Commonwealth Environmental Water Office Monitoring, Evaluation and Research Project:

Lower Murray
2020-21 Summary Report

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

May 2022

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Glossary

Basal food source	A source of carbon (energy) at the base of a food web. For example, primary producers such as phytoplankton or plants.
Base flow	Flows that are confined to the low flow part of the river channel.
Decomposition	The breakdown of organic matter by living organisms (e.g. bacteria and fungi), in this case measured as bacterial respiration.
Direct trade	Generally, water allocation transfers are permitted directly ('direct trades') to South Australia from the trading zones of New South Wales and Victoria, and by 'back trade' to South Australia from the trading zones of the connected New South Wales and Victorian tributaries. Direct trade to South Australia commonly involves operation of Lake Victoria.
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), depth and turbulence.
Freshes	Flows greater than base flow but below bankfull level.
Larvae	Early life stage of fish.
Microinvertebrates	Invertebrates of microscopic size (mostly <1 mm, 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 (carbon) from sunlight through photosynthesis.
Primary production	The process by 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 (downstream of the 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 releasing and fertilising eggs.
Unregulated flow	Unregulated flows occur when the volume of water flowing through 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 storages and rainfall rejection events.
Weir pool	The area of water upstream of a weir that is influenced by the weir. In this report, a weir pool is often referred to as the stretch of river between two weirs and includes tailwater habitat. For example, Weir Pool 1 is the stretch of river between Weir 1 and 2.

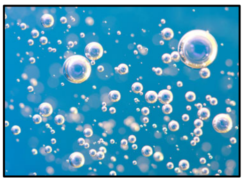
Executive summary

In 2020-21, ~687 GL of Commonwealth environmental water was delivered to the main channel of the Lower Murray River (LMR) through coordinated watering events, to achieve a range of environmental outcomes across the southern connected Murray-Darling Basin. This report presents the key ecological responses measured in the *Lower Murray Selected Area* during 2020-21, as part of the Commonwealth Environmental Water Office (CEWO) Monitoring, Evaluation and Research (MER) Project. A technical report (Ye *et al.* 2022) provides detailed methods, results and evaluation of ecosystem responses to environmental water delivery.

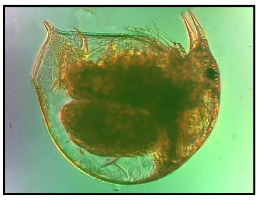
Key outcomes of Commonwealth environmental water in 2020-21

Lower Murray River: Spring flow pulse

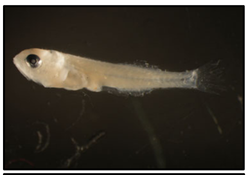
Increased hydrological connectivity: Environmental water increased the **annual flow volume by 31%** at the South Australian border, meeting the Basin-wide environmental watering target (>30%). Commonwealth environmental water increased longitudinal connectivity; the river distance and time period characterised by flow velocity >0.2 metres per second (m/s) was improved by 10,392 kilometre days (an increase of 58%). Lateral connectivity was also improved, with an increase of the maximum inundation area of 1,397 hectares.

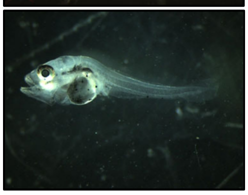


During spring–summer, increased water mixing and oxygen exchange (due to more habitat with flow velocity >0.2 m/s) **decreased the likelihood of low oxygen levels** (e.g. <5 milligrams per litre, mg/L). Aquatic animals generally need oxygen levels >5 mg/L, particularly during spring–summer, which is the main reproductive season of many species.



The amount (density) and variety (diversity) of **microinvertebrates increased** (by 24% and 9%, respectively) due to Commonwealth environmental water, likely through transport from upstream environments as a result of increased longitudinal connectivity. However, the amount of preferred prey species of large-bodied native fish larvae declined by 40%, which may have negatively impacted the survival of fish larvae.





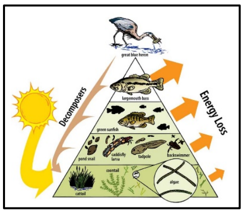
Substantial numbers of silver perch larvae were collected in the LMR during spring–summer. The majority of these larvae originated from spawning in the mid-Murray. The **spawning of silver perch and golden perch**, and downstream larval drift, were likely supported by environmental water delivery. While autumn sampling **did not detect 'recruitment'** (i.e. young-of-year age 0+ fish were not collected), the cohort may be evident in subsequent years as larger fish are more readily sampled. The presence of additional young cohorts (e.g. 2 and 3 year olds) in the golden perch and silver perch populations in 2021 suggests some recruitment occurred during recent in-channel flow years from 2015–2019 and these cohorts have contributed to population resilience.

Increased flowing habitat: The length of river with **'flowing water' habitat** (>0.3 m/s) **increased** by 9% (for at least a four-week period).

Murray cod recruitment was relatively low. Lotic conditions promoted by environmental water were unlikely to benefit spawning as these conditions occurred after the spawning period. However, increased flowing water habitat may have supported the survival and body condition of the limited number of new recruits.

The current fish community in the LMR is characteristic of low river flows. However, Murray cod abundance increased, mainly driven by the survival of fish, now age 1+, from the 2019-20 cohort.

Increased water level variability: Environmental water, in combination with weir pool manipulations, increased water level variability. Subsequent inundation of the riverbank **increased the diversity of native vegetation on the bank** by 42–82% **and the above-ground biomass of understory vegetation** by 121–292%.



In the river channel, **primary production marginally increased** (by ~0–2.5%) due to increases in water level and channel width, increasing the overall area of available light to phytoplankton and aquatic plants. This low-level increase in production was mainly due to generally stable water levels in the regulated LMR. However, the rate of organic matter breakdown (decomposition) increased by 5–13% due to the delivery of Commonwealth environmental water, suggesting increased food resources to the river.

Lower Lakes and Coorong

Maintained connectivity between the river, Coorong estuary and Southern Ocean: Flows through the barrages to the Coorong were continuous throughout the year and comprised of 65% Commonwealth environmental water.

Annual barrage flow: Environmental water substantially **increased salt export** from the Basin, **reduced salt import** into the Coorong and salt flux into the North and South lagoons. This reduced salinity concentrations in the Coorong and maintained estuarine habitats (e.g. for fish and aquatic vegetation), which was crucial in supporting species diversity and ecosystem functions.

Management implications

In 2020-21, the LMR experienced low flow conditions (peak <18,000 ML/d at the South Australian border, compared to bankfull flows ~45,000 ML/d), similar to five of the previous six years (2014-15–2019-2020). During this year, environmental water delivery created a late spring–early summer flow pulse (17,900 ML/d) in the LMR. Consequently, hydrological connectivity and the proportion of weir pools (stretches of river between weirs) characterised by 'flowing water' habitat increased; although not to the extent that once characterised the LMR under natural (pre-regulation) conditions or as a result of higher flows (>20,000 ML/d) under current river management.

Small to moderate increases in flowing water habitat within weir pools and increased riverine connectivity supported a range of ecological outcomes in the LMR. These included reach-scale responses like mitigating the risk of low dissolved oxygen in water, benefiting littoral vegetation in tailwaters and Murray cod recruitment, and broader-scale responses like spawning of flow-cued spawning fishes, and downstream transport of fish larvae and microinvertebrates. Notably, such ecological improvements associated with elevated flows may play an important 'maintenance' role for populations and the LMR ecosystem during periods between natural high flows. Larger flow pulses >20,000 ML/d, supported by environmental water, are required to substantially restore riverine characteristics to the LMR and achieve ecological outcomes of greater magnitude (e.g. significant spawning and recruitment of golden perch), noting hydrological restoration could be complemented by weir pool lowering to increase river velocities.

The timing of flow pulses is likely to affect ecological outcomes. Water delivery should continue to align with ecological objectives and consider biological processes and species' life history requirements. To achieve multiple species outcomes, a holistic approach in flow regime design will be required, which may involve planning for multiple years to achieve different outcomes. Flow management could be informed by multi-years data/learnings from different flow regimes (timing, magnitude, duration, etc.).

