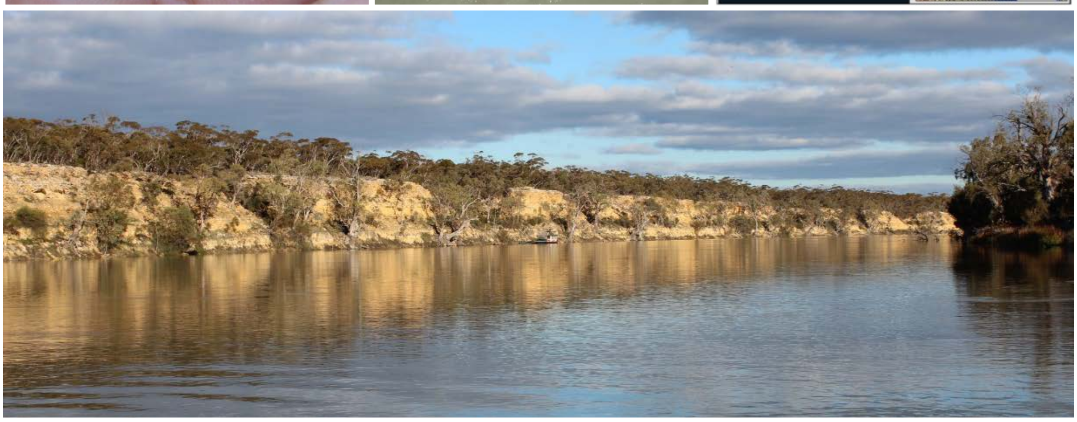
Commonwealth Environmental Water Office Long-Term Intervention Monitoring Project: 2014–2019

Lower Murray River

Summary Report

A summary report prepared for the Commonwealth Environmental Water Office by the Lower Murray River Selected Area team



April 2020

Commonwealth Environmental Water Office Long-Term Intervention Monitoring Project 2014–2019: Lower Murray River Summary Report. A summary report prepared for the Commonwealth Environmental Water Office by the Lower Murray River Selected Area team.

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Glossary

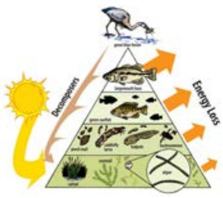
base flow	Flows that are confined to the low flow part of the river channel.
biofilm	A collection of microscopic organisms (made up of algae, bacteria and fungi) attached as a 'film' on living (e.g. tree root) and non-living (e.g. wooden pylon) surfaces.
flowing water habitat	Water with flow velocities greater than 0.3 metres per second.
hydraulics	The physical characteristics of water flow, e.g. velocity (speed) and turbulence.
freshes	Flows greater than base flow but below bankfull level.
hypoxia	Low oxygen levels in water that are detrimental to the health of aquatic animals. Water hypoxia is often associated with 'blackwater' events – when the water becomes dark in colour from decomposing organic matter (e.g. tree bark and leaves).
microinvertebrates	Invertebrates of microscopic size (e.g. rotifers, cladocerans and copepods), which may live in the water column, on the river floor or on vegetation along the river bank.
phytoplankton	Microscopic algae suspended in the water column that make their own food from sunlight through photosynthesis.
primary productivity	The rate at which energy is converted to organic compounds (food) by autotrophs (e.g. algae and plants) during photosynthesis.
recruitment	Survival past the critical stages of early life (e.g. larval) to become juveniles in a population. In this report, a fish that is sampled as a juvenile (~6 months old) in autumn is defined as a new recruit.
southern connected Basin	The southern connected Basin is a network of the Murray River and all tributaries that flow into it between the Hume Dam and the sea. The Lower Darling (below Menindee Lakes) is considered part of the southern connected Basin, whilst all rivers upstream of Menindee Lakes are considered as the Northern Basin.
spawning	The act or process of producing or depositing eggs.
unregulated flow	Unregulated flows occur when water in the system exceeds demands and are declared to be unregulated by the appropriate authority (source: http://www.bom.gov.au/water/awid/id-1026.shtml). They can be driven by substantial rainfall from upper tributaries, spills from headwork storages and rainfall rejection events.

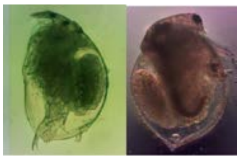
Executive summary

From 2014-15 to 2018-19, ~3,440 GL of Commonwealth environmental water was delivered through a series of watering events to the Lower Murray River (LMR), coordinated to achieve a range of environmental outcomes across the southern connected Murray-Darling Basin. This report presents the key ecological responses measured in the LMR during the five-year Commonwealth Environmental Water Office (CEWO) Long-Term Intervention Monitoring (LTIM) Project. A series of annual technical reports (Ye *et al.* 2020) provide detailed methods, results and evaluation of ecosystem responses to environmental water delivery.

Key outcomes of environmental watering

Key ecological outcomes from environmental water delivery in the LMR Selected Area from 2014-15 to 2018-19:

	The length of river with ‘flowing water’ habitat (greater than 0.3 metres per second) increased, mostly during 2017-18, and water levels were slightly more variable. More flowing water benefits native plants and animals that are adapted to a riverine environment. Variable water levels generally improve bank vegetation health and increase the diversity of biofilms, which is a key component of riverine food webs.
	The likelihood of low oxygen levels (e.g. <5 milligrams per litre, mg/L) during spring–summer was reduced due to increased water mixing and oxygen exchange from environmental water delivery. Aquatic animals generally need oxygen levels above 5 mg/L, particularly during spring–summer, which is the main reproductive season of many species.
	In the river channel, food production and consumption, and transport of nutrients and phytoplankton marginally increased. Greater primary production provides more food to aquatic food webs (e.g. for invertebrates and fish). Transported food resources from the river also benefit food webs in the Lower Lakes and the Coorong.
	Flows through the barrages to the Coorong were almost continuous throughout all years, maintaining connection between the river and the Coorong estuary. Some species need this connection to move between fresh and saltwater habitats to successfully reproduce. Environmental water substantially increased salt export out of the Basin, reduced salt import into the Coorong and reduced salinity concentrations in the Coorong. This was crucial in maintaining estuarine habitats, species diversity and ecosystem functions.

	Increased flows transported microinvertebrates from upstream sources to the LMR, and led to an increase in bank (littoral) organisms. Increased amount (density) and variety (diversity) of microinvertebrates may improve community resilience and better support larger organisms (e.g. larval fish) in the aquatic food web.
	Spawning of golden perch occurred in the LMR, but there was negligible 'recruitment' and diminished population resilience.

Learnings and management implications

The five-year project period was dominated by low flow conditions (<18,000 ML/d at the South Australian border) except for 2016-17, when there was unregulated, overbank flow (peak ~94,600 ML/d in December 2016). Over the five years, Commonwealth environmental water predominantly contributed to base flows and freshes in the LMR, particularly as winter and spring–early summer flow pulses. The proportion of weir pools (stretches of river between weirs) characterised by 'flowing water' habitat increased due to environmental water; although not to the extent that once characterised the LMR under natural (pre-regulation) conditions.

