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Lower Murray River

2017-18 Technical Report

A report prepared for the Commonwealth Environmental Water Office by the South Australian Research and Development Institute, Aquatic Sciences

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Disclaimer

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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EXECUTIVE SUMMARY

Ecological responses to Commonwealth environmental water delivered to the Lower Murray River (LMR) Selected Area were assessed during year four (2017-18) of the five-year Commonwealth Environmental Water Office (CEWO) Long-Term Intervention Monitoring (LTIM) project. During 2017-18, ~894 GL of Commonwealth environmental water was delivered to the LMR, in conjunction with other environmental flows (e.g. the Murray–Darling Basin Authority (MDBA) The Living Murray Initiative), coordinated through a series of watering events across the southern-connected Basin to achieve multi-site environmental outcomes. Environmental water contributed to 43% of the total annual flow in the LMR, with Commonwealth environmental water contributing 33% in isolation. Commonwealth environmental water delivery largely consisted of return flows from upstream watering events (e.g. Goulburn and Murrumbidgee rivers) and promoted spring–early summer in-channel flow pulses (up to ~18,000 ML/d) in the LMR.

Seven indicators were used to evaluate the ecological response to Commonwealth environmental water, with a focus on the main channel of the LMR. Three indicators (***Hydrology (channel)***, ***Stream Metabolism*** and ***Fish (channel)***) primarily aimed to evaluate Basin-scale objectives and outcomes, and in some instances, also local (Selected Area) objectives, following basin-wide standard protocols. Four indicators (***Hydrological Regime***, ***Matter Transport***, ***Microinvertebrates*** and ***Fish Spawning and Recruitment***) aimed to address local evaluation questions, using area specific methods.

Key ecological outcomes

The main aim of Commonwealth environmental water use in the LMR was to contribute to elevated base flows and small freshes in the main channel, and to provide continuous barrage flows into the Coorong. These flows intended to achieve a variety of outcomes including those relating to fish, birds, vegetation, river function, Lower Lakes water levels and salt export, although not all of these are monitored through this project.

Spring–early summer flow pulses, supported by environmental water, promoted longitudinal connectivity and contributed to a broad range of ecological outcomes in the LMR during 2017-18. These included increased velocity and water levels in the river channel (weir pools); maintaining favourable dissolved oxygen concentrations; increased transport of nutrients and phytoplankton; enhanced in-stream production; increased microinvertebrate dispersion; reduced salinities in the Coorong and increased salt export through the Murray Mouth. Flow pulses during spring–early summer did not promote recruitment of golden perch or silver perch, despite golden perch spawning. Key outcomes and responses to Commonwealth environmental water are summarised in Table 1.

Table 1. Summary of the key findings from indicators relating to the CEWO short-term (one-year) evaluation questions (answers in blue text) associated with environmental water releases to the Lower Murray River (LMR) Selected Area during 2017-18. CEW = Commonwealth environmental water, TLM = The Living Murray.

CEWO SHORT-TERM EVALUATION QUESTIONS AND ANSWERS	KEY FINDINGS
Hydrological Regime **(modelling)** What did CEW contribute to: • Hydraulic diversity within weir pools? CEW increased hydraulic diversity by creating up to 20% flowing water (lotic) habitat (i.e. >0.3 m/s) in the LMR over several events from July to November, and up to 50% lotic habitat in the Lock 5 weir pool during December. • Variability in water levels within weir pools? CEW created variability in water levels, with approximately four events of different durations that decreased and then increased water levels at the upper end of each weir pool that otherwise would not have occurred during entitlement flow conditions.	Hydraulic diversity was increased in weir pools by creating relatively small patches (up to 20% of the weir pool) of lotic habitat over July to November that would not have been present otherwise. During December, CEW increased the proportion of weir pools experiencing lotic conditions from very small patches to up to 30–50% of weir pool (depending on the location). Restoring lotic habitat is critical for the rehabilitation of riverine biota and ecological processes in the lower River Murray. Variability in water levels was created by CEW, with periodic increases in water levels at the upper end of each weir pool between 0.1–0.5 m over July–November. CEW contributed to larger increases in water level during December, of 0.6–0.8 m. Periodic increases in water levels increased stream productivity, and could improve the condition of littoral (along the bank) vegetation and increase biofilm diversity, which is a key component of riverine food webs.
Stream Metabolism What did CEW contribute to: • Dissolved oxygen levels? Dissolved oxygen concentrations remained close to saturation, assisted by the enhanced flows associated with environmental water contributions. • Patterns and rates of primary productivity and decomposition? The extended period of environmental flows enhanced the river size, increasing the integrated cross-sectional biotic biomass without substantially reducing metabolic rates, and consequently increasing the integrated rates of gross primary production (GPP) and ecosystem respiration (ER).	The 2017-18 monitoring showed dissolved oxygen (DO) concentrations consistently near to 100% saturation (~8–10 mg/L). Favourable dissolved oxygen (generally >5 mg/L) is critical for aquatic animals, particularly during spring–summer, which is the primary reproductive season of many species. The low flows predicted without environmental water would have greatly increased the likelihood of reductions in DO, and the environmental water contributions helped avoid low DO. Environmental flows over the monitoring period enhanced accumulated production and decomposition by increasing in-channel river volume without causing major detrimental changes in metabolic rates. The increased food production and increased utilisation of food resources indicates an enhanced food web. The increase in cross-sectional GPP and

	ER over the monitoring period was estimated as 5% at Lock 6 and 20% at Lock 1. Maximising benefits to river production will depend on the location, timing, magnitude, duration and frequency of the flows. Some locations, seasonal periods, and river levels will deliver greater benefits from additional flows than others.
Matter Transport (modelling) What did CEW contribute to: • Salinity levels and transport? CEW increased export of salt from the Murray River Channel, Lower Lakes, and Coorong. • Nutrient concentrations and transport? CEW contributed to minor differences in the concentrations of nutrients, but increased transport of all studied nutrients. • Concentrations and transport of phytoplankton? Whilst there was no apparent effect on phytoplankton concentrations, there was increased transport of phytoplankton through the system, due to CEW. • Water quality to support aquatic biota and normal biogeochemical processes? CEW delivery reduced salinity concentrations in the Coorong, creating conditions that are less saline than marine and are typical of estuarine habitat. • Ecosystem function? CEW delivery increased exchange of nutrients and phytoplankton between critical habitats of the LMR, which may have supported primary and secondary productivity in the region and in doing so supported food webs of the LMR, Lower Lakes and Coorong.	Modelling suggested that environmental water generally had a positive impact on the concentrations of dissolved and particulate matter. Environmental water increased salt exports from the Murray River Channel, Lower Lakes, and Coorong. Annual median salinities with all water remaining at a level typical of estuarine habitats (26.2 PSU#) in the Coorong, compared to marine-like conditions (33.8 PSU) that would have occurred without CEW. CEW contributed 69% of salt export out of the Basin via barrage flows in 2017-18. Overall, environmental water reduced the net import of salt to the Coorong from 6.1 million to 0.5 million tonnes. Without CEW, there would have been greater flow of seawater into the Coorong, which would have brought an additional 2.9 million tonnes of salt. Environmental water increased exports of nutrients from the Murray River Channel, Lower Lakes and Coorong. Nutrients are a resource that increase primary production, which is the base of the food web and fixes the carbon that eventually ends up as higher level organisms. Resourcing primary productivity in rivers and estuaries is critical for food webs. There was increased exports, relative to without CEW, of phytoplankton biomass from the Murray River Channel, Lower Lakes and Coorong. This may have provided benefits for the Lower Lakes, Coorong and near-shore environment by providing energy to support secondary productivity, as phytoplankton are consumed by higher trophic organisms.
Micro-invertebrates What did CEW contribute: • To microinvertebrate diversity?	The 2017-18 microinvertebrate assemblage was typical of in-channel flows and less diverse than that during overbank flows in 2016-17, when high numbers of non-planktonic species that are littoral, epiphytic (attached to plants) or epibenthic (on the surface of sediment) in habit were transported

CEW deliveries during December 2017 from disparate upstream sources provided a mixed, species-rich, microinvertebrate assemblage, primarily of warm-water taxa from, for example, the Murrumbidgee and Lake Victoria, with cool-water species from the Goulburn/southern Basin. • Via upstream connectivity to microinvertebrate communities of the LMR? CEW contributed to longitudinal connectivity and most likely the transport of heleoplanktonic* warm-water taxa, including novel taxa for the LMR or the continent, to the LMR in January 2018. These could have derived from northern tributaries, or from populations established in Lake Victoria. • The timing and presence of key species in relation to the diet of large-bodied native fish larvae? Relationship between timing of ambient (present in environment) microinvertebrates, driven by CEW, and their presence in fish diet could not be determined due to low larval sample sizes. • To microinvertebrate abundance? Increased CEW deliveries in late November and late December were followed by pulses in microinvertebrate abundance, with a general increase in densities over the sampling period.	into the main channel. In 2017-18, highest microinvertebrate diversities (>20 spp.) occurred from late November to early January, which coincided with an increase in flow from the Upper Murray and Goulburn rivers (total flow to South Australia >10,000 ML/d) and the increase in abundance or prevalence of taxa known to these catchments. During this period, with the exception of late December, a large proportion of the water that contributed to river flow was environmental water, including TLM and CEW. Microinvertebrate density peaked in early January 2018 during increased water temperature (~25°C). Warmer temperatures favoured warm-water species, including rotifers *Keratella americana*, *K. tropica* and *K. tecta*, which were highly abundant at Lock 1. As demonstrated for other years of LTIM, particularly 2016-17, longitudinal connectivity of river flow is important in the transportation of microinvertebrate taxa from upstream catchments (e.g. Goulburn and upper Murray rivers) to the LMR, contributing to the diverse community in the LMR.
Fish Spawning and Recruitment What did CEW contribute to: • Reproduction of golden perch and silver perch? Delivery of CEW to the lower River Murray in 2017-18 coincided with spawning, but no detectable recruitment of golden perch (to young-of-year, age 0+).	In spring–early summer 2017-18, golden perch spawning occurred in the lower River Murray in association with in-channel flow pulses (peak flow to South Australia 17,800 ML/d). Nevertheless, the absence of young-of-year golden perch and silver perch in 2018, indicates unsuccessful recruitment and/or negligible immigration from spatially distinct spawning sources such as the lower Darling and mid-Murray rivers.

PSU (practical salinity unit) was used for Matter Transport modelling purposes in the report. PSU is approximately equal to 1 part per thousand (ppt or ‰) or 1 g/L.
* heleoplankton = plankton derived from billabongs and other floodplain still, generally-vegetated, waters.

Key learnings and management implications

- In the highly regulated lower River Murray, environmental water could be used to reinstate key features of the natural hydrograph to support hydrodynamic and ecosystem restoration; for example, to restore high, in-channel spring–early summer flow pulses (>20,000 ML/d).
- Hydrodynamic restoration is fundamental to maintaining or reinstating ecosystem function of the lower River Murray. Environmental water delivery can increase hydraulic diversity (e.g. velocity and water levels), potentially leading to ecological benefits by increasing flowing water habitat and restoring riverine ecosystem processes. To maximise ecological outcomes, however, we need to better understand the effect of specific flow (e.g. timing, magnitude and duration) on ecological processes and hydraulic habitat requirements of flow-dependant species to inform flow management
- Environmental water delivery that promotes longitudinal and lateral connectivity will enhance the productivity in the LMR, via increased carbon and nutrient inputs and matter transport, and facilitate the transport and dispersal of aquatic biota (e.g. microinvertebrates, fish larvae).
- Environmental flows are pivotal in maintaining barrage flows and end-of-system connectivity in the MDB, particularly during low flow periods, when there would otherwise be negligible water and matter exchange between the Lower Lakes and Coorong. Barrage flows play a significant role in salt export from the MDB, facilitate important life history processes of estuarine species and reduce the risk of increased estuarine salinities and Murray Mouth closure.
- The timing of environmental flow delivery should continue to align with ecological objectives and consider biological processes and life history requirements (e.g. reproductive season of flow-cued species in spring/summer or spawning migration of diadromous fishes in winter).
- The source of water (i.e. origin) is also important, which can influence water quality (e.g. turbidity, the amount and form of nutrients), ecological processes (e.g. primary/secondary productivity) and biological responses (e.g. larval fish dispersion).
- Furthermore, maintaining flow integrity from its source (e.g. Darling River, Murray upstream or major tributaries) to the end of the River Murray system is important to support broad-scale ecological processes and promote positive outcomes (e.g. improved productivity, migration of diadromous species and enhanced spawning and recruitment of flow-dependent species).

More specific management considerations are provided in Section 4. These were based on ecological outcomes and findings presented in Section 2.

1 INTRODUCTION

1.1 Background

In 2014, the five-year (2014-15–2018-19) Commonwealth Environmental Water Office Long-Term Intervention Monitoring (CEWO 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 (LMR), to enable Basin-scale evaluation in addition to Selected Area (local) evaluation. The overall aims of the project are to demonstrate the ecological outcomes of Commonwealth environmental water delivery and support adaptive management.

The CEWO LTIM project in the LMR focuses on the main channel of the LMR between the South Australian border and Wellington, with only one targeted investigation (i.e. Matter Transport) extending to the Lower Lakes and Coorong (Figure 1). Targeted investigations (for indicators) were conducted at various sites in the LMR Selected Area, covering three riverine geomorphic zones (floodplain, gorge and swamplands) and the Lower Lakes and Coorong (Wellington to Murray Mouth) (Figure 1).

Indicators were used to assess ecological responses to environmental water delivery in the LMR. Three indicators (***Hydrology (channel)***, ***Stream Metabolism*** and ***Fish (channel)***) followed standard protocols to support quantitative Basin-wide and Selected Area evaluation, where applicable (Hale *et al.* 2014). Four indicators (***Hydrological Regime***, ***Matter Transport***, ***Microinvertebrates*** and ***Fish Spawning and Recruitment***) were developed to address objectives and test a series of Selected Area-specific hypotheses with respect to biological/ecological response to environmental flows. Indicators were selected in line with Commonwealth environmental water evaluation questions for the Basin and Selected Area. Details are presented in the Monitoring and Evaluation Plan for the LMR (SARDI *et al.* 2018).

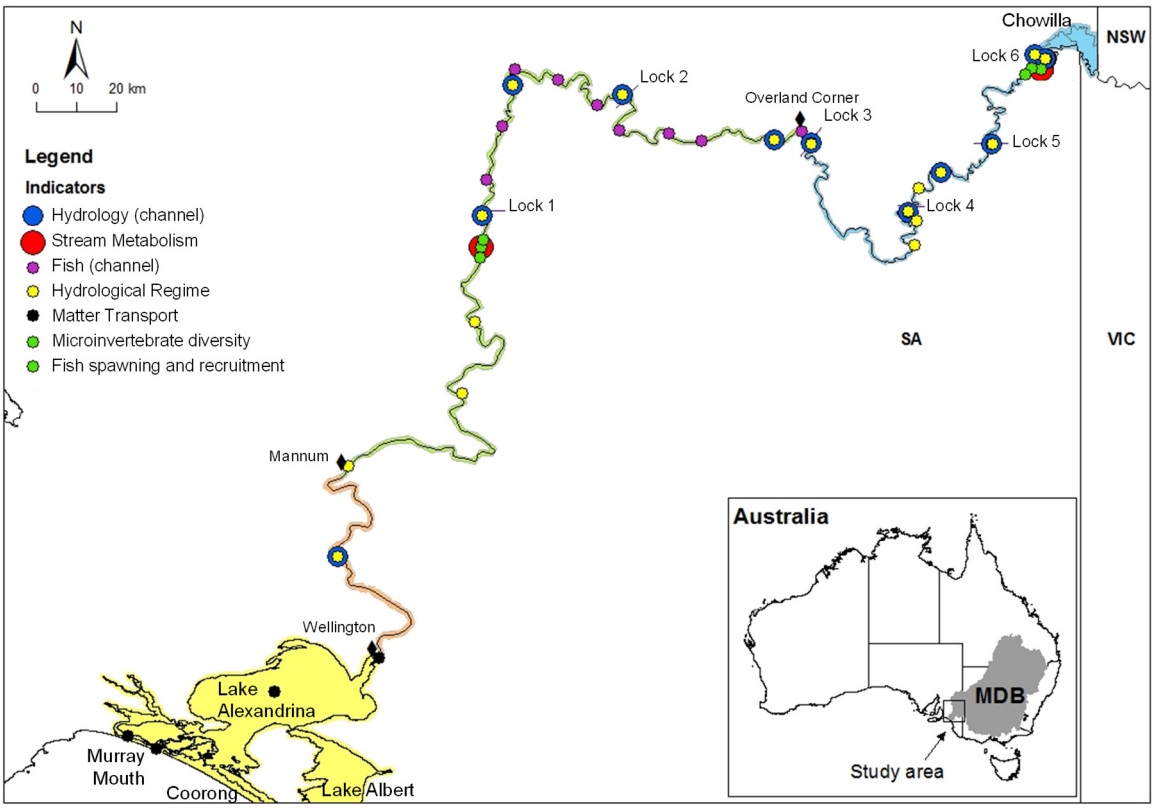

Figure 1. Map of the LMR Selected Area showing the floodplain (blue), gorge (green) and swamplands (orange) geomorphic zones, and the Lower Lakes, Coorong and Murray Mouth (yellow). Sampling sites are indicated by coloured circles. Fish Spawning and Recruitment sites represent larval sampling only.

1.2 Environmental water delivery in 2017-18

Expected outcomes

The overall aim of Commonwealth environmental water use in the LMR during 2017-18 was to contribute to elevated base flows and small freshes in the River Murray channel, and to provide continuous barrage flows into the Coorong. These particular flows intended to achieve a variety of outcomes including those relating to fish, birds vegetation, river function, Lower Lakes water levels and salt export (Appendix A), although not all of these are monitored through this project.

Environmental water delivery

In 2017-18, flow in the LMR (measured at the South Australian border) was variable (<18,000 megailtres per day, ML/d) and remained in-channel (Figure 2). During this year, ~894 GL[a] of Commonwealth environmental water was delivered to the LMR from 1 July 2017 to 30 June 2018, in conjunction with other sources of environmental water, i.e. The Living Murray (184 GL), Victorian Environmental Water Holder (29 GL), River Murray Increased Flows (53 GL) and New South Wales Office of Environment and Heritage (9 GL) (Figure 3)[b]. Environmental water contributed to 43% of the total flow in the LMR, with Commonwealth environmental water contributing 33% in isolation.

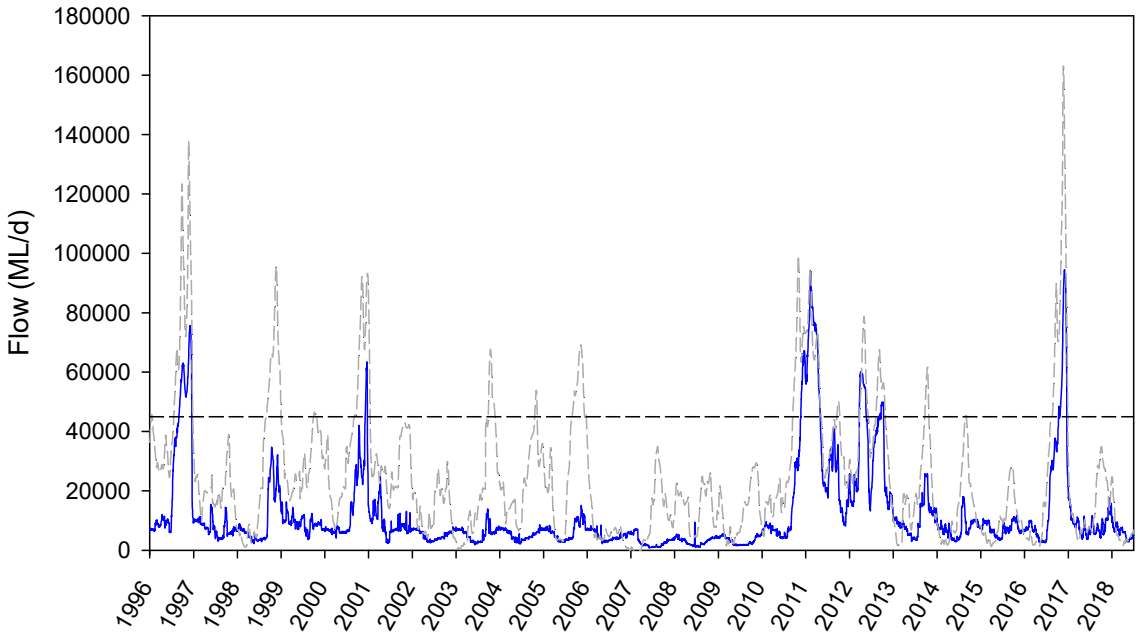

Figure 2. Daily flow (ML/d) in the LMR at the South Australian border (blue solid line) from January 1996 to July 2018, compared to modelled flow under natural conditions (grey dashed line). Approximate bankfull flow in the main channel of the LMR is shown (black dashed line).

Environmental water (almost entirely Commonwealth environmental water) delivered to the LMR from July to October 2017 was attributed to return flows from the Goulburn and Murrumbidgee rivers (Figure 3). These return flows contributed to increasing flow in the LMR (discharge at the South Australian border, QSA) from 3,300 ML/d to 11,700 ML/d in mid-July, and from 4,500 ML/d to 8,700 ML/d in early September

[a] In addition to ~894 GL of Commonwealth environmental water delivered to the South Australian border, approximately 13 GL of this was used by the CEWO to water off-channel wetlands and for net losses associated with weir pool manipulation at Locks 2 and 5 (source: CEWO).

[b] Figure 3 presents the change in flow resulting from water delivered for different watering actions, both ordered as a flow at the South Australian border and return flows from upstream. However, it is important to note that molecules of water, nutrients, and the biological matter transported downstream move more slowly than the wave front that is recorded as the change in flow discharge (Chow et al. 1988), and as such Figure 3 does not represent the physical arrival of matter from upstream actions at the South Australian border. This is better represented by Figure 4.

2017(Figure 3). Return flows, attributed to a pulse in the Goulburn River, increased flow from entitlement flow (5,000 ML/d) to 10,700 ML/d in mid-October 2017 (Figure 3).

From November 2017 to January 2018, environmental water was delivered to the LMR as return flows from Barmah–Millewa Forest and Hattah Lakes and a pulse from the Goulburn River (Figure 3). Environmental water delivery from late November to mid-December, which was mostly The Living Murray water (62%) and Commonwealth environmental water (30%), increased flow from 6,700 ML/d to a peak of 17,800 ML/d on 8 December (Figure 3). Subsequently, another flow pulse (15,800 ML/d) occurred in late December, shaped by an unregulated flow event (Figure 3).

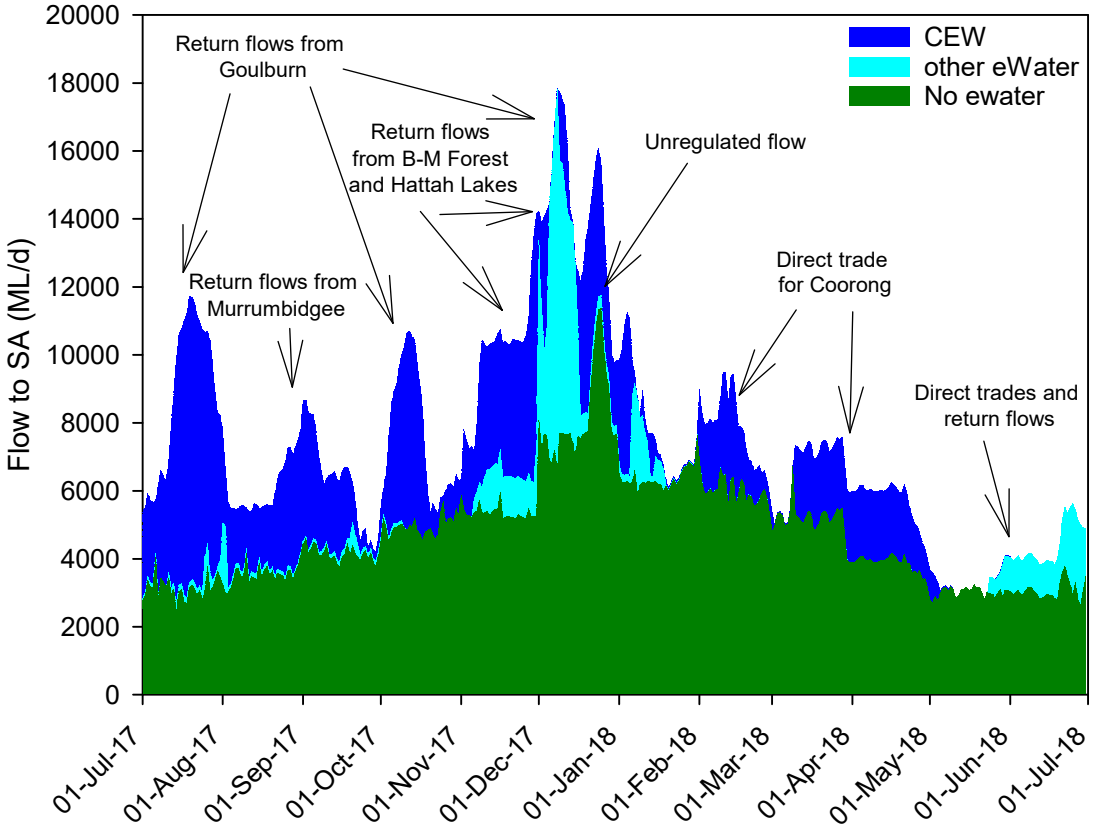

Figure 3. Flow to South Australia from July 2017 to June 2018 showing the contribution of environmental water and timing of major watering actions. CEW = Commonwealth environmental water. Other eWater = The Living Murray, Victorian Environmental Water Holder, New South Wales Office of Environment and Heritage and water delivered as part of River Murray Increased Flows. The 'no eWater' component includes 154.3 GL of South Australian entitlement held by the Commonwealth Environmental Water Holder and 45.0 GL held by TLM.

From February to early May 2018, Commonwealth environmental water (150 GL) was delivered directly to the South Australian border, increasing river flow from 6,500 ML/d to 9,500 ML/d in February, and maintained river flow at or above 6,000 ML/d from mid-March to mid-April, which otherwise would have been at entitlement flow (~4,000–5,000 ML/d) (Figure 3).

Flows to South Australia declined to ~3,000 ML/d in May due to reduced environmental water delivery, before increasing to 5,600 ML/d in late June, following River Murray Increased Flows (RMIF) direct trades and return flows and Victorian

Environmental Water Holder (VEWH) return flows. Outputs from modelling indicated that of Commonwealth environmental water contributed to continuous barrage releases (~757 GL) throughout the 2017-18 water year (1 July 2017 to 30 June 2018).

The physical source of flows to the LMR during 2017-18 can be seen in Figure 4. Flow was mainly comprised of flow from the upper Murray River and Lake Victoria, particularly after February 2018. Proportional flow from Victorian tributaries of the Murray River were greater from July to September and in early November and late December 2017, while proportional flow from the Murrumbidgee River was greater from mid-July to early October 2017 and mid-November 2017 to mid-January 2018 (Figure 4)[c]. Flow from the Darling River had minor contribution (<1,400 ML/d) to flow at the South Australian border during 2017-18.

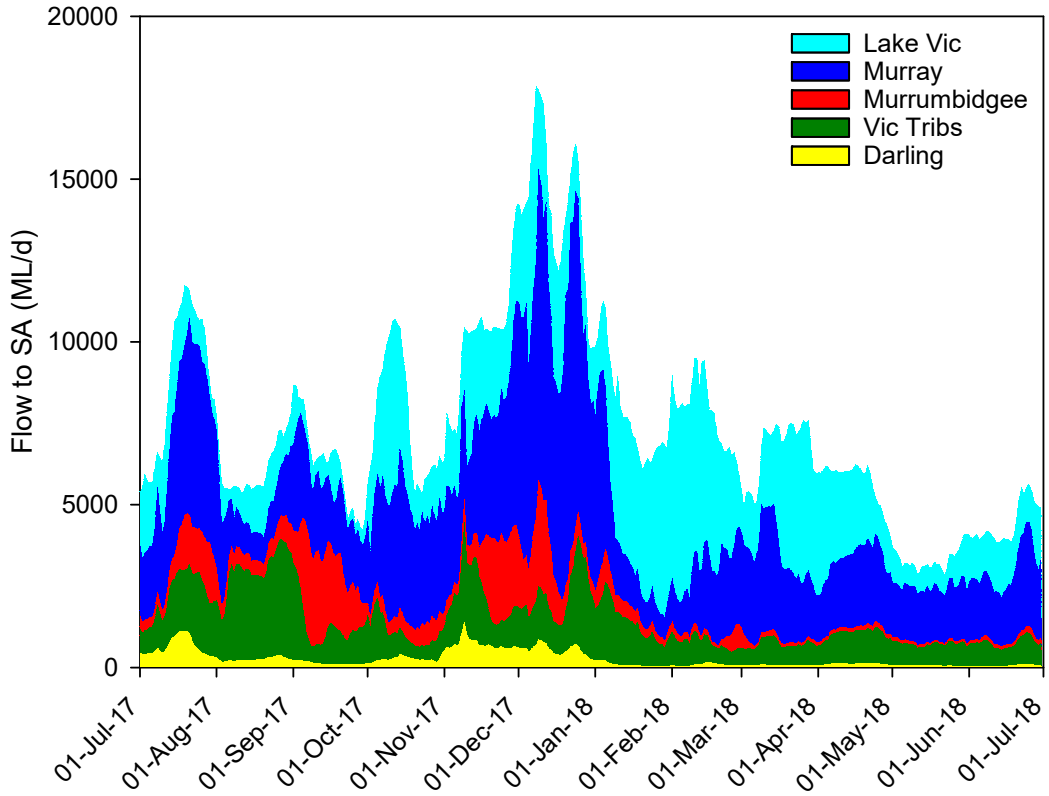

Figure 4. Source of all (environmental and consumptive) water delivered to the South Australian border (MDBA). Caveats for estimated water delivery time are mentioned above. Refer to Figure 23 for location of rivers and tributaries, relative to the LMR.

Concurrently with environmental water deliveries described above, there were other management interventions that occurred within or upstream of the LMR, such as manipulations of Weir Pools 2, 5, 6, 7, 8, 9 and 15 (refer to Appendix B for more information). These events may also have affected ecological responses in the LMR.

[c] MDBA has used Bigmod salinity routines as a proxy for transport of biological matter, to estimate the proportion of the flow at the South Australian border that originated at different upstream tributaries (Ye *et al.* 2018).

1.3 Purpose of the CEWO LTIM report for 2017-18 (year 4)

This report presents a summary of the key findings of indicators in the LMR for the fourth year (2017-18) of LTIM (Section 2), and answers CEWO short-term (one-year) evaluation questions[d] (Section 3). Refer to previous annual evaluation reports (2014-15–2016-17) for Commonwealth environmental water evaluation in the LMR, and a more detailed description of methods (Ye *et al*. 2016; 2017; 2018). The Department for Environment and Water (DEW) short-term evaluation questions, which serve as additional questions for the LMR and relate to ecological targets of the South Australian Murray River Long-Term Environmental Watering Plan (LTWP), are discussed in Appendix C. General recommendations for environmental flow management in the LMR are provided in Section 4, based on monitoring and evaluation outcomes, and expert knowledge. Monitoring and evaluation of Commonwealth environmental water delivery in the LMR from 2014-15 to 2018-19 focusses on spring/summer; therefore, our findings and recommendations on environmental water management are most relevant to this period.

[d] Hydrology (channel) does not directly address any specific CEWO evaluation question, but provides fundamental information for analysis and evaluation of monitoring outcomes against hydrological conditions and environmental water delivery for all other indicators. Results for this indicator are presented in Section 1.2. There are no CEWO evaluation questions for the Fish (channel) indicator for Selected Areas. The Basin-scale evaluation for fish community responses to Commonwealth environmental water are being undertaken by the Centre for Freshwater Ecosystems at La Trobe University. For this report, fish monitoring data were consolidated to evaluate a number of fish targets of DEW's LTWP (Appendix C). Results are presented in Section 2.6.

2 INDICATORS

2.1 Hydrological Regime

Background

The discharge, or *hydrology*, that occurred during 2017-18 in the LMR Selected Area, as well as that expected to have occurred without environmental water components, was determined by the MDBA using a counterfactual modelling approach and can be seen in Section 1.2. However, it is the change in *hydraulics* that biota can sense and respond to, for example changes in velocity or water level. The purpose of this indicator is to quantify the changes in hydraulics due to the delivery of environmental water using hydraulic models.

Methods

In previous LTIM LMR reporting, a dynamic modelling approach was used, where the river between Lock 1 and Lock 6 was modelled for the whole year for each environmental water scenario (see Ye *et al.* 2016). The Lock 6 weir pool has not been considered by this indicator. For the 2017-18 analysis, a steady-state approach was adopted, similar to that used in the Goulburn (Webb *et al.* 2015) and Edward-Wakool (Watts *et al.* 2015) Selected Areas. It is expected that the results from the dynamic or steady-state approaches will be very similar, particularly with limited filling or draining of overbank floodplains that occurred for the in-channel conditions during 2017-18. The steady-state approach also has the benefit of providing useful lookup information to inform future environmental water planning, for example the range in velocities present in a weir pool for a given discharge and weir pool level (see the following Discussion section).

For each weir pool within the LMR Selected Area, i.e. weir pools 1 to 5, a range of steady state flow scenarios were simulated in the hydraulic models, between 2,000–30,000 ML/d, and a range of weir pool levels required to cover the range experienced during the 2017-18 year. For each steady state scenario, hydraulic metrics were computed, including the 10th, 50th and 90th percentile velocities within the weir pool, the proportion of the weir pool exceeding 0.3 metres per second (m/s) (representing flowing water (lotic) conditions, see Bice *et al.* 2017), and water levels at regular locations along the weir pool.

A consistent, permanently inundated, region was used for velocity analysis for each weir pool, using the inundated area for the 5,000 ML/d and normal pool level scenario. It was found that if the full inundated area was used for each scenario in some cases the increase in area from an increase in discharge could increase the proportion of the weir pool with low velocities, due to inundation of backwaters. To enable a consistent comparison of in-channel changes in velocity due to environmental water, the same permanently inundated area was used for all velocity analysis.

Environmental water scenarios

With this hydraulic lookup information, the time series of discharge for each of the environmental water scenarios presented in Section 1.2, and the downstream water level each day for each weir pool was interpolated into a time series of velocity metrics and water levels using linear bivariate interpolation.