Finally, environmental water is critical in supporting continuous barrage flows (i.e. end-of-system flow), particularly during dry years when environmental water can comprise up to 100% of flow. Barrage flows are important to flush out salt from the entire Murray-Darling Basin, reduce salt import into the Coorong, and reduce salt flux into the North and South lagoons. This helps to reduce salinity across the basin and maintain estuarine habitat and ecosystem function within the Coorong, which is critical to support numerous species and biodiversity.

1 Monitoring and evaluation of environmental water in the Lower Murray

1.1 Background

The Commonwealth Environmental Water Office (CEWO) Monitoring, Evaluation and Research (MER) Project (2019-20 to 2022-23) monitors, investigates and evaluates the ecological outcomes of Commonwealth environmental water delivery in the Murray–Darling Basin (MDB). The project extends the monitoring activities of the Long Term Intervention Monitoring Project (2014-15 to 2018-19) across seven Selected Areas throughout the MDB, including the *Lower Murray Selected Area*, to enable evaluation at the Basin and local scales. The aims of the project are to demonstrate the ecological outcomes of Commonwealth environmental water delivery and support adaptive management.

1.2 The Lower Murray and monitoring indicators

The Murray River, downstream of the Darling River junction, is a complex system that comprises the main river channel, anabranches, floodplain/wetlands, billabongs, tributaries and the Lower Lakes, Coorong and Murray Mouth, providing a range of habitats and supporting a diversity of significant flora and fauna. This part of 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' and greatly influencing the character of the ecosystem (Walker 2006).

Figure 1. The Murray River in South Australia comprises various habitats including limestone cliffs in the gorge zone (left) and locks/weir pools (right, Lock 4) (photos: SARDI).

The CEWO MER Project in the Lower Murray focuses on the main channel of the Murray River between the South Australian border and Wellington (named Lower Murray River, LMR), although select monitoring/modelling extends to the Lower Lakes and Coorong (Figure 2). Nine indicators were used to assess ecological responses to environmental water delivery. *Hydrology*, *Stream Metabolism and Water Quality* and *Fish Community* followed standard protocols to support comparisons with other areas of the MDB and the basin-scale evaluation (Hale *et al.* 2014). *Hydraulic Regime*, *Matter Transport and Coorong Habitat*, *Littoral Vegetation Diversity and Productivity*, *Microinvertebrate Assemblage*, *Murray Cod Recruitment* and *Flow-cued Spawning Fish Recruitment* were developed to address objectives and test a series of Lower Murray-specific hypotheses with respect to biological/ecological response to environmental flows. Additional contingency monitoring was conducted for (1) spawning and natal origin of flow-cued spawning fishes and (2) littoral zone soil seed bank composition assessment during 2020-21.

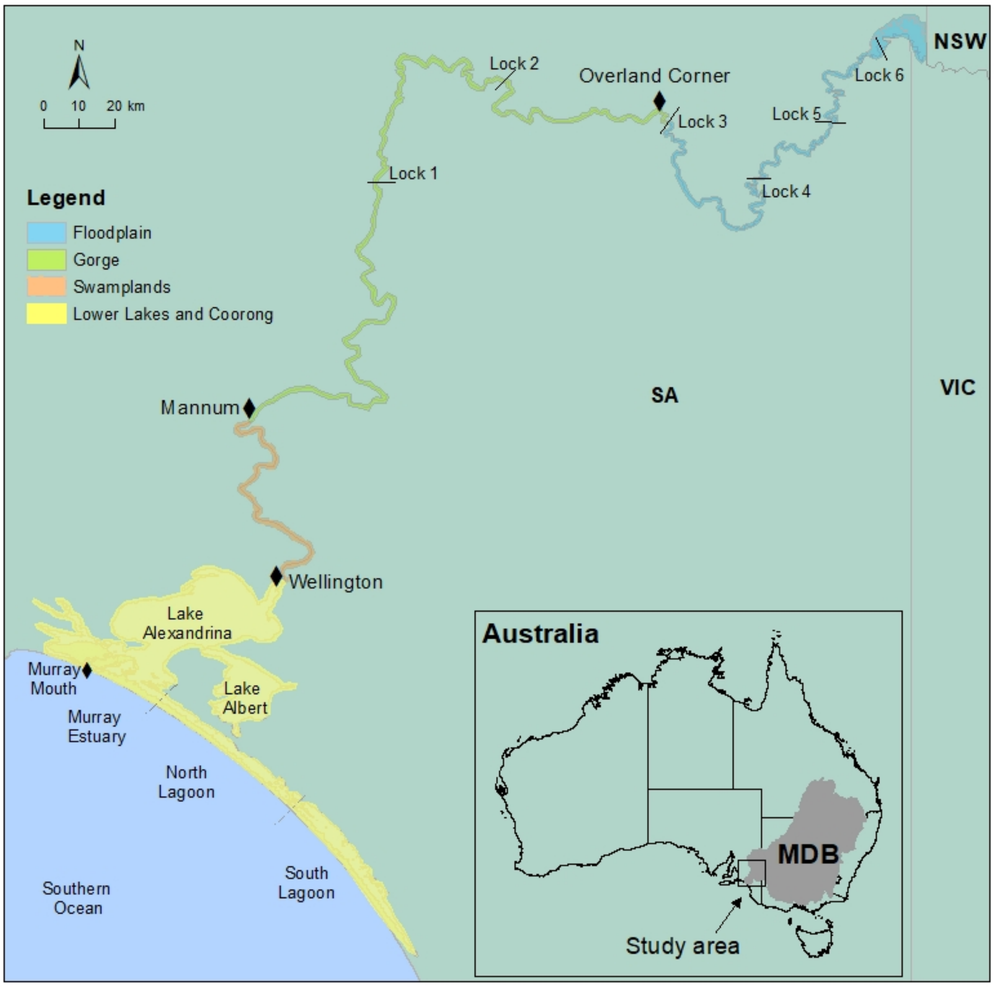


Figure 2. Map of the Lower Murray Selected Area showing the floodplain (blue), gorge (green) and swamplands (orange) river zones, and the Lower Lakes, Coorong and Murray Mouth (yellow).

1.3 Purpose of this summary report

This report provides a summary of environmental water use in the LMR during 2020-21, key outcomes from the watering, and general implications for environmental flow management. The learnings and recommendations build on previous years' monitoring from 2014-15 to 2019-20. Detailed information, including methods, results and evaluation of Commonwealth environmental water, are provided in the technical report (Ye *et al.* 2022, http://www.environment.gov.au/water/cewo/catchment/lower-murray-darling/monitoring).

2 Environmental watering in the Lower Murray in 2020-21

Since 2014-15, an average of 697 gigalitres (GL)[a] of Commonwealth environmental water has been delivered annually to the LMR, in conjunction with other sources of environmental water (e.g. The Living Murray Initiative) (Ye *et al.* 2020; 2021; 2021). Over this seven-year period, hydrology in the LMR was characterised by low flow conditions (i.e. flow <18,000 ML/d at the South Australian border) except for an unregulated, overbank flow (peak ~94,600 ML/d) in spring–summer 2016-17 (Figure 4a). Annually, environmental water contributed to 11–43% of the total flow in the LMR, with Commonwealth environmental water specifically contributing 7–33%.

In 2020-21, flow remained in-channel and was similar to five of the previous six years. During this year, ~687 GL[a] of Commonwealth environmental water was delivered to the main channel of the LMR (22% of the total flow). Following unregulated flows in winter–early spring, environmental water delivery in the LMR between late September and mid-December largely consisted of return flows from upstream watering events (e.g. in the Murray, Goulburn and Murrumbidgee rivers) and promoted flow variability and multiple spring flow pulses, with a peak of 17,900 ML/d in late November (Figure 4b). From summer–late autumn, environmental water was delivered to the LMR, largely via direct trades, mainly to support continuous flows to the Lakes and Coorong. Barrage flows in 2020-21 were comprised of 65% Commonwealth environmental water (Figure 3). Commonwealth environmental water also supported other complementary management, including weir pool manipulations, operations of the Katarapko and Pike floodplain regulators and wetland watering by pumping[a].