Environmental water increased river connection (longitudinally and laterally) and promoted microinvertebrate transport from upstream to this region, thus increasing the amount and variety of these potential food resources. However, the influence of environmental water on riverine food production from primary producers (e.g. algae and plants) was minor due to the largely stable water levels set by regulation (weirs). From 2014 to 2019, golden perch spawning occurred each year, particularly in association with overbank flows in 2016-17, but there was negligible recruitment. It is possible that in-channel flows (<18,000 ML/d, <~40% bankfull level) were insufficient to support significant recruitment in golden perch in the LMR during dry years, whereas in 2016-17, low oxygen levels, associated with blackwater during the spring–early summer spawning season, impacted the survival of eggs and larvae.

Environmental water can be used to help reinstate key features of the natural flow regime (e.g. in-channel spring–summer flow pulses >20,000 ML/d) and support the restoration of flowing water habitats, which will help to restore ecosystem function and rehabilitate riverine plants and animals in the region. With existing volumes of environmental water and delivery constraints, during dry years, reaching and sustaining flows >20,000 ML/d in the LMR is largely reliant on coordinating flow deliveries across the southern connected Basin, including flows from tributaries (e.g. Goulburn, Murrumbidgee, Darling rivers). Under wetter scenarios, flows >20,000 ML/d may be achieved by delivering environmental water with unregulated flows. For hydraulic restoration, infrastructure management such as weir pool lowering to complement flows could also be considered. To maximise ecological outcomes, however, we need to better understand specific flow (e.g. timing, magnitude and duration) and habitat requirements of flow-dependant species to inform flow management.

Despite limited riverine native fish outcomes, environmental water has demonstrated its importance in supporting barrage releases to the Coorong, particularly in low flow years (i.e. 2014-15, 2015-16, 2017-18 and 2018-19). Barrage flows are vital in maintaining freshwater–estuarine habitat connection, exporting salt from the Basin, reducing salt import into the Coorong, and reducing salinity levels in the Coorong. These are essential for maintaining critical habitat and ecosystem function, supporting reproduction of many estuarine species (e.g. fish), and avoiding detrimental loss of aquatic life from the system

1 Monitoring and evaluation of environmental water in the Lower Murray River

1.1 Background

In 2014, the five-year (2014-15–2018-19) Commonwealth Environmental Water Office (CEWO) Long-Term Intervention Monitoring (LTIM) Project was established to monitor and evaluate long-term ecological outcomes of Commonwealth environmental water delivery in the Murray–Darling Basin (MDB). The project was implemented across seven Selected Areas throughout the MDB, including the Lower Murray River, to enable evaluation at the Basin and local scales. The overall aims of the project are to demonstrate the ecological outcomes of Commonwealth environmental water delivery and support improvements to how environmental water is managed.

1.2 The Lower Murray River and monitoring indicators

The Murray River, which includes the South Australian section (herein, Lower Murray River, LMR), is a complex system that comprises the main river channel, anabranches, floodplain/wetlands, billabongs, tributaries and the Lower Lakes, Coorong and Murray Mouth, which provide a range of habitats and support significant flora and fauna. Downstream of the Darling River junction, the Murray River is modified by a series of low-level (<3 m) weirs (Figure 1), changing a connected flowing river to a series of 'weir pools' (Walker 2006).

Figure 1. The Lower Murray River comprises various habitats including limestone cliffs in the gorge zone (left) (photo: SARDI) and locks/weir pools (right, Lock 2) (photo: Michael Bell).

The CEWO LTIM Project in the LMR focuses on the main channel of the LMR between the South Australian border and Wellington, with salt and nutrient transport modelling extending to the Lower Lakes and Coorong (Figure 2). Indicators were monitored at various sites, covering three riverine zones (floodplain, gorge and swamplands) and the Lower Lakes and Coorong (Wellington to Murray Mouth) (Figure 2).

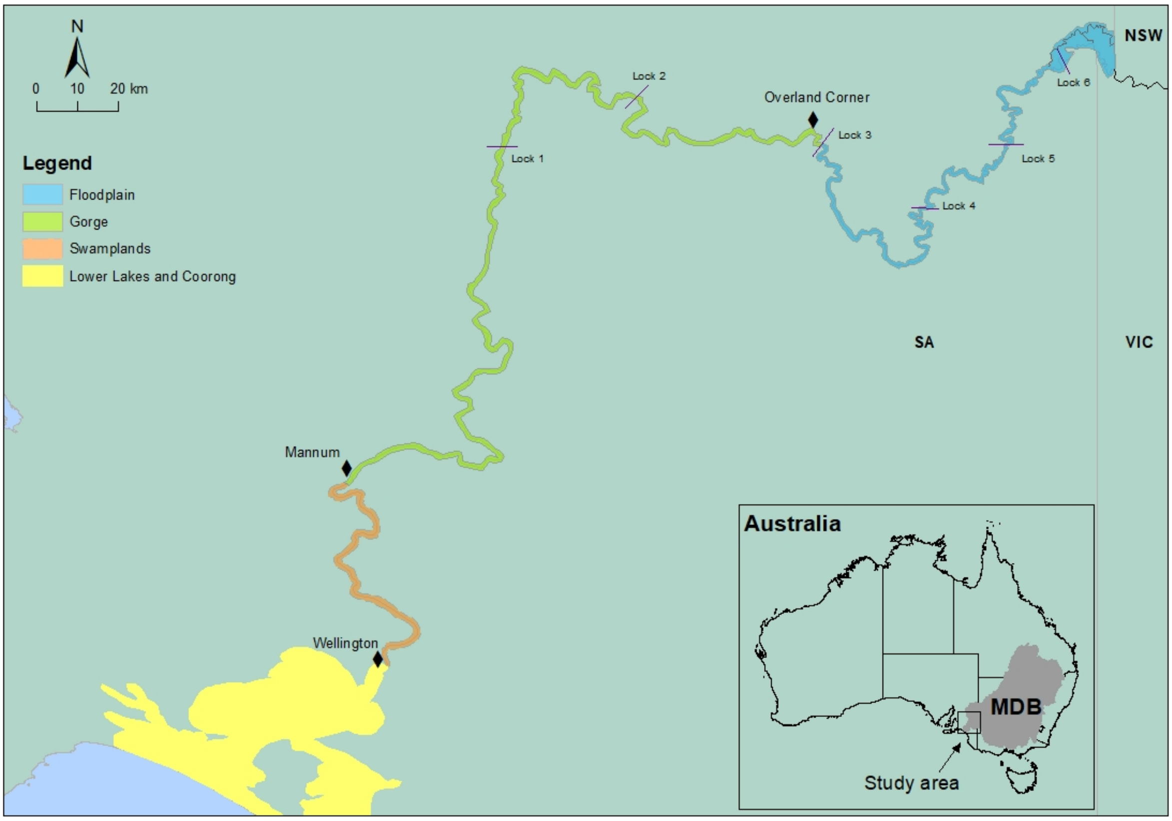


Figure 2. Map of the LMR Selected Area showing the floodplain (blue), gorge (green) and swamplands (orange) zones, and the Lower Lakes, Coorong and Murray Mouth (yellow).