The discharge time series for these scenarios were provided by the MDBA at Locks 1, 3 and 5. Data for Locks 2 and 4 were interpolated using travel time information from the Source Murray Model. These outputs account for the changes in diversions within South Australia with and without environmental water recovery by assuming full utilisation of the entitlements recovered for the environment in the "without environmental water" scenarios.

The observed water levels were used in the "with all environmental water" scenario. For the "without environmental water" scenarios, the weir pool manipulations at Locks 2 and 5 (both lowering and raising) were removed, and instead the water level was assumed to be at normal pool level at these times. Lock 1 was raised during May 2018, and a 0.3 m weir pool raising scenario was included in the results; however, only up to the 15,000 ML/d required to represent this event. As this weir pool raising was not associated with environmental watering it was not removed from the "without environmental water" scenarios.

Results

The water level at the upper end of the weir pool (e.g. directly below Lock 2 for the Weir Pool 1 case) has been presented in Figure 5, as the upper end of the weir pool is the least influenced by the downstream weir and hence most responsive to changes in discharge when the weirs are controlling water levels (below 54,000 ML/d–67,000 ML/d depending on the weir). For velocity, the median modelled velocity in each weir pool is presented as the solid line in Figure 6, and the range in velocities within the weir pool shown as the shaded band (determined from the 10th and 90th percentiles). Finally, the proportion of the reach exhibiting lotic habitat, as defined by a velocity greater than 0.3 m/s (Bice *et al.* 2017), is presented in Figure 7.

Without environmental water, flow to South Australia would have been at entitlement flow (adjusted for trade and deferrals) for most of the year, the minimum flow to be delivered to South Australia under Clause 88 of the MDB Agreement. The exception to this was a short unregulated flow event with a peak of approximately 11,000 ML/d over the last two weeks of December. For this case, the water levels would have been very stable throughout the year, with only small increases in the upper reaches of the weir pools during the unregulated flow event (Figure 5). A similar pattern is expected for velocity, with only small increases in velocity and small proportions of the reach exhibiting lotic habitats (typically less than 10%) (Figure 7).

In contrast, environmental water provided some variability in the hydraulic conditions. Variability in water levels was created, particularly over the first six months of 2017-18, with decreased and then increased water levels at the upper end of each weir pool

from 0.1–0.5 m during September, to 0.6 – 0.8 m during December (with the range produced by the different changes in the different weir pools). Small (up to 0.1 m) weir pool lowerings were undertaken at Locks 2 and 5 in July to increase water level variability, before the September and early October water levels were further increased by weir pool raising events undertaken at Lock 2 (0.5 m increase) and Lock 5 (0.45 m increase). This increase in water level produces an increase in cross sectional area, and a resulting increase in productivity, as described in Section 2.2.

Similar variability was introduced in the range of velocities across the weir pools. An increase in the hydraulic diversity can be seen, with a larger shaded area in blue in Figure 6. Using a velocity of 0.3 m/s to represent lotic conditions, the variability introduced by environmental water created relatively small patches (up to 20% of the weir pool) of lotic habitat over July to November that would not have been present otherwise (Figure 7). During the unregulated flow event in December, environmental water increased the lotic proportion of the weir pools from very small patches to up to 30–50% of weir pool, depending on the location. The environmental water delivered after February 2018, at discharges below 8,000 ML/d had negligible contribution to lotic conditions in the LMR (Figure 8). However, the primary objective of the water delivery at this time was for connectivity and end of system flows, and not for lotic habitat.

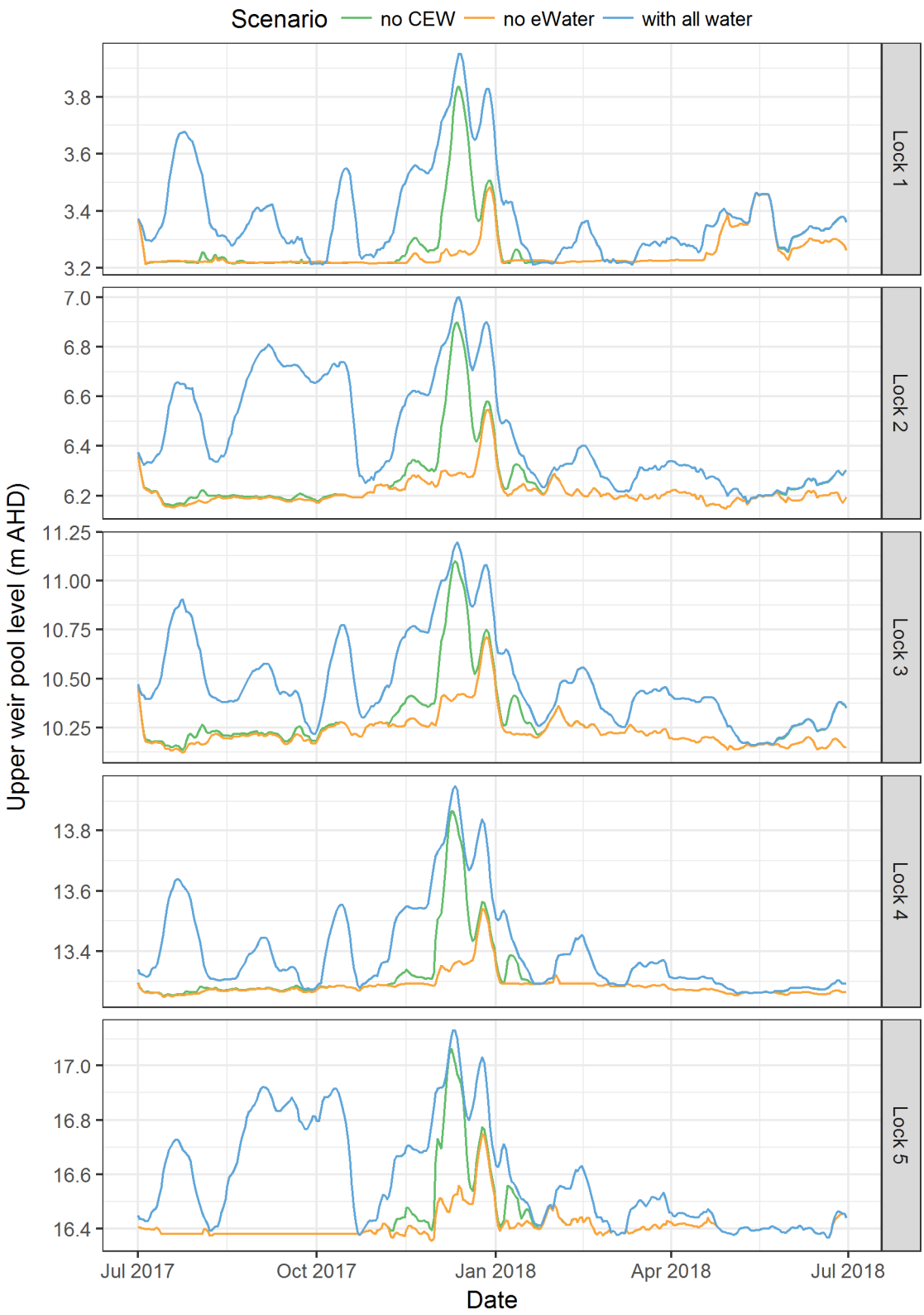

Figure 5. Modelled water level at the upstream end of each weir pool.

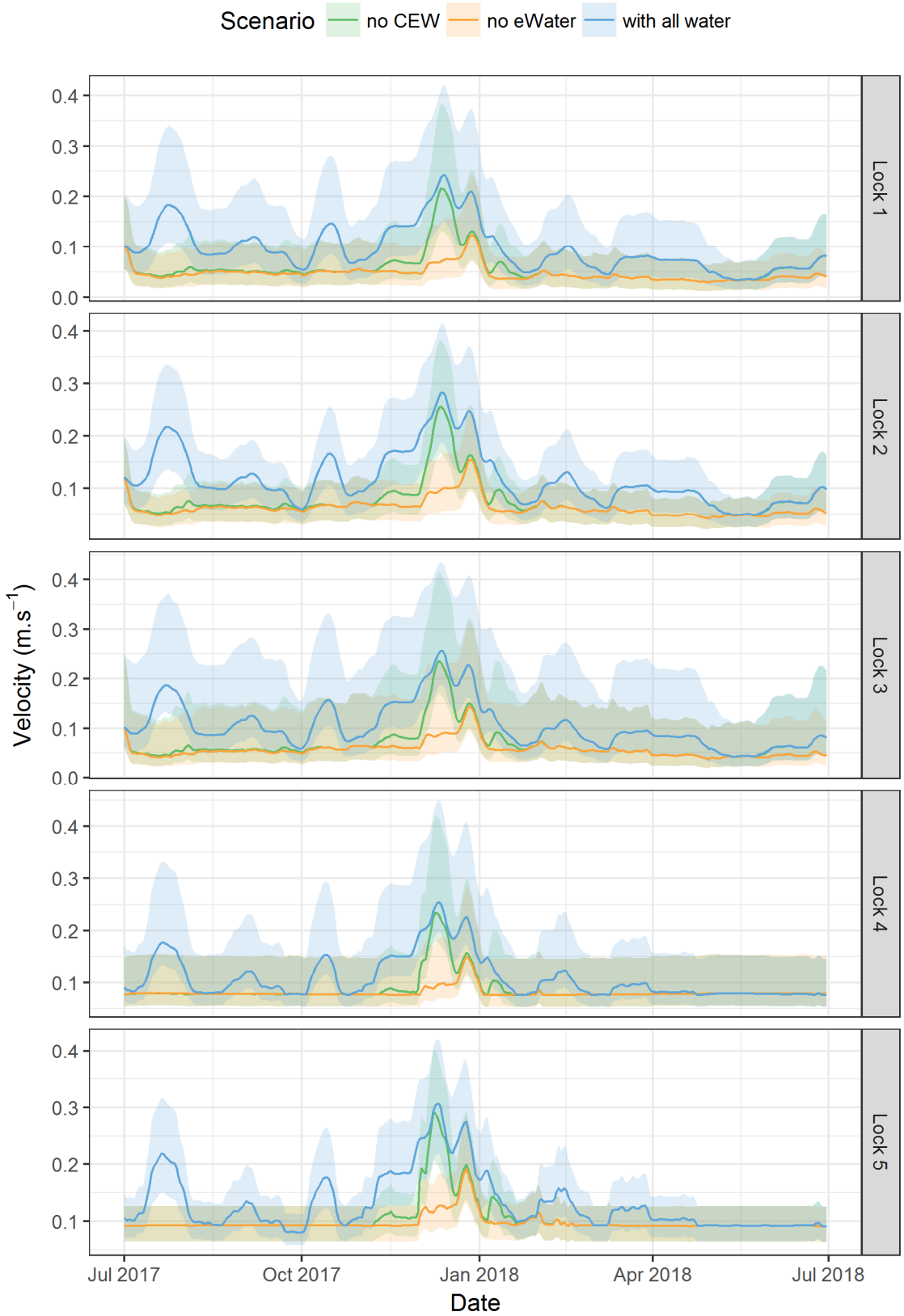

Figure 6. Median modelled velocity in each weir pool (line), with the range in velocities within the weir pool, defined by the 10th and 90th percentiles, the shaded area.

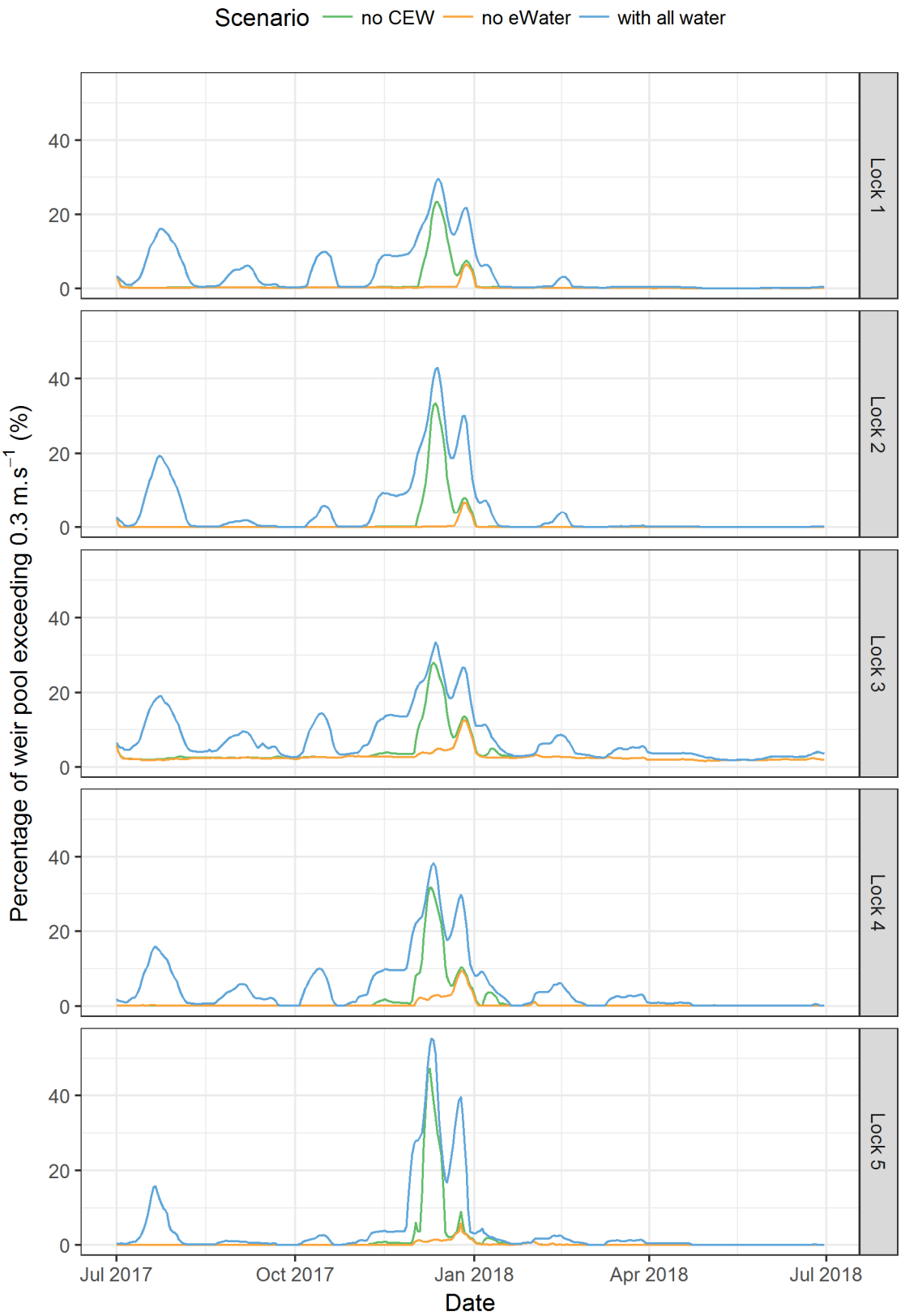

Figure 7. Percentage of the weir pool representing lotic habitat, defined as a velocity greater than 0.3 m/s.

Discussion

The analysis undertaken for 2017-18 has enabled relationships to be developed between the variables that can be controlled to some degree (i.e. upstream discharge and downstream water level at the locks) and the hydraulic response variables (i.e. water levels and velocity metrics). Backwater curves relating water level along each weir pool to discharges between 5,000 ML/d and 15,000 ML/d, including the changes due to weir pool manipulation undertaken at Locks 1, 2 and 5 in 2017-18, can be seen in Figure 8. Response curves between discharge and velocity have also been developed, as the range in velocity within the weir pool (Figure 9), and the proportion of the reach exceeding 0.3 m/s (Figure 10).

From these curves, the "bang for the buck" from further environmental water delivery can be inferred, such as the increase in velocity that could be expected from an increase in discharge due to environmental water. For example, across the weir pools, an increase in discharge to between 10,000 ML/d and 20,000–30,000 ML/d (depending on the location) substantially increases the proportion of the weir pool with velocities greater than 0.3 m/s.

The impact of the weir pool manipulation undertaken at Locks, 1, 2 and 5 also allows the change in velocity to be investigated. For example, at Lock 5, a discharge of 15,000 ML/d produced a velocity greater than 0.3 m/s in approximately 40% of the weir pool. If it was desirable to maintain this proportion during a weir pool raising of 0.5 m, an increase in the discharge to approximately 17,000 ML/d would be required. The changes in velocity from a 0.1 m weir pool lowering can also be seen in Figure 9, with negligible increases in velocity in the Lock 5 weir pool and some increases in velocity in the Lock 2 weir pool for flows greater than 15,000 ML/d.

Lotic habitats, represented by a velocity >0.3 m/s, are important for ecological and life history processes for many native biota that are adapted to flowing riverine environments. For example, they provide stimuli for spawning of flow-cued species (e.g. golden perch) (King *et al.* 2016), facilitate downstream drift and transportation of plankton, macroinvertebrates and fish larvae, and provide diverse hydraulic habitats that are suitable for a range of species (e.g. Murray cod) (Zampatti *et al.* 2014). The reduction in the abundance and distribution of lotic biota (e.g. Macquarie perch *Macquaria australasica* and Murray crayfish *Euastacus armatus*) throughout the MDB (Lintermans 2007) highlights the importance of restoring hydraulic conditions (e.g. lotic habitats), which is particularly needed in the heavily regulated lower River Murray (The Murray River downstream of the Darling River junction).

While the increase in the cross-sectional area due to a weir pool raising will reduce the velocity for a given discharge, the benefit is the increase in water level, and resulting inundation of banks and fringing vegetation (Gehrig *et al.* 2016). The increase in water level with discharge along a reach for a given weir pool level can be seen in Figure 8, while at the downstream end, the water level remains to be controlled by the weir at the discharges presented. Variable water levels, and the coinciding periods of exposure and submergence of substrates beyond the euphotic zone, can

result in the regular "re-setting" of biofilms (Steinman and McIntire 1990). The biofilm is a key component of riverine food webs, and this re-setting of the biofilm algal community produces higher quality food resources dominated by diatoms and unicellular algae (Wallace and Cummings 2016). Wallace and Cummings (2016) assessed biofilm changes during and following a 0.54 m raising of Lock 2 in 2015, and found only small changes in the biofilm composition directly upstream of Lock 2 immediately following the event, and no changes 35 days following the event. Based on this result, the authors suggested that frequent changes in weir pool level that mimic natural variability rather than annual "events" may be required to maintain early successional biofilm communities. Figure 5 indicates that environmental water did introduce more water level variability at the upper reaches of weir pools in 2017-18, however further work is required to understand the ecological benefits of this, and relative benefits of frequency versus magnitude in water level variability on the quality of biofilms as a food resource.

Conclusion

2017-18 was a dry year where, without environmental water, flow to South Australia would have been at entitlement flow for most of the year, except for a small unregulated flow event over the last two weeks of December. Under these conditions, water levels would have been very stable throughout the year, with low hydraulic diversity and minimal fast flowing conditions in the LMR. The environmental water introduced some hydraulic variability that would not have otherwise occurred, particularly over the first six months of 2017-18. As one example, during the unregulated flow event in December, environmental water increased the proportion of the river experiencing lotic conditions from very small patches to up to 30–50% of weir pool, depending on the location.

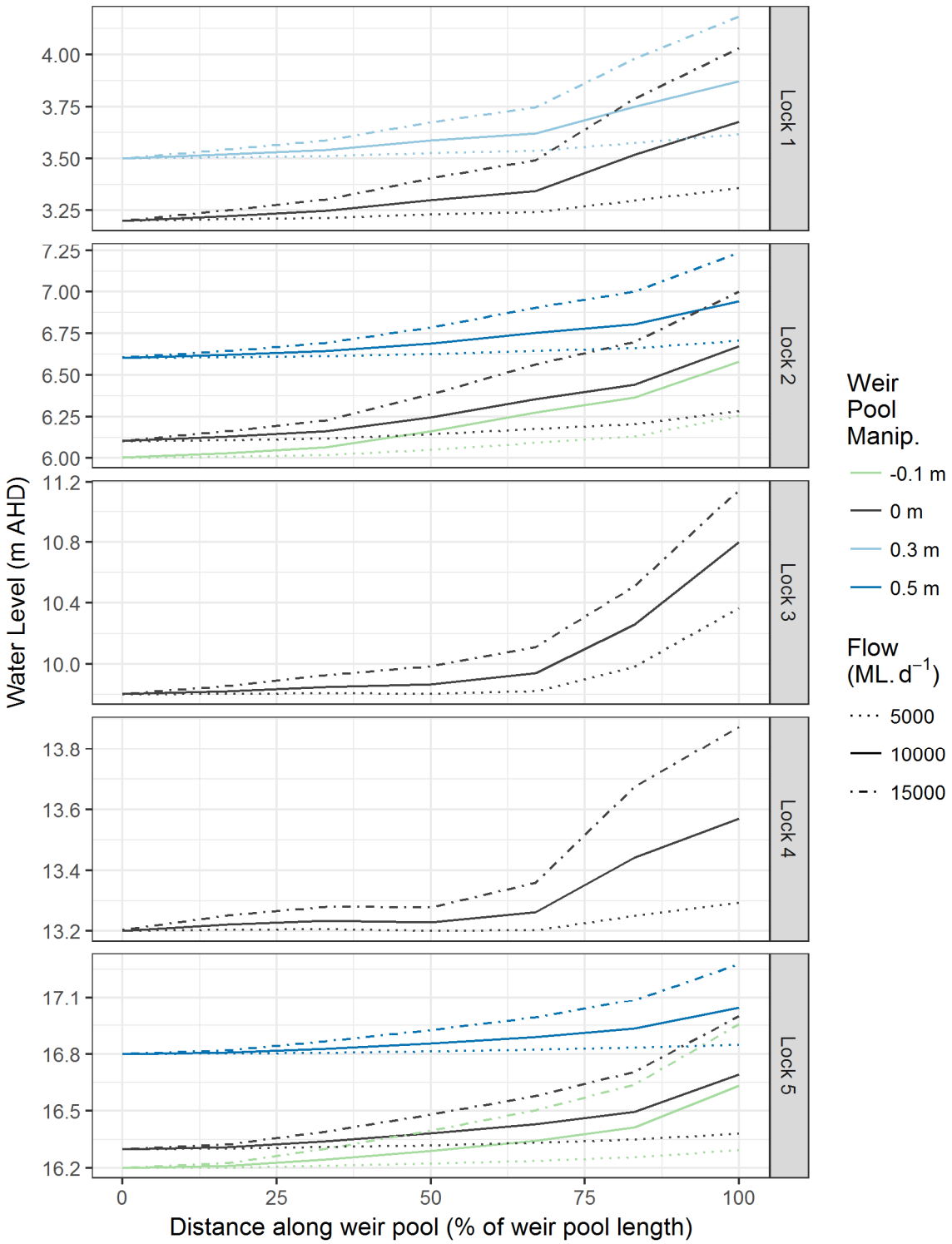

Figure 8. Backwater curve along each weir pool for flows of 5,000 to 15,000 ML/d, to illustrate the changes in level from increasing flow, and the weir pool manipulations undertaken at Locks 2 and 5 in 2017-18.

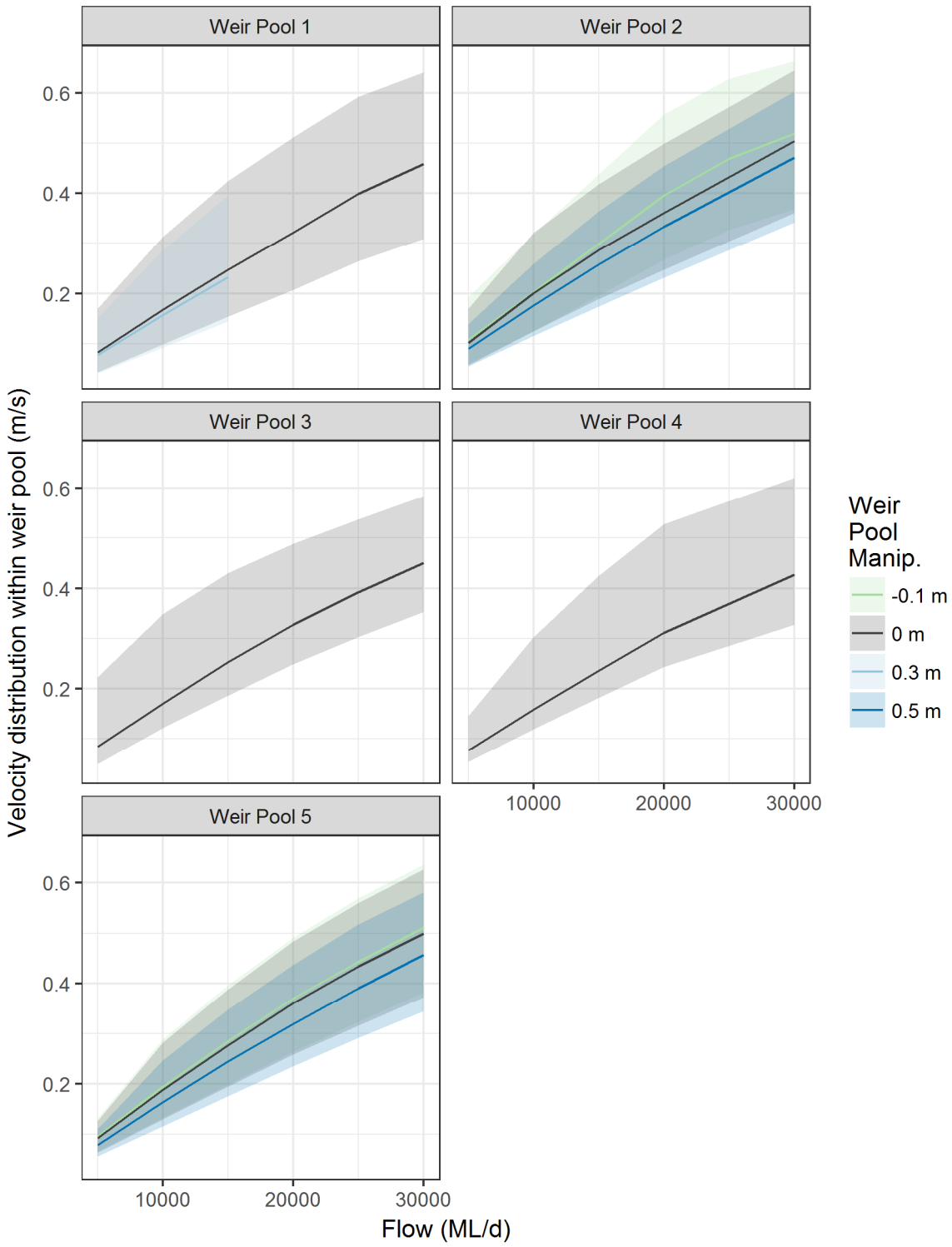

Figure 9. Median (solid line) and range (as 10th and 90th percentiles, the shaded area) velocities within each weir pool with increasing discharge. The changes with weir pool manipulation undertaken at Locks 2 and 5 in 2017-18 is also presented.

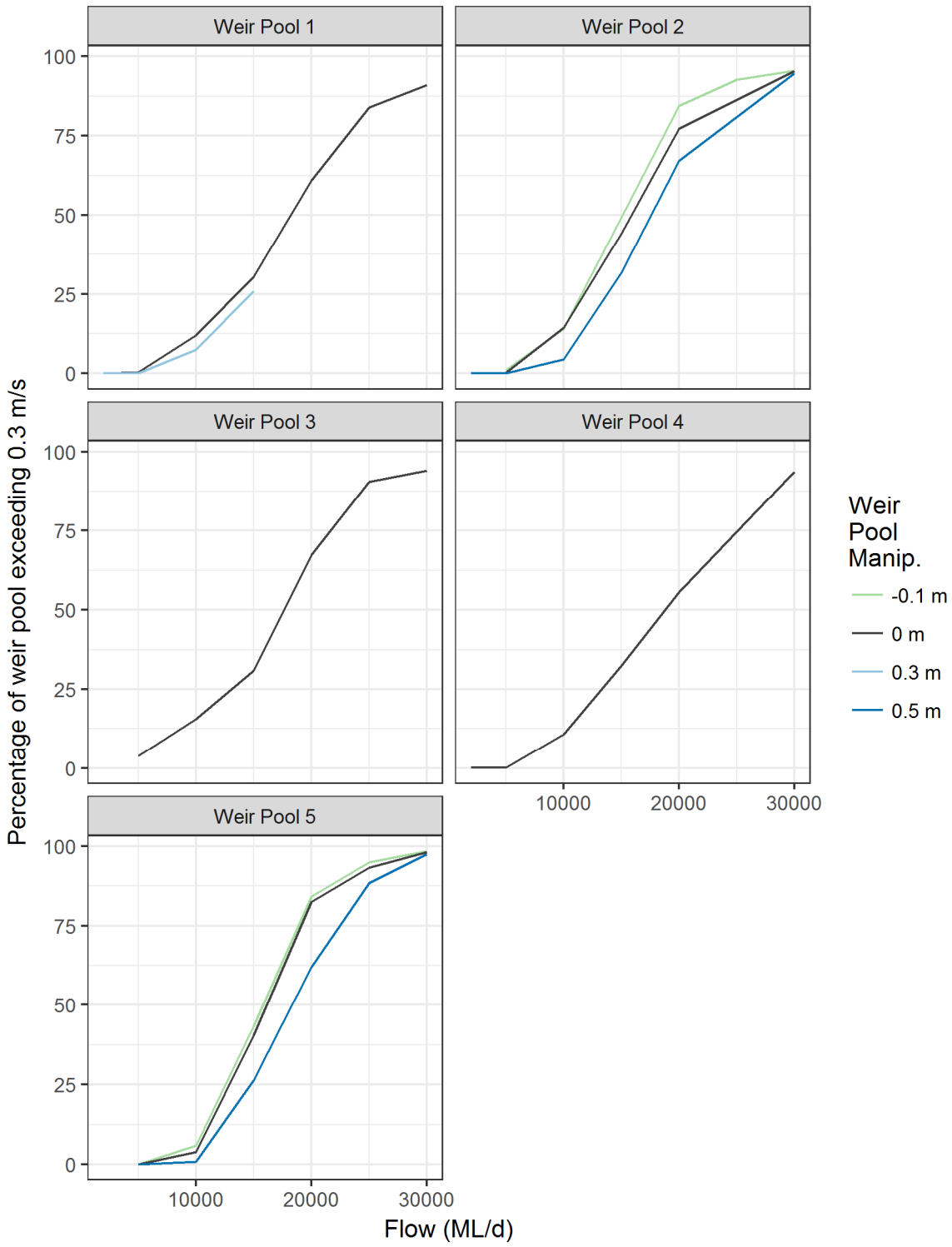

Figure 10. Percentage of the weir pool with lotic habitat (represented by velocities greater than 0.3 m/s) with increasing discharge. The changes with weir pool manipulation undertaken at Locks 2 and 5 in 2017-18 is also presented.

2.2 Stream Metabolism

Background

River metabolism measurements estimate in-stream rates of photosynthesis and respiration, providing information on the sources and utilisation of organic food materials being processed through riverine food webs (Odum 1956; Young and Huryn 1996; Oliver and Merrick 2006). Comparisons of the actual and relative rates of photosynthesis and respiration help describe the fundamental trophic energy connections that characterise different food web types. They indicate whether production or decomposition processes predominate within the aquatic system, and whether the organic food materials have come from within the river (autochthonous sources) or from the surrounding landscape (allochthonous sources). The magnitude and characteristics of the metabolic processes indicate the size of the food web and its capacity to support higher trophic levels, including fish and water birds which are key targets for ecosystem management (Odum 1956; Young and Huryn 1996; Oliver and Merrick 2006). As concentrations of dissolved oxygen are monitored to estimate rates of stream metabolism, these measurements provide ancillary information on the suitability of oxygen levels to support the aquatic biota.

The aims of the stream metabolism monitoring are to assess the following evaluation questions:

- What did Commonwealth environmental water contribute to patterns and rates of primary productivity?
- What did Commonwealth environmental water contribute to patterns and rates of decomposition?
- What did Commonwealth environmental water contribute to patterns and rates of dissolved oxygen levels?

Short-term responses in the measured volumetric rates of photosynthesis and respiration capture the metabolic responses to changing flow and water quality conditions, but do not alone describe the influence of these changes on river productivity. This requires integration of metabolic rates over space and time to calculate total gains and losses of organic material within the river. A focus of this report is on the integration of river metabolism to provide measures of productivity.

Methods

To estimate stream metabolism continuous *in situ* logging of dissolved oxygen (DO) concentration, water temperature and incident light were undertaken at two river sites, one downstream of Lock 1 in the gorge geomorphic zone, and one downstream of Lock 6 in the floodplain geomorphic zone (refer to SARDI *et al.* 2018). Monitoring was continuous from 20 September 2017 to 9 February 2018, with only short interruptions of a few hours during probe maintenance. Discrete, 2 m depth-integrated water quality samples were collected monthly and analysed for

chlorophyll *a*, total nitrogen, combined nitrate and nitrite, ammonium, total phosphorus, dissolved forms of phosphorus, and dissolved organic carbon. The detailed monitoring and analysis protocols described in Hale *et al.* (2014) were followed, but with some minor adjustments as detailed in Ye *et al.* (2018).

Volumetric rates for gross photosynthesis (GPP), ecosystem respiration (ER) and net ecosystem production (NEP) were estimated using the BASE program (Grace *et al.* 2015). This uses Bayesian regression routines to fit the measured changes in dissolved oxygen concentrations to a widely applied mass balance model that describes the daily fluctuations in water column dissolved oxygen concentrations (Odum 1956; Young and Huryn 1996; Oliver and Merrick 2006). Refer to SARDI *et al.* (2018) for detailed sampling design and methods.

Estimates of integrated productivity were based on models of river morphology developed for the hydraulic analyses (Section 2.1). The metabolic rate for a cross-sectional slice of the river, the product of the volumetric metabolic rate and the cross-sectional area, estimates the total metabolic activity per unit length of river. This accounts for differences in flow volume, either between different sized rivers, or within a river. Time integrated production was estimated by summing the measured daily volumetric rates and the cross-sectional rates. Both measures are useful, one providing information on volumetric changes in the organic carbon pool relevant to small, less motile planktonic organisms. The other assesses the integrated production per unit length of river, more relevant to larger, mobile species able to access and harvest food resources from larger volumes of water.

A flow-based metric, the product of the volumetric metabolic rate and the daily flow volume, estimates the daily metabolic activity passing a point on the river bank. This is similar to a "load" calculation as more typically applied to receiving waters such as lakes. In the case of a flowing river, where the reach is not a receiving system as normally envisaged, the calculation provides estimates of a "potential" load. This may be relevant to attached or largely immobile organisms, including algal mats and their associated flora and fauna. These obtain food resources and nutrients from the passing flow, so the volumetric concentration and the flow rate together determine the resource supply.