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

[a] Annual average volumes exclude off-channel watering (e.g. wetland pumping). In addition to ~687 GL of Commonwealth environmental water delivered to the South Australian border in 2020-21, approximately 12.5 GL was used to water off-channel wetlands (source: CEWO).

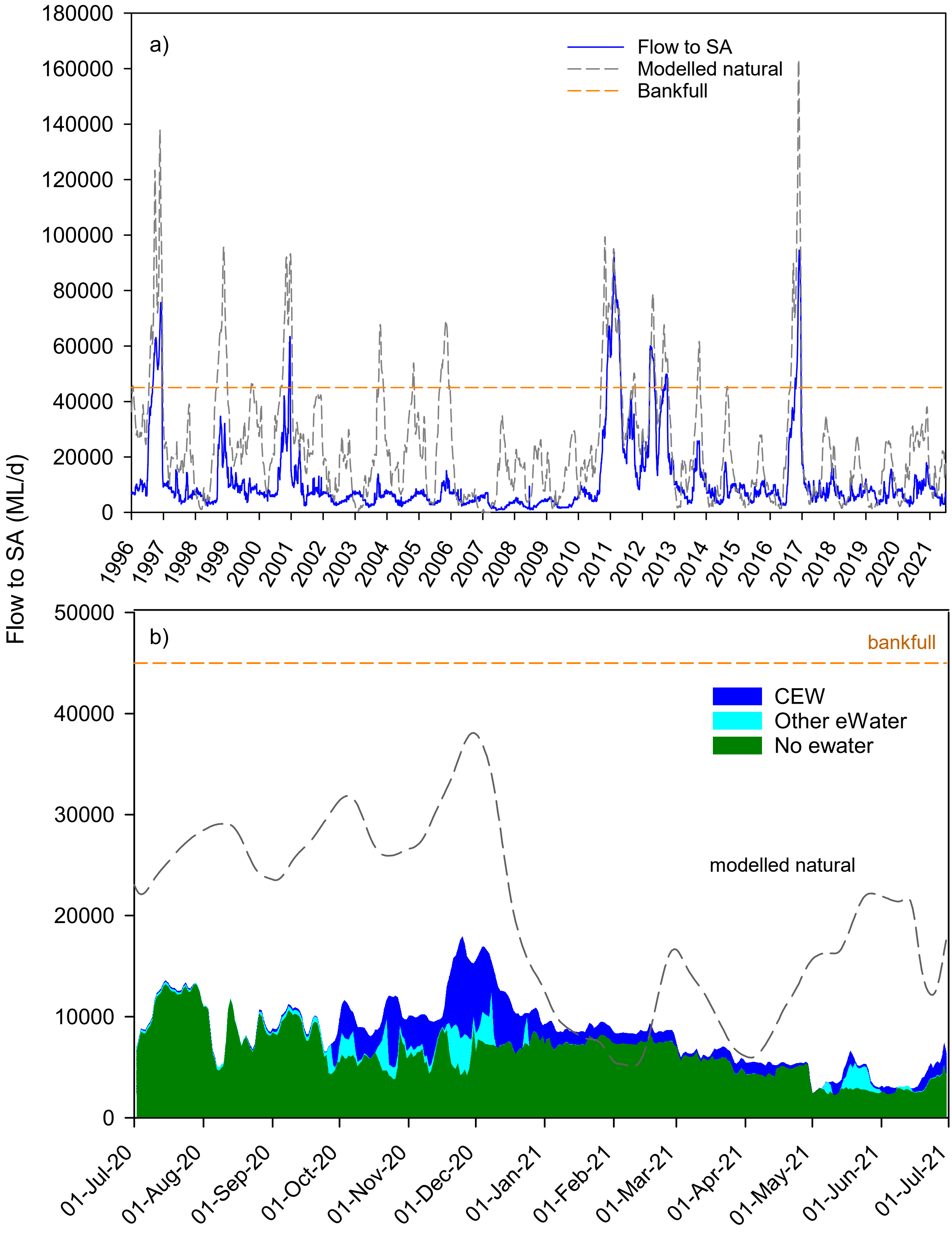


Figure 4. Murray River flow to South Australia (SA) (a) from January 1996 to July 2021 and (b) the contribution of environmental water to flow to South Australia in 2020-21. Observed flow is compared to modelled flow under natural conditions without weirs and extraction (grey dashed line) (source: MDBA). 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) and River Murray Increased Flows (RMIF). The 'No eWater' component includes the South Australian entitlement held by the Commonwealth Environmental Water Holder and TLM. Note: change in y-axis scale between the two figures.

3 Key outcomes from environmental water use

3.1 Expected outcomes

In 2020-21, Commonwealth environmental water 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). Expected outcomes of these flows related to fish, birds, vegetation, ecosystem function, Lower Lakes water levels, salt export and connectivity between freshwater, estuarine and marine environments, although only some of these were monitored through this project (also see Ye *et al.* 2022 (Appendix A); DEW 2021 and https://www.mdba.gov.au/issues-murray-darling-basin/water-for-environment/lower-lakes-coorong-murray-mouth-report-card).

3.2 Monitoring

Lower Murray River: spring flow pulse

Increased flowing habitat and connectivity

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 average water velocities of >0.3 metres per second (m/s), even at low flows <10,000 ML/d (Bice *et al.* 2017). Many native plants and animals that are adapted to a flowing river have suffered major declines due to the largely non-flowing weir pool environments now present in this region (Mallen-Cooper and Zampatti 2018). In 2020-21, due to delivery of Commonwealth environmental water, there was an extra 84 km (25%) of river between Lock 1 and Lock 6 transformed to flowing habitat (i.e. velocities >0.3 m/s) for at least 14 days, and 31 km (9%) of river for 30 days (Figure 5). This may have benefited riverine ecological processes for ~2–4 weeks at a spatial scale of 9–25% of the river's length. Furthermore, the increase in river distance and days with water velocity >0.2 m/s due to Commonwealth environmental water improved hydrological connectivity (by 10,392 kilometre days; an increase of 58%), which likely supported the transport of microinvertebrates and fish eggs and larvae. The amount of flowing habitat in 2020-21, however, was much less than what occurred during unregulated, overbank flows (e.g. in 2016-17, Ye *et al.* 2020), or what would have occurred under natural conditions without weirs and extractions (Figure 5).

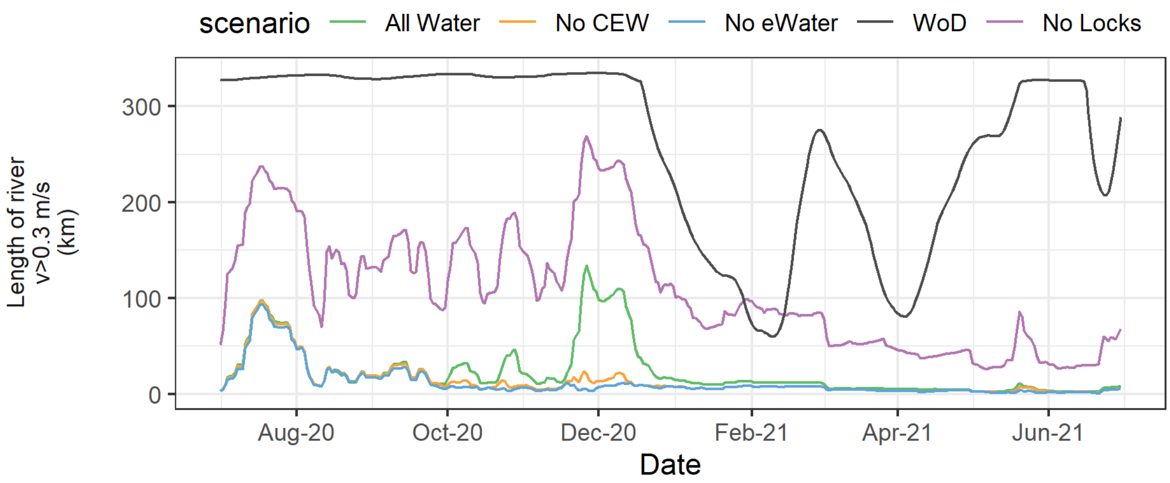


Figure 5. Length of the Lower Murray River between Locks 1 and 6 with flowing water habitat, defined as a velocity greater than 0.3 metres per second. Total length of river assessed = 345 km. Coloured lines (green, orange and blue) represent the modelled environmental water scenarios. The black line represents the modelled natural (without development, WoD) scenario while the purple line represents the influence of the weir and locks across the River Murray removed (No Locks) scenario. CEW = Commonwealth environmental water. eWater = CEW, The Living Murray (TLM), Victorian Environmental Water Holder (VEWH) and River Murray Increased Flows (RMIF).