Seven indicators were used to assess ecological responses to environmental water delivery in the LMR. *Hydrology*, *Stream Metabolism* and *Fish Community* followed standard protocols to support comparisons across other areas of the MDB (Hale *et al.* 2014). *Hydrological Regime*, *Matter Transport*, *Microinvertebrates* and *Fish Spawning and Recruitment* were developed to address objectives and test a series of LMR-specific hypotheses with respect to biological/ecological response to environmental flows.

1.3 Purpose of this summary report

This report provides a summary of environmental water use in the LMR during the CEWO LTIM Project (2014-15 to 2018-19), key outcomes from the watering, and general implications for environmental flow management. Detailed information, including methods, results and evaluation of Commonwealth environmental water, are provided in the technical report (Ye *et al.* 2020, http://www.environment.gov.au/water/cewo/catchment/lower-murray-darling/monitoring). While results specific to the LMR are reported here, a broader Basin-scale analysis including results from all seven Selected Areas will be produced by the Centre for Freshwater Ecosystems at La Trobe University.

2 Environmental watering in the Lower Murray River

During the LTIM Project (2014-15 to 2018-19), a total of ~3,440 gigalitres (GL)[a] of Commonwealth environmental water was delivered to the LMR, in conjunction with other sources of environmental water (e.g. the Murray–Darling Basin Authority, MDBA, The Living Murray Initiative, ~669 GL) (Figure 4). Environmental water contributed to 11–43% of the total flow in the LMR annually, with Commonwealth environmental water contributing 7–33%. Unregulated flow events occurred during the 2016-17 high flow year, at the start of 2014-15 and in December 2017. Without environmental water, flow to South Australia during the rest of the five-year period would have been at South Australian Entitlement levels (<7,000 ML/d), the minimum flow to be delivered to South Australia under Clause 88 of the MDB Agreement.

The five-year project period was dominated by low flow conditions (i.e. flow <18,000 ML/d at the South Australian border, Figure 4), except for 2016-17 (peak ~94,600 ML/d). Commonwealth environmental water delivery to the LMR largely consisted of flows continuing down the river from upstream watering events (e.g. Goulburn and Murrumbidgee rivers and Barmah–Millewa Forest). In most years, environmental water contributed to freshes in the LMR, particularly as winter flow pulses (e.g. 11,700 ML/d in July 2017) and spring–early summer flow pulses (e.g. 17,800 ML/d in December 2017) (Figure 4). In 2016-17, the majority (~96%) of environmental flow was delivered after mid-December 2016 (Figure 4), which assisted in slowing and extending the flood recession in summer. Commonwealth environmental water also supported other complementary management in the LMR, including weir pool manipulations, operation of environmental regulators and wetland watering by pumping. Furthermore, Commonwealth environmental water played a critical role in maintaining barrage releases into the Coorong throughout the five-year period (~590 GL/annum), particularly during the four low flow years (~77% of total barrage flow) (Figure 3).

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[a] In addition to ~3,440 GL of Commonwealth environmental water delivered to the South Australian border over the five years, approximately 53 GL was used by the CEWO to water off-channel wetlands and for net losses associated with other infrastructure events (e.g. weir pool manipulation) (source: CEWO).

Figure 3. Flows through the barrages from the Lower Lakes into the Coorong (photo: SARDI).

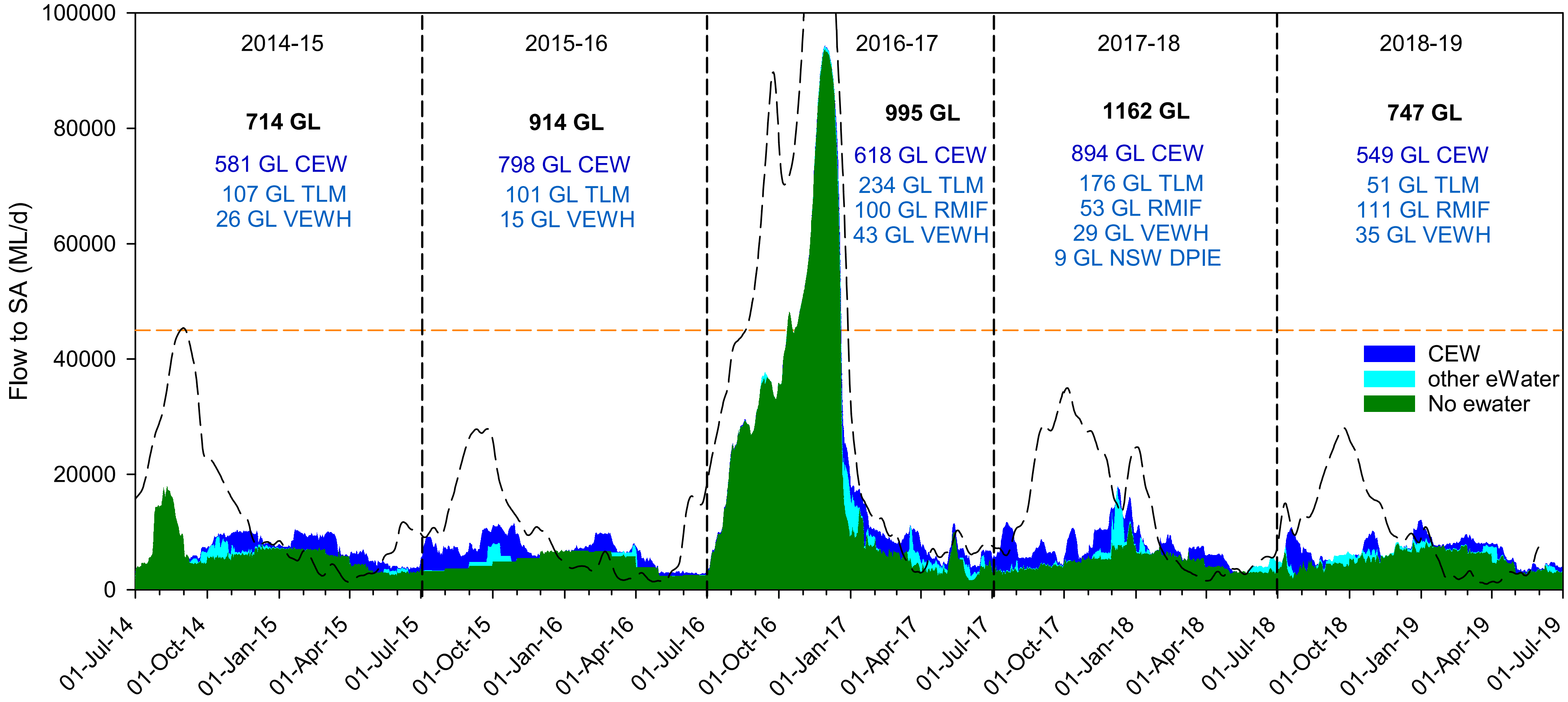

Figure 4. Murray River flow to South Australia (SA) showing the contribution of environmental water, compared to modelled flow under natural conditions without weirs and extraction (black dashed line) (source: MDBA). Orange dashed line represents the flow (45,000 ML/d) required to reach the bank in the Lower Murray River. CEW = Commonwealth environmental water. Other eWater = The Living Murray (TLM), Victorian Environmental Water Holder (VEWH), New South Wales Department of Planning, Industry and Environment (NSW DPIE) and River Murray Increased Flows (RMIF). The 'no eWater' component includes the South Australian entitlement held by the Commonwealth Environmental Water Holder and TLM, which are also excluded from the total volumes in blue text.