During the 2017-18 monitoring period, environmental water contributions to the flow in South Australia were substantial (Figure 3), providing an opportunity to apply these metabolic indicators, and to consider their attributes in assessing the contributions of environmental flows to metabolism.

Results

Dissolved oxygen

The time series of dissolved oxygen concentrations showed similar patterns at both sampling sites, although with increased concentrations at the Lock 1 site during January 2018 (Figure 11). The calculated saturation concentrations for dissolved oxygen (International Oceanographic Tables 1973) were similar across sites and

represented in Figure 11 by the values from Lock 6. For most of the monitoring period dissolved oxygen concentrations were greater than saturation levels. Without environmental water, river flows would have been significantly lower and at levels that increase the likelihood of weir pool stratification and reductions in DO concentrations due to enhanced biotic activity and reduced reaeration (Wallace *et al*. 2014). The environmental flows reduced this risk and enhanced the DO conditions for the biota.

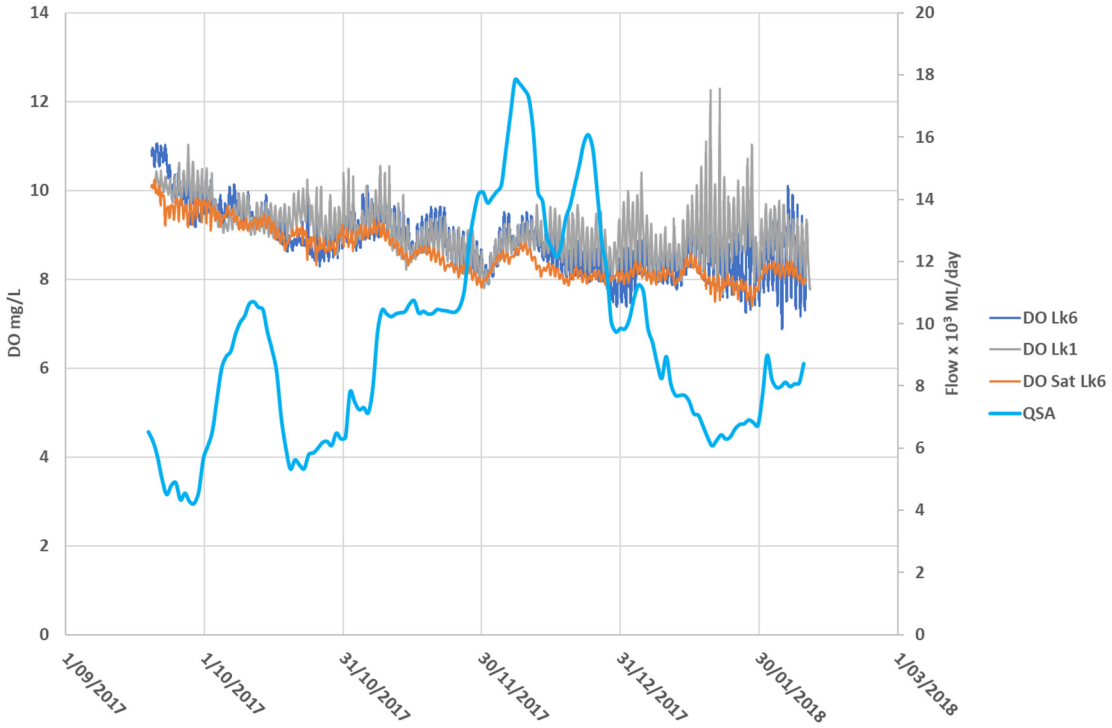

Figure 11. Dissolved oxygen concentrations (DO) at the major LMR monitoring sites compared with the typical saturation oxygen concentration typified by Lock 6 data. The flow to South Australia (QSA) is shown for reference.

Daily metabolic rates

Volumetric metabolic rates measured at the two sampling sites showed similar patterns over the monitoring period (Figure 12), and were of similar magnitude to those from previous years, especially during the early period of each monitoring year and despite large differences in flow (Figure 13).

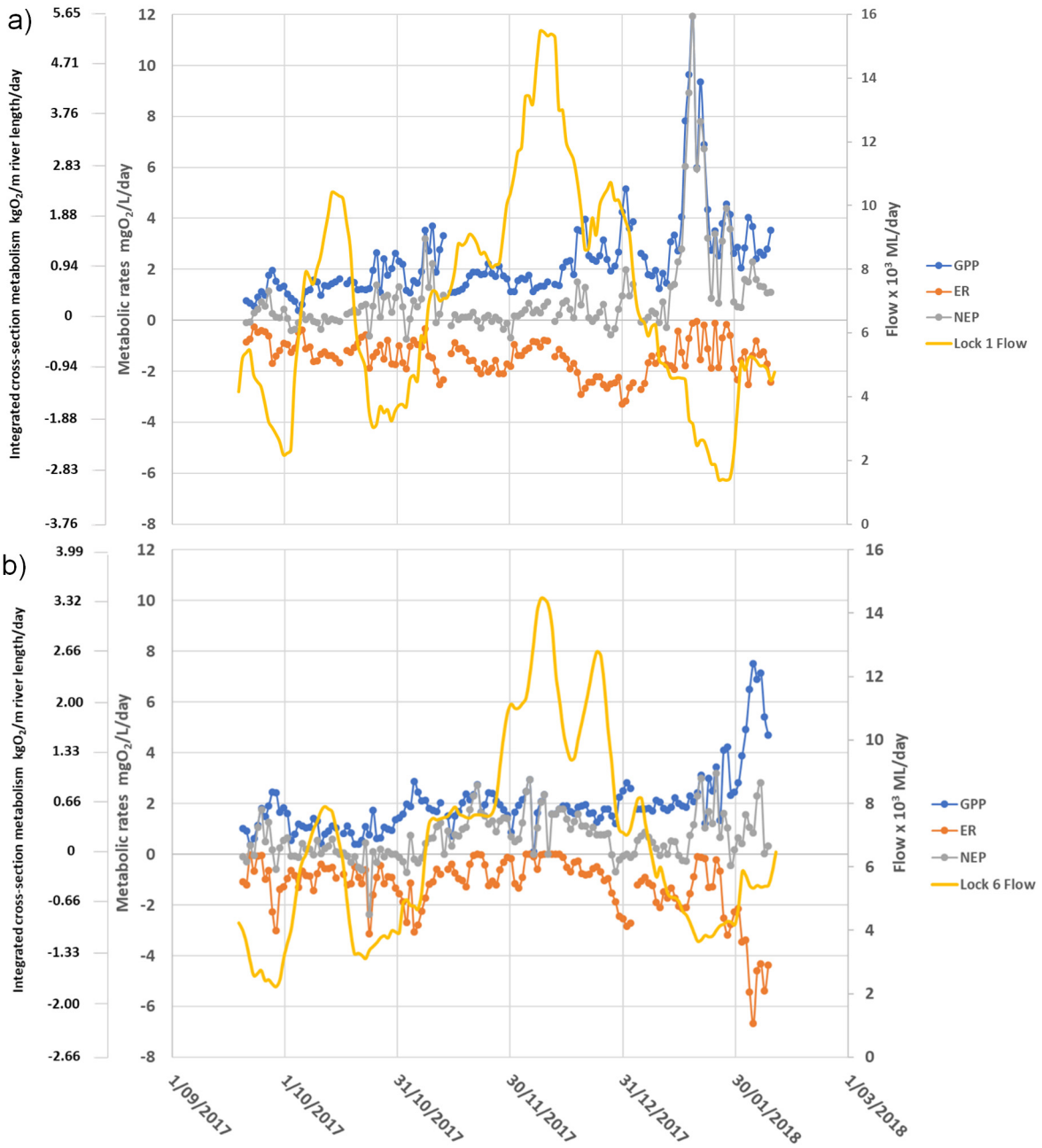

Figure 12. Modelled volumetric rates of gross photosynthesis (GPP), ecosystem respiration (ER) and net ecosystem production (NEP) at the (A) Lock 1 and (B) Lock 6 sites. The flow at each of the Locks is shown for reference. Estimates of indicative cross-sectional rates of metabolism per metre of river length were calculated from the average cross-sectional area over the monitoring period.

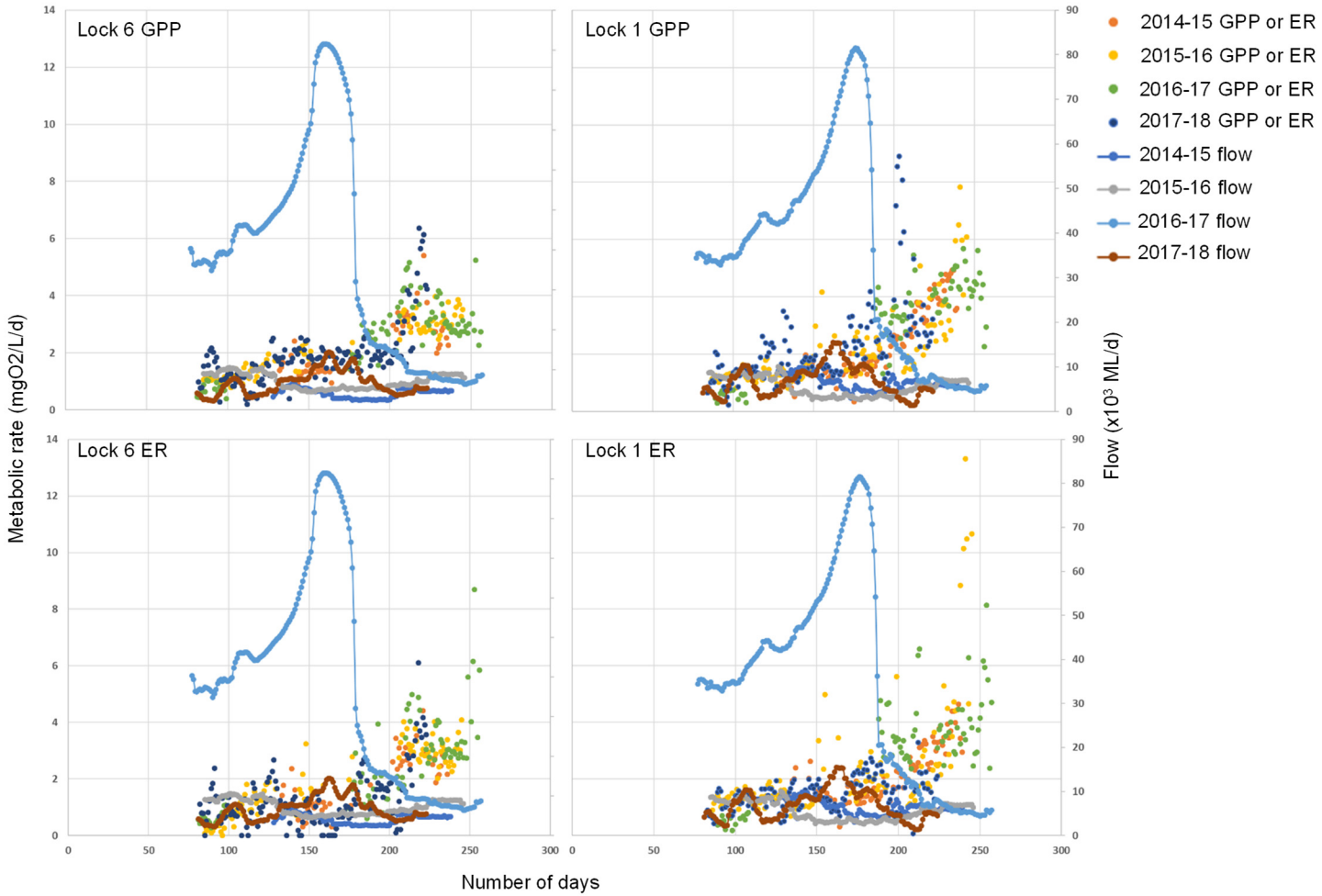

Figure 13. Daily gross photosynthesis (GPP) and ecosystem respiration (ER) rates at each site during each seasonal monitoring period (2014-15 to 2017-18) with associated flows at Lock 1 (for Lock 1 graphs) and Lock 5 (for Lock 6 graphs).

GPP at both sites ranged between 1 and 3 $mgO_2/L/d$ and gradually increased over the monitoring period. A large peak in GPP occurred in Lock 1 during the latter half of January but was not preceded by an upstream peak at Lock 6. A smaller peak in GPP occurred at Lock 6 but in early February.

ER rates at Lock 1 increased over the monitoring period and mirrored the changes in GPP. Consequently NEP values were small until the peak in GPP in late January when ER rates dropped so that NEP also peaked at this time. In contrast, ER values at Lock 6 were relatively low over the monitoring period and NEP values were frequently positive. An increase in GPP in February was mirrored by increases in ER rates.

No consistent associations between metabolic rates and flows were identified, although short-term influences were evident at specific times. For example, the large decline in flow at both sites in late January led to significant reductions in ER without concomitant changes in GPP, resulting in increases in NEP which peaked at both sites. The cause of the decline in ER has not yet been identified but suggests reduced heterotrophic activity.

Integrated metabolic rates

The cross-sectional area of flow was on average 140 m^2 larger at Lock 1 than Lock 6. This was likely due to relatively higher flows at Lock 1 (Figure 12) due to the routing of flow around Lock 6 via Chowilla Creek and additional wind effect pushing water upstream from the Lower Lakes towards Lock 1. At Lock 1 the cross-sectional area varied by 20% over the monitoring period while at Lock 6 it remained more constant. Because of the relatively small changes in cross-sectional area at both sites, the integrated daily cross-sectional rates of metabolism showed similar patterns as the measured volumetric rates, but with a changed scale. Indicative values, using the average cross-sectional area for each site, are shown in Figure 12.

Accumulating metabolic rates

The daily integrated data were summed over time to describe the accumulating influences of the metabolic processes. The time integrated cross-sectional measurements show the shifting balances in metabolism within the river section including changes in rates as for example in Lock 6 (Figure 14).

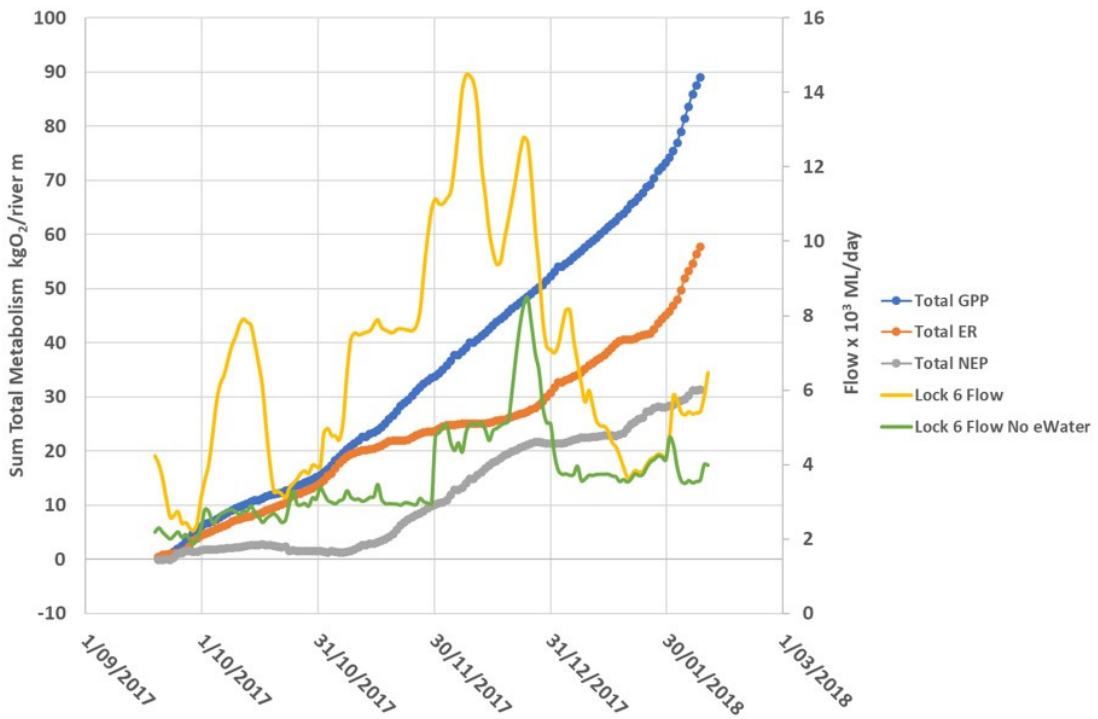

Figure 14. Accumulating cross-sectional metabolic processes per metre of river length for gross photosynthesis (GPP), ecosystem respiration (ER) and net ecosystem production (NEP) at Lock 6 with environmental water (eWater) contributions. The modelled flow without eWater contributions is shown for comparison.

If the final accumulated sums of metabolic processes estimate total fluxes in the river, then the overall carbon balance can be assessed from the monitoring measurements made under the extant, total flow conditions. The integrated cross-sectional estimates for GPP at Lock 1 show there was a total photosynthetically fixed carbon accumulation of 151 kg O_2/m river length over the monitoring period. Assuming a photosynthetic quotient of 1, this is equivalent to 57 kg C/m river length. In volumetric terms, GPP over the monitoring period produced 121.6 g C/L. At Lock 6, the corresponding values gave an accumulation of 89 kg O_2/m river length (Figure 14), equivalent to 33 kg C/m river length, and a volumetric accumulation of 101 g C/L. The differences between sites were due to the average rate of GPP at Lock 6 being 83% of that at Lock 1, and the average cross-sectional area at Lock 6 being 70% of Lock 1.

Similar calculations for ER estimate the total loss of organic carbon from the reach and at Lock 1 amounted to 94.4 kg O_2/m river length, equivalent to 35 kg C/m river length, or in volumetric terms 75 g C/L. At Lock 6, the comparable values were 57.7 kg O_2/m river length, equivalent to 22 kg C/m river length, or in volumetric terms 67 g C/L (Figure 14).

These calculations were applied to NEP (Figure 14), but the interpretation of this parameter is more difficult. In natural systems, a proportion of ER is usually driven by sources of organic carbon not generated by current photosynthetic activity, but instead by organic material created elsewhere, or at other times. Consequently, NEP

does not provide a reliable measure of the remaining organic material available as a food resource, either generated locally through photosynthesis or from imported sources. Analytical tools are being developed to address this issue by distinguishing the sources of respiration. However, as total NEP accumulation over the monitoring period was positive, an estimate of the minimal amount of net material accumulated through photosynthesis was possible by assuming all of ER was due to respiration of photosynthetically fixed material. The accrued amounts were 21 kg C/m river length at Lock 1 and 11.7 kg C/m river length at Lock 6.

Influence of flow on metabolism

No simple relationship between flow and GPP was apparent at either site (Figure 15). This was expected as GPP is also influenced by an array of biotic and physicochemical conditions including phytoplankton biomass, light availability and temperature. Future analyses will assess these effects to better model flow influences on metabolic rates, but to provide preliminary comparisons simplification was necessary. It was assumed that as the majority of GPP measurements occurred within a limited range across all flows, including flows comparable with those expected without environmental water (Figure 15), then the average GPP rates of 2.4 mgO_2/L at Lock 1 and 2 mgO_2/L at Lock 6, provided acceptable average estimates across all flow conditions. At Lock 1, the reduced flow without environmental water resulted in the average cross-section decreasing from 472 to 396 m^2 and so a 20% reduction in GPP per m of river, equivalent to the relative change in cross-sectional area. In contrast, the reduced flow at Lock 6 resulted in a reduction in cross-section from 332 to 317 m^2, causing a 5% reduction in GPP per m of river. The difference in effects at the two sites, despite similar changes in flow, reflects the highly regulated water levels at Lock 6, which maintains the cross-sectional area despite the different flow conditions.

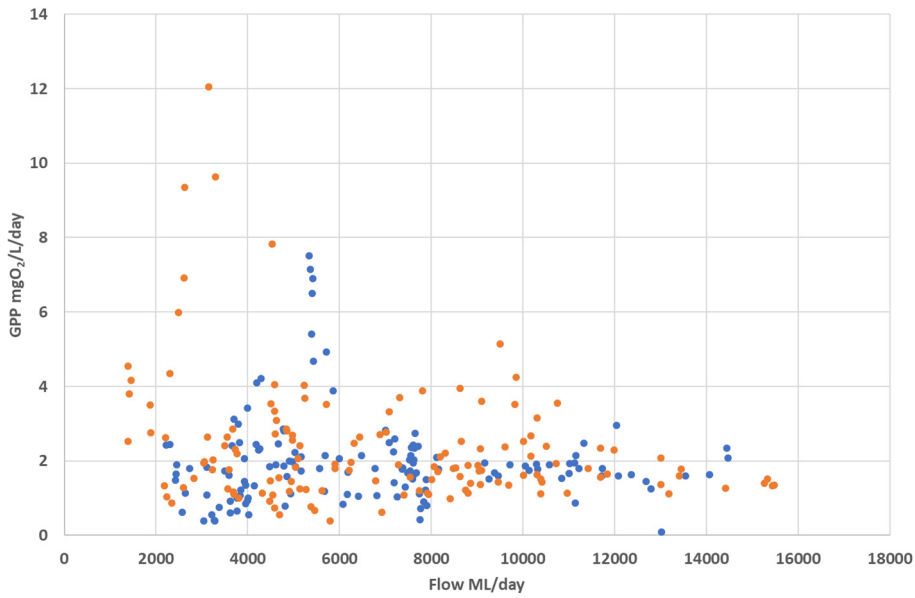

Figure 15. Patterns of daily volumetric gross photosynthesis (GPP) in response to flow rates at Lock 1 (orange) and Lock 6 (blue) sites.

Assuming that the average GPP at each site adequately estimates the metabolic activity at all flows, then differences in "notional" loads with and without environmental water contributions are determined by the differences in flow. Daily average flows with and without environmental water were, respectively, 1007 GL and 466 GL at Lock 1, and 974 GL and 530 GL at Lock 6. At Lock 1 the addition of environmental water increased the passing load by a factor of 2.2, while at Lock 6 it was increased by a factor of 1.8. Similar calculations assuming an average value for ER produce the same proportional results. It is not known whether these differences influence river ecosystems as proposed, in part because the current measurements do not enable separate identification of benthic metabolism, which is the suggested site of influence of the increased "loads".

These findings are indicative only as the assumption that metabolic rates can be represented by average values is an oversimplification, especially as large relative changes in metabolic rates were observed (Figure 15). Changes in metabolism could counter the increases in production expected from enhanced flow rates and river volumes.

Water quality

Only two of the water quality parameters showed changes associated with the flow regime: turbidity and total dissolved solids (TDS). The observed salinity levels were not expected to influence rates of metabolism and are not considered further.

At Lock 6 and nearby downstream sites, turbidity was low in early September, but rose rapidly as river flow increased in early October and then remained high despite flows falling throughout the second half of October (Figure 16). Flows increased again through November and early December, whereas turbidity declined in November then remained stable through December. Rapid declines in flow during January were associated with declining turbidity. The lack of a consistent connection between flow and turbidity is considered due to variations in the sources of water reaching South Australia.

Changes in turbidity influence the light available for photosynthesis by increasing the vertical light attenuation (Oliver *et al.* 2010). The average depth at Lock 6 was relatively constant and the observed increase in turbidity from 20 to 70 NTU was calculated to more than halve the light available to phytoplankton. The influence of this light reduction on GPP at Lock 6 through October was a decrease in volumetric rates (Figure 12b) and a slowing of the rate of accumulation in the integrated cross-sectional GPP (Figure 14).

Below Lock 1 (Swan Reach), turbidity was initially higher than upstream and then increased and peaked in late November, two weeks after the peaks at upstream sites but reaching a similar maximum. Little response was evident in GPP (Figure 12a), probably because the average depth at Lock 1 (2.5 m) is substantially less than at Lock 6 (3.8 m), resulting in an overall higher availability of light in the water column. Due to the depth differences, the maximum turbidity reduced the average light at

Lock 1 to a value similar to that observed at Lock 6 when turbidity was minimal. The data suggest that light limitation of GPP occurred at Lock 6 but not at Lock 1.

Turbidity in the LMR is often influenced by the original source of water arriving at the monitoring sites. The changing sources of flow (Figure 4) were compared with the changes in turbidity, but a clear source of turbidity could not be identified. As the turbidity changes were observed at Lock 9, which is upstream of Lake Victoria, it is concluded that the turbidity came from further upstream. However, the different upstream water sources showed increased flows at the same time, so further analyses will be required of the turbidity of the individual rivers to identify the actual turbidity source.

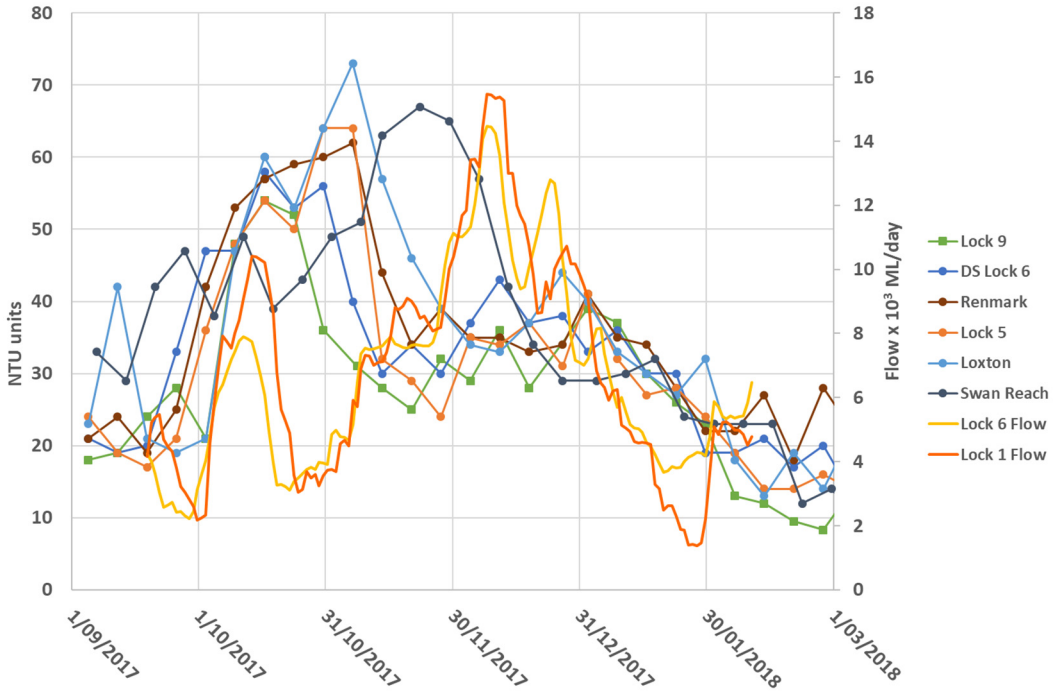

Figure 16. Time series of measurements of turbidity at sites progressively along the lower River Murray from Lock 9, including the two monitoring sites for metabolism, Lock 6 (DS Lock 6) and Lock 1 (Swan Reach).

Discussion

Daytime dissolved oxygen concentrations consistently exceeded the oxygen saturation concentration whilst nighttime concentrations were similar to, or slightly below saturation indicating predominantly autotrophic activity and organic carbon accumulation. The decline in saturation levels over the monitoring period reflects the gradual increase in water temperature. At low flows in the lower River Murray there is an increased probability of stratification in weir pools with reduced oxygen concentrations due to enhanced biotic activity and reduced reaeration. This was not an issue during the 2017-18 monitoring period as environmental water contributions helped maintain higher flows, particularly during the height of summer when deoxygenation is most likely to occur.

Several measures of metabolism were used to assess the influences of environmental flows on metabolic activity. Measured volumetric rates did not show an obvious link with flow, except during a period of very low flows in mid- to late January when ER declined markedly but GPP did not. This was attributed to reduced heterotrophic activity but could be an issue with modelling the oxygen concentration changes during low flows and further investigation is underway. These volumetric rates were of similar magnitude to those observed in previous years, especially during the early period of each monitoring year and despite large differences in flow (Figure 13). The ubiquitous increase in metabolic rates as the season progresses reflects the influence of increasing temperature. Despite overall general similarities, the metabolic rates in any period can differ by up to 10-fold between seasons. Understanding the causes of these differences, and identifying their relationship with flow, will provide water managers with the information required to utilise environmental flows to maximise river production.

Increases in turbidity early in the monitoring period were associated with reductions in volumetric rates of GPP at Lock 6 and attributed to the reduced light penetration decreasing light availability for the phytoplankton. A similar response was not evident at Lock 1 which being shallower did not suffer the same degree of light reduction. Although the turbidity curtailed GPP at Lock 6, the short period of influence meant that the impact on accumulated GPP over the monitoring period was small, reducing it by around 0.01%.

The cross-sectional integrated rate of metabolic activity is a function of the volumetric rate of metabolism and the channel morphology linking flow to cross-sectional area. Consequently, the outcome of a change in flow is dependent on the relative changes in both metabolic rates and the channel characteristics. If metabolic rates remain relatively constant, as assumed here to simplify analyses, then increases in flow, such as the addition of environmental water, will result in an increase in the cross-sectional metabolism. Environmental flows increased average cross-sectional rates of metabolism by 20% and 5%, respectively, at Locks 1 and 6. Similar arguments hold for calculations of the notional load, it being the product of volumetric rates and flow. Environmental flows increased the passing load by a factor of 2.2 and 1.8, respectively, at Locks 1 and 6. However, metabolic rates can change independently of flow (Figure 15), and so critical to the assessment of the influence of environmental water on metabolism is an improved ability to estimate the metabolic rates associated with purported, counterfactual flow regimes without contributions of environmental water.

Although simple in concept, accumulated metabolic activity can be difficult to interpret in a flowing river, where monitoring measures the characteristics of the water moving continuously past, and downstream, often to an unknown fate. For example, the accessibility, utilisation and fate of carbon "accumulated" by photosynthesis over the monitoring period may at one extreme be transported out the end of the river unutilised, or alternatively may be utilised at sites downstream of the monitoring site. Despite these issues, estimates of integrated river production provide useful insights

into system behaviour, even if the effects on the river are at times notional. Interpretation of these measurements would be improved with more intensive monitoring, but there are limits to this and in the end, clarification will rely on an ability to model metabolic responses based on the characteristics of the river environment.

The concept that an increase in flow will lead to increases in river metabolism unless offset by a decline in metabolism, is an important one, suggesting prolonged contributions of environmental water to in-channel flows could enhance river productivity over what might have been expected without them. However, management of river flows, including environmental flows, do not generally alter the overall volume of water in a river catchment, but alter the timing and distribution of flows so some areas have less and some greater flows than expected. The critical management question is how to deliver flows that best provide the metabolism required by the river ecosystem, especially if production is not only a function of the flow volumes, but is also influenced by meteorological conditions, river morphology and water quality. Consequently the net benefits to river metabolism of increased flows will depend on the location, timing, magnitude, duration and frequency of those flows, including consideration of the metabolism forgone at sites where flows are less conducive. Managed flows will better enhance production if appropriately targeted.

Conclusion

In 2017-18, increased flows due to contributions of environmental water are considered to have helped avoid poor DO outcomes that would have been likely under the low flows predicted without these contributions. Assuming no changes in average metabolic rates, environmental water delivery substantially enhanced accumulated production and decomposition over the monitoring period, compared to predicted responses from the low flows without environmental water. However, metabolic rates can change independently of flow as they are strongly influenced by meteorological conditions, river morphology and water quality, and so critical to the assessment of the influence of environmental water on metabolism is an improved ability to predict the metabolic rates associated with different river conditions.

The benefits to river metabolism of increased flows will depend on the location, timing, magnitude, duration and frequency of those flows. Some locations, seasonal periods, and river levels will deliver greater benefits from additional water than others. Targeted use of environmental flows can help to maximise the metabolic benefits, when considering the balances of gains and losses across multiple sites. Comparisons with estimates based on natural flows would be useful to place these goals in context. Improved modelling of environmental influences on the metabolic responses is required to more reliably assess the benefits of additional flows.

2.3 Matter Transport

Background

Salinity is a measure of total dissolved salts and is a key parameter governing the distribution and abundance of aquatic biota. As there is continual deposition of salt onto the landscape from rainfall, it will accumulate unless it is transported by flow and exported from the system. Particulate organic nutrients (phosphorus and nitrogen) are those nutrients incorporated into the tissue of living and dead organisms. Flow can influence their concentrations and transport through a number of mechanisms, including through increased productivity associated with elevated dissolved nutrient concentrations. Nutrients (e.g. nitrogen and phosphorus) drive system productivity and so understanding how they are transported between the various components of riverine ecosystems can offer insights into river and estuary productivity.

Altering the flow regime of riverine systems can alter the concentrations and transport of dissolved and particulate matter (Aldridge *et al.* 2012). For example, reduced flow can result in salinisation through evapoconcentration and the intrusion of saline water; reduced nutrient concentrations due to decreased mobilisation of nutrients from the floodplain; reduced primary productivity because of nutrient limitation; and thus reduced secondary productivity. Such observations have been made in the Murray River, including the LMR, Lower Lakes and Coorong (Brookes *et al.* 2009; Aldridge *et al.* 2011; 2012; Mosley *et al.* 2012).

Environmental flow deliveries may be used to reinstate some of the natural processes that control the concentrations and transport of dissolved and particulate matter (Aldridge *et al.* 2012; 2013; Ye *et al*. 2015a; 2015b; 2016). In doing so, these flows may provide ecological benefits through the provision of habitat and resources for biota. To assess the contribution of environmental water use to matter transport in 2017-18, a hydrodynamic-biogeochemical model was applied for the region below Lock 1 to the Murray Mouth. The model was validated with water quality data.

Methods

Water quality sampling and analyses

Water temperature, electrical conductivity, dissolved oxygen, pH and turbidity were monitored in the Murray River Channel (at Morgan) between July 2017 and June 2018. In addition, integrated-depth water samples were collected and sent to the Australian Water Quality Centre. Samples were analysed for filterable reactive phosphorus (hereafter referred to as phosphate), total phosphorus, nitrate, ammonium, total Kjeldahl nitrogen, dissolved silica and chlorophyll *a* using standard techniques. Organic nitrogen was calculated as the difference between total Kjeldahl nitrogen and ammonium.

Hydrodynamic–biogeochemical modelling

The contribution of environmental water to the transport of salt, nutrients and phytoplankton was assessed with a coupled hydrodynamic-biogeochemical model for the reach below Lock 1 to the Murray Mouth. The model platform used was the coupled hydrodynamic-biogeochemical model TUFLOW-FV-AED, developed by BMTWBM and the University of Western Australia (see Ye *et al.* 2018).