Reduced risk of low dissolved oxygen: In spring–summer 2020-21, like other low flow years (e.g. 2017-18), environmental water decreased the likelihood of low dissolved oxygen levels in the LMR by increasing water mixing and oxygen exchange at the surface (Figure 6). It was estimated that Commonwealth environmental water contributed to reducing the risk of low oxygen levels by 52–79 days, when Commonwealth 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 Murray cod deaths.

Figure 6. Loggers that are deployed in the Lower Murray River to measure dissolved oxygen concentrations (left) and the typical mooring station (right) (photos: SARDI).

Increased microinvertebrate abundance: Microinvertebrates (Figure 7) are a major food source for larger animals, including larger invertebrates (Schmid-Araya and Schmid 2000) and 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. In 2020-21, environmental flows were estimated (through modelling) to increase aquatic microinvertebrate abundance and diversity in the LMR by 24 and 9%, respectively.

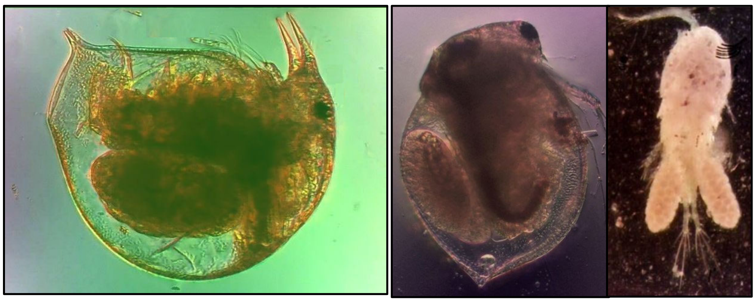


Figure 7. Microinvertebrates of the Lower Murray River that are prey for large-bodied fish larvae. Left: Cladocera (Bosminidae), middle: Cladocera (Daphniidae), right: Copepoda (Cyclopoida: Cyclopidae) (photos: University of Adelaide).

However, in this year it was estimated that the density of preferred microinvertebrate prey of large-bodied native fish larvae decreased by 40% during spring–early summer 2020 due to Commonwealth environmental water delivery to the LMR. While this may have negatively affected the survival of fish larvae (e.g. Murray cod), the decrease was driven by a single species (the cladoceran, *Bosmina meridionalis*). While *B. meridionalis* has been identified in the gut of larval Murray cod, the importance in diet of this species over the many other prey species identified is not well understood. Furthermore, environmental conditions prior to the water delivery may have influenced the subsequent change in microinvertebrate prey density. Therefore, results should be treated with caution.

Golden perch recruitment: Spawning and recruitment of golden perch in the southern MDB typically corresponds with increases in water temperature and river flow that occur in spring–summer (Zampatti and Leigh 2013a; 2013b). In the LMR, the population is comprised of fish derived from local spawning, and immigrants from other spawning sources, such as the Darling River (Ye *et al.* 2020).

In the LMR from 2014–2021, golden perch spawning occurred annually, at low levels, during spring–summer in association with in-channel flow pulses and overbank flows (2016-17 only). The absence of juvenile (<1 year old) golden perch in annual autumn electrofishing surveys suggested negligible recruitment. In 2021, however, cohorts derived from spawning between 2015-16 and 2018-19 have become apparent and now collectively make up 21% of the population (Figure 8). It appears that low levels of recruitment during years of in-channel flows (<18,000 ML/d) have indeed occurred, and that recruitment may not be evident until later years when older fish are more susceptible to sampling. The presence of these younger cohorts in the golden perch population indicates increased resilience to environmental disturbances (e.g. drought).

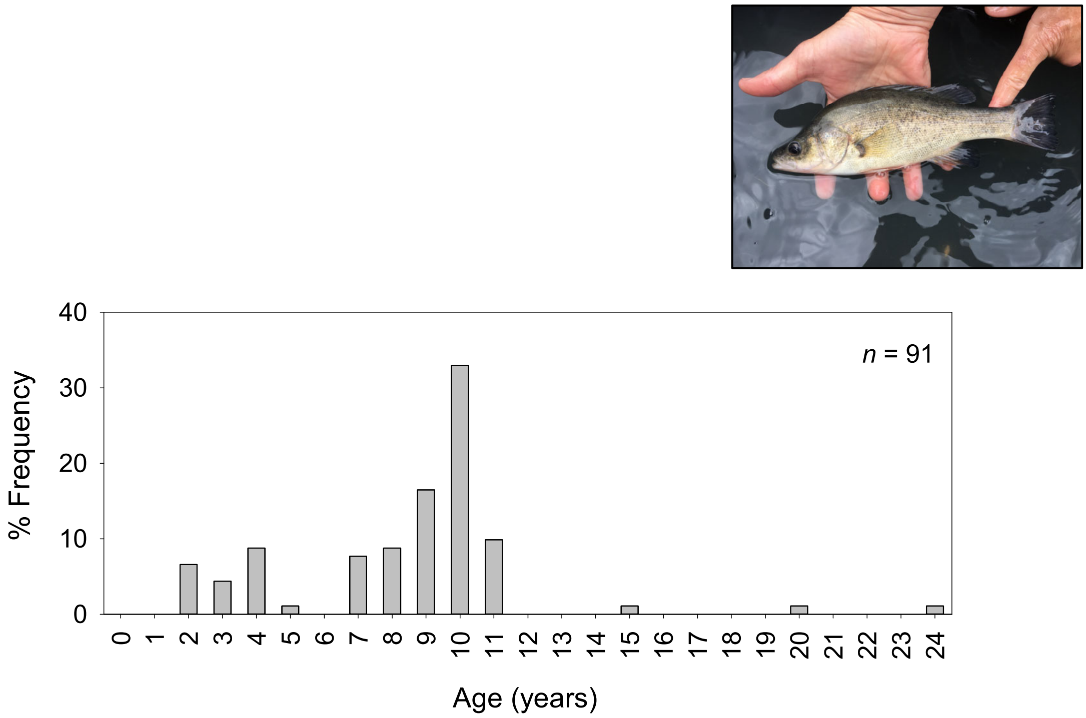
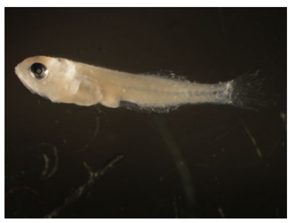


Figure 8. Ages of golden perch, expressed as a percentage of the overall population, from the Lower Murray River in 2021 (photo: SARDI).

Silver perch spawning: Silver perch display similar life history characteristics and population dynamics to golden perch, although in the lotic reaches of the Murray River, silver perch may reproduce each year (Tonkin *et al.* 2019). Annual increases in flow (spring flow pulses) were a distinct hydrological feature of the unregulated Murray River (Mallen-Cooper and Zampatti 2018). In the LMR, the silver perch population may also be comprised of fish derived from local spawning, and immigrants from other spawning sources, in particular the mid-Murray River (Ye *et al.* 2020).

During 2020-21, substantial numbers of silver perch larvae were collected in the LMR (Figure 9), coinciding with environmental water delivery during late spring–early summer in 2020-21. Most larvae had a natal origin from the lower reaches of the mid-Murray River (i.e. upstream of the Darling River junction), while a small proportion were from the Murray River between Lock 6 and Lock 10. This suggested that the flow regimes during spring–summer in mid-Murray to LMR were conducive to promote silver perch spawning and downstream larval drift. No juvenile (<1 year old) fish were sampled in the LMR during autumn 2021 electrofishing surveys, suggesting negligible or low-level recruitment. Future sampling will strengthen this assessment.

Figure 9. Silver perch larvae (photo: SARDI).



Low recruitment of Murray cod: Spawning of Murray cod occurs in spring–early summer, irrespective of flow (Rowland 1998), but recruitment in the main channel of the LMR is more successful with increased flow and lotic habitat (Ye *et al.* 2000; Zampatti *et al.* 2014). In 2019-20, there was strong recruitment of Murray cod, indicated by an increase in the relative abundance of juveniles (<1 year old) throughout the LMR (Figure 10). The greater extent and duration of lotic habitat (Figure 5) immediately prior to and during their reproductive season (from mid-October to mid-November 2019) may have benefited Murray cod recruitment, potentially by enhancing spawning habitat area and survival of early life stages. During 2020-21, most of the environmental water delivery and promotion of lotic conditions occurred from late November to mid-December 2020, after the key spawning period. There was low recruitment of Murray cod during this year, but good survival of recruits from the previous year (2019-20) cohort as age 1+ (Figure 10). The mechanisms that influence recruitment success need further investigation and are currently being explored via the Selected Area research (Section 3.3).

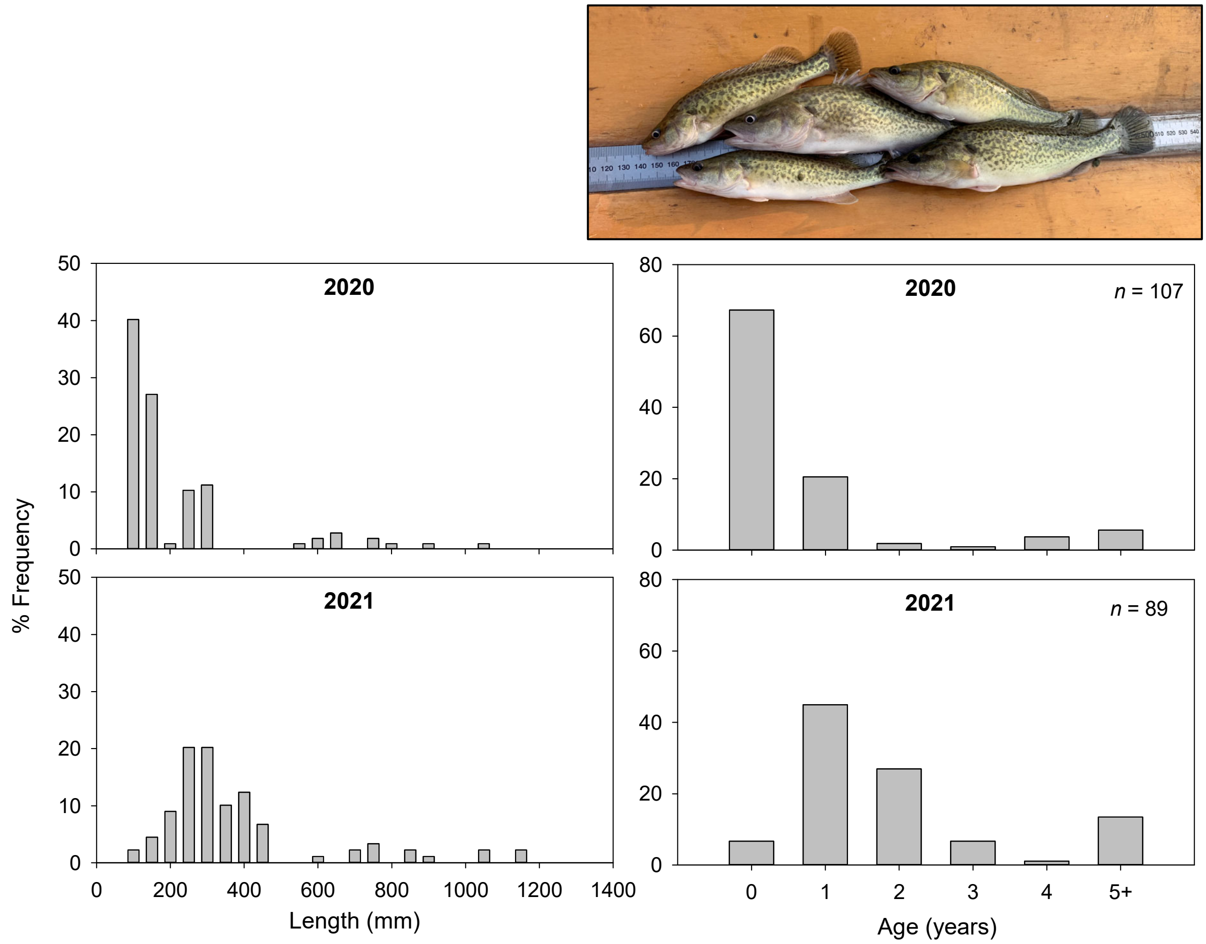


Figure 10. Lengths (left) and estimated ages (constructed using age–length relationships, right) of Murray cod, expressed as a percentage of the sampled population from the Lower Murray River during electrofishing in autumn 2020 and 2021 (photo: SARDI). Note: change in y-axis scale between figures.

Fish assemblage: While there has been a lack of strong recruitment from native, flow-cued spawners (e.g. golden perch and silver perch), strong recruitment of Murray cod in 2019-20 and the survival of these fish to age 1+ in 2021 has led to an increase in abundance of this species, relative to 2015 and 2016. Small-bodied fish (e.g. carp gudgeon) abundances were variable from 2015–2021, characterised by low abundance following high flow in 2016/17, but high abundance in all other years.

Increased water level variability

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 2, Figure 11). In 2020-21, the interquartile range (a measure of variation) in water level increased by 0.12 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 11).

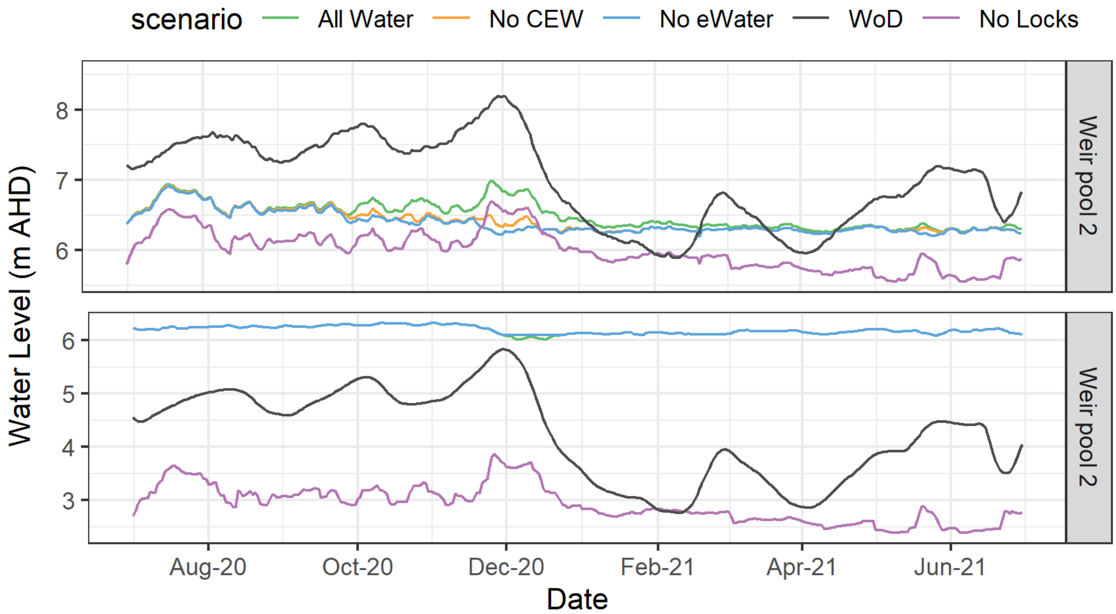


Figure 11. Modelled water level (metres relative to the Australian Height Datum) at the upstream (top) and downstream end (bottom) of the Lock 2 weir pool in the Lower Murray River. Coloured lines (green, orange and blue) represent the modelled environmental water scenarios. The black line represents the modelled natural (without development, WoD) scenario while the purple line represents the influence of the weir and locks across the River Murray removed (No Locks) scenario. Note the different scaling on the y-axis.

Increased littoral vegetation diversity: Vegetation monitoring in February 2021 demonstrated increased native plant species diversity by 42–82% across multiple reaches following the inundation of littoral zones by increased water levels from spring–early summer flows in the LMR, supported by environmental water. While river red gum seedlings were generally absent in 2020-21, saplings were abundant and in good condition indicating high survivorship of seedlings from the 2019 flow pulse (Figure 12). In 2020-21, the spring flow pulse produced conditions suitable for the recruitment of specialised riparian species (e.g. Australian mudwort, lesser joyweed, spreading nut-heads) that are adapted to fluctuating water levels, therefore increasing plant functional diversity.

Figure 12. River red gum saplings in the Lock 4 reach (photo: SARDI).

Slightly increased food production: Increased flow and water levels from Commonwealth environmental water widened the river, increasing the volume of water available to aquatic plants and animals. As a result, the rates of food production (measured as cross-sectional gross primary production) increased slightly (by ~0–2.5% each year from 2014-15 to 2020-21), 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). Decomposition rates (i.e. the rate of breakdown of organic material) increased by 5–13% due to environmental water. This suggests an increased input of basal food resources to the river.

Lower Lakes and Coorong: barrage flow

Salt transport and maintained connectivity between the Murray River, Coorong estuary and Southern Ocean

Increased salt export: 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, 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 (Ye *et al.* 2020). Since July 2017, during low flow, Commonwealth environmental water played a vital role in salt export from the MDB (through the barrages). In 2020-21, Commonwealth environmental water was responsible for the export of 1.07 million tonnes of salt, representing 58% of total export (Ye *et al.* 2022).

Reduced salt import and enhanced Coorong habitat: Commonwealth environmental water has also been critical in reducing salt import via the Murray Mouth (Figure 13), particularly during the low flow years. Without Commonwealth environmental water, over the period 2017-18 to 2020-21, an additional ~3.2 million tonnes of salt would have entered the Coorong via the Murray Mouth and 2.1 million tonnes of salt accumulated in the South Lagoon (Figure 14). This would have produced salinities (~3.5 times seawater) in the South Lagoon reminiscent of the Millennium Drought that led to detrimental loss of aquatic life. Maintaining suitable salinity levels in the Coorong is crucial for supporting estuarine habitats, species diversity and ecosystem function. In 2020-21, without Commonwealth environmental water, the area of suitable habitat would have decreased by 8%, 7% and 6% (modelled) for mulloway, congolli and smallmouth hardyhead, respectively, due to increased salinity. Over last four years (i.e. 2017-18 to 2020-21), this equated to avoiding a potential habitat reduction of 34%, 39% and 42% (modelled) for the three respective fish species. Additionally, over these four years, environmental flows led to a 70% increase in the suitable habitat area to support seed production and life-cycle completion of the aquatic plant *Ruppia tuberosa* in the southern Coorong.

Figure 13. The Coorong estuary (and Murray Mouth) of the Murray–Darling River system connecting the river to the Southern Ocean (photo: Adrienne Rumbelow, DEW).

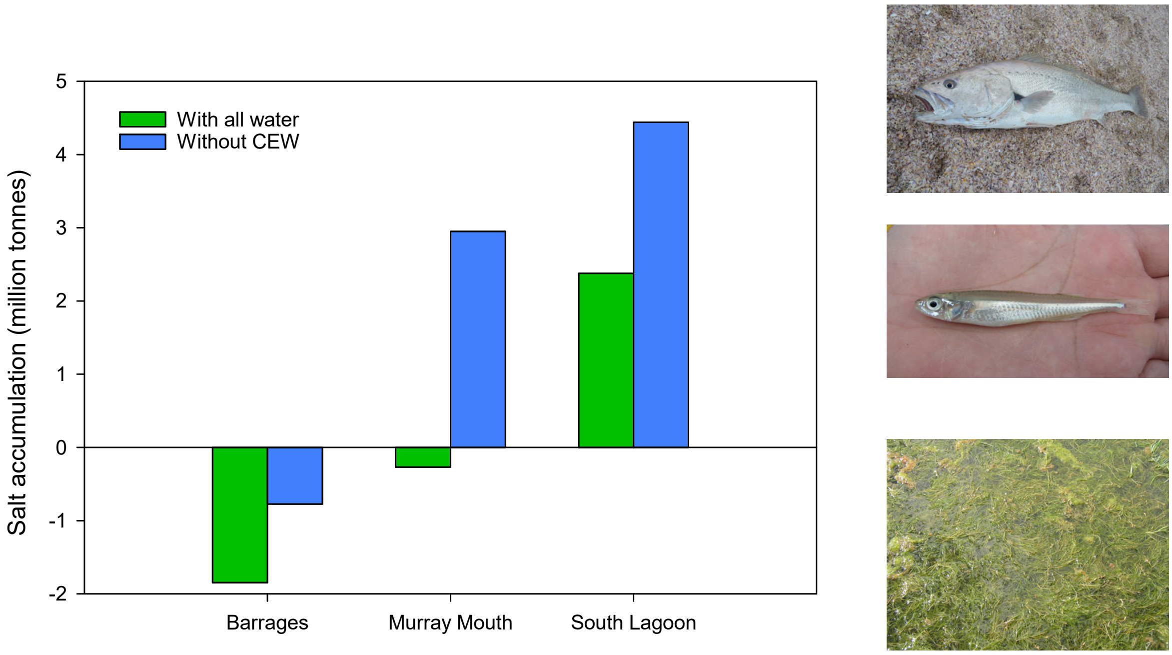


Figure 14. Modelled salt export (million tonnes) out of the Murray–Darling Basin (barrages) and accumulation in the Coorong through the Murray Mouth and the South Lagoon from 2017-18 to 2020-21. CEW = Commonwealth environmental water (photos: mulloway (top), smallmouth hardyhead (middle) and *Ruppia* (bottom), SARDI).

3.3 Research

The objective of the research project in the LMR is to investigate how energy (carbon) transfers through the aquatic food web to predators (e.g. juvenile Murray cod), and ultimately how flow (hydrology and hydraulics) affects energy sources and transfer (Figure 15). Specific questions are:

- What is the diet of larval and juvenile Murray cod?
- What 'basal sources' of the food web (e.g. river channel vs. floodplain, micro-algae vs. plants) support the growth of early life stage Murray cod?
- How do these flow-related food web processes relate to Murray cod growth, body condition and recruitment?

Understanding what drives improved growth rates, condition, survival and ultimately recruitment of Murray cod, is key knowledge required to inform environmental water delivery and flow management in the LMR.

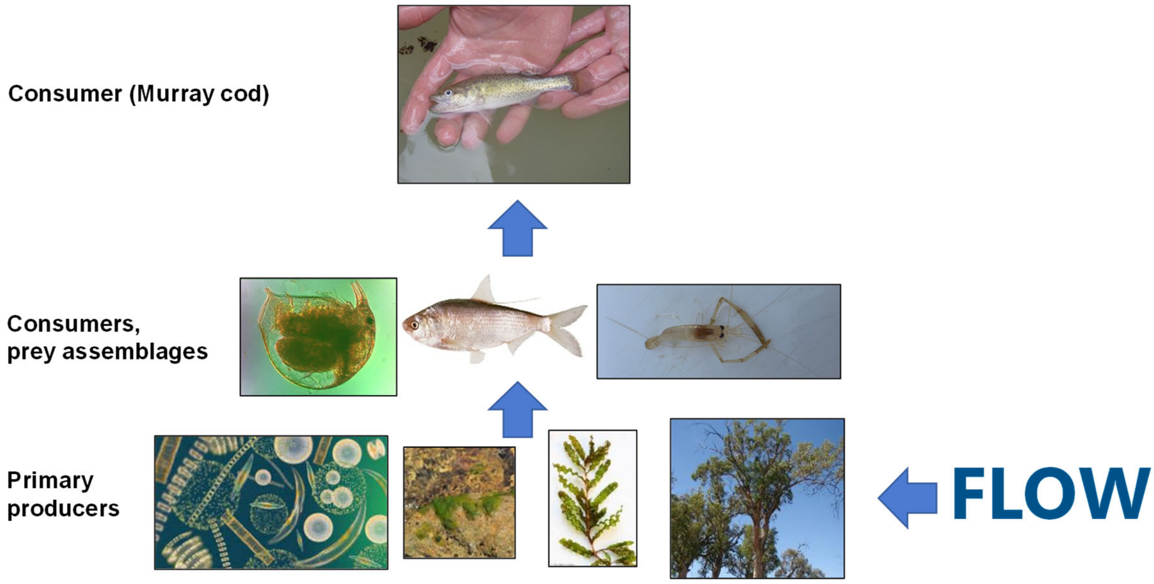


Figure 15. Basic conceptual model of energy flow in the Lower Murray food web.

Techniques

This research project integrates the monitoring from several indicators of the CEWO MER Project in the LMR (Section 1.2). Multiple laboratory techniques are used to answer our specific research questions:

- **Gut-content analysis** of larval/juvenile Murray cod using standard microscope approaches to assess diet.
- **Molecular analyses** to characterise prey communities, and the diet of larval/juvenile Murray cod.
- **Compound-specific stable isotope analysis** (CSIA) to investigate the contribution of different basal food sources (e.g. river red gum, microalgae) in supporting juvenile Murray cod growth.

Preliminary findings – diet analysis

- **Gut content analysis using microscopy:** The diet of larval (<40 mm) Murray cod collected from 2014–2020 was almost entirely microcrustaceans (i.e. copepods and cladocerans).
- **Molecular analyses** of larval gut content suggested microcrustaceans and rotifers were important in diet. The diet of larvae was distinct from that of juveniles 40–150 mm in length.
- In 2019-20, when <1 year old Murray cod were sampled in all months, there was little difference in diet among juveniles collected from January (~40 mm) to May (~150 mm) – they mostly ate shrimp (Figure 16).
- The diet of juveniles (~150 mm) collected in autumn from 2015–2021 was dominated by decapod crustaceans, particularly shrimp, and was similar among years.

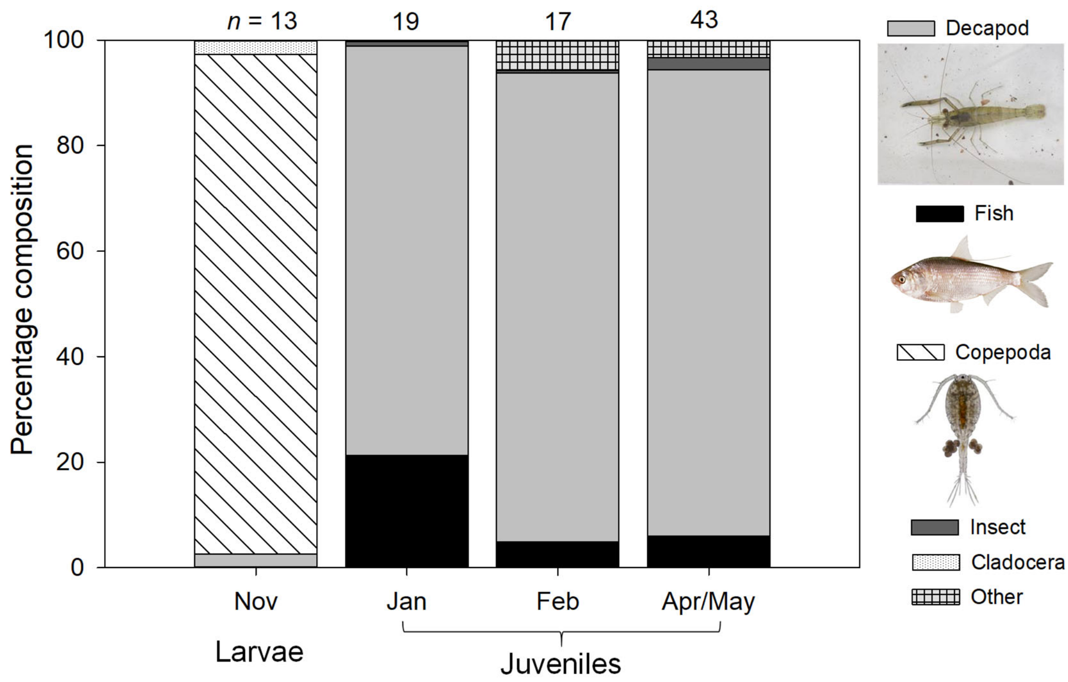


Figure 16. Percentage composition of major prey in the guts of Murray cod larvae (November, by number) and juveniles (January–May, by weight) from the Lower Murray River in 2019-20. Sample numbers are presented above each bar. Other = other crustaceans, rotifers, vegetation and unidentified material.

3.4 Communications and engagement

The Engagement and Communication (E&C) activities in the Lower Murray aim to strengthen the existing communication with managers/stakeholders and broaden engagement with the general public, focusing on recreational fishing and indigenous groups. Building on our existing relationships and ongoing communication with CEWO and other key stakeholders (e.g. the Selected Area Working Group), we have implemented a range of additional E&C activities and developed multiple communication products over the last year, including:

- Indigenous engagement – Indigenous Ecology in Action workshops run collaboratively with Calperum Station in June and October 2021 (Figure 17).
- Capacity building workshop with Richard Snashall, "Making your science visible using photos, videos and storytelling".
- Recreational fishing engagement – Qifeng Ye and George Giatas presented at the Annual Fishcare Volunteers Forum, in November 2021 (Figure 18).
- Highlight stories on the Lower Murray webpage on the Flow-MER website
- Hard copy and audio-visual communication products, including the 'Sharing our Science' video (Figure 19 and 20).
- Quarterly outcome newsletters featured on the CEWO and Flow-MER websites.
- Consulting and co-designing future activities with indigenous and recreational fishing groups.

Figure 17. Indigenous Ecology in Action Workshop participants.

Figure 18. Qifeng Ye giving a presentation at the Annual Fishcare Volunteers Forum. Photo credit: PIRSA.

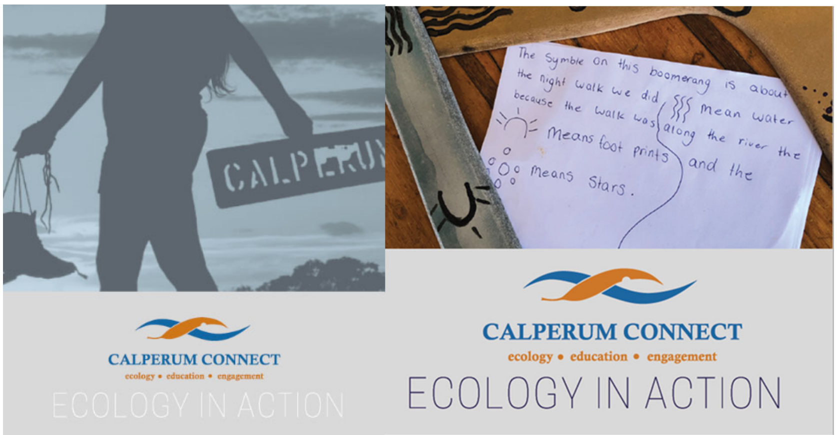


Figure 19. Flyers used to promote Indigenous Ecology in Action workshops.

Figure 20. Still image of "Sharing our Science" video (https://youtu.be/gCldgGF_Ris)

Engagement and communication activities during 2020-21 needed to be flexible and adaptive as we managed through ongoingCOVID-19 uncertainties. We focused on developing and providing online communication products to tell our stories and keep the community engaged. As part of this strategy, we filmed our field teams in action and produced a comprehensive video showing the field and lab work undertaken by the Lower Murray researchers for the Flow-MER Project (May 2022 release). An animation video demonstrating how Water for the Environment contributes to ecological restoration in the Lower Murray River has also been developed (May 2022 release). During a window in which face-to-face community engagement was possible, we worked with Calperum Station managers, ecologists and indigenous rangers and local school teachers/indigenous advisors to implement an on-ground training program integrating traditional and modern science for indigenous students. We continued to meet with indigenous and recreational fishing groups and look for opportunities to build relationships and trust through meaningful engagement with Lower Murray MER in future years. .

4 Implications for future management of environmental water

In the LMR, 2020-21 was a hydrologically dry year with a total discharge volume of 3,084 GL (at the South Australian border, 1991-92 to 2021-22 long-term average = 4,763 GL/year, DEW unpublished data). Of this volume, 934 GL was environmental water, including 687 GL of Commonwealth environmental water, primarily delivered to the main channel of the LMR through coordinated watering events across the southern MDB. Environmental water delivery supported a spring–early summer flow pulse peaking at 17,900 ML/d at the South Australian border (for comparison, 'bankfull' flow is ~45,000 ML/d) in late November 2020 (Figure 4). This contributed to improvements in hydrological connectivity (velocity >0.2 m/s) and increased the proportion of weir pools (stretches of river between weirs) characterised by 'flowing water' (>0.3 m/s) habitat. These improvements, however, could be considered 'small to moderate' and were not to the extent that once characterised the LMR under natural (pre-regulation) conditions (Figure 5).

Small to moderate increases in flowing water habitat and riverine connectivity can support a range of 'reach scale' ecological outcomes in the LMR. Our monitoring since 2014-15 has demonstrated the ecological outcomes in this region associated with increased flows between 10,000–18,000 ML/d, including mitigating the risk of low dissolved oxygen in water, increasing vegetation diversity and productivity along the river bank in tailwater reaches, and increasing Murray cod recruitment. Processes that typically operate at broader spatial scales, like the spawning and recruitment of flow-cued spawning fishes, have been partially supported, with low-levels of spawning and recruitment detected in several years. Notably, such ecological improvements supported by elevated flows may be important in maintaining resilience in key populations and the LMR ecosystem. Delivery of water for the environment during these dry years is likely critical to support ecological 'maintenance' between natural high flow events.

More substantial increases in flow (e.g. higher in-channel spring–early summer flow pulses >20,000 ML/d) are required to restore riverine characteristics to the LMR and achieve specific ecological outcomes (e.g. significantly influence riverine food production, widespread spawning and strong recruitment of golden perch), and should be considered a priority for management. With existing volumes of water for the environment 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), and through water delivery that is responsive and flexible to rain events.

In the LMR, main-channel weirs have fragmented the river and altered hydraulic conditions. The weirs act to deepen and slow the flow of the river, relative to natural. As such, the modern LMR has only short and discontinuous stretches of flowing habitat in weir tailwaters during low flow years (Figure 5 andFigure 21). Pre-regulation, the LMR was characterised by flowing habitats, with average water velocities commonly >0.3 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 weirs (Bice et al. 2017). Many native plants and animals, adapted to riverine habitats, are now extinct or suffered major declines due to impact of weirs on river hydraulics (Walker 2006; Mallen-Cooper and Zampatti 2018). To support the rehabilitation of riverine species, weir pool lowering could be applied to complement flows to further improve flowing water habitats. For example, hydraulic modelling suggests that at flows of 15,000 ML/d, lowering weir pools by 1 m could result in a similar extent of flowing water habitat to flows of 20,000 ML/d in the main channel of the LMR (Figure 21).

Furthermore, the timing of flow delivery is important. When flow aligns with biological processes and species' life history requirements (e.g. spawning season of Murray cod, golden perch, etc), it is more likely to achieve the targeted ecological objectives. For example, the spring flow pulse delivery in 2019-20 in the LMR occurred immediately prior to and during the spawning season of Murray cod (mid-October to mid-November), and may have contributed to the strong recruitment of this species. Alternatively, flow pulses that occur later in summer coincide with higher water temperatures (>20°C) and the spawning season of golden perch (typically with peak spawning between November and January in the LMR, based on data from 2010–2013 wet years), and if of sufficient magnitude, may promote spawning and recruitment of golden perch. To achieve multiple species outcomes, a holistic approach in flow regime design will be required, which may involve planning for multiple years to achieve diverse outcomes. Flow management could be informed by multi-years monitoring data and learnings regarding the effect of specific aspects of flow (e.g. timing, magnitude and duration) on life-history processes, the hydraulic requirements of flow-dependent species, and the availability of food resources. Whilst the timing of flow is important, a large proportion of environmental water is delivered to the LMR as return flows (e.g. in winter/spring/early summer), and as such, timing of delivery to the LMR is reliant on the timing of these upstream actions. This reinforces that a coordinated approach to environmental water planning and delivery across the southern Basin is essential.

Finally, environmental water is critical in maintaining end-of-system flows. This is particularly important during dry years when environmental water can comprise up to 100% of flow. Barrage flows are crucial in maintaining connectivity (including fishway operations) and facilitating key life-history processes (e.g. lamprey migration). Barrage flows are required to flush out salt from the entire MDB, whilst also influencing local salinity regimes. Barrage flow reduces salt import from the Southern Ocean into the Coorong, and reduces salt flux into the North and South lagoons. This helps reduce salinity levels throughout the Coorong, which is essential to maintain estuarine habitat (e.g. for fish and aquatic plant *Ruppia*) and ecosystem function, and prevent detrimental loss of aquatic life as observed during the Millennium Drought (2001–2010).

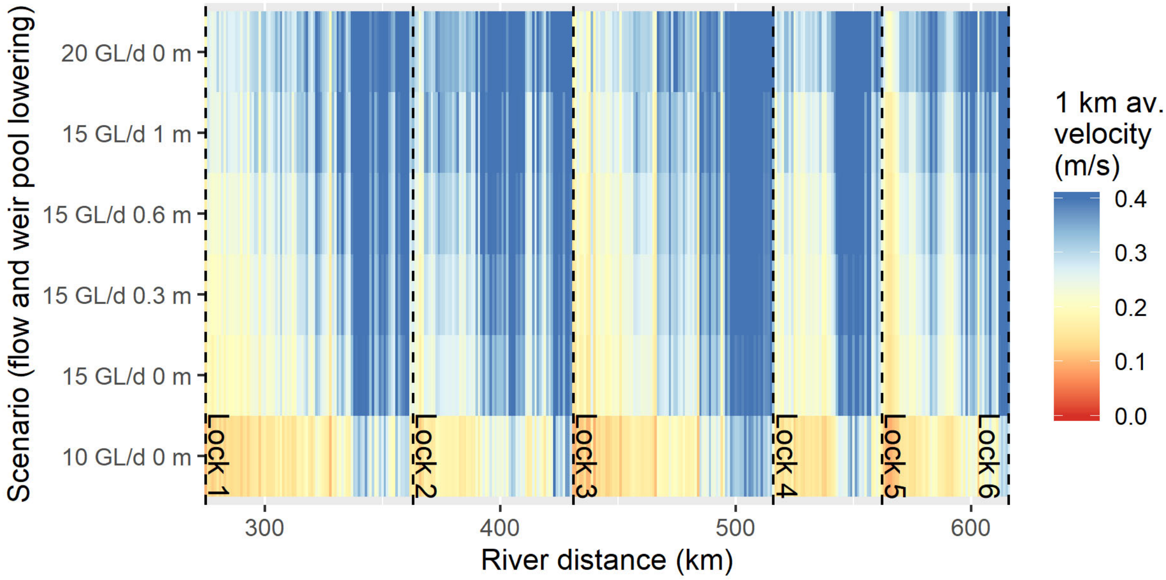


Figure 21. 1 km average velocity from Lock 1 to Lock 6 for scenarios of different flows to South Australia and weir pool lowering.

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