3 Key outcomes from environmental water use

3.1 Expected outcomes

Within the five-year monitoring and evaluation period, Commonwealth environmental water use in the LMR contributed to elevated base (low) flows and pulses of flow within the Murray River channel, and provided flow to the Lower Lakes and Coorong (see Section 2). Objectives of these flows related to fish, birds, vegetation, river function, Lower Lakes water levels, salt export and connectivity between freshwater, estuarine and marine environment, although only some of these were monitored through this project (also see Ye *et al.* 2020 (Appendix A) and https://www.mdba.gov.au/managing-water/water-for-environment/lower-lakes-coorong-murray-mouth-report-card-2017-18).

3.2 River hydraulics

Water velocities

Improving riverine hydraulics (e.g. water velocity (speed) and turbulence) is critical for restoring the ecology of the LMR. Pre-regulation, the Murray River downstream of the Darling River, was characterised by flowing, riverine habitats, with water velocities of ~0.2–0.5 m/s, even at low flows <10,000 ML/d (Figure 5, Bice *et al.* 2017). Many native plants and animals that are adapted to a flowing river are currently extinct or have suffered major declines due to the largely non-flowing weir pool environment in this region (Mallen-Cooper and Zampatti 2018). From 1 July 2014 to 30 June 2019, there were minor changes in the length of river with flowing habitat (i.e. velocities exceeding 0.3 metres per second, m/s) in the LMR due to environmental water. However, the exception was in 2017-18 when there was an extra 49 km (14%) of river reach (between Lock 1 and Lock 6) transforming to flowing habitat for at least 14 days, or 36 km (10%) of river for 30 days due to the Commonwealth environmental water (Figure 5). This may have benefited riverine ecological processes for ~2–4 weeks at a spatial scale of 10–14% of river length. This event was associated with a greater flow increase to ~18,000 ML/d, compared to other dry years. However, the velocity increase in 2017-18 remained a moderate improvement in contrast to substantial increases in flowing water habitat throughout the LMR in 2016-17, due to unregulated, overbank flows.

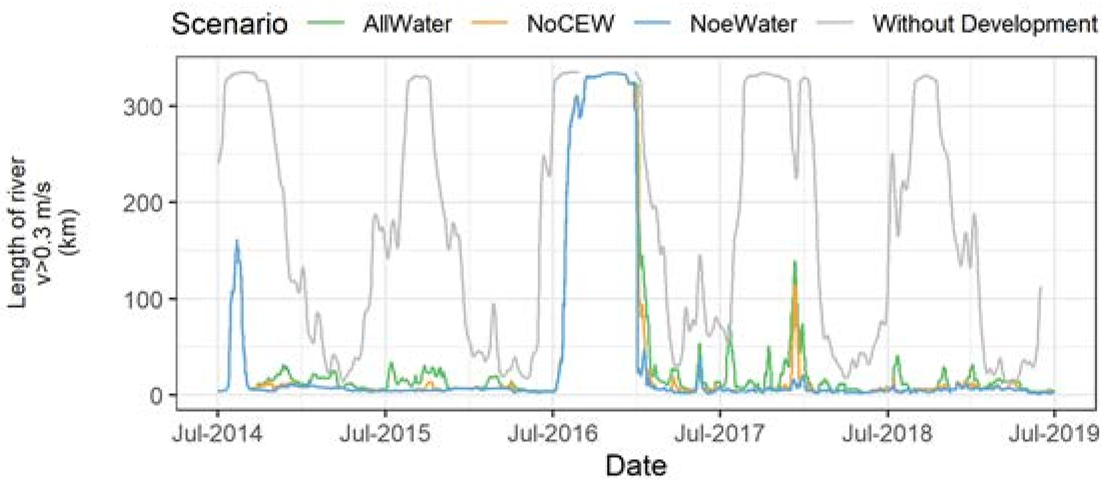

Figure 5. Length of the Lower Murray River between Locks 1 and 6 with flowing water habitat, defined as a velocity greater than 0.3 metres per second. Total length of river assessed in the LMR = 345 km. Coloured lines represent the modelled environmental water scenarios.

Water levels

The combination of environmental water delivery and weir pool manipulation created variability in water levels that would not have occurred otherwise, particularly during spring–summer at the upstream end of weir pools (tailwaters) (e.g. Weir Pool 5, Figure 6). For example, in 2017-18, the interquartile range (a measure of variation) in water level increased by 0.17 m in the tailwaters across Weir Pools 1–5, due to Commonwealth environmental water. This variability tended to mimic the seasonal timing of the without development pattern of river height, albeit at a smaller magnitude (Figure 6). Without environmental flows, water levels would have been stable throughout most of 2015-16, 2017-18 and 2018-19. Periodic increases in water levels can improve the condition of bank vegetation (Gehrig *et al.* 2016) and increase the diversity of biofilms (Steinman and McIntire 1990), which is a key component of river food webs.

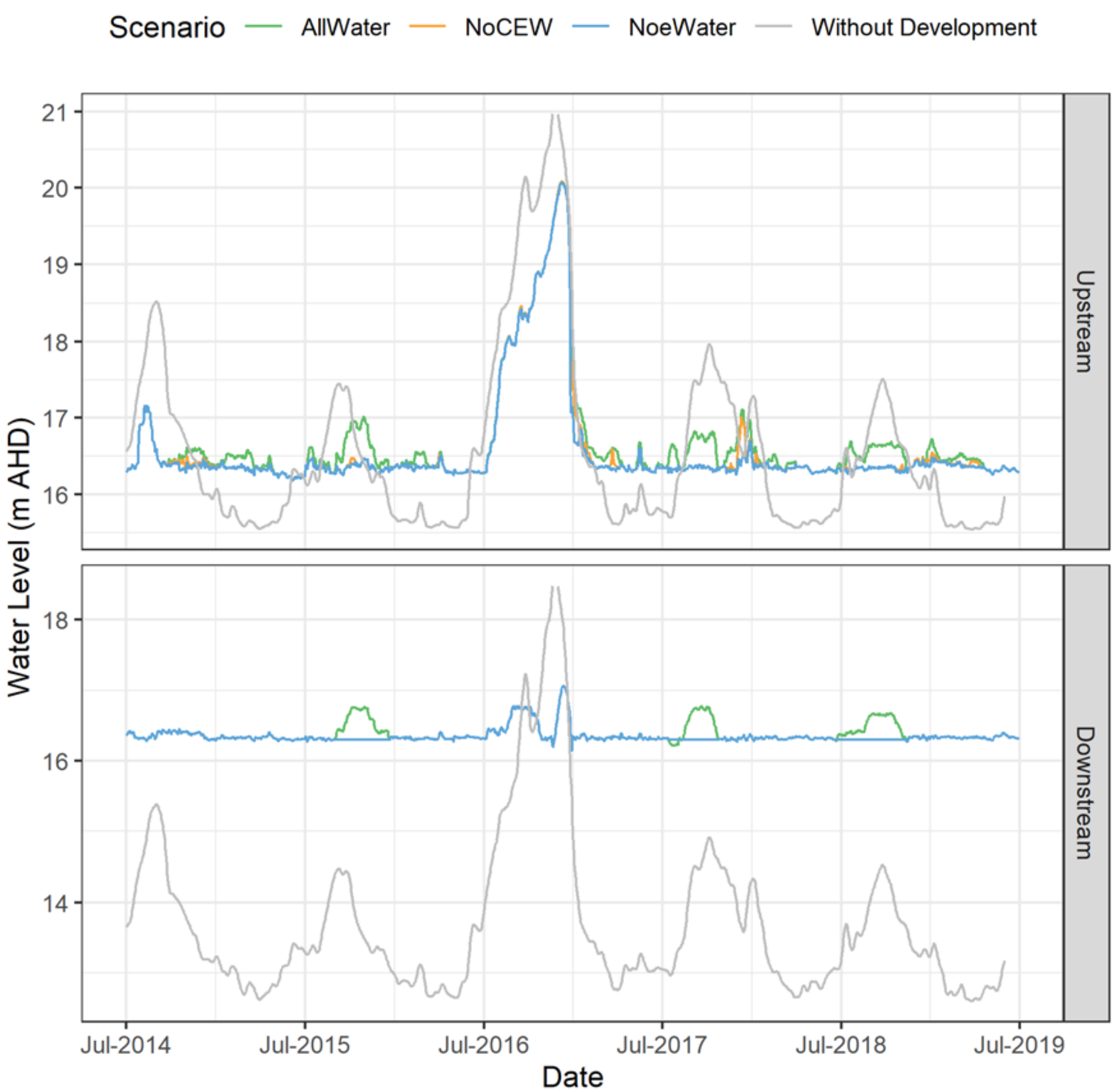

Figure 6. Modelled water level (metres relative to the Australian Height Datum) at the upstream and downstream end of the Lock 5 weir pool in the Lower Murray River. Coloured lines represent the modelled environmental water scenarios.

3.3 River metabolism

Dissolved oxygen

From 2014-15 to 2018-19, environmental water decreased the likelihood of low dissolved oxygen levels during spring–summer in the LMR by increasing water mixing and oxygen exchange at the surface (Figure 7). For example, in 2014-15, it was estimated that environmental water contributed to reducing the risk of low oxygen levels by 31 extra days, when environmental water contributed to increasing water velocities above 0.18 m/s. Favourable dissolved oxygen concentrations (generally >5 mg/L) in water are critical for the survival of aquatic biota. The consequences of low oxygen on the survival of larger aquatic animals are evident from the flood year in 2016-17, when dissolved oxygen levels fell to zero in the LMR for a short period (Ye *et al.* 2018) and resulted in extensive kills of Murray cod.

Figure 7. Loggers that are deployed in the Lower Murray River to measure dissolved oxygen concentrations (left) and the typical mooring station (right) (photos: University of Adelaide).

Food production and consumption

Increased flow from environmental water deliveries widened the river, increasing the volume of water available for aquatic plant and animals. As a result, the rates of food production (measured as cross-sectional gross primary production) increased slightly (by ~2% each year), indicating a marginally increased food supply from primary producers (e.g. algae and plants) in the food web. The influence of environmental water on riverine food production in the LMR was only minor due to the largely 'fixed' water levels set by regulation (weirs).

3.4 Salt, nutrient and phytoplankton transport

Salt transport

There is approximately 100 billion tonnes of salt in groundwater in the MDB and an additional 1.5 million tonnes of salt is deposited in the MDB each year by rainfall (Herczeg *et al.* 2001). Unless salt is exported from the basin with flow, there will be an accumulation of salt within the MDB, potentially leading to salinisation of habitats, particularly wetlands. In the high flow year (2016-17), when annual barrage flow was ~7,161 GL, 1.5 million tonnes of salt was exported from the MDB and Commonwealth environmental water contributed 8% of salt export. In low flow years (2014-15, 2015-16 and 2017-18, 2018-19), however, Commonwealth environmental water played a vital role in salt export from the MDB, contributing to 64–87% of salt export (Ye *et al.* 2020) (Table 1).

Table 1. Five year record of modelled salt export (tonnes) through the barrages to the Coorong. CEW = Commonwealth environmental water, eWater = environmental water. Note the results are based on modelled barrage flows, eWater and CEW for matter transport modelling.

Scenario	2014-15	2015-16	2016-17	2017-18	2018-19
With all water	446,855	288,516	1,504,541	349,893	228,293
Due to CEW	285,064	251,632	120,867	240,722	160,897
Due to eWater	294,449	257,485	186,750	300,970	228,293

Commonwealth environmental water has also been critical in reducing salt import via the Murray Mouth, particularly during the low flow years. While there has been a net import of salt into the system during these years, Commonwealth environmental water has reduced salt import by 2.5–4.6 million tonnes per year (Figure 8). This reduced salinity concentrations in the Coorong, which was crucial for maintaining estuarine habitats, species diversity and ecosystem function. Without environmental water, an additional 20 million tonnes of salt would have entered the Coorong via Murray Mouth over the period 2014–2019, producing salinity (~five times seawater) in the South Lagoon reminiscent of the end of the Millennium drought that led to detrimental loss of aquatic life.

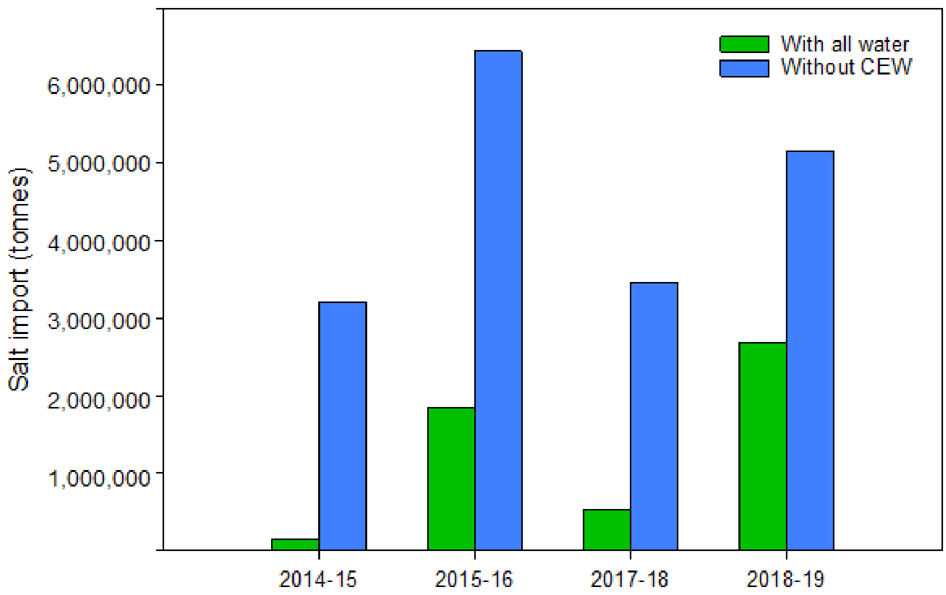

Figure 8. Modelled salt import (tonnes) into the Coorong through the Murray Mouth during low flow years of LTIM. CEW = Commonwealth environmental water, eWater = environmental water.

Nutrient and phytoplankton transport

In addition to the transport of salt, there was increased transport of nutrients and phytoplankton, which would likely stimulate food production in downstream ecosystems, providing potential benefit to food webs of the LMR, Lower Lakes, Coorong and Southern Ocean, adjacent to the Murray Mouth (Figure 9). However, our current understanding of the balance of the desirable loads between these systems is limited. Environmental flow deliveries during dry periods when there would otherwise be negligible water exchange between the Lower Lakes and Coorong promote connectivity and allow exchange of living and non-living (e.g. salt) matter between these two water-bodies.

Figure 9. The Coorong estuary mouth (Murray Mouth) of the Murray–Darling River system connecting the river to the Southern Ocean (photo: Adrienne Rumbelow, DEW).

3.5 Microinvertebrate diversity and transport

Aquatic microinvertebrates (Figure 10) are a major food source for larger animals (e.g. larger invertebrates) (Schmid-Araya and Schmid 2000), and important for early life stages of fish (i.e. larvae) (Tonkin *et al.* 2006). Therefore, a diverse and abundant microinvertebrate community may be important for the survival and growth of larval fish and in turn, fish recruitment.

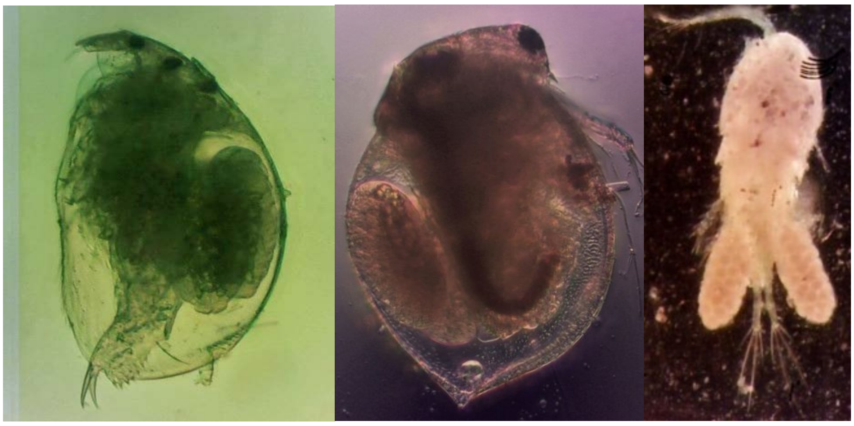

Figure 10. Microinvertebrates of the Lower Murray River that are prey for large-bodied fish larvae. Left: Cladocera (Chydoridae), middle: Cladocera (Daphniidae), right: Copepoda (Cyclopoida: Cyclopidae) (photos: University of Adelaide).

The delivery of environmental water from 2014–2018, combined with the use of management levers such as weir pool manipulation and the operation of the Chowilla Creek regulator, coincided, at times, with increased amount (density) and variety (diversity) of microinvertebrates. Although, due to concurrence of multiple events and factors, the mechanisms facilitating these increases are not fully understood. The transport of microinvertebrates from upstream sources (e.g. Goulburn River/southern Basin) to the LMR throughout spring–summer during the low flow years (i.e. 2014-15, 2015-16 and 2017-18), which contributed to increased diversity, was also often associated with environmental water delivery. The increased dispersion of microinvertebrates suggested improved connection in food sources along the length of the river system, which is important for river function. During the 2016-17 flood, increased transport of microinvertebrates from upstream catchments (i.e. Goulburn, Murrumbidgee, upper Murray and Darling rivers) and between off-channel and main channel habitats resulted in greater microinvertebrates densities and diversities, relative to low flow years.

3.6 Golden perch reproduction

Spawning and recruitment of golden perch in the southern MDB corresponds with increases in water temperature and river flow (Zampatti and Leigh 2013a; 2013b). In the LMR, the golden perch population is comprised of fish derived from local spawning, and immigrants from other spawning sources, such as the lower Darling River (Figure 11).

From 2014-15 to 2018-19, golden perch spawning occurred annually during spring–summer in the LMR, often in association with in-channel flow pulses. Nevertheless, the absence of juvenile (<1 year old) golden perch in annual autumn electrofishing surveys suggested negligible recruitment. It is possible that in-channel flows (<18,000 ML/d) were insufficient to support significant golden perch spawning and/or recruitment in the LMR during dry years, whereas in 2016-17, low oxygen levels, associated with blackwater during the spring–early summer spawning season, impacted the survival of eggs and larvae.

Poor reproductive success of golden perch in the LMR over the last five years (2014–2019) has resulted in a lack of young golden perch (<5 years old) in the LMR population (Figure 11). In 2019, the population was comprised mainly of older fish (7 to 9 years old) that were recruited at the end of the Millennium drought and the wet years that followed (2009–2012). These fish originated from the lower Darling and Murray rivers (Figure 11). A lack of younger cohorts and low number of age classes in the population indicates low resilience to environmental disturbances (e.g. drought).

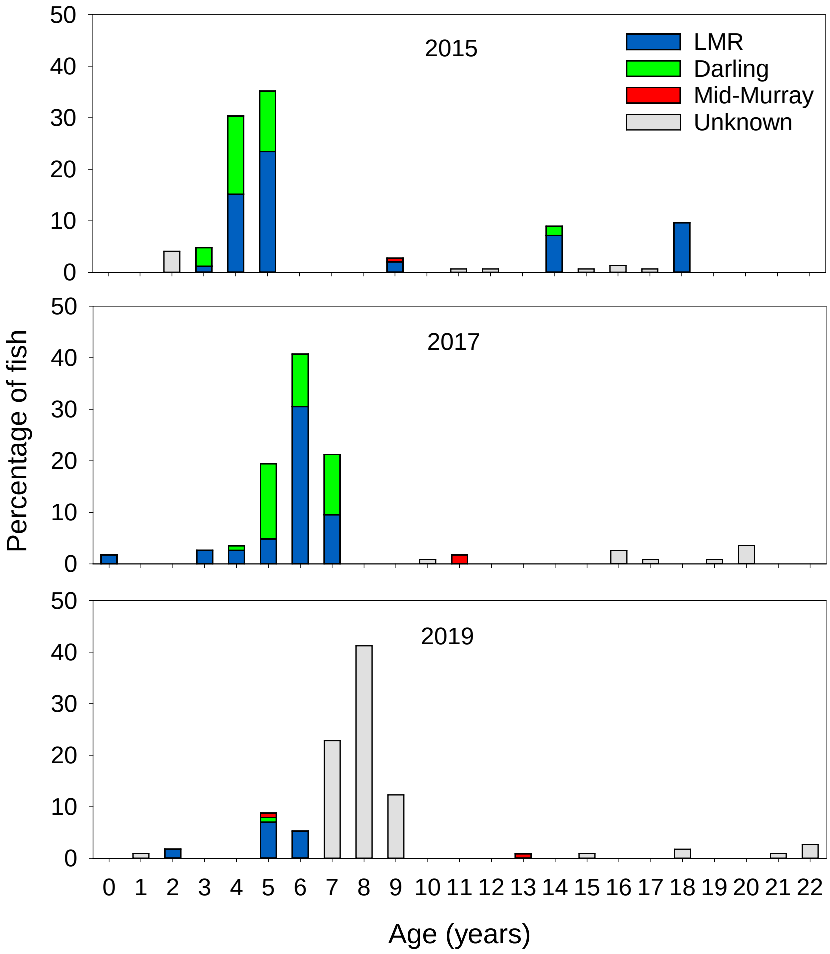

Figure 11. Ages of golden perch (expressed as a percentage) from the Lower Murray River (LMR) in 2015 (145 fish sample) and 2019 (114 fish sampled) showing the birth (spawning) location (i.e. Murray River below the Darling River (LMR); Murray River between the Darling River and Lock 11; and the Darling River) of fish inferred from fish earbone and water chemistry. Grey bars indicate the groups of fish which were not assessed for birth location (photo: SARDI).

4 Other findings from monitoring: Fish community

Background

Fish monitoring data from the LMR (autumn 2015–2019) were analysed to investigate annual changes in the fish community (Ye *et al.* 2020). Evaluation of fish community responses to Commonwealth environmental water is being undertaken at the Basin-scale (e.g. King et al. 2019). The patterns described here have not been associated with environmental water delivery.

Fish community changes

During 2015 and 2016, in the main channel of the LMR, the fish community was characterised by high abundances of small-bodied species (e.g. carp gudgeon), likely due to the presence of preferred 'wetland' like habitats for small-bodied fish (e. g. submerged vegetation, still water and stable water levels) (Figure 12). Such habitats, and associated fish community, in the main river channel during low flows are a result of river regulation. These two years were also characterised by a lack of recruitment of native, large-bodied flow-cued spawning species (e.g. golden perch and silver perch). This fish community was like that during drought in 2007–2010 (Bice *et al.* 2014) and characteristic of low river flows. Following high flows in 2016-17, the fish community shifted towards one characterised by low abundances of small-bodied species and high abundance of a large-bodied invasive species, common carp, which uses floodplain habitats for spawning. This community was more typical of high flows, like 2010–2012 (Bice *et al.* 2014), but unlike this period, recruitment of native, large-bodied flow-cued spawners (e.g. golden perch) in 2016-17 was negligible. This was likely due to the impact of low dissolved oxygen (hypoxia) associated with a blackwater event. During 2018 and 2019, a return to low, in-channel flows (<18,000 ML/d) resulted in the fish community trending back towards that of 2015 and 2016, which was with high abundances of small-bodied fishes; a lack of recruitment from native, flow-cued spawners; and a decrease in common carp abundance.

Recruitment of large-bodied species

Spawning of freshwater catfish and Murray cod occurs in spring–early summer, irrespective of flow (Davis 1977; Rowland 1998). Recruitment of both species, however, may be more successful with increased flow (Zampatti *et al.* 2014; Ye *et al.* 2015). No small freshwater catfish (i.e. <150 mm) were sampled in the LMR during the CEWO LTIM Project from 2015–2019, indicating poor recruitment. In the LMR, recruitment of freshwater catfish is poorly understood and the current population abundance in this region is historically low (Ye *et al.* 2015).

For five consecutive years (2015–2019), small Murray cod (<150 mm) were sampled in the LMR, indicating successful recruitment (Figure 13). These year classes of fish were sampled as larger individuals in subsequent years, indicating growth and survival.

Whilst larger (>150 mm) Murray cod were not sampled in the last year of LTIM monitoring (2019), these year classes are still present in the population (Fredberg *et al.* 2019; SARDI unpublished data).

Figure 12. A catch of small-bodied fish (predominately carp gudgeon) (top left) with structural habitat (submerged vegetation) (top right) conducive to small-bodied fish, carp recruits (bottom left) and flowing water habitat (bottom right) (photos: SARDI).

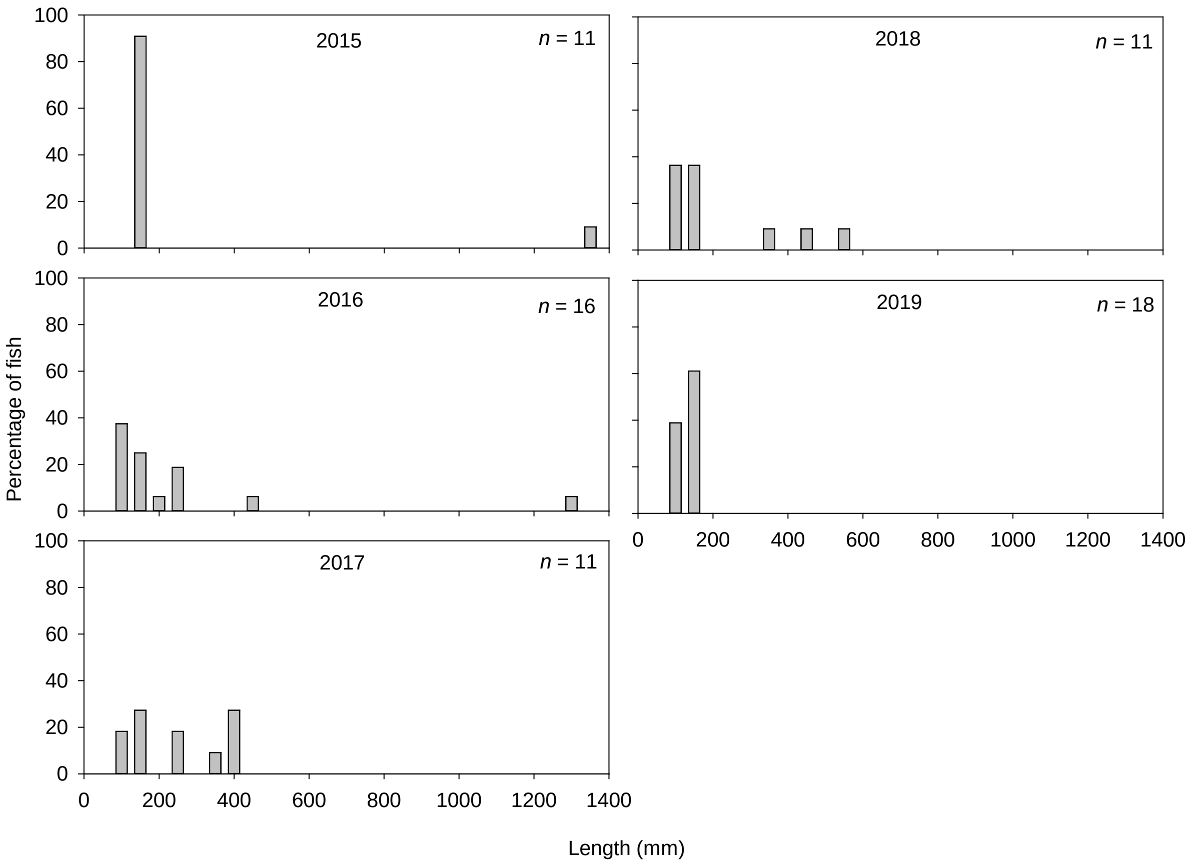

Figure 13. Lengths of Murray cod, expressed as a percentage of the sampled population from the Lower Murray River during electrofishing in autumn 2015–2019 (photo: SARDI).

5 Implications for future management of environmental water

During the LTIM Project (2014–2019), 4,532 GL of environmental water, including 3,440 GL Commonwealth environmental water, was delivered to the LMR. In most years, environmental water contributed to winter and spring–early summer flow pulses. Ecological outcomes of environmental water deliveries included: increased flowing water habitats; maintaining dissolved oxygen concentrations to support riverine biota; enhanced in-stream food resources; increased connectivity and microinvertebrate dispersion; reduced salt import and lower salinities in the Coorong; and increased salt export from the Basin.

While environmental water promoted pulses of flow in the LMR (up to ~40% of bankfull level in spring–summer 2017), the magnitude and duration of these flow pulses were well below modelled flow under natural (pre-regulation) conditions (Figure 3). Pre-regulation, the Murray River, downstream of the Darling River, was characterised by flowing habitats, with water velocities ranging ~0.2–0.5 m/s, even at flows <10,000 ML/d; whereas currently much greater flow (>~20,000 ML/d) is required to reinstate a 'flowing river' due to the presence of weirs (Bice *et al.* 2017). Many native plants and animals, adapted to riverine habitats, are now extinct or suffered major declines due to the largely weir pool environment in this region (Walker 2006; Mallen-Cooper and Zampatti 2018).

Environmental water to support the restoration of flowing water habitats will help to restore ecosystem function and rehabilitate riverine plants and animals in the LMR. Furthermore, reinstating key features of the natural flow regime in this region, such as high, in-channel spring–early summer flow pulses (>20,000 ML/d), will improve riverine habitats and should be considered a priority for management. With existing volumes of environmental water and delivery constraints, during dry years, reaching and sustaining flows >20,000 ML/d in the LMR is largely reliant on coordinating flow deliveries across the southern connected Basin, including flows from tributaries (e.g. Goulburn, Murrumbidgee, Darling rivers). Under wetter conditions, flows >20,000 ML/d may be achieved by delivering environmental water with unregulated flows. For example, the amount of river reach with flowing water habitat will increase from between 10–30% to greater than 90% when flow at the South Australian border is increased from 10,000 ML/d to 30,000 ML/d (Figure 14). Additionally, infrastructure management actions such as weir pool lowering could be considered to complement flows, to rehabilitate flowing water habitats. To inform flow management and maximise ecological outcomes, however, we need to better understand specific flow (e.g. timing, magnitude and duration) and habitat requirements of flow-dependant species.

Barrage flows are critical in exporting salt from the MDB, maintaining freshwater–estuarine habitat connectivity, reducing salt import and maintaining suitable salinity levels in the Coorong. These are crucial in maintaining habitat and estuarine function, supporting reproduction of estuarine species (e.g. fish), avoiding demise of aquatic life and mitigating Coorong ecosystem degradation. The importance of environmental water in supporting barrage releases to the Coorong, particularly in low flow years (i.e. 2014-15, 2015-16, 2017-18 and 2018-19) was demonstrated.

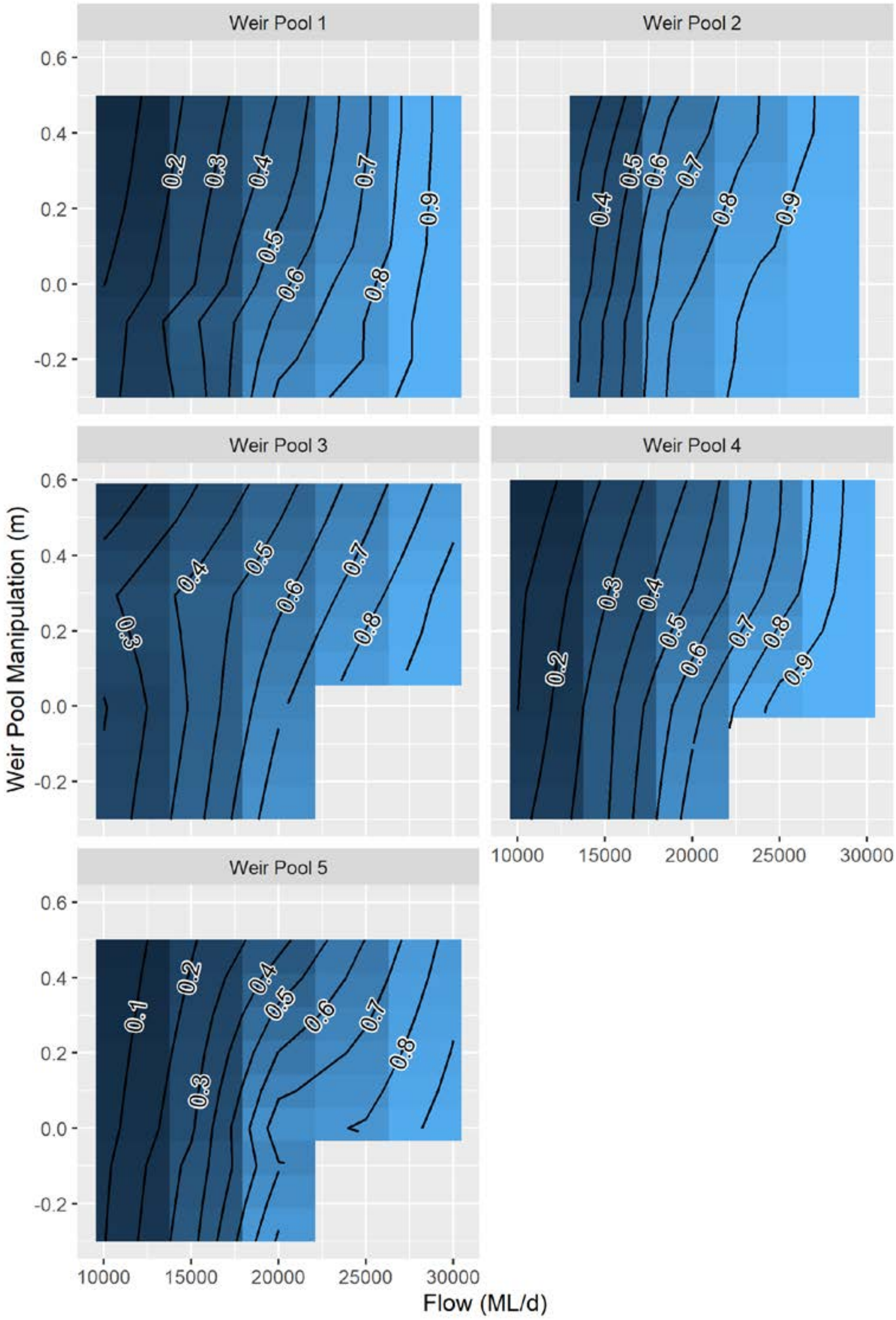

Figure 14. The proportion of a weir pool with flowing water habitat (velocities exceeding 0.3 m/s) for changes in discharge and weir pool level in the LMR.

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