The model runs were initialised with data from a range of data sources. Inflow data (Lock 1), used to drive the main river domain, were provided by the MDBA for three scenarios: (1) 'with all water' (i.e. observed, including all environmental and consumptive water); (2) without Commonwealth environmental water ('no CEW'); and (3) without any environmental water ('no eWater'). These simulations were run for the period between July 2017 and June 2018.

The influence of environmental water on the concentrations of matter was assessed through a comparison of modelled concentrations for the various scenarios for the Murray River Channel (Wellington), Lower Lakes (Lake Alexandrina Middle) and Coorong (Murray Mouth). Modelled concentrations are presented as medians of modelled cells within areas surrounding sampling sites (Figure 17). A range in concentrations within those cells is also presented for the 'with all water' scenario.

The transport of matter was assessed through modelled exports from the Murray River Channel (Wellington), Lower Lakes (Barrages) and Coorong (Murray Mouth). Findings are presented for salinity, ammonium, phosphate, dissolved silica, organic nitrogen, organic phosphorus and chlorophyll *a*. Salinity is presented as practical salinity units (PSU), a measurement of the measured conductivity to standard potassium chloride (KCl) conductivity. PSU was used for validating model outputs as it overcomes observed differences in electrical conductivity caused by changes in water temperature. One PSU is approximately equal to part per thousand.

When modelling, it is necessary to make assumptions on the relationships between flow and nutrients or salt, nutrient dynamics in sediments and floodplain habitats, and the utilisation of nutrients by phytoplankton. This leads to a degree of uncertainty in model outputs; however, it is considered that this uncertainty is within reasonable bounds (Aldridge *et al.* 2013) and the results can be used to assess the general response to environmental water.

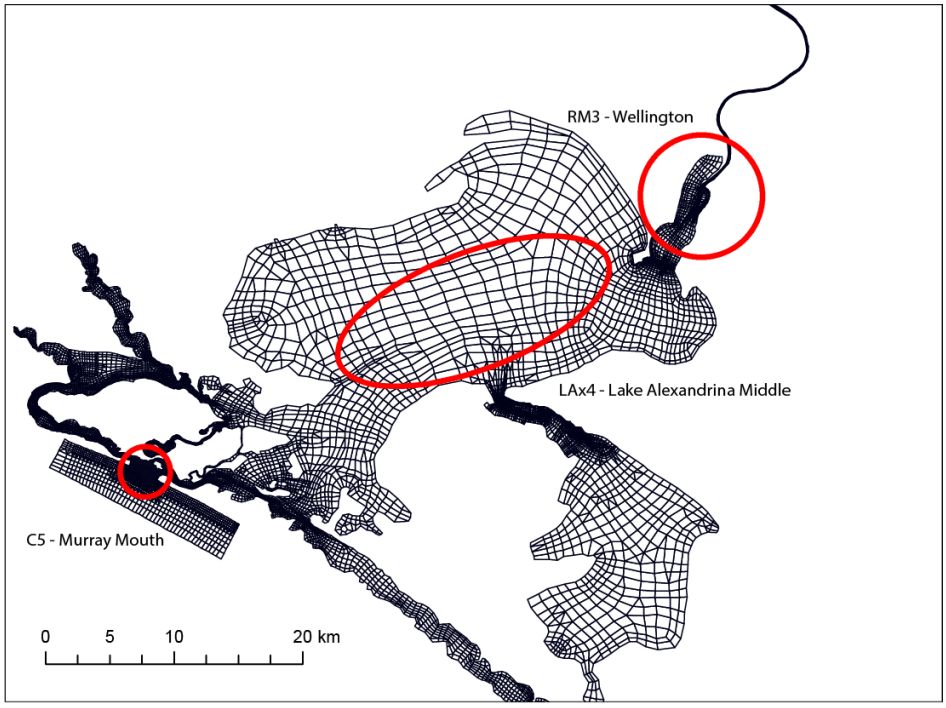

Figure 17. Modelled cells (circled) used for calculating the modelled concentration of nutrients or salt at the Wellington, Lake Alexandrina Middle and Murray Mouth sites.

Results

Salinity

In 2017-18, environmental water reduced salt concentrations in the Murray River Channel (Wellington), Lake Alexandrina and the Coorong at the Murray Mouth (Table 2). For example, the median salinity in the Coorong at the Murray Mouth was 26.20 PSU across the entire year. Without Commonwealth environmental water, it would have been approximately seawater salinity (33.84–34.99 PSU).

Environmental water increased salt export over the barrages by 300,970 tonnes, of which, 240,722 tonnes was attributable to Commonwealth environmental water (Figure 18; Table 2). There was a net import of salt into the Coorong of 527,042 tonnes. Without environmental water, the net import of salt would have been 6.1 million tonnes. Environmental water decreased salt import by 5.6 million tonnes, of which 2.9 million tonnes was attributable to Commonwealth environmental water.

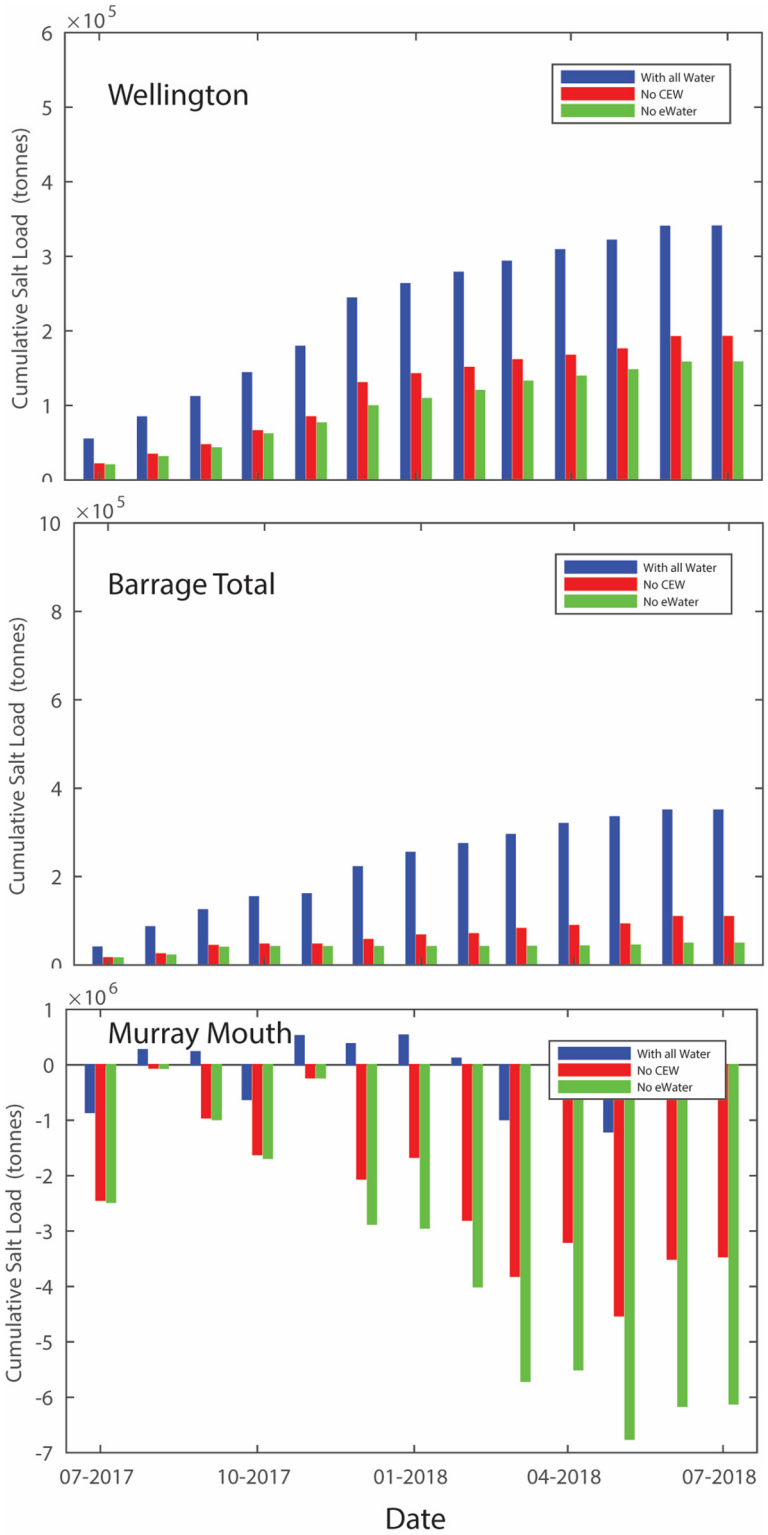

Figure 18. Modelled cumulative salt exports (net) with and without environmental water delivery. Scenarios include with all water, without Commonwealth environmental water (no CEW) and without any environmental water (no eWater).

Dissolved nutrients

The median concentrations of nitrogen and phosphorus do not vary considerably for any of the three modelled scenarios (Table 2). Phosphate in Lake Alexandrina showed the greatest proportional difference, however, the difference between phosphate with no environmental water and with all water was only 3.7 µg/L.

Environmental water contributed considerably to the transport of nutrients, but this was primarily due to additional flow not a change in the nutrient concentrations. The phosphate load over the barrages would have been 2.3 tonnes without environmental water and 3.2 tonnes without Commonwealth environmental water. With all water, phosphate export was 10.5 tonnes (Table 2).

The particulate nutrient load was much higher than the dissolved fractions. Particulate nitrogen export over the barrages (with all water) was 1249.4 tonnes and particulate organic phosphorus export was 116.1 tonnes (Table 2). Commonwealth environmental water contributed approximately 69% of the export of particulate organic nutrients.

The median silica concentrations varied in 2017-18, depending upon site and flow with the highest concentrations observed in Lake Alexandrina. The silica load over the barrages was 13619.9 tonnes, considerably higher than the load (2088.7 tonnes) that was predicted to occur if not environmental water was available (Table 2).

Chlorophyll a

Commonwealth environmental water contributed towards 157 tonnes of chlorophyll transport over the barrages to the Murray Mouth (Table 2). Furthermore, 141 tonnes of chlorophyll export through the Murray Mouth was attributed to Commonwealth environmental water.

Table 2. Median concentrations and loads (tonnes) of salinity, nutrients and chlorophyll *a* during 2017-18 for the modelled scenarios at three selected sites. Scenarios include with all water, without Commonwealth environmental water (no CEW) and without any environmental water (no eWater).

Type	Site	Scenario	Salinity (PSU)	Ammonium (mg/L)	Phosphate (mg/L)	Silica (mg/L)	Particulate organic nitrogen (mg/L)	Particulate organic phosphorus (mg/L)	Chlorophyll *a* (mg/L)
Conc.	Wellington	With all water	0.1859	0.0011	0.0019	2.6679	0.7667	0.0782	15.8614
		No CEW	0.2282	0.0012	0.0017	4.4705	0.7875	0.0789	13.8905
		No eWater	0.2432	0.0014	0.0018	5.0456	0.7809	0.0789	13.8179
	Lake Alexandrina Middle	With all water	0.2753	0.0011	0.0052	9.7625	1.0323	0.0977	14.4393
		No CEW	0.3074	0.0010	0.0082	12.4194	1.1413	0.1071	15.1590
		No eWater	0.3184	0.0010	0.0089	13.2426	1.1837	0.1102	15.3541
	Murray Mouth	With all water	26.2044	0.0205	0.0051	4.5693	1.0376	0.0775	11.4649
		No CEW	33.8453	0.0232	0.0047	2.0717	1.0158	0.0700	8.9916
		No eWater	34.9926	0.0235	0.0046	1.4439	1.0058	0.0687	8.7086
Loads (tonnes)	Wellington	With all water	340,106.1	1.0	6.0	3,649.3	1,459.8	144.1	363.9
		No CEW	192,096.1	0.8	1.3	2,549.4	737.5	75.6	167.3
		No eWater	157,866.4	0.8	0.6	2,218.1	552.8	58.4	119.3
	Barrages	With all water	349,892.8	8.0	10.5	13,619.9	1,249.4	116.1	221.5
		No CEW	109,170.6	2.1	3.2	4,842.4	395.6	36.8	63.9
		No eWater	48,923.0	0.7	2.3	2,088.7	176.6	16.0	25.7
	Murray Mouth	With all water	-527,042.5	-9.0	8.7	12,929.1	987.5	93.5	212.3
		No CEW	-3,459,211.5	-16.4	1.3	4,386.5	66.8	11.4	70.9
		No eWater	-6,115,353.2	-19.1	0.6	2,923.2	-128.0	-4.8	43.3

Discussion

Salinity

In 2017-18, environmental water diluted salt in the LMR channel (Wellington), Lake Alexandrina and the Coorong at the Murray Mouth. The salinity was well within the range required for potable water in the river and lake, but water was about 10% fresher with the environmental flows. The salinity in the Murray Mouth in 2017-18 (median salinity 26.20 PSU) was higher than in 2016-17, where flow into South Australia peaked at 94,600 ML/d and the median salinity was 12.97 PSU. Nevertheless, Commonwealth environmental water created fresher conditions in the Coorong at the Murray Mouth in 2017-18 compared to without environmental water.

Salinity in the Coorong is a function of riverine inflows and tidal movement. When barrage flows are low, seawater enters the Murray Mouth and salt can accumulate in the Coorong. The relatively low flow in 2017-18 meant that there was considerable import of salt (i.e. 527,042 tonnes) from the sea to the Coorong, but without environmental water, the net import of salt would have been 6.1 million tonnes. It is evident that the environmental water not only exports salt from the MDB but it also plays a critical role in reducing excessive salt import into the Coorong. During the Millennium Drought and particularly in 2008 and 2009 the import of salt into the Coorong resulted in salinity in the South Lagoon that was five times seawater salinity, and demise of much of the aquatic life. The environmental water provides freshening flows but also acts to inhibit seawater intrusions, thereby maintaining more appropriate salinity conditions in the Coorong.

Nutrients

Environmental water contributed considerably to the transport of nutrients, but this was primarily due to additional flow not a change in the nutrient concentrations. It is evident that environmental flows contribute a considerable load of nutrients to the Murray Mouth. From this evidence, it can be concluded that environmental flows would be a key driver in promoting estuarine productivity. The particulate nutrient load was much higher than the dissolved fractions. Particulate nitrogen export over the barrages was 1,249.4 tonnes and particulate organic phosphorus export was 116.1, with Commonwealth environmental water contributing towards approximately 69% of the particulate organic nutrients. The silica load over the barrages with all environmental water was 13,619 tonnes, considerably higher than the load that was predicted to occur if environmental water was not available (2,088.7 tonnes).

The load of nutrients exported from the basin over the barrages is an interesting issue; on one hand nutrient export drives estuarine productivity, but on the other hand it is desirable to maintain appropriate levels of nutrients in the catchment where they can support aquatic productivity. The loads are discussed here in terms of magnitude under various flow scenarios but it is not possible, with the current understanding, to make a judgement about appropriate levels for both the catchment and Coorong under different flow scenarios.

Chlorophyll a

Chlorophyll a is a photosynthetic pigment that is ubiquitous in the phytoplankton, so is often used as a measure of the relative size of the phytoplankton community. A considerable amount of the total organic nutrients is likely to be bound within phytoplankton, and so the chlorophyll loads reflect the loads of particulate organic nitrogen and phosphorus. Chlorophyll export can be interpreted as a transfer of food resources from one site to another. Therefore, Commonwealth environmental water likely played a role in promoting estuarine productivity contributing 157 tonnes of chlorophyll over the barrages to the Murray Mouth.

Conclusion

In 2017-18, the contributions of environmental water appear to have significantly increased the exchange of dissolved and particulate matter through the LMR to the Southern Ocean. In low flow years, environmental flow delivery can play a key role in salt export from the Basin, contributing 64−87% of salt export (Ye *et al.* 2016; 2017). Environmental flow deliveries during periods when there would otherwise be negligible water exchange between the Lower Lakes and Coorong can promote connectivity and allow matter exchange between these two water-bodies.

To help guide future environmental water use, a review is required on the costs and benefits of nutrient export from the MDB. On one hand there are potential positive benefits of nutrient delivery to the estuary to fuel productivity and fisheries, but on the other hand losing nutrients from the landscape could be viewed as a detrimental outcome for the catchment. An assessment is required to determine what an appropriate nutrient load is from the river to the estuary to maintain productivity but not lead to adverse outcomes for both freshwater and estuarine systems.

2.4 Microinvertebrates

Background

Aquatic microinvertebrates (microcrustaceans, rotifers and protists) are a major food source for larger organisms (e.g. macroinvertebrates) in freshwater systems (Schmid-Araya and Schmid 2000; Pernthaler and Posch 2009), and important for early life stages of fish (i.e. larvae) (Arumugam and Geddes 1987; Tonkin *et al.* 2006). The aquatic microinvertebrates of the MDB have short generation times and are rapid responders to environmental changes (Tan and Shiel 1993). To assess the responses of microinvertebrates in the LMR to delivery of Commonwealth environmental water during 2017-18, we aimed to answer the following evaluation questions:

What did Commonwealth environmental water contribute:

- to microinvertebrate diversity?
- to microinvertebrate abundance (density)?
- via upstream connectivity to microinvertebrate communities of the LMR?
- to the timing of microinvertebrate productivity and presence of key species in relation to diet of native, large-bodied fish larvae?

Methods

Sampling sites and procedure

Mid-channel microinvertebrate assemblages were sampled by a Haney plankton trap (4.5 L capacity) approximately fortnightly between 3 October 2017 and 4 January 2018. Three replicate 9 L (4.5 L top and 4.5 L bottom depth) samples were taken during the day at three sites below Lock 1 and Lock 6, concurrent with fish sampling (Ye *et al.* 2018). Microinvertebrates were preserved (70–95% ethanol) in the field and returned to the laboratory for processing.

Statistical analyses

To assess the influence of Commonwealth environmental water on microinvertebrate assemblages over the short-term (1 year), temporal variation (between sampling trips) was investigated. Between-trip temporal variation in microinvertebrate densities and taxa richness was analysed qualitatively for all sites using graphical plots of mean values ± standard error. Temporal variation in daytime microinvertebrate assemblage structure was investigated using a two-factor (i.e. sampling trip x lock) permutational multivariate analysis of variance (PERMANOVA) in the software package PRIMER v. 6.1.12 (Clarke and Gorley 2006) and PERMANOVA + v.1.02 (Anderson *et al.* 2008).

Larval gut analysis

To determine if Commonwealth environmental water contributed to the timing of microinvertebrate productivity and presence of key species in relation to diet of large-bodied fish larvae, diet composition of fish larvae was assessed. Gut contents of thirteen golden perch, ten freshwater catfish and three Murray cod post-larvae,

collected opportunistically through larval fish sampling as part of the Fish Spawning and Recruitment indicator, were analysed using traditional taxonomic methods.

Results

Microinvertebrate catch summary

Over the 2017-18 sampling period (early October 2017 to early January 2018), 173 microinvertebrate taxa were discriminated from 126 trap samples from the gorge (below Lock 1) and floodplain (below Lock 6) geomorphic zones of the LMR (Table 3). The 2017-18 assemblage was dominated by protists (largely testate rhizopods) and rotifers. Not recorded in 2014-15–2016-17 trap samples, 12 taxa (7%) comprised protists (2), rotifers (7), cladocerans (1), copepods (1) and juvenile macroinvertebrates (1).

Table 3. Number of microinvertebrate taxa from major taxonomic groups sampled by Haney Trap (daytime only) below Lock 1 and 6 in the gorge and floodplain geomorphic zones, respectively, from 2014-15–2017-18. *n* = number of trap samples.

Taxa	2014-15 (*n* = 108)	2015-16 (*n* = 144)	2016-17 (*n* = 144)	2017-18 (*n* = 126)
Protists	66	55	105	68
Rotifers	80	94	105	84
Cladocerans	13	11	15	9
Copepods	5	5	8	3
Ostracods	2	2	1	2
Macroinvertebrates (juveniles)	6	5	8	6
Total	**172**	**172**	**242**	**172**

Densities and taxa richness

Mean microinvertebrate densities during spring/summer 2017-18 ranged from 154 to 1,791 individuals per litre (ind/L) (Figure 19). Density below Lock 6 rapidly increased from 154 ind/L in late October to 1,076 ind/L in early November, where it remained stable throughout November. Density then declined slightly in mid-December to 734 ind/L, before increasing to a peak of 1,791 ind/L in early January. Density below Lock 1 remained low (<300 ind/L) from early October to mid-November, before increasing steadily to a peak of 1,660 ind/L in early January (Figure 19). Densities showed a general increase throughout the sampling period with increasing water temperature, but did not follow any close patterns of hydrology, although increases in abundance followed pulses in flow (Figure 19).

Mean microinvertebrate taxa richness (indicating diversity) in 2017-18 was variable at both locks throughout the sampling period, but generally increased from mid-October to early January (Figure 19). Low taxa richness (~6 spp.) accompanied the low densities in mid-October 2017 (Figure 19). The ciliate *Codonaria* and the cladoceran *Bosmina* were the only plankters in appreciable numbers at Lock 6, while testates, *Keratella australis* and mixed microcrustaceans were dominant at Lock 1.

Thereafter in-channel diversity increased at both locks through November 2017 to January 2018 (>22 spp.), with a mixed rotifer assemblage predominating (brachionids, conochilids, synchaetids, trichocercids, trochosphaerids) (Figure 19).

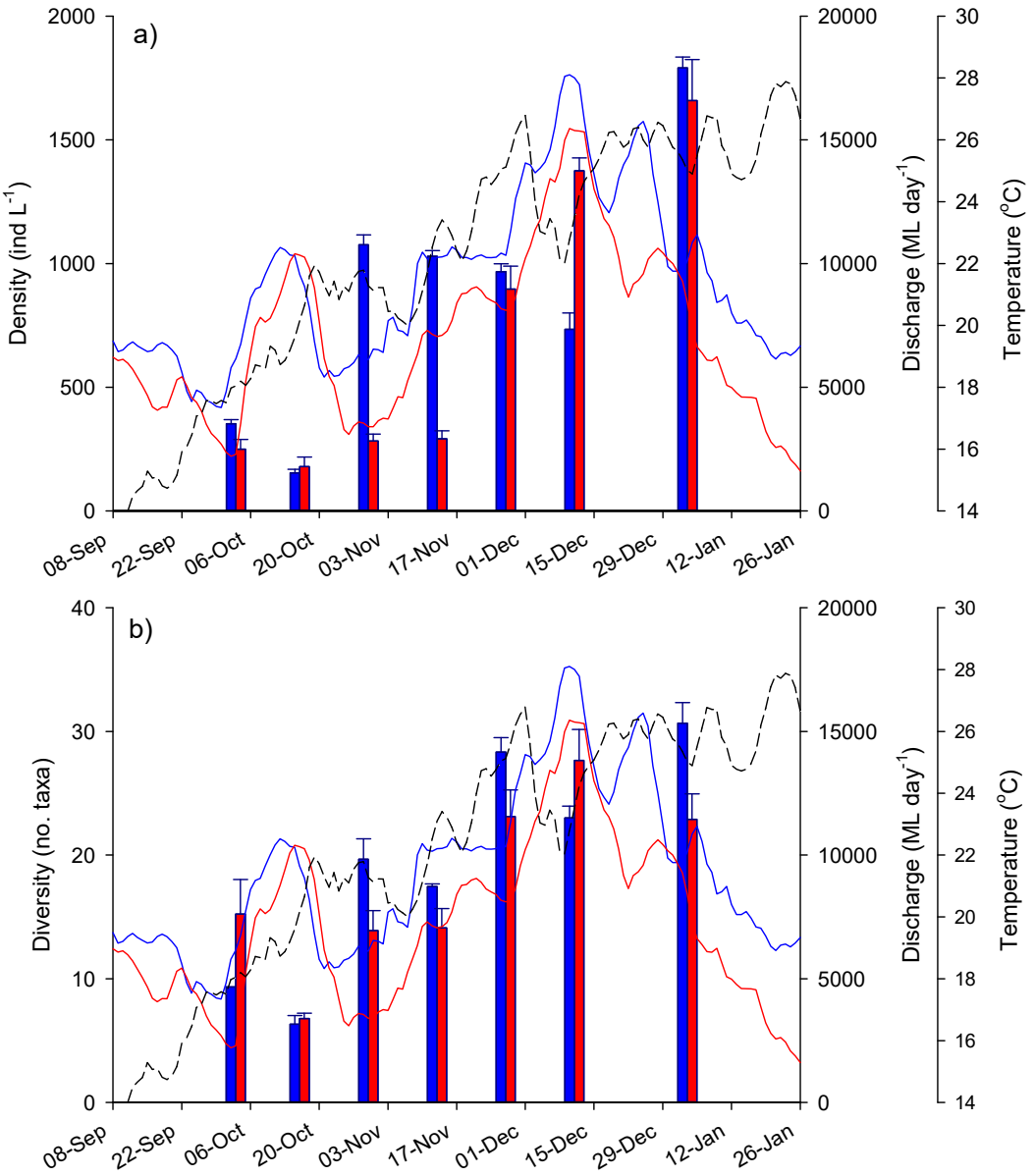

Figure 19. Mean (±S.E.) (a) density and (b) taxa richness of microinvertebrates collected in the LMR at sites below Lock 1 (red) and Lock 6 (blue) in 2017-18. Data are plotted against discharge (ML/d) in the LMR at the South Australian border (solid blue line) and below Lock 1 (solid red line), and against water temperature (°C) (dashed black line). Sampling was undertaken approximately fortnightly from 3 October 2017 to 3 January 2018.

Microinvertebrate assemblage structure

A significant interaction was detected between locks and sampling trips for microinvertebrate assemblages (two-factor PERMANOVA; *Pseudo-*$F_{6,41}$ = 3.5262, p = 0.0001), suggesting inconsistent spatio-temporal variation among sampling trips between locks. Pairwise tests were conducted separately for below Lock 6 and Lock 1 to examine differences over time (i.e. between sampling trips) (Table 3 and Table 4). For both locks, most assemblages from a certain trip were not significantly different from their preceding trip, with the exception of late October (Lock 6) and early January (Lock 1), showing a progressive change in assemblage structure with time/season.

Lock 6

For sites below Lock 6, microinvertebrate assemblages were similar between the first two sampling trips in early and mid-October, but significantly different to almost all later sampling trips (PERMANOVA, Table 4; Figure 20). Early and mid-October trips were characterised by higher abundance of the cladoceran *Bosmina meridionalis*, relative to the last five sampling trips, which had higher abundances of the rotifers *Trichocerca agnatha and Trichocerca* sp. e (SIMPER). Assemblages were similar amongst the middle three sampling trips from late October to late November, and the last three sampling trips from late November to early January (PERMANOVA, Table 4). Microinvertebrates driving the gradual change in assemblage over this period was the cladoceran *Ceriodaphnia* sp. (early and mid-October) and rotifers *Synchaeta* sp. b (late October), *Trichocerca* sp. b (early November), *Hexarthra intermedia* (December), *Polyarthra dolichoptera* (December and January), *Filinia terminalis* and *Hexarthra braziliensis* (January) (SIMPER). MDS ordination of the Lock 6 assemblages supports results from pairwise comparisons; there was strong separation of the first two sampling trips from the remainder (Figure 20).

Table 4. Within sites below Lock 6 pair-wise results of microinvertebrate log(x+1) abundance data amongst sampling trips, showing Monte-Carlo p-values. After B–Y method FDR correction, a = 0.0137 for comparisons between trips (21 comparisons). n.s. = groups not significantly different.

Sampling trip	3-Oct	16-Oct	30-Oct	13-Nov	27-Nov	11-Dec
16-Oct	n.s.					
30-Oct	0.0118	0.0135				
13-Nov	0.0095	n.s.	n.s.			
27-Nov	0.0049	0.084	n.s.	n.s.		
11-Dec	0.0032	0.0083	0.0093	0.0094	n.s.	
3-Jan	0.0026	0.0045	0.0083	0.0043	n.s.	n.s.

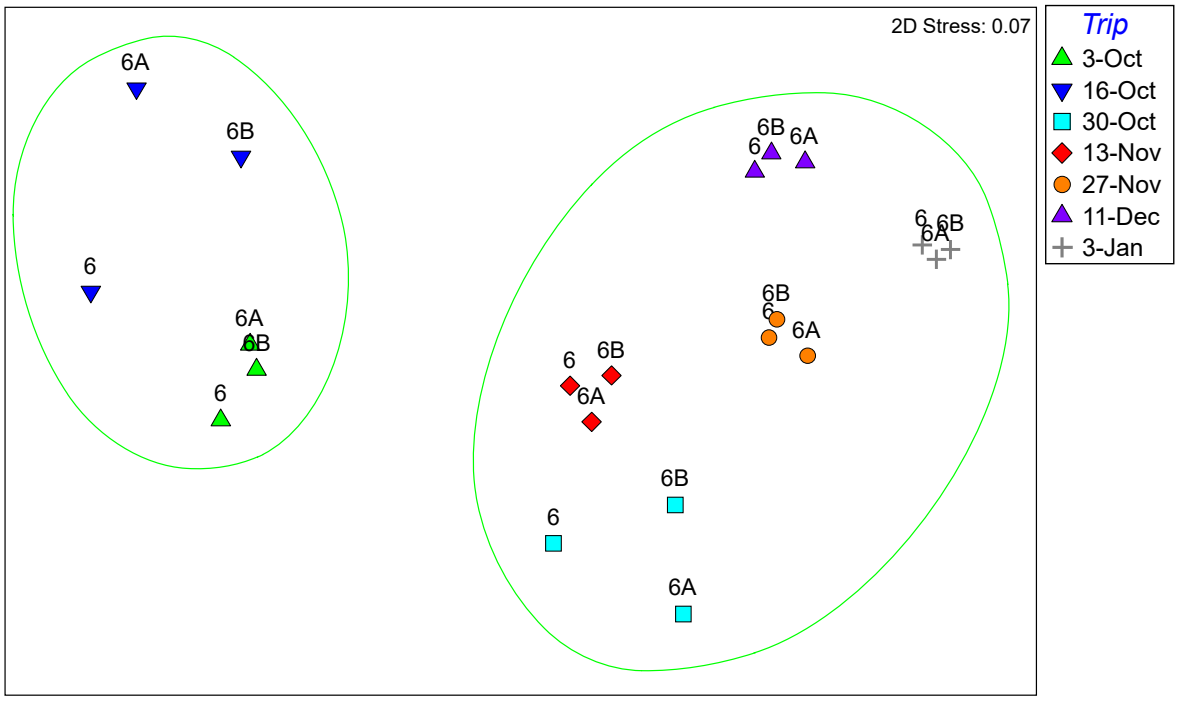

Figure 20. MDS ordination of microinvertebrate assemblage data (log transformed) from sites below Lock 6, with samples identified by sampling trip. Samples are grouped at a Bray-Curtis similarity of 40% (green circles) (SIMPROF).

Lock 1

For sites below Lock 1, microinvertebrate assemblages in the first four sampling trips in early and mid-November were characterised by high within-trip variability and were not significantly different from each other (B–Y method corrected *a* = 0.0127, Table 5; Figure 21). These first four sampling trips were characterised by higher abundance of the rotifer *Keratella australis* (SIMPER). The first two sampling trips were significantly different to the last three sampling trips from late November to early January, which were characterised by higher abundance of the invasive rotifer *Keratella americana*, relative to the first two. The early January assemblage was also significantly different to all preceding trips, mostly due to higher abundance of the rotifer *Keratella tecta*. Microinvertebrates driving the gradual change in assemblage over this period were the rotifers *Synchaeta* sp. b and c (late November), *Keratella tropica* (late November and December), *Filinia terminalis* (December), *Polyarthra dolichoptera* (December and January) and *Keratella tecta* (January) (SIMPER).

Table 5. Within sites below Lock 1 pair-wise results of microinvertebrate log(x+1) abundance data amongst sampling trips, showing Monte-Carlo p-values. After B–Y method FDR correction, a = 0.0137 for comparisons between trips (21 comparisons). n.s. = groups not significantly different.

Sampling trip	3-Oct	16-Oct	30-Oct	13-Nov	27-Nov	11-Dec
16-Oct	n.s.					
30-Oct	n.s.	n.s.				
13-Nov	n.s.	n.s.	n.s.			
27-Nov	0.0058*	0.0076*	n.s.	n.s.		
11-Dec	0.0039*	0.0066*	0.0085*	0.0081*	n.s.	
3-Jan	0.002*	0.0057*	0.0058*	0.004*	0.0068*	0.009*

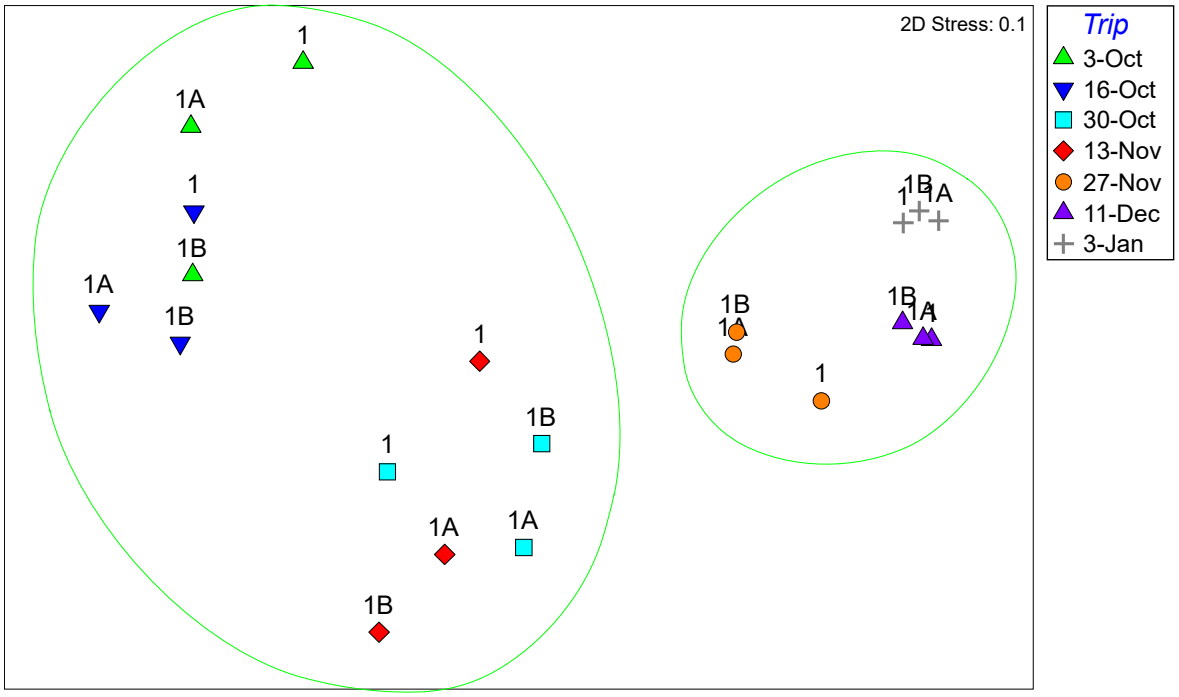

Figure 21. MDS ordination of microinvertebrate assemblage data (log transformed) from Lock 1, with samples identified by sampling trip. nMDS was based on Bray-Curtis Similarities. Samples are grouped at a Bray-Curtis similarity of 40% (SIMPROF).

Larval gut content

Ambient 'fish prey' assemblage

In 2017-18, the cladoceran *Bosmina meridionalis* was the most abundant microcrustacean species, particularly at Lock 6 during early and mid-October (Figure 22). The cladocerans *Ceriodaphnia* sp. (non-cornuta) and *Daphnia lumholtzi* and calanoid copepod *Boeckella triarticulata* were also abundant from early October to mid-November. Unidentifiable copepodites and nauplii from order Cyclopoida were abundant at Lock 1 in early January (Figure 22).

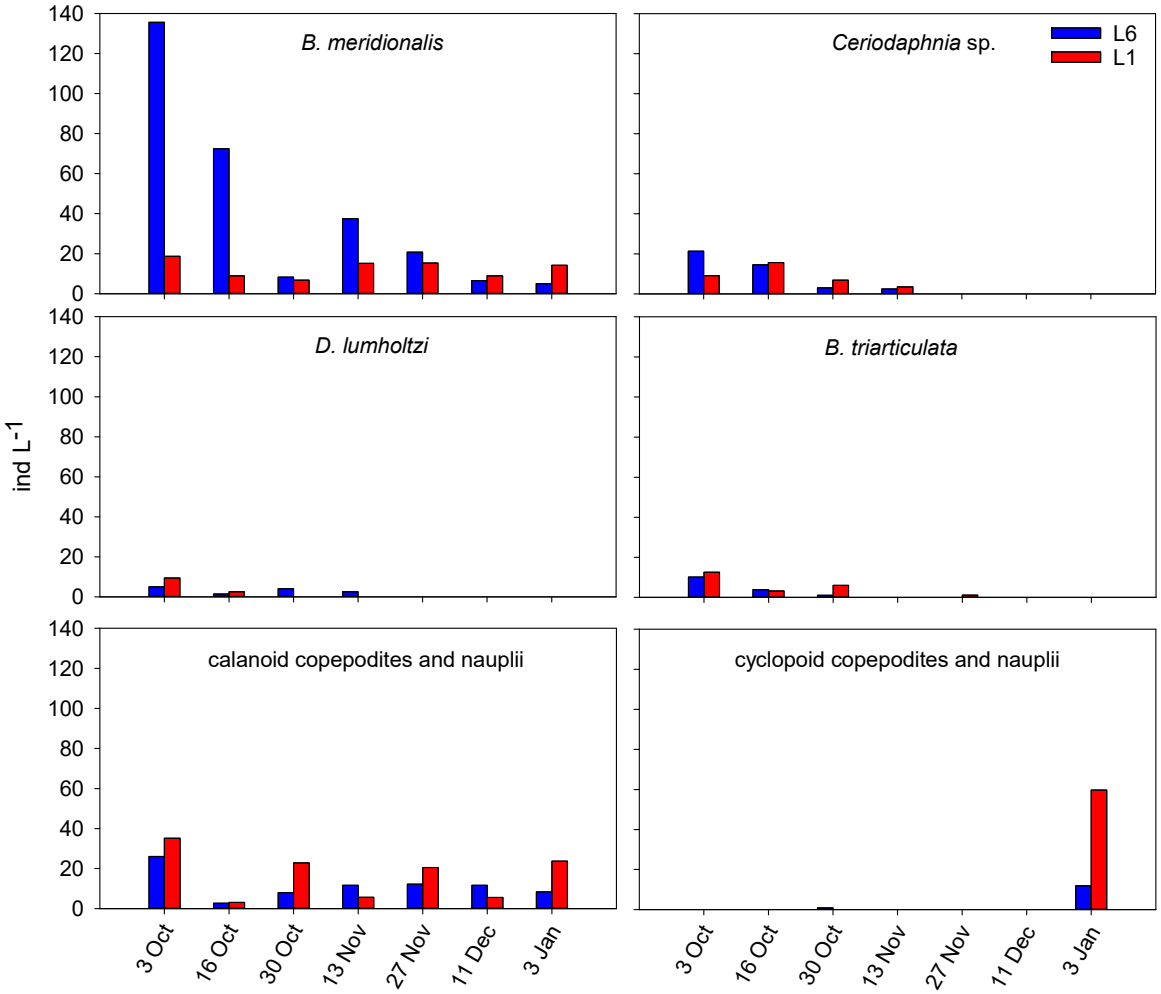

Figure 22. Mean relative abundances (ind/L) of most abundant cladocerans and copepods by trip and lock (daytime only) for 2017-18.

Larval gut analysis

All Murray cod larvae (*n* = 3) had empty guts and were excluded from any analyses, while the guts of 24% of golden perch and 20% of freshwater catfish were empty. The calanoid copepod *Calamoecia* sp. and cladocerans *B. meridionalis* and *Chydorus* cf. *sphaericus* were consumed by multiple golden perch individuals and numerically contributed to 46% of the overall diet for this species (Table 6). The calanoid copepod *B. triarticulata* occurred in the guts of 3/8 freshwater catfish larvae. This prey item along with the cladoceran *C.* cf. *sphaericus* numerically contributed to 42% of the overall diet of this species (Table 6).

Table 6. Summary of gut content analysis of post-flexion golden perch (*n* = 10; TL = 6.5–20 mm) and freshwater catfish (*n* = 8; TL = 14–16 mm). %N represents the numerical proportion of a prey item towards the total within each species and %F represents the percentage frequency of occurrence of a prey item within each species.

	Golden perch		Freshwater catfish	
Prey	%F	%N	%F	%N
Copepoda				
Calanoida				
Boeckella triarticulata	10	4.2	37.5	21.1
Calamoecia sp.	20	20.8		
copepods	10	4.2		
copepodites	20	12.5	12.5	5.3
Unid. copepod fragments			12.5	5.3
Cladocera				
Bosmina meridionalis	20	16.7		
Ilyocryptus sp.	10	4.2		
Daphnia lumholtzi	10	4.2		
Daphnia sp.	10	4.2		
Ceriodaphnia sp.	10	4.2	25	10.5
Chydorus cf. *sphaericus*	20	8.3	12.5	21.1
Oligochaeta (Naididae)	10	4.2		
Malacostraca				
Amphipoda	10	4.2		
Decapoda				
Atyidae			12.5	10.5
Insecta				
Diptera	10	8.3	25	15.8
Hemiptera			12.5	5.3
Unid. insect larvae			12.5	5.3

Discussion

In 2017-18, microinvertebrate densities and diversities at Locks 6 and 1 were lowest during mid-October 2017. This coincided with low water temperatures (<20°C), the recession of water levels following raising of Weir Pools 2 and 5 (Figure B1 in Appendix B), and a flow pulse, including flow from Lake Victoria (Figure 4). Declines in microinvertebrate diversities and densities during November 2015 also aligned with the recession of water levels following weir pool raising (Ye *et al.* 2017). During both of these in-channel flow years, weir pools were raised 0.45–0.5 m above normal pool level (NPL). In contrast, microinvertebrate densities increased on the recession of water levels during late October 2016, particularly at Lock 6, following raising of Weir Pools 2 and 5 (0.75 and 0.48 m above NPL, respectively). During October 2016, however, there was the influence of overbank flows (>45,000 ML/d) and drawdown of the Chowilla regulator. Overbank flows transported non-planktonic species (up to

70% at some sites) into the main channel, accounting for the higher diversity in 2016-17. It is unclear if the declines in diversity and density during these in-channel flow years are related to the effects of the recession of weir pools (e.g. toxic leachates from a newly wetted area, Portinho *et al.* 2016), or other influences, such as a 'new' water source with low microinvertebrate abundance and diversity. Reductions in dissolved oxygen measurements below Lock 6 and 1 in 2015-16 (Section 2.2; Ye *et al.* 2017) and 2017-18, following the drawdown of water from weir pools, are not evident.

In 2017-18, highest microinvertebrate diversities (>20 spp.) occurred from late November to early January, which coincided with an increase in flow from the Murray, Murrumbidgee and Goulburn rivers (total flow to South Australia >10,000 ML/d) (Figure 4). During this period, with the exception of late December, a large proportion of the water that contributed to river flow was environmental water, including The Living Murray and Commonwealth environmental water (Figure 3). Earlier microinvertebrate LTIM data has shown that each catchment provides a subset of microinvertebrates unique to that catchment, which is a function of the latitudinal extent of the MDB. When water (including environmental) is being delivered from different sources concurrently, it becomes difficult to tease out 'who is where' if that particular source was not sampled. Dominant taxa from the late November to early January assemblages at all locations were a mix of Murray and Goulburn River species. *Trichocerca* cf. *agnath*a, for example, known only from two Murray River records (R. Shiel, unpublished data; D. Furst, pers. comm), may have come from an upstream Murray River source (e.g. Barmah-Millewa return flows in October and November 2017, Appendix B). A floodplain source is likely for trichocercids, for example, because they are littoral rather than planktonic in habit.

Microinvertebrate density peaked in early January 2018 during increased water temperature (~25°C). Warmer temperatures favoured warm-water species: a suite of brachionids (notably *B. budapestinensis, B. caudatus, B. durgae, B. falcatus, B. keikoa*) and *Hexarthra braziliensis* at Lock 6, and *Keratella* spp. and *Polyarthra dolichoptera* at Lock 1. In previous in-channel flow years (2014-15 and 2015-16) (Ye *et al.* 2016; 2017), population density increases of microinvertebrates below Lock 6 and Lock 1 during January were attributable to downstream passage of the upstream assemblage. Warm water rotifers *Keratella americana* and *K. tropica* were both sampled in high abundance (>200 ind/L) from late November to early January at Lock 1, contributing to the high microinvertebrate densities during this period. The origin of these *Keratella* spp. populations are unclear. These species occurred in very low abundance (<10 ind/L) at Lock 6 from early October to mid-December and there was insufficient travel time for these small numbers to build up by instream reproduction to the abundances recorded at Lock 1. Source populations downstream of Lock 6, e.g. a weir pool or backwater, are possible, and water temperatures over 25 °C a probable cue for population increases. The appearance of *K. tecta,* also likely introduced, and also a warm stenotherm, new to South Australia, at Lock 1 followed a similar pattern; only three individuals were collected at Lock 6 during the sampling period, but high densities (to 180 ind/L) were recorded at Lock 1 from December–January. It is not

evident whether *K. americana*/*K. tropica* and the later-appearing *K. tecta* came from the same source catchment, with *K. tecta* a month or so later in the successional cycle, or if the *K. tecta*-containing pulse represented a different water source, e.g. return flows from Barmah–Millewa Forest, Hattah Lakes, or the Goulburn River, all of which occurred during November–December (Figure 3), or a discrete source population below Lock 6.

Microcrustacean (large-bodied, larval fish prey) abundance, which was primarily driven by *Bosmina meridonalis*, was highest at Lock 6 during early and mid-October 2017 and generally declined throughout the sampling period. In contrast, abundance of microcrustaceans at Lock 1 was fairly consistent throughout the period. Golden perch larvae were sampled during four sampling trips: mid-October, late November, early December and early January. Despite *B. meridonalis* being highly abundant at Lock 6 during mid-October, golden perch larvae sampled at Lock 6 fed on other prey (i.e. calanoid copepods *Calamoecia* spp. and *Boeckella triarticulata* and cladoceran *Ceriodaphnia* sp.). Golden perch fed on *B. meridionalis* in early January when other calanoid copepod and cladoceran species were in low abundances or absent, potentially indicating a preference for these prey species (e.g. calanoid copepods *B. triarticulata* and *Calamoecia* spp.) over *B. meridionalis*. Results also suggest a preference for the cladoceran *Chydorus* cf. *sphaericus*, which was not sampled by Haney Trap in 2017-18, but consumed by golden perch in early December and early January. It is difficult to try to tie the presence of these suspected preferred prey with particular flow deliveries or sources, particularly since two important prey species (*Calamoecia* spp. and *C.* cf. *sphaericus*) were not collected during microinvertebrate Haney Trap sampling in 2017-18. The low number of golden perch larvae sampled also limits the reliability of results. Therefore, the contribution of Commonwealth environmental water on the dietary composition of golden perch larvae could not be evaluated.

Conclusion

The 2017-18 assemblage was similar to other low-flow years (i.e. 2014-15 and 2015-16) and less diverse than that during 2016-17, when high numbers of non-planktonic species that are littoral (along the bank), epiphytic (attached to plants) or epibenthic (on the surface of sediments) in habit were transported into the main channel during overbank flows. Like other in-channel flow years, the microinvertebrate assemblage during 2017-18 underwent a seasonal succession change, and densities and diversities generally increased throughout the sampling period with increasing water temperatures. Increased diversity (e.g. warm-water taxa) in late November and mid-December 2017 was associated with increased river flows, of which environmental water contributed a large proportion.

As demonstrated for other years of LTIM, particularly 2016-17 (Ye *et al.* 2018), longitudinal connectivity of river flow is important in the transportation of microinvertebrate taxa from upstream catchments (e.g. Goulburn and upper Murray rivers) to the LMR, contributing to the diverse community in the LMR.

2.5 Fish Spawning and Recruitment

Background

Spawning and recruitment of golden perch in the southern MDB corresponds with increases in water temperature and discharge, either in-channel or overbank (Mallen-Cooper and Stuart 2003; Zampatti and Leigh 2013a; 2013b). Silver perch display similar life history characteristics and population dynamics, although in the lotic reaches of the River Murray, silver perch may spawn circa-annually (Tonkin *et al*. 2017). Due to these flow-related traits, golden perch and silver perch are candidates for measuring ecological response to environmental water allocations. Understanding the influence of hydrology on the population dynamics of golden perch and silver perch, however, is reliant on accurately determining the hydrological conditions at the time and place of crucial life history processes. For example, to be able to accurately associate river flow with spawning, the time and place of spawning must be known.

Over the five-year term of this project, we aim to identify potential associations between reproduction (spawning and recruitment) of golden perch and silver perch and environmental water delivery. The specific objectives are to identify the timing of spawning and source (i.e. natal origin) of successful recruits to enable association of ecological response with hydrology; and to explore population connectivity between regions of the southern-connected MDB. We expect that: (1) increased flow (nominally >15,000 ML/d, Zampatti and Leigh 2013a) in spring–summer will promote the spawning and recruitment (to young-of-year, YOY), and (2) multiple years of enhanced spring–summer flow will increase the resilience of golden perch and silver perch populations in the LMR.

Methods

To evaluate the contribution of Commonwealth environmental water to the spawning and recruitment of golden perch and silver perch in the LMR in 2017-18, we: (1) sampled larval and young-of-year (YOY) fish at sites in the gorge and floodplain geomorphic zones of the LMR (Figure 1); (2) used otolith microstructure and chemistry, specifically strontium (Sr) isotope ratios ($^{87}Sr/^{86}Sr$), to retrospectively determine the time and place of spawning; and (3) used electrofishing to collect a representative subsample of the golden perch and silver perch populations in the LMR to enable determination of population age structure.

Analysis of water $^{87}Sr/^{86}Sr$ at sites across the southern MDB

To determine spatio-temporal variation in water strontium (Sr) isotope ratios ($^{87}Sr/^{86}Sr$) over the spring–summer of 2017-18, water samples were collected weekly–monthly from eleven sites across the southern MDB (Figure 23; Table 7). At most sites, water samples were collected from early September 2017 to early February 2018.

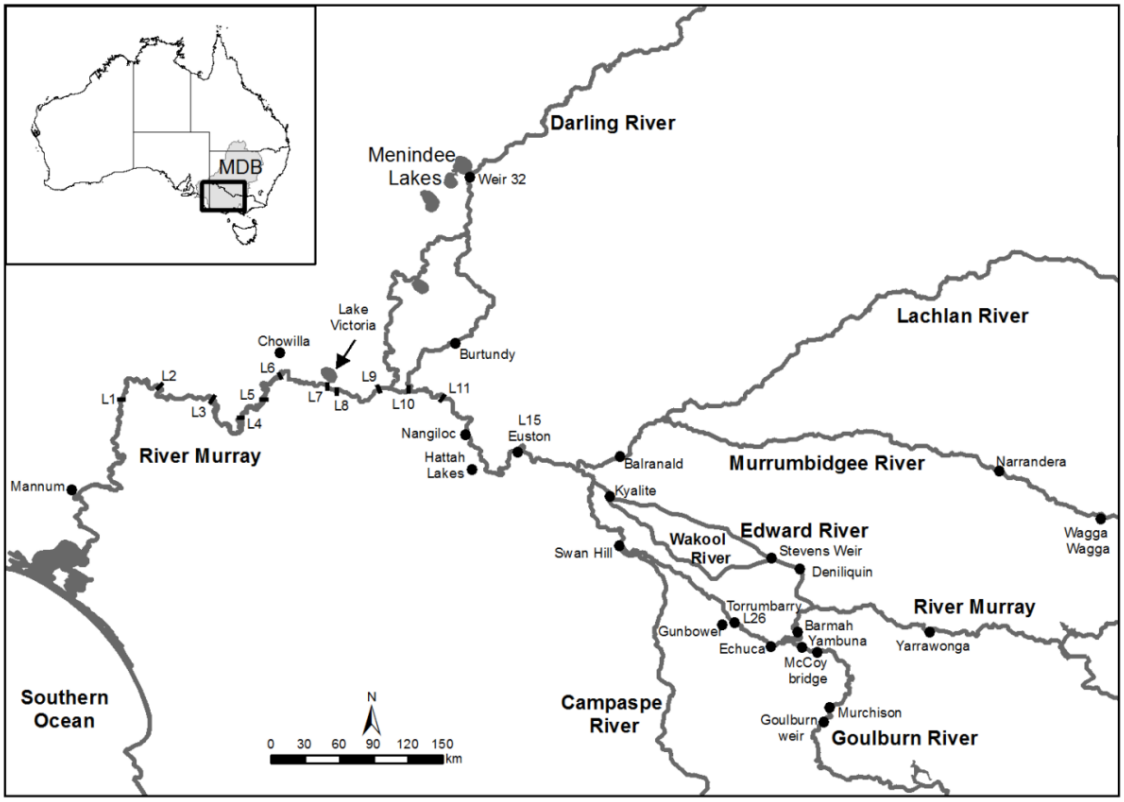

Figure 23. Map showing the location of the Murray–Darling Basin and the major rivers that comprise the southern Murray-Darling Basin, the numbered Locks (L) and Weirs (up to Lock 26, Torrumbarry), the Darling, Lachlan, Murrumbidgee, Edward–Wakool, Campaspe and Goulburn rivers and Lake Victoria, an off-stream storage used to regulate flows in the lower River Murray.

Table 7. Location of water sample collection for $^{87}Sr/^{86}Sr$ analysis.

River	Location	Sampling period	Total number of samples
Murray	Lock 1	11/09/17–12/02/18	11
Murray	Lock 6	15/09/17–13/02/18	12
Murray	Lock 9	11/09/17–13/02/18	12
Murray	Lock 11	13/09/17–1/03/18	11
Murray	Torrumbarry	15/09/17–29/01/18	11
Murray	Barmah	14/11/17–12/12/17	2
Darling	Weir 32	16/09/17–19/03/18	17
Edward–Wakool	Deniliquin	28/09/17–15/02/18	11
Murrumbidgee	Narrandera	11/10/17–16/02/18	9
Goulburn	Yambuna	10/10/17–06/12/17	6
Goulburn	Pyke Road	25/10/17–06/12/17	5

Sampling eggs and larvae

Larval fish sampling was conducted approximately fortnightly between 3 October 2017 and 4 January 2018 at six sites in the LMR (Ye *et al.* 2018). Sites were located 5, 7 and 9 km downstream of Locks 1 and 6 (Figure 1). Three day-time and three night-time plankton tows were undertaken on the same day at sites 5 km below each lock, while one day-time plankton tow was undertaken at all other sites. Fish were preserved (70–95% ethanol) in the field and returned to the laboratory for processing. Golden perch and silver perch eggs are unable to be visually differentiated. When eggs were present, a subsample were transported to the laboratory and hatched out to confirm the species.

Sampling YOY and population age-structure

Adult and juvenile golden perch and silver perch were sampled using a 7.5 kW Smith Root (Model GPP 7.5) boat electrofishing unit at 16 sites in the LMR (Ye *et al.* 2018).

Sampling was undertaken in April–May 2018 to maximise the likelihood of collecting YOY spawned in the spring–summer 2017-18 spawning season. Electrofishing was conducted during daylight hours and all available littoral habitats were surveyed. At each site the total time during which electrical current was applied ranged from approximately 1089 to 2880 seconds. All individuals were measured to the nearest mm (total length, TL) and a subsample of golden perch proportionally representing the length-frequency of golden perch collected was retained for ageing. In 2018, only two silver perch were collected.

Ageing

Daily increments in otolith microstructure were examined to estimate the spawn date of larval and YOY golden perch. Larvae/juveniles were measured to the nearest millimetre and sagittal otoliths were removed.

We investigated length and age-frequency distributions to assess the age structure and year-class strength of golden perch and silver perch. Golden perch (n = 107) and silver perch (n = 2) retained for ageing were euthanised and sagittal otoliths were removed.

Otolith $^{87}Sr/^{86}Sr$ analysis

In situ microsampling analysis of $^{87}Sr/^{86}Sr$ in the otoliths of larval and juvenile golden perch (and silver perch) was achieved by laser ablation – inductively coupled plasma mass spectrometry (LA-MC-ICPMS).

Results

Water $^{87}Sr/^{86}Sr$ and hydrology

From September 2017–February 2018, water $^{87}Sr/^{86}Sr$ remained reasonably stable in the Darling River, and the Murray River and its tributaries, upstream of the Darling River junction. The highest ratios (>0.7190) were measured in the Murray River at Barmah

and the Edward River, and the lowest (<0.7080) in the Darling River (Figure 24). Water $^{87}Sr/^{86}Sr$ in the lower River Murray was temporally variable, with ratios decreasing with increased Darling River discharge in November and December 2017 (Figure 4). Water $^{87}Sr/^{86}Sr$ also generally decreased longitudinally along the Murray River as tributaries with distinct $^{87}Sr/^{86}Sr$ (e.g. Goulburn River) contribute to discharge. There was, however, overlap in water $^{87}Sr/^{86}Sr$ between some tributary and main-stem Murray River sites, e.g. the Murrumbidgee River and Lock 9 in the lower River Murray during late October and early January. Water $^{87}Sr/^{86}Sr$ was most variable at Lock 9 in the lower River Murray (0.7126–0.7156) (Figure 24).

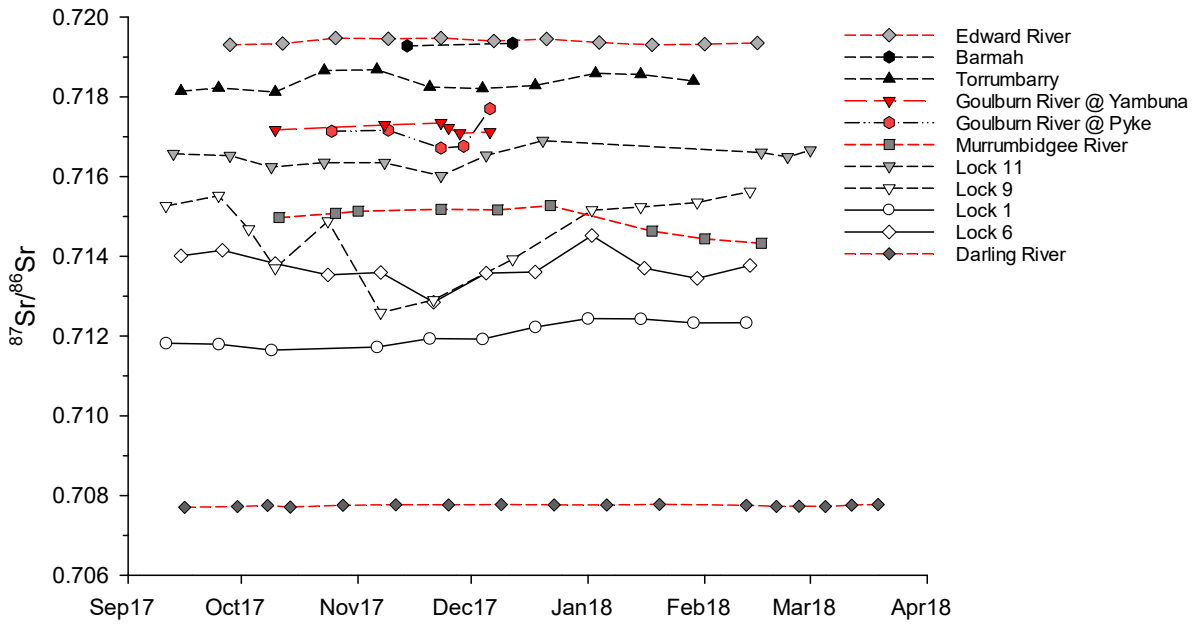

Figure 24. $^{87}Sr/^{86}Sr$ ratios in water samples collected from mid-September 2017 to April 2018 in the Murray (Lock 1, 6, 9, 11 Torrumbarry and Barmah), Darling, Goulburn, Edward and Murrumbidgee rivers.

Golden perch and silver perch larval collection and spawn dates

In 2017-18, 13 golden perch larvae were collected in the LMR (Table 8). Larvae were collected in mid-October (*n* = 1), early December (*n* = 4) and early January (*n* = 4) at Lock 6, and in late November (*n* = 3) and early December (*n* = 1) at Lock 1. Ages of these larvae ranged 3–42 days, corresponding to spawn dates of 26 September–27 December 2017 (Table 8; Figure 25). Golden perch eggs were collected below Lock 1 on 28 November 2017 and below Lock 6 on 16 October 2017 (Figure 25). No silver perch eggs or larvae were sampled in 2017-18.

Table 8. Capture location and date, length (mm), age (days), spawn date and otolith core $^{87}Sr/^{86}Sr$ values for larval golden perch collected from the floodplain and gorge geomorphic zones of the LMR by larval tows. * indicates that age was estimated based on ages of golden perch with similar total lengths.

Capture location	Capture date	Length (mm)	Age (days)	Spawn date	$^{87}Sr/^{86}Sr$
Lock 6	16-Oct-17	11	20	26/09/2017	0.71375
Lock 6	11-Dec-17	10	13	28/11/2017	0.71389
Lock 6	11-Dec-17	7.8	5	6/12/2017	0.71537
Lock 6	11-Dec-17	6.5	5	6/12/2017	
Lock 6	11-Dec-17	7	3	8/12/2017	
Lock 6B	03-Jan-18	8	7	27/12/2017	0.71702
Lock 6B	03-Jan-18	8	7	27/12/2017	0.71456
Lock 6B	03-Jan-18	7	8	26/12/2017	
Lock 6	03-Jan-18	11	15	19/12/2017	0.71479
Lock 1	28-Nov-17	6	5	23/11/2017	
Lock 1	28-Nov-17	5	3*	25/11/2017	
Lock 1	28-Nov-17	3.5	3*	25/11/2017	
Lock 1	12-Dec-17	20	42	31/10/2017	0.71201

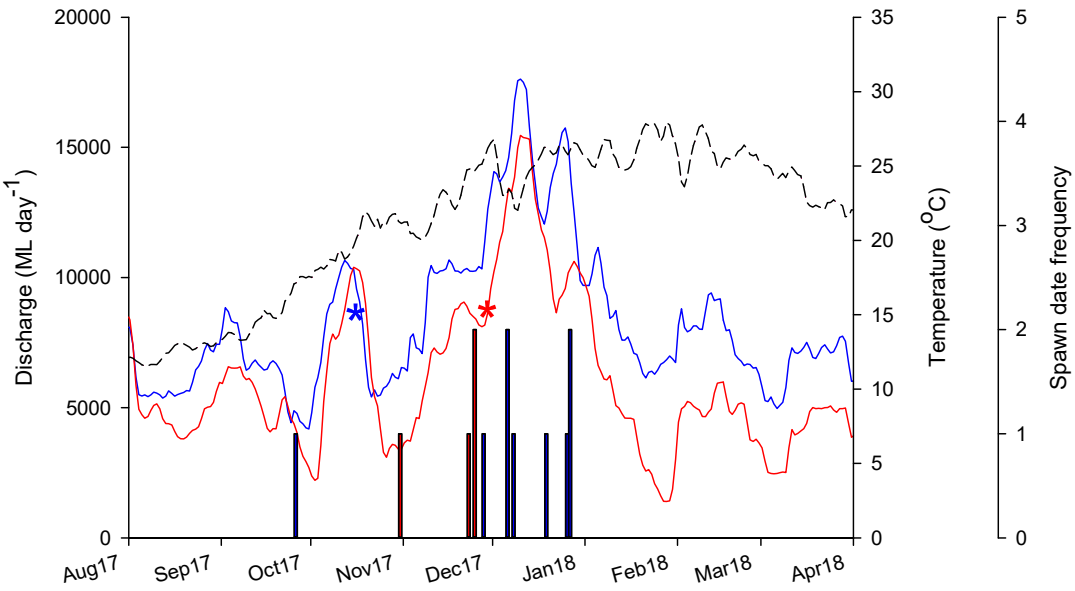

Figure 25. Back-calculated spawn dates for larval golden perch captured at Lock 6 (blue bars; *n* = 9) and Lock 1 (red bars; *n* = 4) in the floodplain and gorge geomorphic zones of the LMR during 2017-18, plotted against discharge (ML/d) in the Lower Murray River at the South Australian border (solid blue line) and downstream of Lock 1 (solid red line), and water temperature (°C) (dotted black line). Golden perch egg collection dates are shown for Lock 6 (blue asterisk) and Lock 1 (red asterisk).

Otolith $^{87}Sr/^{86}Sr$ of larval golden perch

A sample of seven of the 13 golden perch larvae/YOY were analysed for $^{87}Sr/^{86}Sr$ (Table 8). The otoliths of most remaining larval golden perch were too small for LA-ICPMS analysis. Five larvae had otolith core $^{87}Sr/^{86}Sr$ indicative of the lower River Murray in the vicinity, or in the region upstream (i.e. Lock 6–Lock 9), of their capture location (i.e. 0.7120–0.7148) (Table 8; Figure 26). In contrast, one larvae collected at Lock 6 on 3 January 2018, which had a spawn date of 27 December 2017, had otolith core $^{87}Sr/^{86}Sr$ of 0.71702, indicative of the mid-Murray River at Lock 11. Another larvae, collected at Lock 6 on 11 December 2017, which had a spawn date of 6 December 2017, had an otolith core $^{87}Sr/^{86}Sr$ of 0.7154, indicative of the Murrumbidgee River or the mid-Murray River between Lock 9 and Lock 11. The age of this fish (5 days) and its otolith $^{87}Sr/^{86}Sr$ profile suggests it most likely originated from between Lock 9 and Lock 11.

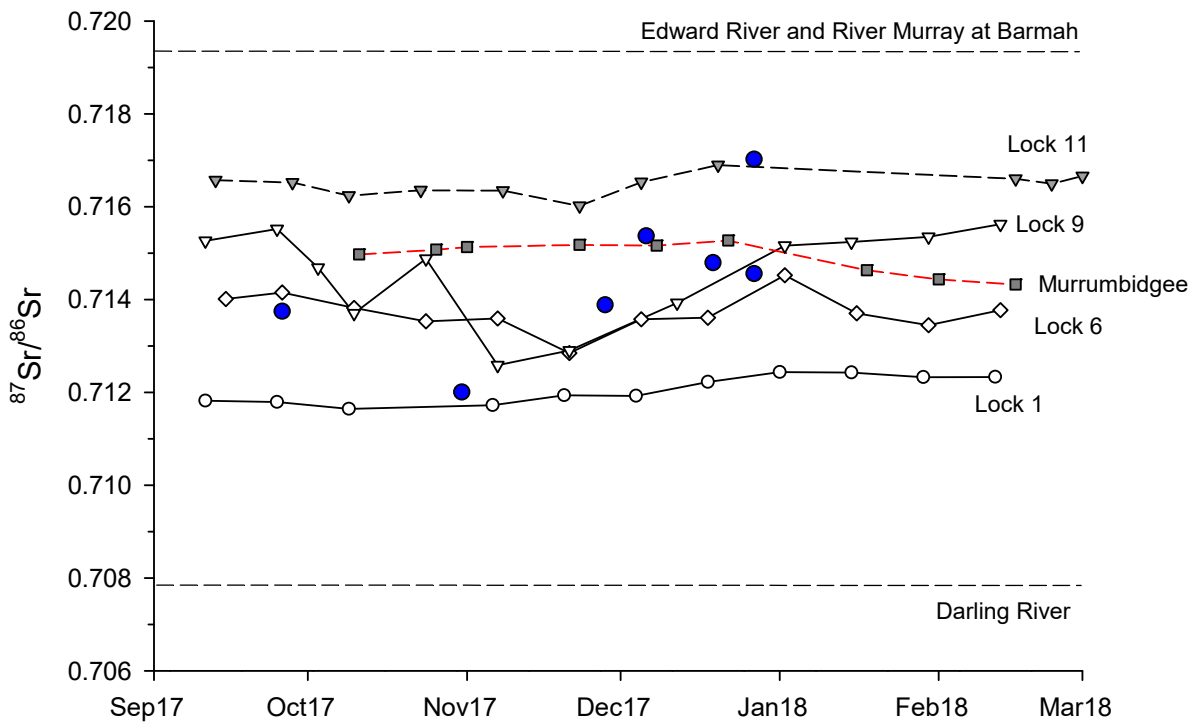

Figure 26. $^{87}Sr/^{86}Sr$ in water samples collected from late September 2017 to late February 2018 at sites in the southern MDB. $^{87}Sr/^{86}Sr$ in the Darling River and Edward River/Murray River at Barmah are presented as dashed straight lines as these were temporally stable and represent the maximum and minimum $^{87}Sr/^{86}Sr$ measured in water samples in the southern MDB in 2016/17. Closed blue circles represent spawn date and otolith core $^{87}Sr/^{86}Sr$ of larval golden perch collected in the LMR from October 2017 to January 2018.

Transects of $^{87}Sr/^{86}Sr$ from the otolith core to edge can elucidate the movement history of golden perch from birth to death, but may also reflect temporal variability in ambient $^{87}Sr/^{86}Sr$ in water. Transects of otolith $^{87}Sr/^{86}Sr$ for five of the six golden perch larvae (5–20 days old) captured below Lock 6 indicated that these individuals were spawned in the lower River Murray, somewhere between Lock 6 and the Darling River junction, and remained in this region throughout their early life (Figure 27b and c). The

other golden perch larvae, captured below Lock 6, had an otolith $^{87}Sr/^{86}Sr$ indicating that this fish was spawned in the mid-Murray River, close to Lock 11, and subsequently moved (passively/actively) to the capture location in the Murray River below Lock 6 (Figure 27d). The transect of otolith $^{87}Sr/^{86}Sr$ for the 42 day old golden perch larvae captured below Lock 1, with a spawn date of 31 October 2017, indicated that this individual was spawned in the lower River Murray, in close proximity to the capture location, and remained in this region throughout their early life (Figure 27a).

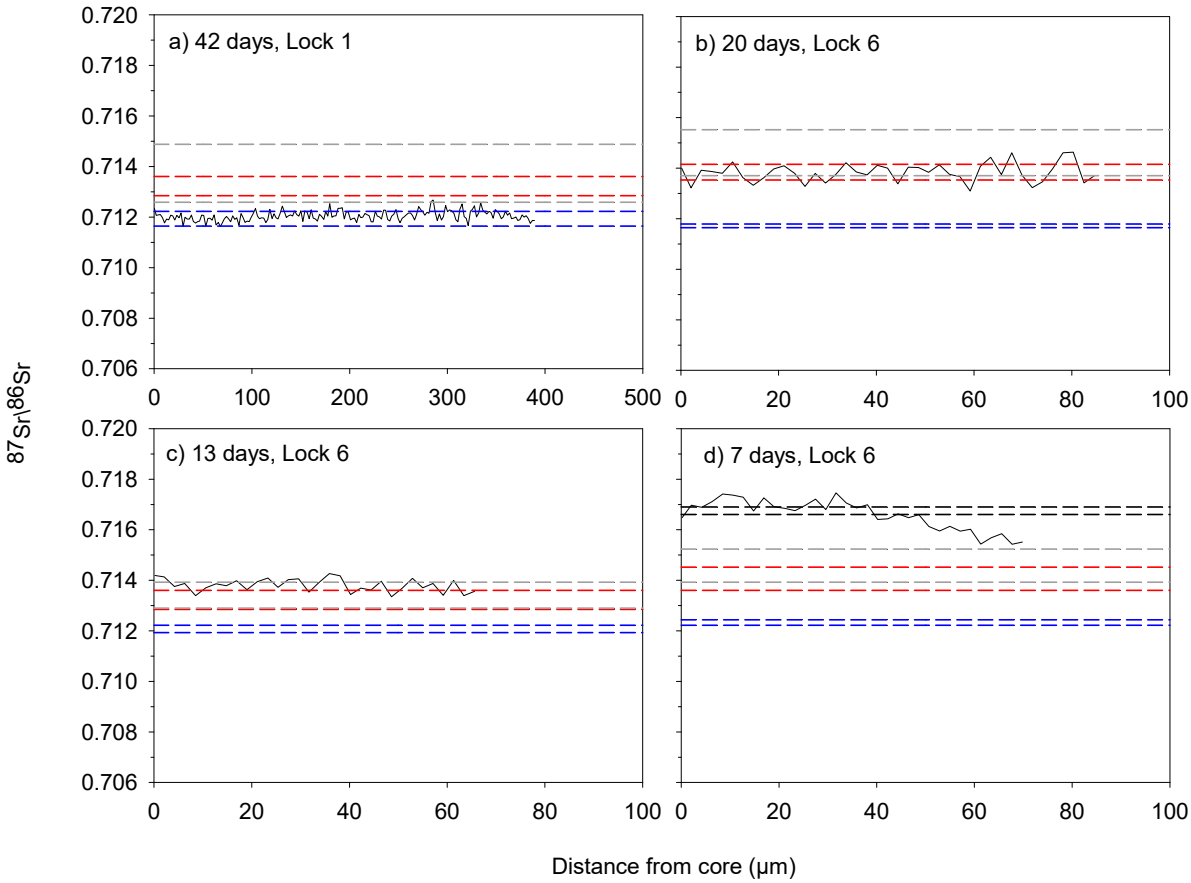

Figure 27. Individual life history profiles based on otolith Sr isotope transects (core to edge) for golden perch larvae collected below Lock 6 and Lock 1, in the LMR. Age at capture and capture location are provide above each transect. Dashed lines denote minimum and maximum $^{87}Sr/^{86}Sr$ ratios in the Murray River at Lock 1 (blue), Lock 6 (red), Lock 9 (grey), and Lock 11 (black) between spawn and capture dates of each individual.

Golden perch and silver perch length and age structure

In 2018, no YOY golden perch or silver perch were collected in the LMR. Golden perch sampled ranged in age from 1+ to 21+ years, with dominant cohorts of age 6+, 7+ and 8+ fish, spawned in 2011-12, 2010-11 and 2009-10, respectively (Figure 28). Age 6+, 7+ and 8+ fish comprised 17, 47 and 18% of the sampled population in the LMR, respectively. Age 21+ fish spawned in 1996-97 comprised 7% of the sampled population. In 2018, one age 1+ (151 mm FL) and one age 7+ (373 mm FL) silver perch were sampled in the LMR (Figure 29).

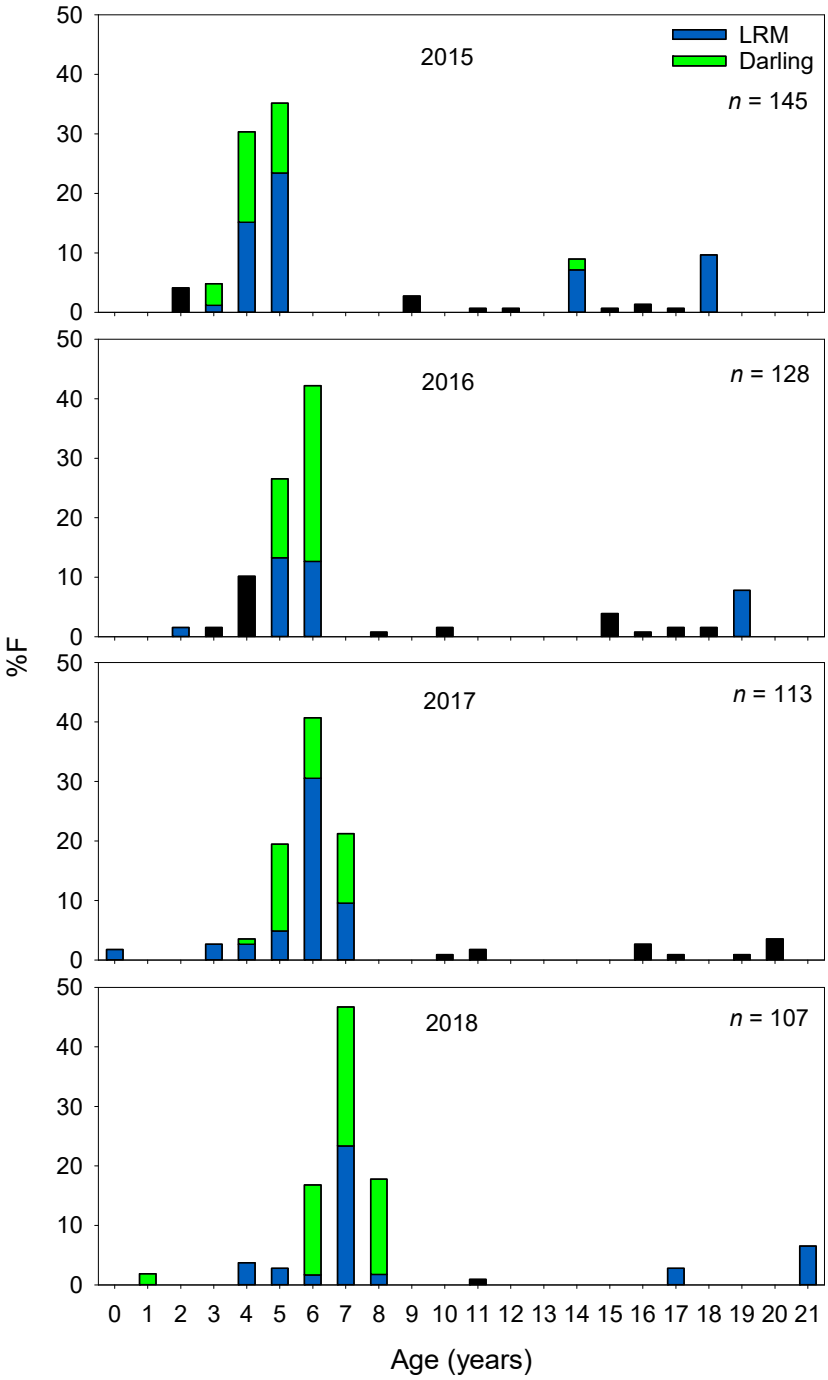

Figure 28. Age frequency distribution of golden perch from the LMR from 2015–2018 showing the natal origins (i.e. lower River Murray (LRM) and Darling River) of dominant cohorts inferred from otolith core signatures of the sampled fish in comparison to the water sample reference collection (Figure 30). Percentage of origin for each cohort are based on the subsampled population. Age cohorts with black bars were not assessed for natal origin.

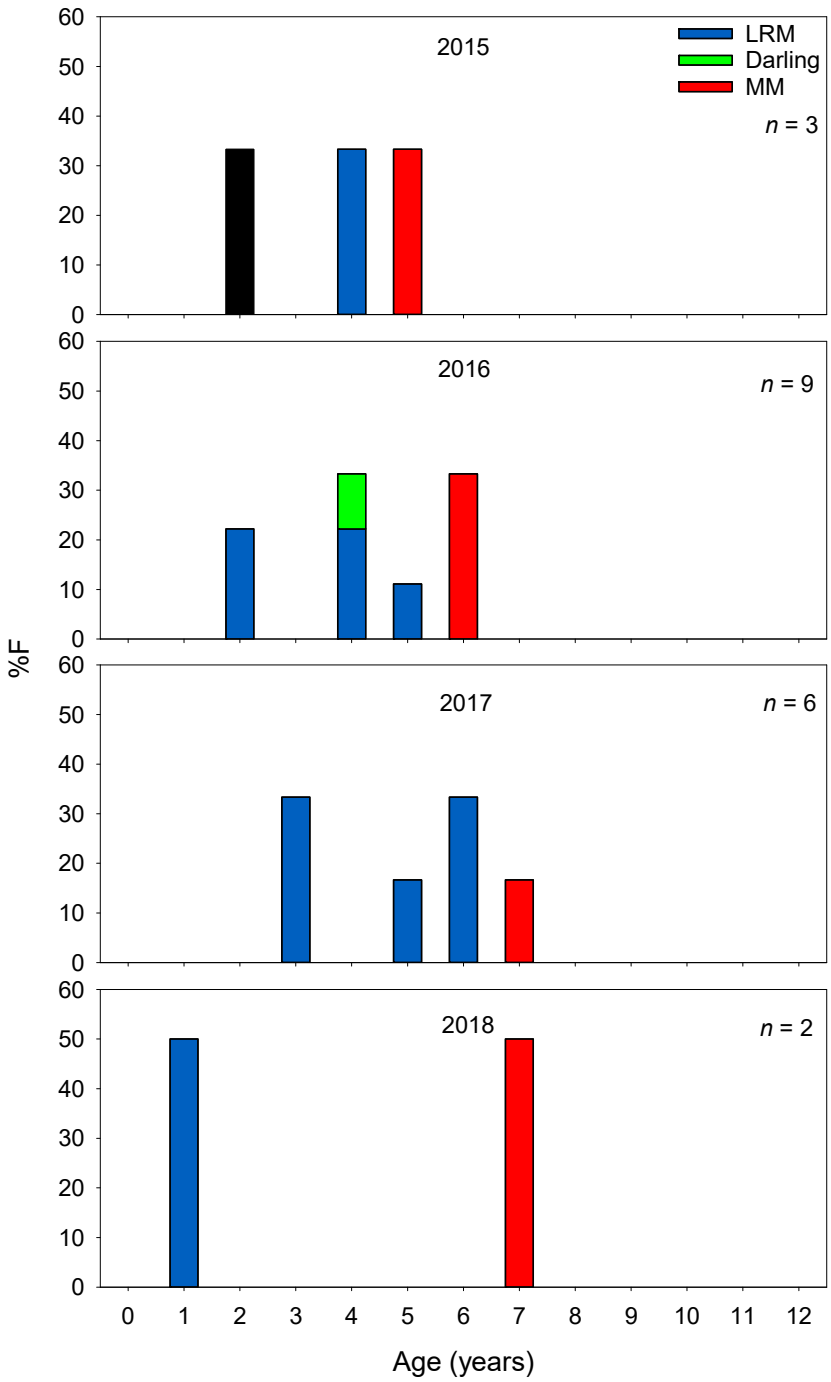

Figure 29. Age frequency distribution of silver perch from the LMR (floodplain and geomorphic zones combined) from 2015–2018 showing the natal origins (i.e. lower River Murray (LRM), mid-Murray River (MM) and Darling River) of dominant cohorts inferred from otolith core signatures of the sampled fish in comparison to the water sample reference collection (Figure 30). Age cohorts with black bars were not assessed for natal origin.

Otolith $^{87}Sr/^{86}Sr$, natal origin and migration history of golden/silver perch

To investigate the natal origin and migration history of dominant cohorts of golden perch and silver perch in the LMR in 2017-18, we analysed $^{87}Sr/^{86}Sr$ from the otolith core to edge in a subsample of fish. We compared these transects to water $^{87}Sr/^{86}Sr$ measured at sites across the southern MDB from 2011–2018 (Zampatti *et al.* 2015; this report; SARDI unpublished data) (Figure 30).

Golden perch

A total of 57 golden perch were analysed for natal origin and migration history from age 1+ (*n* = 2), 4+ (*n* = 4), 5+ (*n* = 3), 6+ (*n* = 10), 7+ (*n* = 20), 8+ (*n* = 10), 17+ (*n* = 3) and 21+ (*n* = 5) cohorts. Both age 1+ golden perch (spawned 2016/17) exhibited otolith core $^{87}Sr/^{86}Sr$ comparable to water $^{87}Sr/^{86}Sr$ in Darling River of ~0.7075, indicating these fish were spawned in the Darling River (Figure 28; Figure 30). Transects of otolith $^{87}Sr/^{86}Sr$ indicate these fish transitioned from the Darling River into the lower River Murray as early stage juveniles (Figure 31a).

All age 4+, 5+, 17+ and 21+ golden perch, spawned 2013/14, 2012/13, 2000/01 and 1996/97, respectively, exhibited otolith core $^{87}Sr/^{86}Sr$ comparable to water $^{87}Sr/^{86}Sr$ in the lower River Murray (~0.7080–0.7140) (Figure 28; Figure 30). Transects indicate all fish had spent their entire lives in the lower River Murray (Figure 31c).

Individuals from the three dominant cohorts (age 6+, 7+ and 8+, spawned 2011/12, 2010/11 and 2009/10, respectively) exhibited otolith core $^{87}Sr/^{86}Sr$ comparable to water $^{87}Sr/^{86}Sr$ in the lower River Murray and the Darling River (Figure 28; Figure 30). This indicates that some fish from these cohorts were spawned in and spent their entire lives in the lower River Murray, whilst the majority were spawned in the Darling River and transitioned into the lower River Murray in their first (i.e. age 0+) or second year (i.e. age 1+, Figure 31b), and remained in this region until capture in 2018.

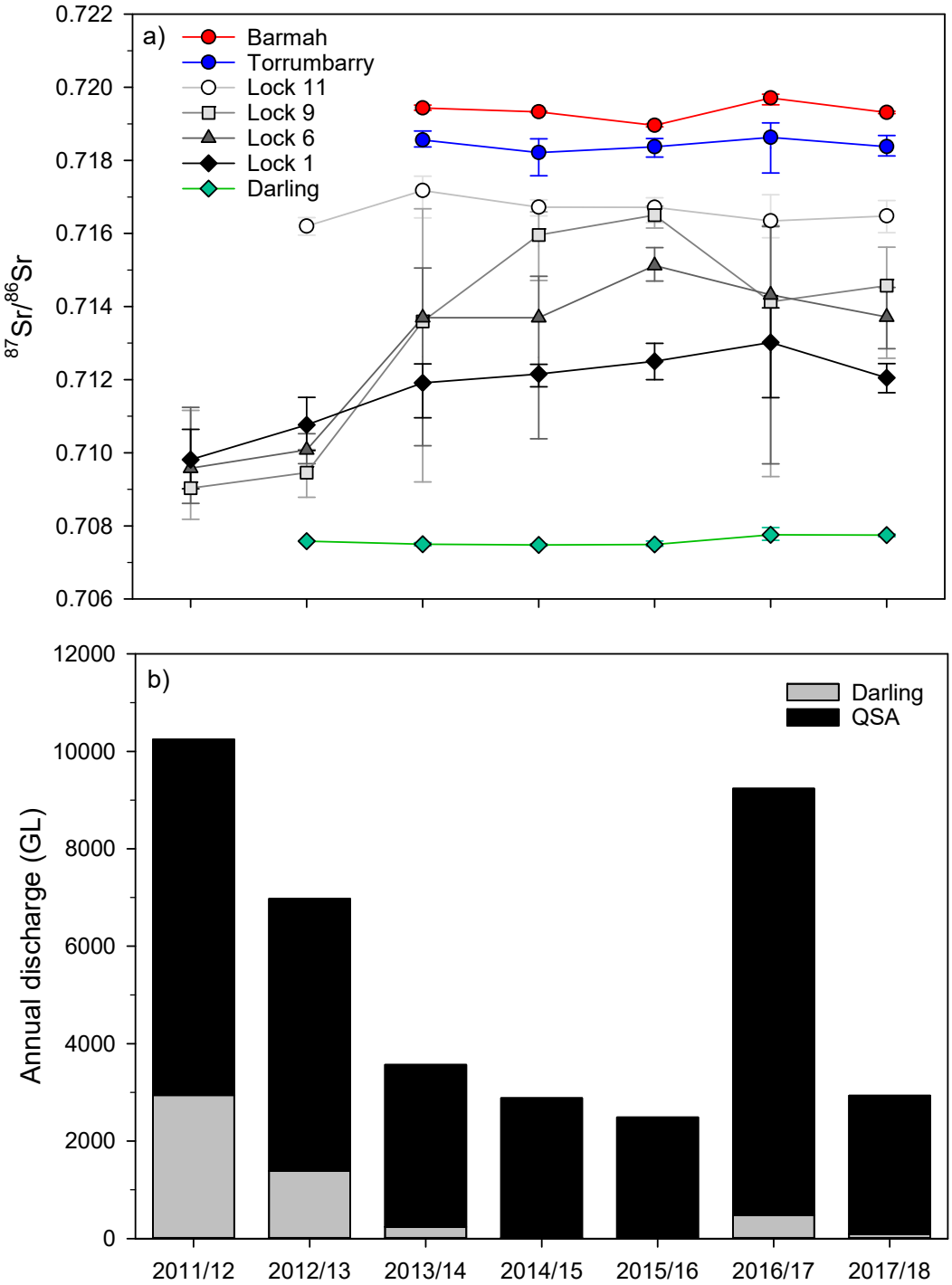

Figure 30. (a) Mean $^{87}Sr/^{86}Sr$ (with minimum and maximum values as error bars) in water samples collected from spring–summer in the mid-Murray (Barmah, Torrumbarry and Lock 11), lower Murray (Lock 9, 6 and 1) and Darling rivers from 2011–2018, and (b) annual discharge (GL) in the Murray River at the South Australian border (QSA) and the proportion of discharge from the Darling River at Burtundy that contributed to QSA.

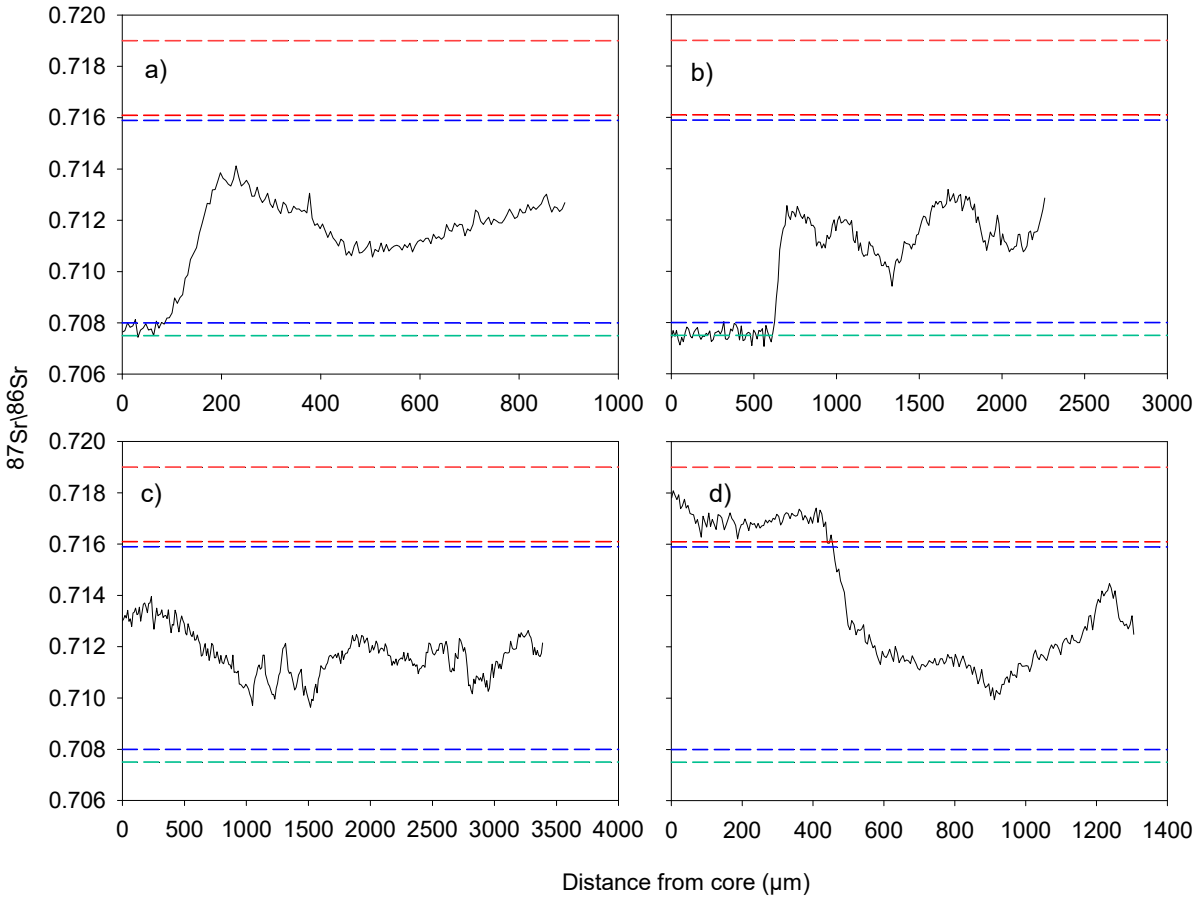

Figure 31. An individual life history profile based on transect analysis of $^{87}Sr/^{86}Sr$ from the core to edge of an otolith from (a) age 1+ golden perch from Lowbank, (b) age 8+ golden perch from Cobdogla, (c) age 21+ golden perch from Swan Reach and (d) age 7+ silver perch from Loxton in the lower River Murray. Green dashed line indicates the temporally stable water 87Sr/86Sr of the lower Darling River (i.e. ~0.7075) and the blue dashed lines represent the range of water 87Sr/86Sr in the lower River Murray (i.e. ~0.7080–0.7160). Red dashed lines represent the range of water 87Sr/86Sr in the mid-Murray River (Lock 11–Torrumbarry, ~0.7160–0.7190).

Silver perch

In 2018, two silver perch (age 1+ and 7+) were analysed for natal origin and migration history. The age 1+ silver perch (spawned 2016/17) exhibited otolith core and transect $^{87}Sr/^{86}Sr$ indicative of a lower River Murray spawning origin and occupation of this region throughout its life (Figure 29; Figure 30). In contrast, the age 7+ silver perch (spawned 2010/11) exhibited otolith core $^{87}Sr/^{86}Sr$ indicative of a mid-Murray River spawning origin (upstream of the Darling River confluence and downstream of Torrumbarry). The transect of otolith $^{87}Sr/^{86}Sr$ indicates that this fish transitioned into the lower River Murray as age 1+ (Figure 31d).

Discussion

In 2017-18, flow in the LMR was characterised by multiple in-channel spring–early summer flow pulses during early October (peak flow 10,700 ML/d), early December (17,800 ML/d) and late December (15,800 ML/d). These flow pulses were promoted by Commonwealth environmental water delivery in October and late December, and The Living Murray environmental water in early December. Flow then decreased to 6,100 ML/d in mid-January.

In 2017-18, golden perch eggs and larvae were collected from the LMR between mid-October and early January, with the majority of larvae (*n* = 12) collected between 28 November and 3 January 2017. The ages of these larvae (predominantly 3–15 days) corresponded to spawn dates of 23 November–8 December and 19–27 December, and otolith $^{87}Sr/^{86}Sr$ indicated most of these fish were spawned in the lower River Murray between the Darling River junction and Lock 6. A 20-day and 42-day old golden perch larvae were also collected at Lock 6 on 16 October and Lock 1 on 12 December, respectively, and otolith $^{87}Sr/^{86}Sr$ indicated that these fish were spawned in the lower River Murray, close to their respective capture locations.

Overall, the presence of eggs and young larvae with a lower River Murray provenance indicates that in 2017-18, golden perch spawning in the lower River Murray extended from late November to late December and occurred in association with the ascending limb of an early December flow peak (17,800 ML/d) and descending limb of a late December flow peak (15,800 ML/d). As such, some spawning coincided with the period when environmental water was used to promote flow pulses in the LMR.

In 2018, the golden perch population in the LMR was dominated by age 8+, 7+ and 6+ fish. No age 0+ golden perch were collected in the LMR in 2018 indicating negligible recruitment from spawning in spring–summer 2017-18.

Conclusion

Golden perch and silver perch recruitment in the LMR is promoted by spawning associated with spring–summer increases in flow (in-channel and overbank) in the lower and mid-Murray River, and lower Darling River (Zampatti and Leigh 2013a; Zampatti *et al*. 2015; Ye *et al*. 2017). As well as local spawning, immigration of age 0+ or 1+ fish can substantially enhance populations, particularly during years of high flow (Zampatti *et al*. 2015; Zampatti *et al*. 2018).

In spring–summer 2017-18, golden perch (but not silver perch) spawning occurred in the lower River Murray in association with flow pulses contained within the river channel (QSA peak flow ~17,800 ML/d). Recruitment to YOY in 2018, however, was negligible, indicating localised recruitment failure and low levels of immigration from spatially distinct spawning sources such as the lower Darling and mid Murray rivers.

There has been no substantial recruitment of golden perch in the lower River Murray since 2012-13, leading to a population dominated by only a few distinct cohorts. To

improve the resilience of golden perch populations in the lower River Murray, it would be pertinent in the coming years to provide flows in the lower Murray that may facilitate golden perch spawning and recruitment. Specifically, Commonwealth environmental water could contribute to spring/early summer in-channel flow pulses (~15,000–25,000 ML/d).

2.6 Fish (Channel)

Background

In 2018, we collected fish assemblage data in the main channel of the LMR to inform Basin-scale evaluation of fish community responses to Commonwealth environmental water. This evaluation is being undertaken by the Centre for Freshwater Ecosystems at La Trobe University. In this report, our objectives are to: (1) Provide summary statistics of the catch rates and population demographics for nominated species; (2) Describe temporal variation in fish assemblage and population structure from 2015–2018; and (3) Discuss key findings based on published research and our current understanding of fish life histories and population dynamics in the LMR. Our interpretations of the data for this indicator do not infer association with Commonwealth environmental water delivery.

Methods

During March–April 2018, small- and large-bodied fish assemblages were sampled from the gorge geomorphic zone of the LMR (Figure 1) using fyke nets and electrofishing, respectively. Prescribed methods outlined in Hale *et al.* (2014) were used and population structure data were obtained for seven target species (Figure 32). Refer to SARDI *et al.* (2018) for detailed sampling design and methodology.

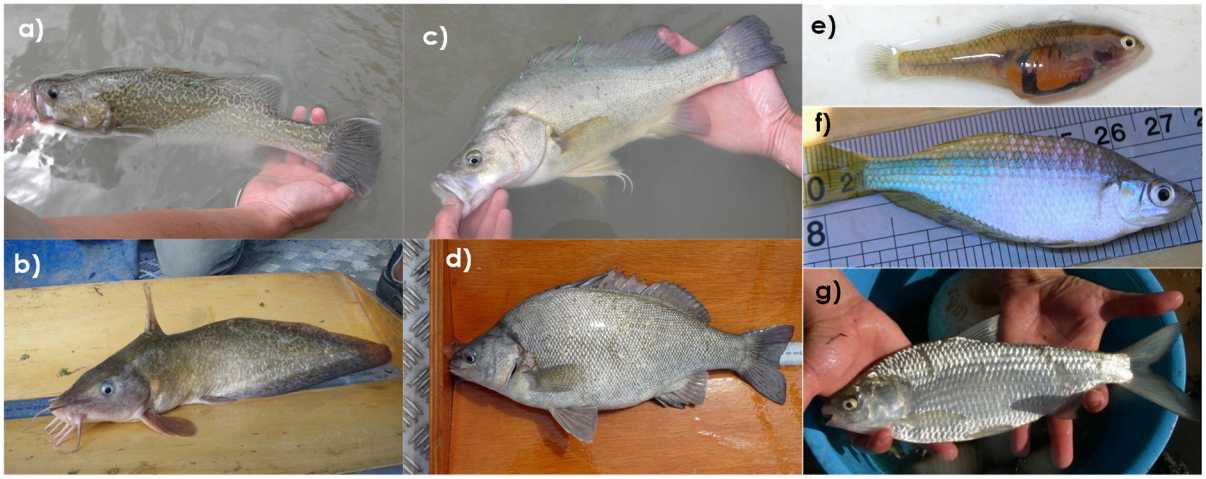

Figure 32. Target species for the LMR: (a) Murray cod and (b) freshwater catfish (equilibrium life history); (c) golden perch and (d) silver perch (periodic life history); and I carp gudgeon, (f) Murray rainbowfish and (g) bony herring (opportunistic life history).

Temporal variation in fish assemblage structure (species composition and abundance), between sampling years (i.e. 2015, 2016, 2017 and 2018), was investigated using Non-metric Multi-Dimensional Scaling (MDS), permutational multivariate analysis of variance (PERMANOVA) and Similarity Percentages (SIMPER) analysis in the software package PRIMER v. 6.1.12 (Clarke and Gorley 2006) and PERMANOVA + v.1.02 (Anderson *et al.* 2008). To determine temporal variation in population structure, length frequency histograms were qualitatively compared between sampling years.

Results

Catch summary for 2018

A total of 9,947 individuals from eight large-bodied species were collected by electrofishing. Bony herring was the most abundant species (94% of the catch), followed by common carp (*Cyprinus carpio*) (4%) and golden perch (*Macquaria ambigua*) (2%) (Figure 33a).

A total of 37,678 individuals from six small-bodied species were collected by fyke nets. Carp gudgeon (*Hypseleotris* spp.) was the most abundant species (86% of catch), followed by Gambusia (*Gambusia holbrooki*) (9%), unspecked hardyhead (*Craterocephalus fulvus*) (3%) and Murray rainbowfish (*Melanotaenia fluviatilis*) (2%) (Figure 33b).

Temporal variability in fish assemblage structure

MDS ordination of electrofishing data demonstrated separation of samples by year, with 2017 distinct from other years (Figure 34a). PERMANOVA indicated that large-bodied fish assemblages were significantly different between years (*Pseudo-*$F_{3,34}$ = 5.6069, p = 0.0001). Pairwise comparisons revealed significant differences between all years (Table 9).

Table 9. PERMANOVA pairwise comparison test results for large- and small-bodied fish assemblages in the gorge geomorphic zone of the LMR from autumn 2015–2018.

Comparison	Large-bodied		Small-bodied	
	t	***P (perm)***	***t***	***P (perm)***
2015 vs. 2016	2.0305	0.0078	1.1551	0.2499
2015 vs. 2017	3.5839	0.0008	2.0746	0.0126
2015 vs. 2018	1.7638	0.0396	1.2100	0.2125
2016 vs. 2017	2.2942	0.0047	3.7835	0.0002
2016 vs. 2018	1.7945	0.0274	0.8144	0.5851
2017 vs. 2018	2.6821	0.0012	3.1570	0.0009

There were significant differences between years (*Pseudo-*$F_{3,39}$ = 4.9658, p = 0.0002) for small-bodied fish assemblages. Interspersion of 2015, 2016 and 2018 samples and separation of 2017 samples in MDS ordination of fyke netting data (Figure 34b) was supported by PERMANOVA pair-wise comparisons, which revealed significant differences in small-bodied fish assemblages between 2017 and all other years, but not between 2015, 2016 and 2018 (Table 9).

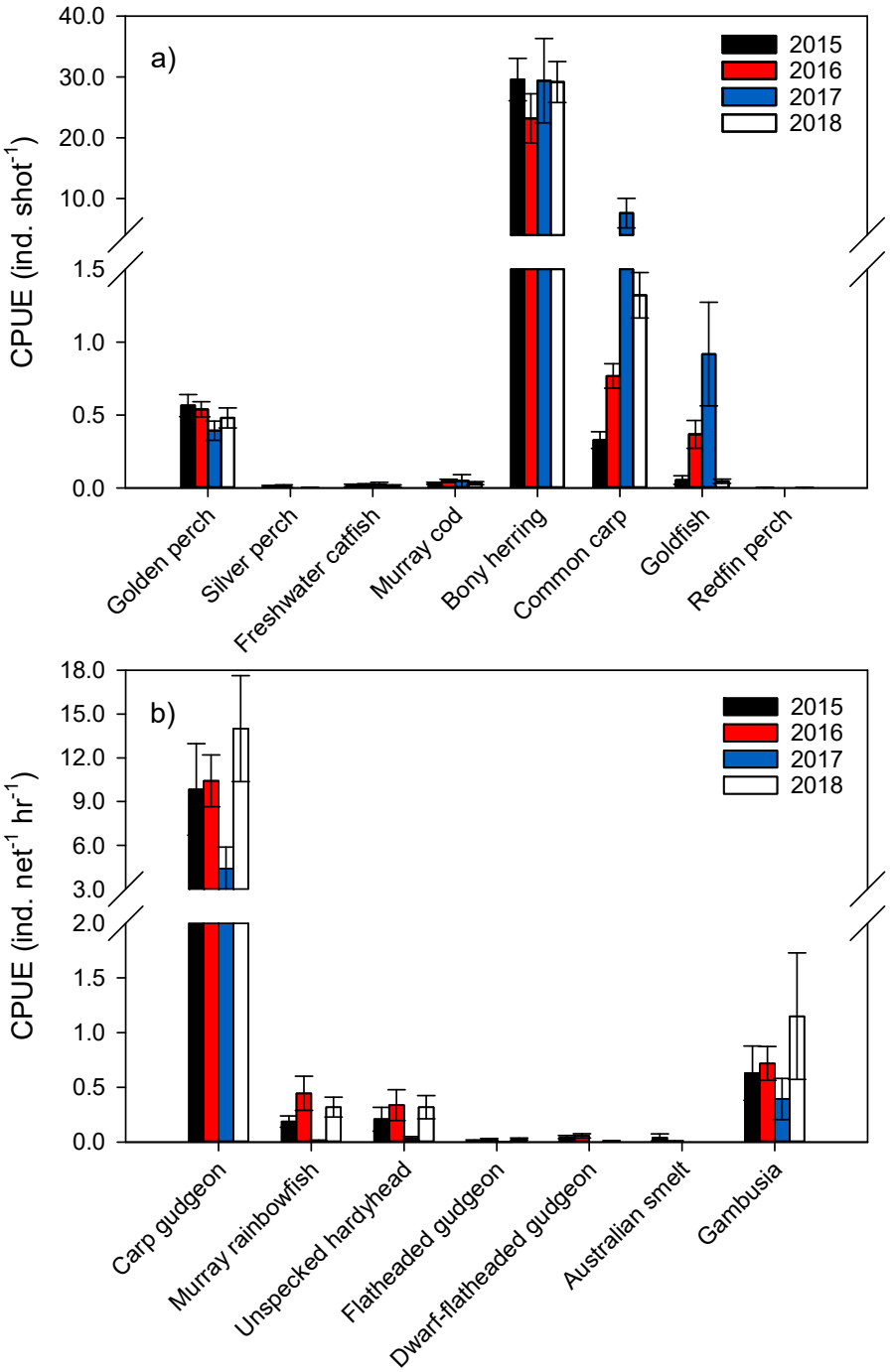

Figure 33. Mean catch-per-unit-effort (CPUE) ± standard error of (a) large-bodied fish species captured using electrofishing (individuals per 90 second shot) and (b) small-bodied fish species captured using fine-mesh fyke nets (individuals per net per hour) in the gorge geomorphic zone (10 sites) of the LMR in Autumn from 2015–2018. Electrofishing CPUE data from five sites are presented for 2017 as other sites were sampled during winter 2017.

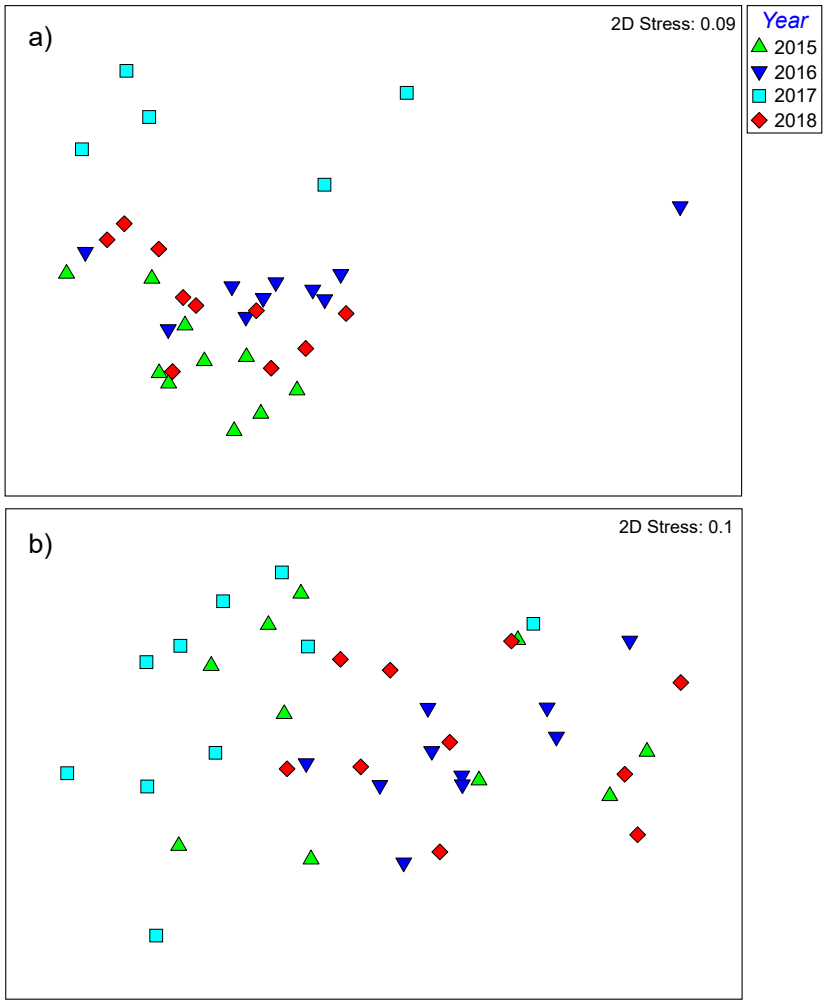

Figure 34. Non-metric multi-dimensional scaling (MDS) plot of (a) large-bodied fish assemblages sampled by electrofishing and (b) small-bodied fish assemblages sampled by fyke netting in the gorge geomorphic zone of the LMR. Sites 1, 3, 4, 6 and 7 sampled in winter 2017 were removed from the ordination.

SIMPER indicated that differences between years for large-bodied fish assemblages were primarily driven by higher abundance of common carp in 2017, lower abundance of common carp in 2015 and 2016, lower abundance of bony herring in 2016 and higher abundance of bony herring in 2018 (Figure 33). SIMPER indicated that differences between 2017 and all other years for small-bodied fish assemblages were driven by a lower relative abundance of carp gudgeon in 2017 (Figure 33).

Temporal variation in length/age structure of large-bodied species

In 2018, the sampled golden perch population was mostly comprised of age 6+ (23%), 7+ (51%), 8+ (19%) and 21+ (4%) fish (Figure 35). In 2018, only one silver perch (*Bidyanus bidyanus*) was sampled (age 1+, 151 mm fork length, FL). Similarly to golden perch, the length distribution of freshwater catfish (*Tandanus tandanus*) contracted from 350–480 mm in 2015 to 437–493 mm in 2018, due to the absence of new recruits and an ageing population (Figure 36).

In 2018, the sampled Murray cod population was represented by individuals 74–140 mm (age 0+), 307 mm (age 1+), 409 mm (not sacrificed, potentially age 2+ or 3+) and 515 mm (not sacrificed, potentially age 3+ or 4+). (Figure 37). In 2018, bony herring aged 0+, 1+, 2+, 3+ and 4+ comprised 86%, 3%, 4%, 7% and 1% of the sampled population, respectively.

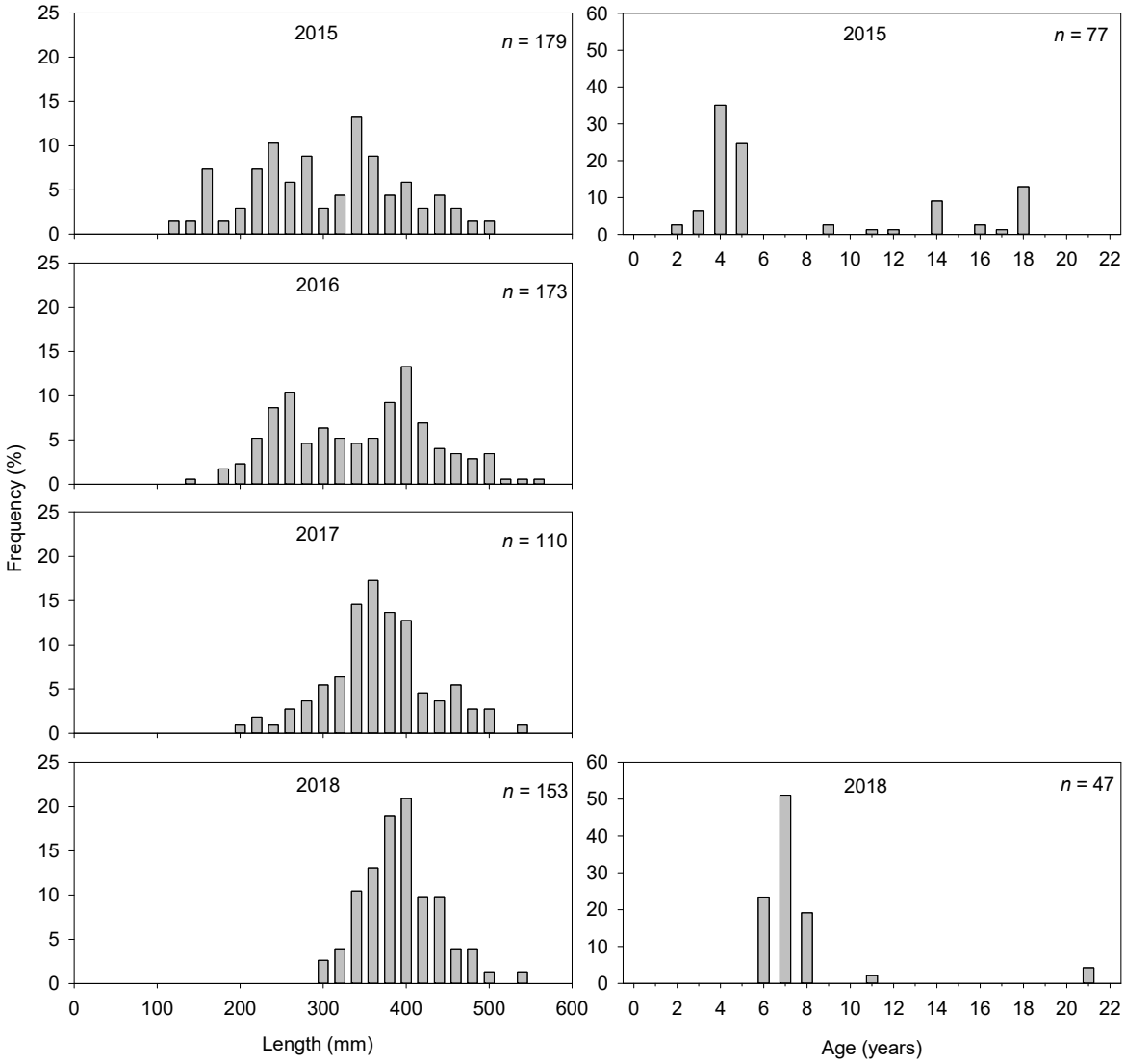

Figure 35. Length frequency distributions and age structures of golden perch collected from the gorge geomorphic zone of the LMR from 2015–2018.

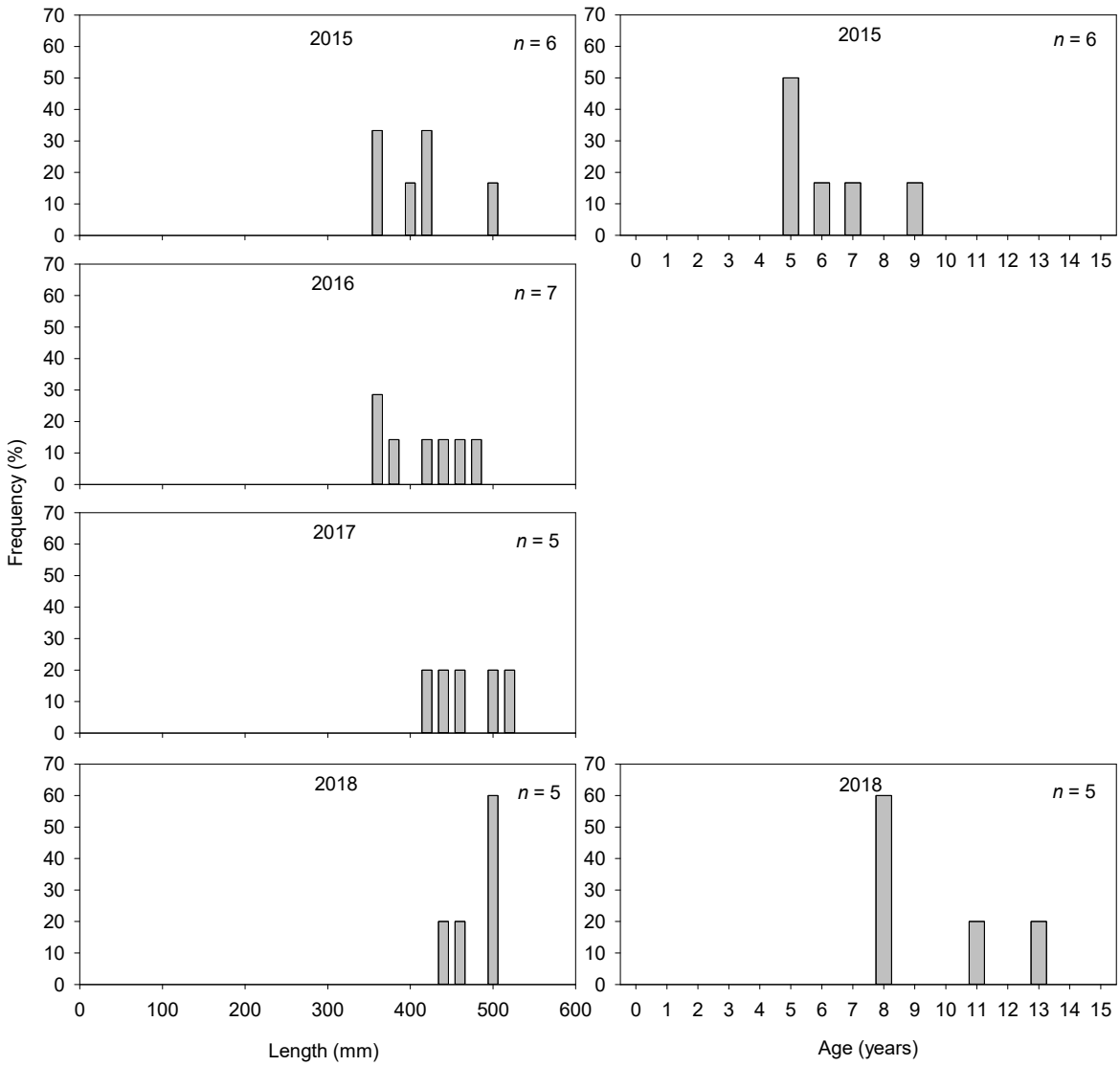

Figure 36. Length frequency distributions and age structures of freshwater catfish collected from the gorge geomorphic zone of the LMR from 2015–2018.

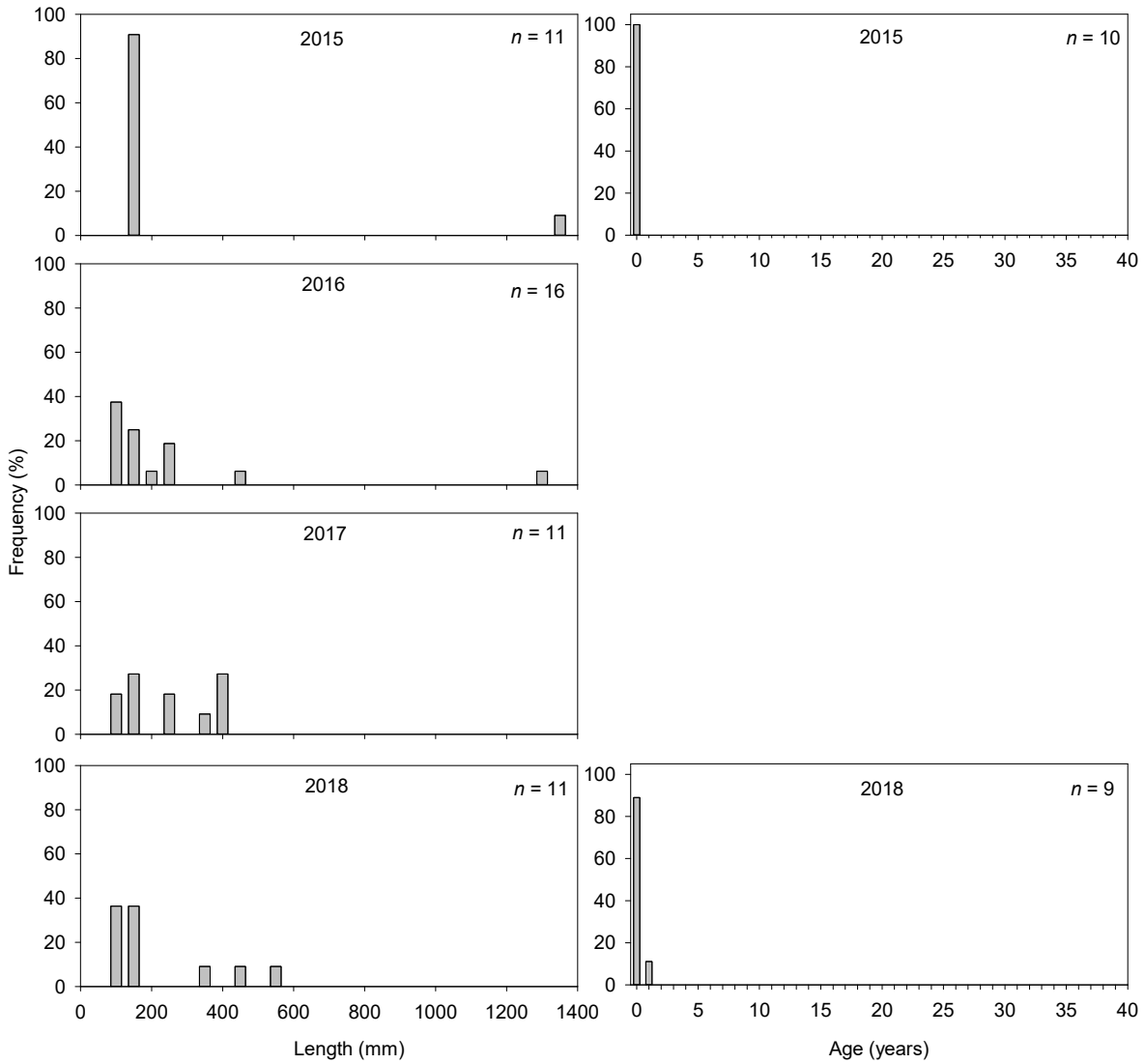

Figure 37. Length frequency distributions and age structures of Murray cod collected from the gorge geomorphic zone of the LMR from 2015–2018.

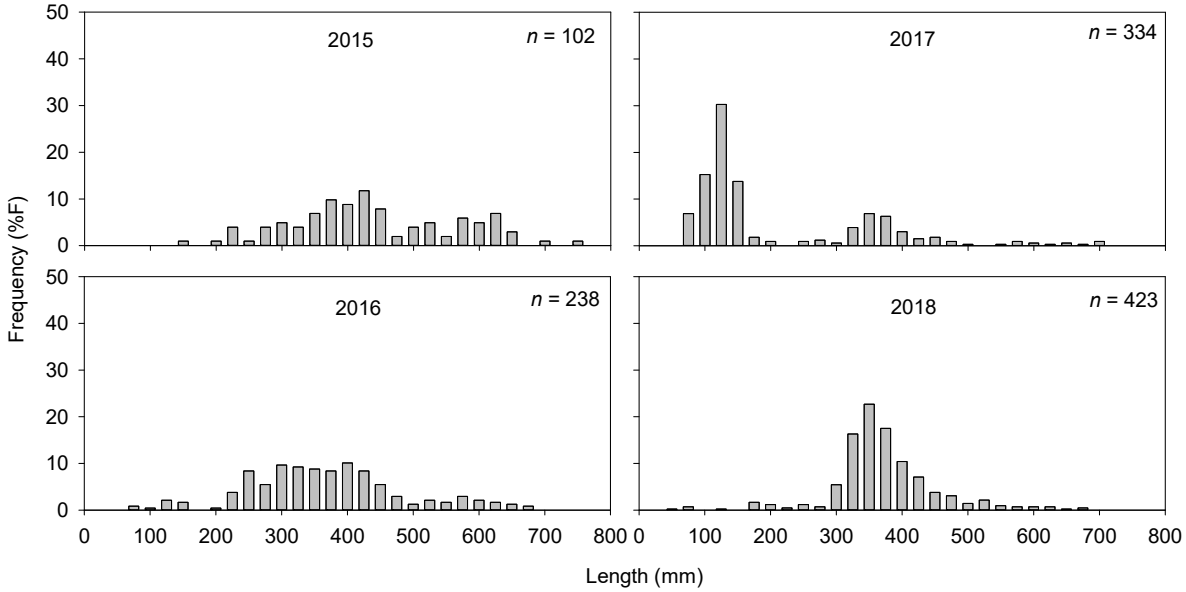

Figure 38. Length frequency distributions of common carp from the gorge geomorphic zone of the LMR from 2015–2018.

Discussion

During 2014-15 and 2015-16, relatively low (<15,000 ML/d), stable flows predominated in the LMR. In these years, small-bodied fish abundance and diversity were high and remained stable. Abundances of flow-cued spawning species (i.e. golden perch and silver perch) remained similar in both years and overall, fish assemblage structure was characteristic of a low flow scenario and similar to that during drought in 2007–2010 (Bice *et al.* 2014).

In 2017, following flooding (peak flow ~94,600 ML/d) in spring–summer 2016, there was a significant change to the small- and large-bodied fish assemblages, with an overall decrease in the abundances of small-bodied species and an increase in the abundance of common carp. Reduced submerged vegetation in the main channel of the LMR during 2016-17, due to a combination of increased water depth/decreased light penetration and physical scour, likely resulted in the decreased abundance of small-bodied fishes. Increased abundance of common carp in 2017 appeared to be driven by a large recruitment event in 2016-17 associated with flooding. Following a recession in water levels in summer 2017, large numbers of age 0+ common carp likely entered the main channel from off-channel floodplain and wetland habitats (their typical spawning habitat) and were captured during sampling in autumn and winter 2017.

The fish assemblage in 2017 was more typical of high flows, similar to the one in 2010–2012 (Bice *et al.* 2014). Nevertheless, recruitment of native, large-bodied flow-cued spawners (e.g. golden perch) was negligible in 2016-17, despite a flow regime that was potentially conducive to spawning of these species (Mallen-Cooper and Stuart 2003; Zampatti and Leigh 2013a; 2013b) (also see Section 2.5). Hypoxic conditions

during the spring–early summer spawning season may have impacted the survival of their eggs and larvae.

Following in-channel flows (up to 17,800 ML/d) in spring–early summer 2017-18, small-bodied fish species composition and abundance reverted back to that of pre-flood conditions (i.e. 2016 and 2015), presumably due to structural and hydraulic habitats (i.e. submerged vegetation and stable water levels) conducive to small-bodied fish recruitment in the main river channel. The large-bodied fish assemblage trended towards one typical of 'low flows' (e.g. 2016, 2015 and 2008, Bice *et al.* 2014) due to a reduction of common carp abundance in 2018, relative to 2017. Common carp abundance, however, was still significantly greater in 2018, relative to 2016 and 2015, indicating the progression of fish from the 2016-17 cohort (age 0+) into the population as age 1+ (Figure 38).

Freshwater catfish and Murray cod spawn over a well-defined period in spring to early summer, irrespective of flow (Rowland 1998; Davis 1977). Recruitment of both species, however, may be enhanced by increased flow (Ye *et al.* 2015; Zampatti *et al.* 2014). Based on electrofishing length frequency data, no recruitment (to age 0+), was observed for freshwater catfish in the LMR from 2014-15–2017-18. In the LMR, recruitment dynamics of this species are poorly understood and their current spawning biomass in this region is historically low (Ye *et al.* 2015). For the fourth consecutive year, small Murray cod (<150 mm TL, likely age 0+) were sampled in the LMR during 2018, indicating successful recruitment. Furthermore, the age cohorts from 2014-15–2016-17 seemed to have persisted in 2017-18. Over the period 2014-15–2017-18, recruitment of Murray cod has been associated with low, stable, in-channel flows (<12,000 ML/d), a moderate in-channel flow pulse (15,000–18,000 ML/d) and a flood (>90,000 ML/d).

Conclusion

Following moderate, in-channel flows (15,000–18,000 ML/d) in spring–summer 2017-18, the 2018 fish assemblage trended back towards that in 2015 and 2016, following an increase of small-bodied abundance and lack of recruitment from native, flow-cued spawners. Common carp abundance remained relatively high in 2018, following recruitment in the 2016-17 flood year.

3 SYNTHESIS AND EVALUATION

To assess ecological response to Commonwealth environmental water, a series of evaluation questions were investigated for CEWO, which were adapted from Basin-scale questions to be relevant for the LMR (SARDI *et al.* 2018). The contribution of environmental water to hydraulic condition and matter transport was assessed throughout the year using a modelling approach, whereas other indicators of ecological responses (stream metabolism, microinvertebrates and fish spawning and recruitment) were assessed by monitoring during spring—summer. In this fourth year's report of the LTIM Project, the focus was to evaluate the ecological outcomes of Commonwealth environmental water delivery during 2017-18 and answer CEWO short-term (one-year) evaluation questions (Table 10).

Overall, 2017-18 was a climatically and hydrologically dry year. Without environmental water, flow to South Australia would have been at entitlement (~4,000–6,000 ML/d) for most of the year, except for a small unregulated flow event in late December. A total of ~894 GL of Commonwealth environmental water was delivered to the LMR in this year, in conjunction with other sources of environmental water (268 GL) (e.g. MDBA The Living Murray). This contributed to multiple in-channel flow pulses (up to 17,800 ML/d), particularly during spring–early summer.

The flow pulse in the LMR in October (peak flow 10,700 ML/d) was primarily supported by return flows of Commonwealth environmental water attributed to a watering event in the Goulburn River, with flows from the upper Murray River and releases from Lake Victoria being the key physical contributors of this flow event. The environmental flow delivery coincided with draw down of the previously raised weir pools (at Locks 2 and 5) and increased hydraulic diversity by creating small patches (between 3 and 14% of the weir pool) of lotic habitat (i.e. >0.3 m/s). Water levels at the upper end of each weir pool also increased 0.3–0.5 m. This period corresponded with small increases in river production and respiration in the LMR by increasing in-channel river volume without causing major changes in metabolic rates. Environmental flows helped maintain DO at ~8–10 mg/L, favourable for aquatic animals, throughout the spring−summer, whereas without these flows reductions in DO were likely in the weir pools. There was reduced microinvertebrate diversity and density, although it was unclear whether this was due to the effects of the recession of weir pools, or source water containing low microinvertebrate abundance and diversity at the time. There was limited golden perch spawning associated with this flow pulse.

Greater flow pulses were generated in December (up to 17,800 ML/d), supported mainly by The Living Murray and Commonwealth environmental water, during an unregulated flow event. These led to greater increases in lotic habitat in the LMR, for example, in up to 50% of Weir Pool 5. Improving riverine hydraulics (e.g. water velocity and turbulence) is critical for ecological restoration in the lower River Murray. Many native biota that have life histories adapted to a flowing river are currently extinct or suffered major declines due to the largely weir pool environment in this region (Mallen-Cooper and Zampatti 2017). Pre-regulation, the lower River Murray was characterised

by lotic, riverine habitats, with water velocities ranging ~0.2–0.5 m/s, even at discharges <10,000 ML/d (Bice *et al.* 2017).

During December, there were also larger increases in water level (0.6–0.8 m) at the upper end of each weir pool. Periodic increases in water levels could improve the condition of littoral vegetation (Gehrig *et al.* 2016) and increase biofilm diversity (Steinman and McIntire 1990), which is a key component of riverine food webs. Overall increased river volume, aided by environmental water, substantially enhanced river production and respiration in the LMR. Increased flow facilitated microinvertebrate transport from upstream sources (e.g. Goulburn River/Upper Murray) to the LMR, which contributed to increased diversity and potentially provided a more diverse food source for larger animals (e.g. fish). Golden perch spawning occurred in the LMR during this period, and flow also facilitated the downstream transport of larval golden perch from above the LMR. Nevertheless, these spawning events did not result in golden perch recruitment to young-of-year (age 0+). The mechanisms leading to low survival of golden perch spawned in 2017–18 remain unknown and form important avenues for future research.

During 2017-18, Commonwealth environmental water contributed to continuous barrage flows throughout the entire water year. Subsequently, there were reduced salinity levels in the Coorong, creating conditions favourable for estuarine species, and increased salt export out of the Basin. Environmental flows also increased transport of nutrients and phytoplankton, which would likely stimulated primary and secondary productivity in downstream ecosystems, providing potential benefit to food webs of the LMR, Lower Lakes, Coorong and Southern Ocean, adjacent to the Murray Mouth.

Table 10. CEWO short-term (one-year) evaluation questions by indicators for the Lower Murray River (LMR). Evaluation questions are sourced or adapted from Gawne *et al.* (2014). Hydrology (channel) and Fish (channel) did not directly address specific CEWO evaluation questions thus are not presented, but Hydrology (channel) provided fundamental information for analysis and evaluation of monitoring outcomes against hydrological conditions and environmental water delivery for all indicators. Evaluation of CEW for Hydrological Regime and Matter Transport indicators is based on modelled data. CEW = Commonwealth environmental water, VEWH = Victorian Environmental Water Holder, RMIF = River Murray Increased Flows.

Indicator	CEWO key one-year evaluation questions	Outcomes of Commonwealth environmental water delivery
Hydrological Regime (modelling)	What did CEW contribute to hydraulic diversity within weir pools?	CEW increased hydraulic diversity by creating up to 20% flowing water (lotic) habitat (i.e. >0.3 m/s) in the LMR over several events from July to November, and up to 50% lotic habitat in the Lock 5 weir pool during December.

Indicator	CEWO key one-year evaluation questions	Outcomes of Commonwealth environmental water delivery
Hydrological Regime (modelling)	What did CEW contribute to variability in water levels within weir pools?	CEW created variability in water levels, with approximately four events of different durations that decreased and then increased water levels at the upper end of each weir pool that otherwise would not have occurred during entitlement flow conditions.
Stream Metabolism	What did CEW contribute to dissolved oxygen levels? What did CEW contribute to patterns and rates of primary productivity and decomposition?	Dissolved oxygen concentrations remained close to saturation, assisted by the enhanced flows associated with environmental water contributions. The extended period of environmental flows enhanced the river size, increasing the integrated cross-sectional biotic biomass without substantially reducing metabolic rates, and consequently increasing the integrated rates of gross primary production and ecosystem respiration.
Matter Transport (modelling)	What did CEW contribute to salinity levels and transport? What did CEW contribute to nutrient concentrations and transport? What did CEW contribute to concentrations and transport of phytoplankton? What did CEW contribute to water quality to support aquatic biota and normal biogeochemical processes? What did CEW contribute to ecosystem function?	CEW increased export of salt from the Murray River Channel, Lower Lakes, and Coorong. CEW contributed to minor differences in the concentrations of nutrients, but increased transport of all studied nutrients. Whilst there was no apparent effect on phytoplankton concentrations, there was increased transport of phytoplankton through the system, due to CEW. CEW delivery reduced salinity concentrations in the Coorong, creating conditions that are less saline than marine and are typical of estuarine habitat. CEW delivery increased exchange of nutrients and phytoplankton between critical habitats of the LMR, which may have supported primary and secondary productivity in the region and in doing so supported food webs of the LMR, Lower Lakes and Coorong.

Indicator	CEWO key one-year evaluation questions	Outcomes of Commonwealth environmental water delivery
Micro-invertebrates	What did CEW contribute to microinvertebrate diversity?	CEW deliveries during December 2017 from disparate upstream sources provided a mixed, species-rich, microinvertebrate assemblage, primarily of warm-water taxa from, for example, the Murrumbidgee and Lake Victoria, with cool-water species from the Goulburn/southern Basin.
	What did CEW contribute via upstream connectivity to microinvertebrate communities of the LMR?	CEW contributed to longitudinal connectivity and most likely the transport of heleoplanktonic* warm-water taxa, including novel taxa for the LMR or the continent, to the LMR in January 2018. These could have derived from northern tributaries, or from populations established in Lake Victoria.
	What did CEW contribute to microinvertebrate abundance?	Increased CEW deliveries in late November and late December were followed by pulses in microinvertebrate abundance, with a general increase in densities over the sampling period.
	What did CEW contribute to the timing and presence of key species in relation to the diet of large-bodied native fish larvae?	Relationship between timing of ambient (present in environment) microinvertebrates, driven by CEW, and their presence in fish diet could not be determined due to low larval sample sizes.
Fish Spawning and Recruitment	What did CEW contribute to reproduction of golden perch and silver perch?	Delivery of CEW to the lower River Murray in 2017-18 coincided with spawning, but no detectable recruitment of golden perch (to young-of-year, age 0+).

*heleoplankton = plankton derived from billabongs and other floodplain still, generally-vegetated, waters.

4 MANAGEMENT IMPLICATIONS AND RECOMMENDATIONS

To restore riverine ecosystems, environmental water has been used to re-establish key features of the natural flow regime in the MDB (MDBA 2012; Koehn *et al.* 2014; Gawne *et al.* 2014; Webb *et al.* 2017), targeting significant ecological assets including the main channel of the Murray River (MDBC 2006). In the LMR, this may involve adding to base flows (~South Australian entitlement flows), increasing the magnitude, duration and/or frequency of freshes (in-channel flow pulses) and contributing to overbank flows. Over the long-term, this is expected to make a significant contribution to achieving ecological outcomes in the LMR, through restoring ecological processes and improving habitat for biota in the main channel and floodplain/wetlands.

Commonwealth environmental water can be used to increase flow variability in the lower River Murray, e.g. promote in-channel flow pulses. Spring–early summer in-channel flow pulses were key features of the natural hydrograph in the lower River Murray, which are conspicuously absent from the contemporary flow regime. These flow pulses increase longitudinal connectivity and contribute to a broad range of ecological outcomes in riverine and estuarine ecosystems (e.g. increased matter transport, lotic habitats and spawning and migratory cues for fishes). As demonstrated in 2017-18, such in-channel flow pulses can be generated in the LMR via return environmental flows through coordinated watering events across the southern-connected Basin.

Moreover, improving riverine hydraulics (e.g. water velocity and turbulence) is critical for ecological restoration in the lower River Murray. Flows of 20,000–45,000 ML/d can significantly improve hydraulic conditions, with >50% of a weir pool transforming from lentic (slower flowing water, median velocities ≤0.3 m/s) to lotic habitats (faster flowing water, >0.3 m/s) (Ye *et al.* 2018). Restoring such hydrodynamic conditions will underpin riverine ecological processes and support the rehabilitation of many declining biota that are adapted to a flowing environment in the lower River Murray. In addition, infrastructure management, such as weir pool lowering, should be considered to complement flows to achieve hydraulic restoration.

Overall, environmental water delivery that promotes longitudinal and lateral connectivity will enhance the productivity in the LMR through increased carbon and nutrient inputs, and matter transport. Longitudinal connectivity of river flow is also important for the transport and dispersal of aquatic biota (e.g. microinvertebrates, fish larvae) to and throughout the LMR. This study demonstrated that transportation of microinvertebrate taxa, facilitated by environmental flow delivery, from upstream catchments (e.g. Goulburn and upper Murray rivers) contributed to the diverse community in the LMR.

Also important is the source of water (i.e. origin). Because water quality (e.g. turbidity, the amount and form of nutrients) and biological constituents (e.g. plankton, fish

larvae) may vary between different sources of water, flows from different upstream sources can influence ecological outcomes in the LMR.

Furthermore, maintaining flow integrity from upstream (e.g. Darling River or mid-Murray) to the lower River Murray is important to support broad-scale ecological processes and promote positive outcomes (e.g. improved productivity, enhanced spawning and recruitment of flow-dependent fishes). In this regard, consideration needs to include: (1) maintaining hydrological integrity (i.e. magnitude, variability and source) of flow from upstream; and (2) the potential effects on water quality and biological attributes by river operations that re-route (e.g. through floodplains or wetlands) or fragment the flow (e.g. by diversions or water storages), which could lead to changes in ecological response and the structure and function of aquatic food webs.

Additional specific management considerations[e] are provided below based on monitoring outcomes from LMR indicators:

- For restoring hydraulic diversity (e.g. velocity and water level) in the lower River Murray, backwater and velocity response curves (Figures 8–10) are provided to aid managers in determining what hydraulic targets can be achieved through environmental water delivery. While the increase in the cross-sectional area due to a weir pool raising will reduce the velocity for a given discharge, the benefit is the increase in water level, and resulting inundation of banks and fringing vegetation. Targeted monitoring is required to understand the degree to which the modelled changes in water levels have resulted in improved ecological responses.
- The benefits to river production of increasing flows depend on the location, timing, magnitude, duration and frequency of flows due to multi-factorial effects on stream metabolism. To maximise the metabolic benefits, targeted use of environmental water could be planned in a system wide context, considering the balances of gains and losses across multiple sites to support riverine food webs.
- During low flows (e.g. entitlement), environmental water delivery is likely to reduce risk of low DO in the river channel of the LMR, which is important for avoiding detrimental impacts on aquatic biota, particularly during the warmer months. Maintaining flow rate >10,000 ML/d would mitigate the risk of cyanobacteria blooms in the LMR.
- Maximum exports of matter from the Murray Mouth are likely to be achieved by delivering environmental water during periods of low oceanic water levels (e.g. summer). In contrast, environmental water delivery to the Murray River

[e] Management recommendations provided in this report are subject to environmental water availability and operational feasibility. Furthermore, priorities of ecological objectives and trade-offs associated with watering actions must be considered at a local- and Basin-scale. A multi-year approach should be adopted, guided by ecological restoration principals.

Channel at times of high oceanic water levels is likely to increase the exchange of water and associated nutrients and salt through the Coorong, rather than predominately through the Murray Mouth. This may decrease salinities and increase productivity within the Coorong more than what would occur if water is delivered at times of low oceanic water levels.

- Environmental flows are pivotal in maintaining barrage flows, particularly during low flow periods, when there would otherwise be negligible water and matter exchange between the Lower Lakes and Coorong. Maintaining barrage flows is critical for exporting salt from the Basin, maintaining freshwater–estuarine habitat connectivity for diadromous species, reducing salinity levels in the Coorong, increasing estuarine habitat and productivity, and increasing reproductive success of many estuarine species (e.g. fish).
- While environmental flows facilitate nutrient transport and export from the MDB, a review/assessment is required to determine appropriate nutrient levels that fuel productivity and support food webs across the riverine, estuarine and marine environments.

5 CONCLUSION

Overall, 2017-18 was a climatically and hydrologically dry year. Without environmental water, flow to South Australia would have been at entitlement for most of the year. A total of ~894 GL of Commonwealth environmental water was delivered to the LMR, in conjunction with other sources of environmental water (e.g. The Living Murray water), during this year. Environmental water contributed to multiple spring–early summer in-channel flow pulses (up to 17,800 ML/d) and a range of ecological outcomes in the LMR. These included increasing areas of flowing water habitats; maintaining favourable dissolved oxygen concentrations to support riverine biota; enhanced in-stream food resources; increased connectivity and microinvertebrate dispersion; reduced salinities in the Coorong; and increased salt export from the Basin.

While environmental water promoted freshes (up to ~40% bankfull level) in the LMR during spring–summer 2017-18, the magnitude and duration of these flow pulses were well below modelled flow under natural (pre-regulation) conditions. Pre-regulation, the lower River Murray was characterised by flowing riverine 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' (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. Over the last four years, there has been no reproductive success in flow-cued spawning fish species (e.g. golden perch) despite some spawning. The current (2018) fish assemblage in the main channel of the LMR represents one typical of low flows, abundant with small-bodied fish.

Environmental water deliveries to support the restoration of flowing water habitats will help to restore ecosystem function and rehabilitate riverine plants and animals in the LMR. 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 significantly improve riverine habitat conditions and should be considered a priority for management. To maximise ecological outcomes, however, we need to better understand the effect of specific flow (e.g. timing, magnitude and duration) on ecological processes and hydraulic habitat requirements of flow-dependant species to inform flow management.

Despite outcomes for riverine flow-cued spawning fish not being achieved from 2014-15 to 2017-18, environmental water has demonstrated its importance in supporting barrage releases to the Coorong, particularly in low flow years (i.e. 2014-15, 2015-16 and 2017-18). Barrage flows are critical in exporting salt from the MDB, maintaining freshwater–estuarine habitat connectivity, reducing salinity levels in the Coorong and improving habitat and breeding success for many estuarine species (e.g. fish).

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7 APPENDICES

APPENDIX A: EXPECTED OUTCOMES OF COMMONWEALTH ENVIRONMENTAL WATER USE IN THE LOWER MURRAY RIVER DURING 2017-18.

Table A1. Summary of broad watering actions and expected outcomes for the Lower River Murray, Lower Lakes, Coorong and Murray Mouth in 2017-18 (Source: CEWO). Volumes of Commonwealth environmental water (CEW) are given at the South Australian (SA) border.

Watering action and target	Delivery details	Expected outcomes
River Murray channel – base flows and small freshes CLLMM – continuous barrage flows into the Coorong (1 July 2017 to 30 June 2018) CEW volume: 893,736 ML	● Return flows from environmental watering upstream, particularly Goulburn, Murrumbidgee, Barmah Millewa Forest and Hattah Lakes, were delivered to South Australia from late winter through spring and into autumn. Return flows from upstream watering events in spring resulted in a series of 'freshes' at the South Australia border. ● With upstream watering events largely concluding by late summer, additional Commonwealth and RMIF environmental water was delivered to South Australia over late summer and autumn (direct trade) to enable continuous barrage releases while protecting water levels in the Lower Lakes. ● The Commonwealth and TLM held South Australian allocation was delivered proportional to entitlement flow throughout the year. ● Water delivery to the CLLMM could be described as continuous baseflows with connection	**Lower River Murray:** ● Maintaining current species diversity, extending distributions and improving breeding success and numbers of short, moderate and long-lived native fish species by: - Increasing the presence of fast flowing fish habitat along the River Murray and, where feasible, increased lateral connectivity with anabranches and low elevation floodplain wetlands. - Providing in-stream habitat for fish and thereby supporting recruitment of fish, particularly by increasing the availability of food resources and habitat during periods where flows would be unnaturally low. - Improving the body condition of mature fish during winter/spring ('pre-spawning conditioning') and providing opportunities for spawning during spring (subject to appropriate seasonal conditions). - Contributing to the maintenance of critical habitat, water quality and the provision where possible of localised refuge sites as required. ● Maintaining the extent and condition of riparian and in-channel vegetation by: - Increasing periods of growth for non-woody vegetation communities that closely fringe or occur within the River Murray channel, anabranches and low elevation floodplain wetlands. ● Maintaining current species diversity, extending distributions and improving breeding success and numbers of water dependent bird species by: - Supporting suitable habitat conditions and food resources for waterbird growth and survival, maintenance of population condition and diversity along the River Murray valley. - Supporting waterbird breeding events if seasonally appropriate. ● Contributing to riverine functioning by: - Supporting primary and secondary production along the River Murray through the mobilisation and transport of nutrients, carbon cycling and biotic dispersal. - Supporting the managed export of salt and nutrients from the River Murray system. **Coorong, Lower Lakes and Murray Mouth**: Given the critical condition of the Coorong, the primary water use objective was to deliver Commonwealth environmental water into the Coorong via a hydrological regime that:

Watering action and target	Delivery details	Expected outcomes
	between the Lower Lakes and Coorong (fishways at a minimum open at all times), punctuated by a number of key events during the year. Where conditions allowed, baseflows were preferentially released through barrage bays adjacent to fishways to strengthen attractant flows and guide fish to fishways.	● aims to maximise estuarine habitat by prolonging barrage releases to support water levels and improve water quality in the north lagoon, in order to: - protect habitat conditions to maintain benthic invertebrate food resources for annual migratory waders within the Coorong. - protect habitat for native fish and facilitate movement. - potentially reduce peak salinity in the Coorong in summer-autumn to reduce the risk of irreversible damage to *Ruppia tuberosa*. ● provides increased barrage flow during September to December to support recruitment of Ruppia and spawning of estuarine fish (particularly black bream – discussed further below). Environmental water delivered to the Lower Lakes is expected to also support the following outcomes: ● Export of salt from the Lower Lakes. ● Maintenance of water quality for consumptive water users in the Lower Lakes. ● Maintenance of minimum water levels consistent with Basin Plan objectives. ● Maintenance of the health of fringing vegetation. ● Provision of habitat for native fish, frogs and colonial waterbirds.

Table A2. Summary of specific watering actions and expected outcomes for the Lower River Murray, Lower Lakes, Coorong and Murray Mouth in 2017-18 (Source: CEWO). Volumes of Commonwealth environmental water (CEW) are given at the South Australian (SA) border.

Watering action and target	Delivery details	Expected outcomes
Small freshes in the river and pulses over the barrages (July-September 2017) CEW volume: 326,320 ML	● Return flows from Goulburn winter fresh arrived during July, followed by Murrumbidgee return flows in August/September 2017. ● A number of 'pulses' over the barrages (Goolwa, Mundoo and Tauwitchere) occurred, with daily discharges ranging from 6,000 to 16,000 ML/day, through to early September 2017. ● Baseflows were 2-3,000 ML/day between the pulses, targeting attractant bays beside the fishways.	Fish habitat and condition, riverine function, lamprey migration, Coorong water quality/habitat suitability
Small freshes in the river and releases over the barrages to create salt wedge conditions (October 2017-January 2018) CEW volume: 354,807 ML	● Return flows from Goulburn spring pulses, Barmah-Millewa Forest and Hattah Lakes arrived at SA border from October 2017 to January 2018, including contributions from other water holders. A small unregulated event also occurred during December 2017. ● These return flows provided variable flow rates at the SA border, with a peak just below 18,000 ML/d. ● During this time period, water was released through Goolwa, Mundoo, Ewe Island and Tauwitchere barrages (ranging from 1,500 ML/d up to a peak of 12,000 ML/d) to create suitable salt wedge conditions for black bream spawning (in addition to a range of other benefits in the Coorong).	Fish habitat and condition, riverine function, black bream spawning and recruitment, Coorong water quality/habitat suitability
Elevated baseflows in the river and continuous barrage releases to support freshening of Coorong (February – May 2018) CEW volume: 203,279 ML	● Return flows from upstream watering events in late summer/autumn were negligible. ● 150,000 ML of Commonwealth environmental water was made available under a new 'trigger-based' approach based on Lower Lakes water levels. The approach entailed providing water for barrage releases, with the aim of maximising freshwater releases to the Coorong North Lagoon ahead of rising water levels in the Southern Ocean moving into the North Lagoon and pushing the freshwater towards the Coorong South Lagoon. ● A simultaneous managed 'drawdown' of Lower Lakes water levels to 0.5-0.55m occurred, with environmental water delivery at the SA border triggered by lake levels to protect against water levels dropping below 0.5m, thereby underwriting both lake level drawdown and barrage releases to the Coorong. ● Oceanic, and therefore North Lagoon, water levels seemed to rise earlier than other years (i.e. early March 2018) which limited the capacity to release water through the barrages with low lake levels (i.e. limited head difference), however over 50,000 ML of Commonwealth environmental water was released during February and March 2018.	Fish habitat and condition, riverine function, freshening of Coorong, vegetation diversity and migratory bird habitat fringing the Lower Lakes
Elevated baseflows in the river and continuous barrage releases (June 2018) CEW volume: 9,331 ML	● A small volume of Commonwealth environmental water was delivered in June 2018, mostly used for small barrage releases to the Coorong, with larger volumes from other water holders (particularly RMIF) used to rebuild Lower Lakes water levels following the drawdown.	Fish habitat and condition, riverine function, freshening of Coorong

APPENDIX B: OVERVIEW OF OTHER WATERING AND MANAGEMENT ACTIVITIES DURING 2017-18

In addition to environmental water deliveries to the LMR in 2017-18 (Figure 3), the following management actions are relevant to the analyses and interpretations in this report.

Other watering and management activities in the LMR

Manipulation of water levels in Weir Pools 2, 5 and 6

Water levels were lowered in Weir Pools 2 (between Locks 2 and 3, gorge geomorphic zone), 5 (between Locks 5 and 6, floodplain geomorphic zone) and 6 (between Locks 6 and 7, floodplain geomorphic zone) in the LMR. Water levels were lowered to 0.08 m below the normal pool level (NPL) in each weir pool during late July 2017 (Figure B1). Water levels in Weir Pool 6 were also lowered to 0.16 m below NPL from early May to late June 2018.

Raising of Weir Pools 2 and 5 occurred between early August and late October 2017. Water levels within Weir Pools 2 and 5 were raised to a maximum of 0.50 and 0.45 m above NPL, respectively, in September before undergoing a drawdown in early October back to NPL (Figure B1). Approximately 4.1 GL of Commonwealth environmental water was delivered to account for losses (e.g. evaporation) during the manipulation of Weir Pools 2 and 5 (source, CEWO).

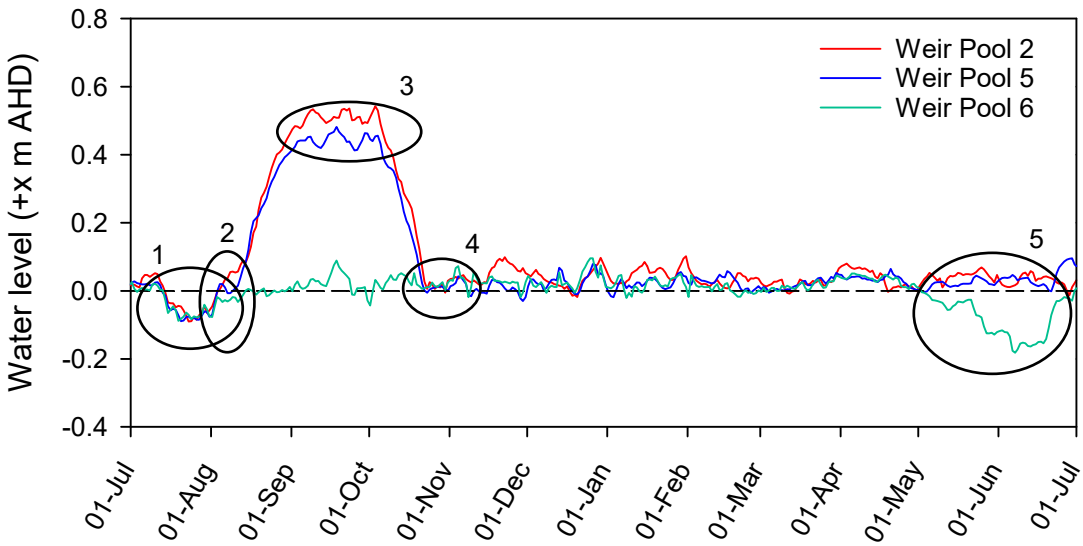

Figure B1. Water levels in the Lock 2 (US Lock 2) and Lock 5 (US Lock 5) weir pools between July 2017 and March 2018, showing weir pool manipulations between August and October 2017 (DEW). Water levels are measured at Lock 2 US (A4260518), Lock 5 US (A4260512) and Lock 6 US (A4260510) sites. Black circles indicate the (1) lowering of weir pools, (2) commencement of weir pool raising at Weir Pools 2 and 5, (3) maximum pool levels, (4) return to normal pool levels and (5) lowering of Weir Pool 6.

Watering and management activities outside of the LMR

Manipulation of water levels in Weir Pools 7, 8, 9 and 15

Water levels in Weir Pools 7, 8, 9 & 15 were raised and lowered, and Torrumbarry Weir Pool (Lock 26) lowered only, relative to their NPL during 2017-18 (Table A1). The aim of this was to improve ecological outcomes by introducing a more natural wetting and drying cycle to the riverine environment. Approximately 3 GL of Commonwealth environmental water was used to account for 'net' use, i.e. combined loss from raising and savings from lowering for the duration of the environmental watering event and for all weirs involved in the event. The total estimated water-use during raising was ~5,180 ML and water saving during lowering was ~1,910 ML producing a final water-use estimate in the order of 3,270 ML for the weir pool variability program in 2017-18 (to end May 2018).

Table A1. Timing of water manipulation actions for weir pools upstream of the LMR Selected Area during 2017-18 (source, MDBA). FSL = Full Supply Level (equivalent to NPL = normal pool level). The MDBA considered estimates of modelled natural river level and also advice from the States in implementing variable weir pool operations during 2017-18. A number of important issues are continuing to be investigated by MDBA and the States, which may affect the magnitude and timing of weir pool variability operations in the future.

Weir pool	Action	Duration	Watering information
7	Raising of weir pool up to +0.55 m above FSL (spring raising)	During September to December	Higher flows in Lindsay River associated with raising Lock 7 complemented pumping water to Lake Wallawalla.
	Lowering of weir pool up to -0.55 m below FSL (winter lowering), and up to -0.10m below FSL (autumn lowering)	During June to August & During March to May	Lowering of Lock 7 in autumn was balanced with the need to maintain passing flow into Lindsay River.
8	Raising of weir pool up to +0.35 m above FSL (spring raising)	During September to November	Spring raising was preceded by winter lowering, giving a total seasonal operational range of about 1.35m.
	Lowering of weir pool up to -1.00 m below FSL (winter lowering), and up to -0.32m below FSL (autumn lowering)	During June to August & During March to May	Lowering of Lock 8 in autumn was balanced with the need to maintain passing flow into Potterwalkagee Creek.
9	Raising of weir pool up to +0.23 m above FSL (spring raising)	During September to October	Lock 9 was raised up to 0.23m above FSL in early spring but then returned to FSL because a seepage issue was identified around the levee of the Carrs 1 structure.
	Lowering of weir pool up to -0.12 m	During March to May	Note: No weir pools were lowered below FSL in summer, as a measure to assist mitigate the risk of shortfalls in delivering

Weir pool	Action	Duration	Watering information
	below FSL (autumn lowering)		water to users downstream in hot conditions.
15	Raising of weir pool to +0.35 m above FSL (spring-summer raising)	During September to March	Lock 15 pool level ranged between FSL and +0.35m above FSL for much of spring and summer. The period of raising was extended into summer (ie. beyond what modelled natural was indicating), as a measure to assist mitigate the risk of shortfalls.
	Lowering of weir pool to -0.45 m below FSL (winter lowering)	During June to August	A level of -0.45m was reached.

Barmah–Millewa Forest

Between August and December 2017, environmental water (290 GL Commonwealth environmental water; 80 GL The Living Murray; 32 GL River Murray Increased Flows; and 9 GL NSW Office of Environment and Heritage) was delivered from Hume Dam for 'whole of Murray system' outcomes. A small volume was used in July for in-channel outcomes, with further water delivered during September to maintain stable flows for Murray Cod nesting in the mid-Murray River. Concurrently, from August to October 2018, ~3.3 GL of Commonwealth environmental water (along with ~7.7 GL of environmental water from The Living Murray) was delivered through Barmah–Millewa Forest regulators (source, CEWO). During October and November, environmental water contributed to overbank flows through the Barmah Millewa Forest for a range of outcomes, with flows that returned to the river being delivered to South Australia (Figure B2).

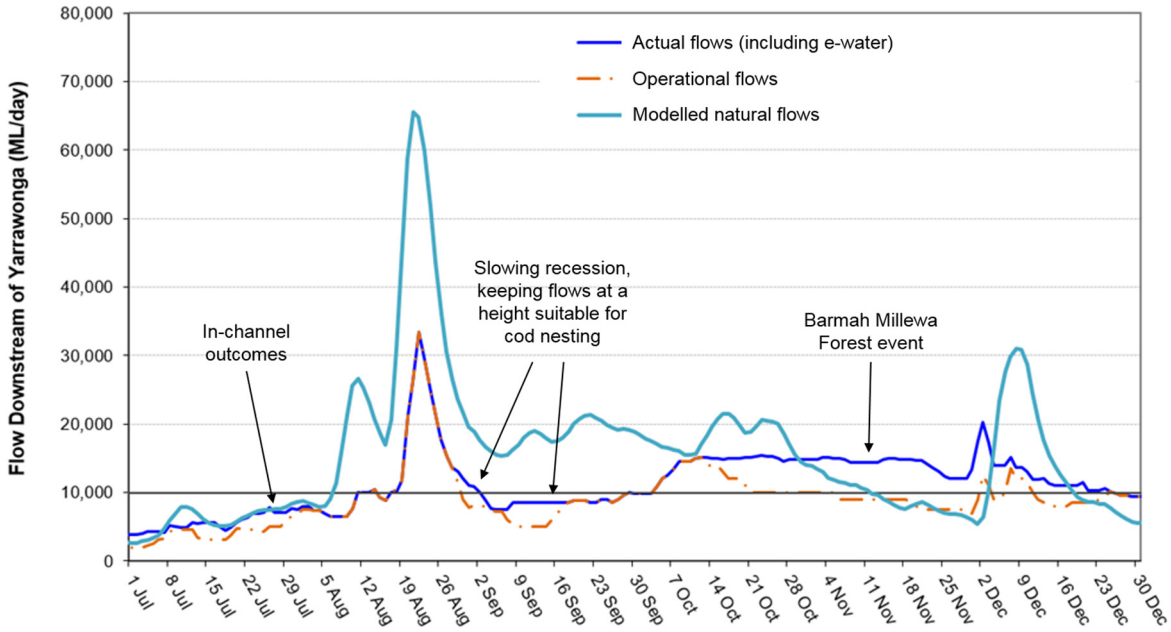

Figure B2. Flow (ML/d) in the Murray River, downstream of Yarrawonga weir from July 2017 to January 2018 (source of underlying hydrograph: MDBA River Murray Operations (RMO).

Goulburn River (and other Victorian tributaries)

Environmental water (236 GL Commonwealth environmental water; 78 GL The Living Murray; 38 GL Victorian environmental water; and Inter Valley Transfer, IVT) was delivered to the Goulburn River during 2017-18 (source, CEWO).

Environmental water promoted a July winter fresh (peak of ~8,500 ML/d) and two spring freshes in early October (peak of ~7,100 ML/d) and late November (peak of ~4,500 ML/d) (Figure B3). Flow in the Goulburn River peaked in early December at ~15,500 ML/d as a result of an unregulated flow event. Following this event, a small portion of the environmental water was delivered on the flow recession for blackwater mitigation. From February to early June 2018, Inter Valley Transfers accounted for the majority of flows in the Goulburn River (Figure B3). A winter fresh commenced in late June 2018 and extended into August 2018.

Return flows from other Victorian tributaries also contributed to environmental flow to South Australia during 2017-18. For example, 7 GL of Commonwealth environmental water (along with 19 GL Victorian environmental water and 5 GL The Living Murray water) reached South Australia as a result of watering events in the Campaspe River.

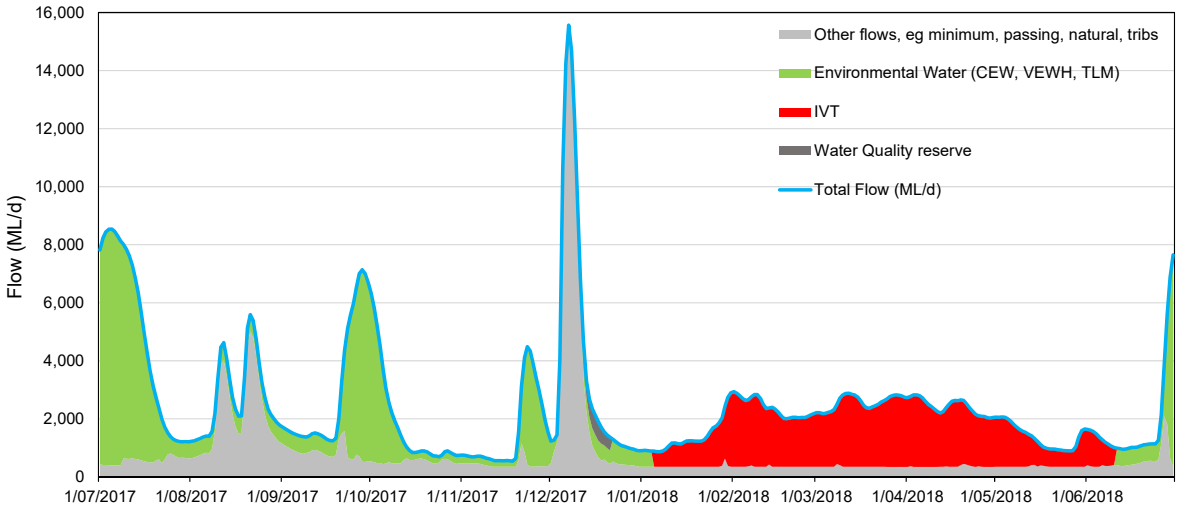

Figure B3. Flow (ML/d) in the Goulburn River at McCoys Bridge from April 2017 to June 2018 (source, CEWO).

Murrumbidgee River

During July and August 2017, 159 GL of Commonwealth environmental water (along with 77 GL of NSW Office of Environment and Heritage water) was delivered to reconnect the Murrumbidgee River with mid-Murrumbidgee wetlands, areas of the Lowbidgee floodplain and the Murray Junction Wetlands. A total of 68 GL of Commonwealth environmental water reached South Australia as return flows during August and September 2017.

Lower Darling River

In 2017-18, ~2.7 GL of Commonwealth environmental water and ~23.1 GL of The Living Murray water was delivered to the Lower Darling River to support spawning and dispersal of Murray cod, golden perch and silver perch. Environmental water provided base flows for fish habitat in early spring (The Living Murray) and assisting in shaping the recession of operational releases in late spring–early summer (The Living Murray and Commonwealth environmental water), which reached ~1,800 ML/d at Weir 32 in mid-October (Figure B4). Return flows reached South Australia during July to October 2018, comprising 5.7 GL of Commonwealth environmental water (including return flows from water delivered to the Darling River and Great Darling Anabranch during late 2016-17) and 12.3 GL of The Living Murray. An annotated 2016–2018 Darling River hydrograph, describing water releases, is available at https://www.mdba.gov.au/sites/default/files/pubs/1253-flow-at-weir-32-v3.pdf.

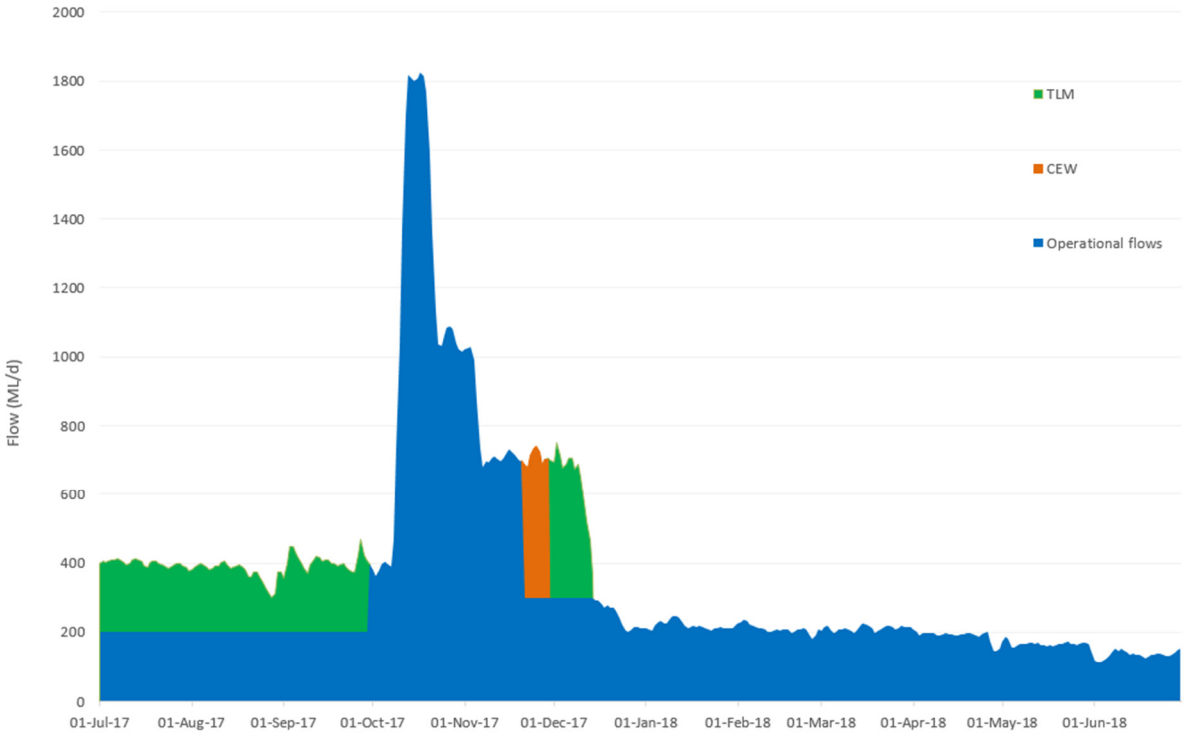

Figure B4. Flow (ML/d) at Weir 32 (lower Darling) in 2017-18 (source, CEWO).

Lower Lakes

A managed 'drawdown' of Lower Lakes water levels to 0.5–0.55 m AHD occurred in autumn 2018 to simultaneously improve Coorong salinity conditions and support Lower Lakes fringing vegetation. Commonwealth environmental water was used to protect against water levels dropping below 0.5m, thereby underwriting both lake level drawdown and barrage releases to the Coorong. As a result of the lake levels dropping more rapidly than expected, some barrages were closed earlier than planned and additional water was ordered to ensure lake levels did not drop below the target 0.5 m AHD (levels did drop just below 0.5m for four days in mid-April 2018).

APPENDIX C: DEW SHORT-TERM EVALUATION QUESTIONS

Table C1. DEW short-term (one-year) evaluation questions for CEWO LTIM indicators. Evaluation questions are based on ecological targets from the Long-Term Environmental Watering Plan (LTWP) for the South Australian Murray River. DEW evaluation questions serve as 'additional' questions as there may be some CEWO questions that are also relevant to DEW's targets from the LTWP. CEW = Commonwealth environmental water.

Indicator	One-year evaluation question(s)	Answers to one-year evaluation question(s)
Hydrology (channel)	What did CEW contribute to providing a seasonal hydrograph that encompassed variation in discharge, velocity and water levels?	Some variability in discharge (up to 18,000 ML/d), velocity (created some patches of lotic habitat, >0.3 m/s) and water level (increases exceeding 0.6 m at times in each weir pool) was created by CEW in the first six months of 2017-18 that would have not occurred otherwise in a year that was at entitlement flow for most of the year, with the exception a small unregulated flow event over the last two weeks of December.
Hydrological Regime	What did CEW contribute to providing diverse hydraulic conditions and complex habitat for flow dependant biota and processes? What did CEW contribute to providing 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?	Hydraulic diversity was increased in weir pools by creating relatively small patches (up to 20% of the weir pool) of lotic habitat over July to November that would not have been present otherwise. During the unregulated flow event in December, CEW increased the proportion of weir pools experiencing lotic conditions from very small patches to up to 30–50% of weir pool (depending on the location). Discharge exceeding 10,000 ML/d is expected to result in a well-mixed column where propagules that are denser than water would still be maintained in suspension (Wallace *et al.* 2014). In 2017-18, CEW contributed to create these conditions for short periods in July, October, November and December. Further research is required to determine relationships between velocity classes and a well-mixed water column, for dispersal of organic and inorganic material between reaches.

Indicator	One-year evaluation question(s)	Answers to one-year evaluation question(s)
Stream Metabolism	What did CEW contribute to temporarily shifting open water productivity towards heterotrophy?	There is no indication that CEW flows enhanced heterotrophy, but rather reduced ecosystem respiration (ER) rates during the period of highest flows while the rate of gross primary production (GPP) accumulation was sustained, resulting in increases in net ecosystem production (NEP). This was particularly noticeable at Lock 6 and much reduced at Lock 1. Increased NEP may have fuelled enhanced heterotrophy downstream of the monitoring site as an increase in NEP is expected to be associated with an increased biomass of biota.
	What did CEW contribute to increased nutrients and DOC levels?	CEW flows contributed little to nutrients or dissolved organic carbon (DOC) concentrations as flows were contained within channel and concentration changes were not strongly associated with flow changes.
	What did CEW contribute to maintaining dissolved oxygen levels above 50% saturation throughout the water column at all times?	The 2017-18 monitoring showed dissolved oxygen (DO) concentrations consistently near to saturation. The low flows predicted without environmental water would have greatly increased the likelihood of reductions in DO, and the environmental water contributions are considered to have reduced this risk.
Matter Transport	What did CEW contribute to maintaining water quality to support aquatic biota and normal biogeochemical processes?	The modelling suggests that environmental water impacted positively on the concentrations of dissolved and particulate matter. This was observed through a considerable reduction in salinity in the Coorong, where there was a modelled median salinity of 26.20 practical salinity units (PSU) with all water during 2017-18, compared to 33.84 PSU without CEW. Salinity is known to have a significant impact upon biogeochemical processes and so maintaining salinities in the Coorong within that of normal estuarine conditions may have maintained normal biogeochemical processes for this region. