021-22 Chowilla environmental regulator operation and the 2022–23 flood event.

Species	Mean ± S.E.	
	Regulator operation (2021–22)	**Flood event (2022–23)**
Eastern sign-bearing froglet (*Crinia parinsignifera*)	0.44 ± 0.19	0.01 ± 0.01
Eastern banjo frog, long-thumbed frog and spotted marsh frog (*Limnodynastes* spp.)	17.67 ± 6.97	11.98 ± 2.11
Peron's tree frog (*Litoria peronii*)	7.23 ± 2.60	7.28 ± 2.25
Southern bell frog (*Litoria raniformis*)	3.56 ± 0.80	3.67 ± 1.02
Painted burrowing frog and Sudell's burrowing frog (*Neobatrachus* spp.)	72.93 ± 18.61	8.82 ± 1.78
Total	**163.04 ± 38.51**	**36.66 ± 6.17**

Lock 6 Road Floodplain and Lake Littra had the highest mean tadpole abundances per fyke net of the four wetlands surveyed in both years. Abundances of painted burrowing and Sudell's burrowing tadpoles were highly variable across these two wetlands, which might be due to differences in abundances across sampling rounds. The Peron's tree frog and southern bell frog had comparable abundances during both events, and the southern bell frog was most abundant in Lock 6 Road Floodplain (Figure 12-2).

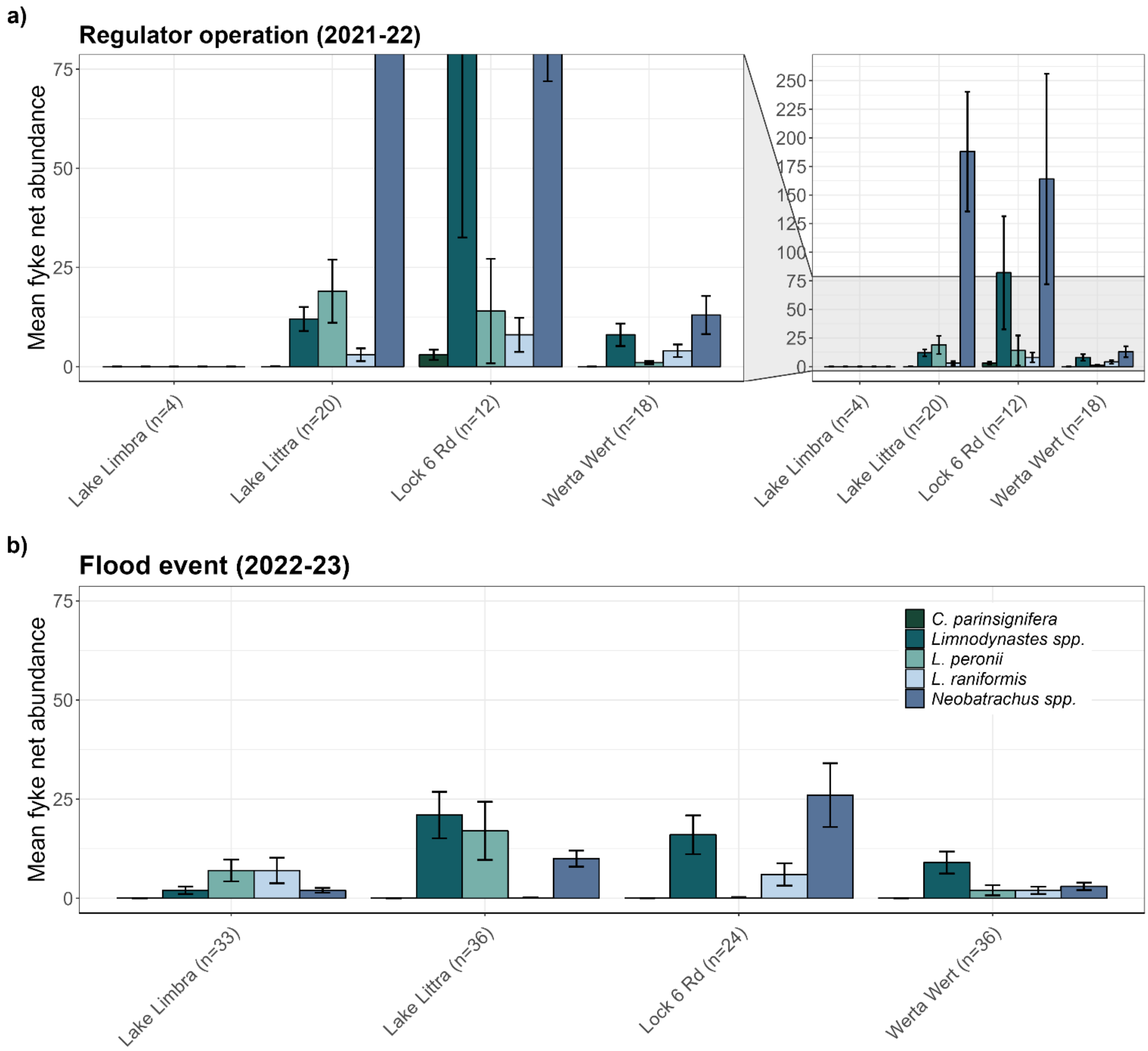


Figure 12-2. Mean tadpole abundance per fyke for the five frog taxa that were detected during a) the 2021–22 environmental regulator operation, and b) the 2022–23 flood event, on the Chowilla floodplain. "*n* =" denotes the number of fyke nets sampled in each wetland. Note: Lake Limbra was only surveyed once in September in 2022.

The distributions of tadpole development stages indicate that individuals reached stage ≥42 (i.e. a metamorph) for all taxa (excluding the eastern sign-bearing froglet) in both 2021–22 (Figure 12-3) and 2022–23 (Figure 12-4). As time progressed under each event, the proportions of early-stage tadpoles reduced and late-stage tadpoles increased for all taxa. During 2021–22, completion of metamorphosis (stage 46) was recorded for eastern banjo frogs, long-thumbed frogs, spotted marsh frogs, painted burrowing frogs, and Sudell's burrowing frogs, while metamorphs (stages 42 to 45) were recorded for southern bell frogs (stage 42) and Peron's tree frogs (stage 44). Therefore, successful recruitment was recorded for eastern banjo frog, long-thumbed frog, spotted marsh frog, painted burrowing frog, and Sudell's burrowing frog, and it was likely that some southern bell frogs and Peron's tree frogs also successfully recruited (see *n* = in Figure 12-3).

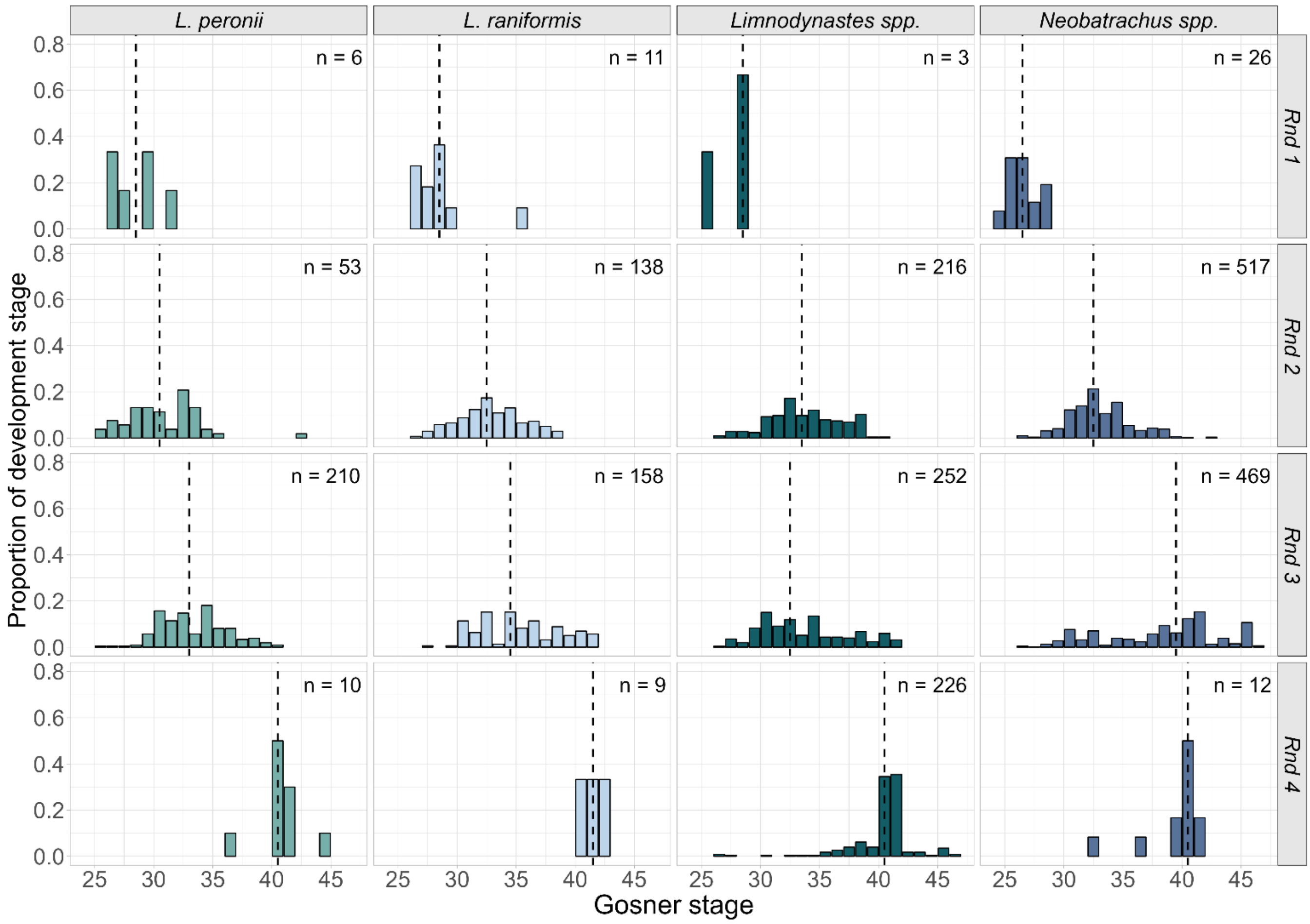


Figure 12-3. The proportion of each developmental stage (range: 24–46) for four amphibian taxa sampled in Chowilla wetlands during the environmental regulator event in 2021–22. Development stages indicate tadpole progression and growth towards adulthood (stage 46). '*n =*' denotes the total number of individuals staged for that species and sampling round, while the dashed line represents the median development stage. The eastern sign-bearing froglet (*C. parinsignifera*) is not shown due to low detection.

During the River Murray flood event in 2022–23, painted burrowing frog and Sudell's burrowing frog tadpoles were numerous in early to middle developmental stages evident during the first round in September, while no other species were recorded during this time. Despite this, each of the four amphibian taxa were recorded in the last stage of metamorphosis (stage 45) or having completed metamorphosis (stage 46), and therefore, successful recruitment to juvenile frogs is assumed.

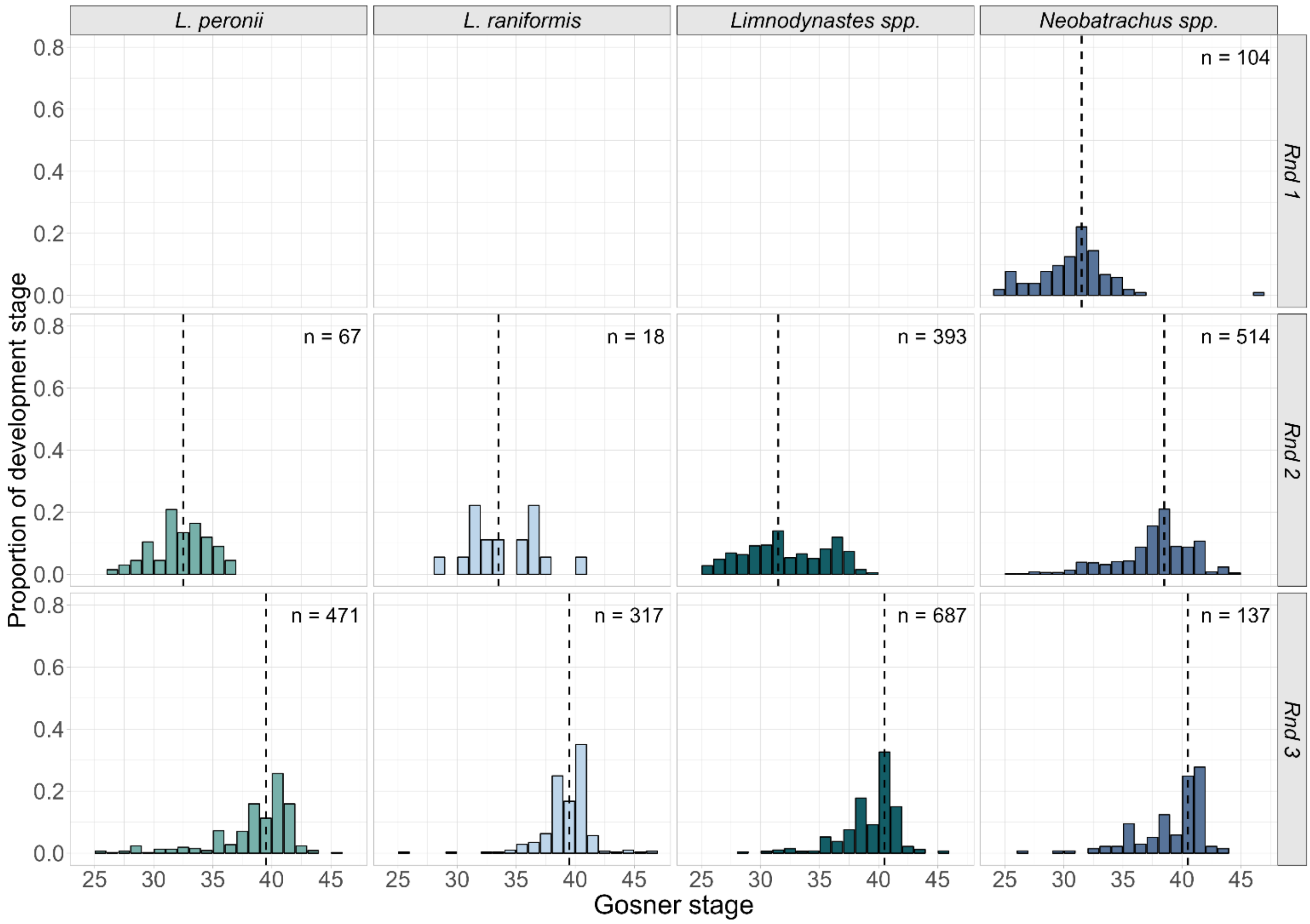


Figure 12-4. The proportion of each developmental stage (range: 24–46) for four amphibian taxa sampled in Chowilla wetlands during the flood event in 2022–23. Development stages indicate tadpole progression and growth towards adulthood (stage 46). '*n* =' denotes the total number of individuals staged for that species and sampling round, while the dashed line represents the median development stage. The eastern sign-bearing froglet (*C. parinsignifera*) is not shown due to low detection.

12.4 Evaluation

Inundation of temporary wetlands and floodplains through both delivery of water for the environment and natural flood events facilitate breeding activity and contribute to tadpole development. Conditions on the Chowilla floodplain in 2021–22 were conducive to breeding activity and successful recruitment of all eight expected frog species. Considering that differences in inundation extent between 2021–22 and 2022–23, the broadly equivalent responses (although varying in certain aspects; see below) in frog breeding, tadpole and successful recruitment indicate that delivery of water for the environment is an effective management tool in the absence of natural flooding. An important aspect of the riverine-floodplain environment is the mosaic of permanent and ephemeral waterbodies, which support the various life stages (e.g. breeding, metamorphism and dispersal) of amphibians (Cayuela et al. 2020; Wassens et al. 2008).

River regulation and water extraction has altered the flow regime of the SA River Murray, reducing the frequency of inundation of temporary wetlands below critical thresholds for amphibian species (Mathwin et al. 2023). Delivery of water for the environment aims to mitigate the effects of altered flow regimes and can provide habitat and recruitment opportunities for frogs in the SA River Murray (Hoffmann 2018). Strategic delivery of water for the environment helps to target specific wetland and floodplain sites, maximising the outcomes for amphibians and other water-dependent taxa at those sites where such intervention is possible. Although the targeted delivery of water for the environment is an effective management tool (particularly during periods of low QSA), it has limited spatial influence at the scale of the whole SA River Murray in comparison to natural flood events, which result in a greater regional response in riverine frogs (Hoffmann 2018; Wassens et al. 2008).

12.4.1 Breeding activity

Frog calls were recorded for all eight frog species detected during the 2021–22 regulator event, and for seven of eight species during the 2022–23 flood. A minimum of seven frog species were detected at each wetland during the regulator event (2021–22), and the diversity of calling was greater than detected in the years preceding the regulator operation (Hodder & Vial 2022). This was likely due to greater breeding opportunities associated with a greater inundation area, compared to the previous five watering operations (Hodder & Vial 2022). Positive relationships between wetland inundation and the abundance of male calling spotted marsh frogs, long-thumbed frogs, eastern sign-bearing froglets, and Peron's tree frog have been observed in wetlands in the northern MDB (Sarker et al. 2022). Sampling from both years suggests that watering operations have benefited breeding in the southern bell frog (Hodder & Vial 2024; Mathwin et al. 2023; Mathwin et al. 2021).

Maximum calling abundances of wetland dependent frog species (i.e., eastern banjo frog, long-thumbed frog, eastern sign-bearing froglet, Peron's tree frog, and southern bell frog) were similar during the regulator and flood events. The spotted marsh frog was abundant at many surveyed wetlands across both sampling years, considered to be a dispersive generalist species (Wassens et al. 2013). However, there were much higher calling abundances of Sudell's burrowing frogs and painted burrowing frogs recorded during the regulator event. This likely indicates a significant breeding event following preceding years of decreased breeding opportunity (Hodder & Vial 2022). For example, painted burrowing frogs and Sudell's burrowing frogs create underground cocoons for aestivation periods, minimising water loss during extended dry periods, emerging when sufficient rainfall occurs, and breeding when temporary pools become available (Ocock & Wassens 2018). Sudell's burrowing frog was not observed for at least five years, and painted burrowing frogs for at least eight years, on the Chowilla floodplain prior to 2021–22, although earlier winter breeding may have been a cause for this (Hodder & Vial 2022). However, emergence cues from greater rainfall (see Figure 3-1) combined with breeding opportunities from temporary wetlands inundated by the regulator operation likely contributed to the 2021–22 breeding event, supported by the high tadpole abundance of painted burrowing frogs and Sudell's burrowing frogs. Comparatively lower calling responses from these burrowing frogs in 2022–23 may suggest a migration to other semi-arid or arid areas during the larger scale inundation (Hodder & Vial 2024) or increased dispersal across available habitat outside the sampling area.

12.4.2 Tadpole development

Tadpoles were recorded across all wetlands during both events (aside from Lake Limbra in 2021–22), and total tadpole abundances were greatest during the late-October and November to early-December surveys in both years (Hodder & Vial 2024). It is likely that all eight riparian species were successfully breeding, indicated by tadpole presence and calling activity; however, this could not be confirmed for the eastern banjo frog, long-thumbed frog, spotted marsh frog, painted burrowing frog or Sudell's burrowing frog, due to similarities in appearance during early developmental stages (Bino et al. 2018). The low captures of the eastern sign-bearing froglet tadpoles during both events may be due to sampling technique, i.e. their size compared to net mesh width and/or the early development window of this species (Hodder & Vial 2022; Wassens et al. 2013).

The disparity in tadpole abundance of painted burrowing frogs and Sudell's burrowing frogs between the two sampling years (Table 12–3; Figure 12-2) supports the high likelihood that a breeding event occurred in 2021–22. However, tadpole abundance of other species was similar across both survey years. Tadpole abundances of Peron's tree frogs and southern bell frogs were similar at wetlands sampled across both years (Table 12–3; Figure 12-2). Moreover, tadpole abundance of eastern banjo frogs, long-thumbed frogs and spotted marsh frogs were comparable across both sampling years, aside from Lock 6 Road Floodplain, perhaps due to the lignum-dominated habitats at this wetland providing greater protection (Hodder & Vial 2022). The similarity in tadpole abundance for these taxa are noteworthy, however the substantially higher volumes of water during the flood may have diluted tadpole catches compared to the previous year, indicating a higher overall tadpole abundance during the flood year than are represented in sampling.

12.4.3 Recruitment

Successful recruitment of all species was likely during both years, with some differences evident. Painted burrowing frogs and Sudell's burrowing frogs were the fastest taxa to metamorphise in both years, considering their responsiveness to rainfall and early winter breeding. Eastern banjo frog, long-thumbed frog, and spotted marsh frog recruitment was likely during both events considering some species within the genera are known to be dispersive generalists suited to a variety of aquatic habitats (Wassens et al. 2013). Successful metamorphosis of Peron's tree frog and southern bell frog tadpoles were likely during the regulator event and the natural flood, with metamorphs (stage >42) observed in both years during the final sampling round (Figure 12-3; Figure 12-4). However, there were two distinct patterns in tadpole development in these species. Firstly, there was a slower metamorphism of Peron's tree frogs and southern bell frogs during the natural flood, perhaps related to the absence of tadpoles during September sampling (Hodder & Vial 2024). Secondly, there were slightly more metamorphs and completed tadpoles (stage 46) by the sampling event in 2022–23, perhaps due to a more favourable hydroperiod for tadpole development.

Hydroperiod (length of water residency) strongly influences recruitment success in wetlands, and in Riverland frog species a minimum summer-autumn hydroperiod of 3–4 months is required for larval development (Hoffmann 2018). Receding waters can lead to greater open water and less habitat complexity. Wetlands during the regulator operation (2021–22) remained inundated for four months (September to December); however, water levels began to recede by November, just as water temperatures reached 20°C (Hodder & Vial 2022). The receding water levels likely explain the marked reduction in Peron's tree frog and southern bell frog tadpole abundance by December (Hodder & Vial 2022). Conversely, as tadpole development can be accelerated by drying habitats with increasing temperatures (Albecker et al. 2023), it is possible that tadpole development of Peron's tree frogs and southern bell frogs was accelerated across this period (Hodder & Vial 2022; Hoffmann 2018). Therefore, the greater availability of inundated vegetation is an important factor in successful metamorphosis of Peron's tree frog and southern bell frog tadpoles during the flood, whilst completed stages might be missing from the 2021–22 data due to accelerated metamorphosis.

12.4.4 Managed inundations

It is important to note that other than at Chowilla, Pike and Katarapko managed floodplains, the generation of managed inundation events is not achievable at the majority of the remainder of the SA floodplains which are dependent upon the restoration of increases in River Murray flows to generate overbank flooding conditions. These results demonstrate that managed inundations can support local frog populations, but the health of regional populations is largely unknown.

12.5 Conclusion

Targeted delivery of water for the environment to the Chowilla floodplain (through raising Weir 6 and operating the Chowilla environmental regulator in 2021–22) created conditions conducive to breeding activity for all eight frog species found in the region. This event was expected to have led to the successful recruitment for all eight frog species. This targeted delivery of water, including water for the environment, therefore provides an effective management tool for supporting the maintenance of frog populations in the absence of natural flooding.

The importance of large, unregulated floods was also demonstrated, as Peron's tree frogs and southern bell frogs likely had greater successful recruitment over a much greater area during the 2022–23 River Murray flood event. Considering the inundation differences between the two years (i.e. 5,500 ha in 2021–22 and 17,000 ha in 2022–23), the broadly equivalent responses (although varying in certain aspects) in frog breeding, tadpole, and successful recruitment are promising for the ongoing management of parts of the Chowilla floodplain able to be influenced by the managed inundation and targeted delivery water for the environment to pumped wetlands.

13 Glossary and Abbreviations

13.1 Abbreviations

AHD	Australian Height Datum
ARI	Average Return Intervals
CEWH	Commonwealth Environment Water Holder
CPUE	Catch-per-unit-effort
DEW	Department for Environment and Water (South Australia)
DOC	Dissolved organic carbon
EWRs	Environmental watering requirements
FDR	False Discovery Rate
LTIM	Long Term Intervention Monitoring
LTWP	Long-term Watering Plan
AHD	Australian Height Datum
MDB	Murray–Darling Basin
MDBA	Murray–Darling Basin Authority
MER	Monitoring, Evaluation and Research
PEA	Priority Environmental Asset
PIRSA	Primary Industries and Regions South Australia
QSA	Flow at the South Australian border
SARDI	South Australian Research and Development Institute
SARFIIP	South Australian Riverland Floodplains Integrated Infrastructure Program
STIM	Short Term Intervention Monitoring
TCI	Tree Condition Index
TL	Total Length
TLM	The Living Murray
WRP	Water Resource Plan
YOY	Young-of-year

13.2 Glossary

Aestivation	A state of dormancy, similar to hibernation.
AHD	The datum that sets mean sea level as zero elevation.
Amphibious vegetation	Plants that can survive in both aquatic and terrestrial environments.
Bank-full flows	Flows large enough to fill the river channel only.
Basin Plan	A widespread, across governments, agreement to manage and protect water in the Murray–Darling Basin.
Biota	A grouping of animals, plants, fungi, and other organisms that all share the same geographical region.
Blackwater	An event that occurs when large amounts of decaying organic matter such as soil and leaves enter the river from floodwaters.
Diadromous (fish)	A fish that travels between salt water and fresh water as part of its life cycle.
Drum nets	A fish trap consisting of mesh supported by three large diameter bands to form a body or shape which is closed at one end and a cove at the other.
Ecosystem	A group of living organisms that live in and interact with each other in a specific environment.
Electrofishing	Fishing that uses an electrical current to temporarily immobilise fish.
Fecundity	The ability to produce an abundance of offspring.
Fishway	A structure that provides fish with passage past an obstruction (i.e. a barrage).
Froglet	A developmental stage of a frog. At this point a tadpoles gills have disappeared and its lungs have enlarged.
Food web	A natural interconnection of food chains showing what eats what, starting with primary production based on Carbon fixation by plants.
Fyke net	A fish net that consists of netting mounted on rings. It can have wings which guide the fish into the net.
Gill nets	A fishing net which is hung vertically from a line with regularly spaced floaters that hold the line on the surface.
Hydraulics	The flow of water in rivers.
Invertebrates	Cold-blooded animals without a backbone or bony skeleton, such as insects, worms and crabs.
Lateral connectivity	Connectivity outwards towards the floodplain
Lignum	A drought and salinity tolerant plant, native to inland Australia, which produces dense tangled growth.
Littoral zone	The part of the river that is close to shore.
Lentic	Water that is still or very slow flowing.

Lock	A device used for raising and lowering boats, ships and other watercraft between stretches of water of different levels.
Longitudinal connectivity	Connectivity between upstream and downstream.
Lotic	Actively moving water.
Macronutrients	The nutrients required by plants in large amounts, such as nitrogen, phosphorus, sulfur, calcium and potassium, all of which are obtained from the soil.
Managed floodplain inundation	Floodplain inundation events that are attributed to management actions rather than flow related increases in water level.
Metamorphs	An organism that has undergone metamorphosis.
Metamorphosis	The process of transformation from an immature form to an adult form in two or more distinct stages.
Microinvertebrates	A small microscopic animal without a backbone, that resides in water, such as worms, snails, mites and insects.
Migratory shorebird	A group of waterbirds with long legs and bills relative to their body size, which forage in shallow water habitats and undergo international migrations.
Millennium Drought	From late 1996 to mid 2010, much of southern Australia (except parts of central Western Australia) experienced a prolonged period of dry conditions, known as the Millennium Drought. The drought conditions were particularly severe in the more densely populated southeast and southwest and severely affected the Murray–Darling Basin and virtually all of the southern cropping zones. The period from 2007–2010 was particularly extreme with extended periods of no flow through the barrages to the Coorong.
Murray–Darling Basin	An area of about 1 million km^2 in the south east of Australia, it is almost 1,400 km long and about 800 km wide.
Overbank flows	Flow that rises over the riverbank and connects the river to the surrounding floodplains and wetlands.
Pelagic	Inhabiting the water column.
Photosynthesis	The process by which plants use sunlight, water, and carbon dioxide to create oxygen and energy in the form of sugar.
QSA	Flow at the South Australian border, often expressed as mega litres per day (ML day^{-1}).
Quadrat	A frame used to isolate a standard unit of area for study.
Ramsar Convention	An international environmental treaty that protects areas that are classified wetlands of international importance.
Respiration	The process of plants using up the sugars made through photosynthesis and turning them into energy for growth, reproduction, and other life processes.
Regulator	A weir-like structure designed to raise water levels to enable inundation of large areas of the floodplain and wetlands.
Re-snagging	The reintroduction of woody debris to the river.

Riparian	The transition zone between the aquatic and upland areas.
Salt-wedge	Seawater intrusion in an estuary as a wedge-shaped bottom layer which hardly mixes with the overlying fresh water layer.
Seedbank	A natural storage of seed in the soil or under leaf litter that enables the production of plants in future generations.
Shedding-floodplain	The part of the floodplain that will shed, rather than retain water.
Silviculture	The act of controlling the establishment, growth, composition, health, and quality of forests and woodlands to meet landowners and wildlife needs.
Species richness	The number of species within a defined region.
Taxa	A unit used to biologically classify fungi, plants and animals.
Transpiration	The water movement from the soil to the atmosphere via plants.
Tree Condition Index (TCI)	A system used to score the condition of floodplain trees based on the extent and density of their crown.
Velocity	The speed of water flow.
Water for the environment	Environmental water is 'held' or 'planned' environmental water, defined in the Water Act 2007. *Held* environmental water is available under a water access right for the purposes of achieving environmental outcomes; *planned* environmental water is committed to environmental outcomes and cannot be used for any other purpose unless required in emergency circumstances.
Weir	A barrier which is built across a river in order to control the flow of water
Weir pool	The body of water stored behind a weir.
Weir pool raising	The raising of a weir pool height to increase water levels.
YOY	Young of Year (fish). The fish of a species younger than one year of age.

14 References

Introduction

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Case Study: Frogs at Chowilla Floodplain

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Appendices

Appendix A: *Summary of the LTWP targets set for understorey vegetation*

Shedding-floodplain sites	
Functional distribution	**Functional richness**
Minimum of **20% of cells** containing native flood dependent or amphibious taxa **once every three years** on average with maximum interval no greater than 5 years.	Native flood dependent and amphibious **species richness >15** at least **once every three years**.
Minimum of **40% of cells** containing native flood dependent or amphibious taxa **once every five years** on average with maximum interval no greater than 7 years.	Native flood dependent and amphibious **species richness >25** at least **once every five years**.
Minimum of **65% of cells** containing native flood dependent or amphibious taxa **once every seven years** on average with maximum interval no greater than 10 years.	Native flood dependent and amphibious **species richness >40** at least **once every seven years**.

Appendix B: *Annual achievement and maximum return intervals for the percentage of cells containing flood-dependent and/or amphibious taxa*

Year	**Shedding-floodplain sites**					
	≥20% cells – 1 in 3 yrs.		**≥40% cells – 1 in 5 yrs.**		**≥65% cells – 1 in 7 yrs.**	
	Annual	**Max. return interval (5 yrs.)**	**Annual**	**Max. return interval (7 yrs.)**	**Annual**	**Max. return interval (10 yrs.)**
2006	0	Insuffic. data	0	Insuffic. data	0	Insuffic. data
2007	1	Met	0	Insuffic. data	0	Insuffic. data
2008	0	Met	0	Insuffic. data	0	Insuffic. data
2009	0	Met	0	Insuffic. data	0	Insuffic. data
2010	1	Met	0	Insuffic. data	0	Insuffic. data
2011	1	Met	1	Met	0	Insuffic. data
2012	1	Met	1	Met	0	Insuffic. data
2013	0	Met	0	Met	0	Insuffic. data
2014	0	Met	0	Met	0	Insuffic. data
2015	1	Met	0	Met	0	Not met
2016	0	Met	0	Met	0	Not met
2017	1	Met	1	Met	1	Met
2018	1	Met	0	Met	0	Met
2019	1	Met	0	Met	0	Met
2020	0	Met	0	Met	0	Met
2021	0	Met	0	Met	0	Met
2022	1	Met	0	Met	0	Met
2023	1	Met	1	Met	1	Met
2017	1	Met	1	Met	0	Insuffic. data
2018	1	Met	0	Met	0	Insuffic. data
2019	1	Met	0	Met	0	Insuffic. data
2020	0	Met	0	Met	0	Insuffic. data
2021	0	Met	0	Met	0	Insuffic. data

Year	Shedding-floodplain sites					
	≥20% cells – 1 in 3 yrs.		≥40% cells – 1 in 5 yrs.		≥65% cells – 1 in 7 yrs.	
	Annual	**Max. return interval (5 yrs.)**	**Annual**	**Max. return interval (7 yrs.)**	**Annual**	**Max. return interval (10 yrs.)**
2022	0	Met	0	Met	0	Insuffic. data
2023	1	Met	1	Met	1	Met
2015	NA	NA	NA	NA	NA	NA
2016	NA	NA	NA	NA	NA	NA
2017	1	Met	1	Met	1	Met
2018	1	Met	1	Met	0	Met
2019	1	Met	1	Met	0	Met
2020	1	Met	0	Met	0	Met
2021	1	Met	1	Met	0	Met
2022	1	Met	1	Met	0	Met
2023	1	Met	1	Met	1	Met

Appendix C: *Interval achievement of targets for flood-dependent and/or amphibious species richness*

Year	Shedding-floodplain sites					
	15 species – 1 in 3 yrs.		25 species – 1 in 5 yrs.		40 species – 1 in 7 yrs.	
	Annual	Max. return interval (5 yrs.)	Annual	Max. return interval (7 yrs.)	Annual	Max. return interval (10 yrs.)
2006	0	NA	0		0	
2007	1		1		0	
2008	0		0		0	
2009	0		0		0	
2010	1		0		0	
2011	1		1		0	
2012	1		1		0	
2013	1		0		0	
2014	0		0		0	
2015	1		0		0	
2016	0		0		0	
2017	1		1		0	
2018	0		0		0	
2019	1		0		0	
2020	0		0		0	
2021	1		0		0	
2022	1		1		0	
2023	1		1		0	
2017	0	Insuffic. data	0	Not met	0	Insuffic. data
2018	0	Insuffic. data	0	Not met	0	Insuffic. data
2019	0	Insuffic. data	0	Not met	0	Insuffic. data
2020	0	Insuffic. data	0	Not met	0	Insuffic. data
2021	0	Not met	0	Not met	0	Insuffic. data
2022	0	Not met	0	Not met	0	Insuffic. data

Year	Shedding-floodplain sites					
	15 species – 1 in 3 yrs.		25 species – 1 in 5 yrs.		40 species – 1 in 7 yrs.	
	Annual	**Max. return interval (5 yrs.)**	**Annual**	**Max. return interval (7 yrs.)**	**Annual**	**Max. return interval (10 yrs.)**
2023	1	Met	0	Not met	0	Insuffic. data
2015	1	Met	1	Met	0	Insuffic. data
2016	NA	Met	NA	Met	NA	Insuffic. data
2017	1	Met	1	Met	1	Met
2018	1	Met	1	Met	0	Met
2019	1	Met	1	Met	0	Met
2020	1	Met	0	Met	0	Met
2021	1	Met	0	Met	0	Met
2022	1	Met	1	Met	0	Met
2023	1	Met	1	Met	1	Met

Appendix D: *Summary details of inundation amounts due to the operation of the environmental regulators at the three floodplains*

Year	Regulator height reached (m AHD)	Inundation extent (ha)	Floodplain area (ha)
Chowilla			
2014	19.1	2,300	17,700
2015	17.6 (in channel rise)	700	""
2016	19.75	7,650	""
2017			""
2018	18.5 (with concurrent pumping)	2,250	""
2019			""
2020			""
2021	19.65	5,500	""
2022	19.55	6,230	""
Pike			
2020	15.25	495	6,700
2021	15.8	990	""
2022	16.1	1,356	""
Katarapko			
2020	12.8	480	9,000
2021	13.2	796	""
2022	Only minor regulator operated	2 to 33	""

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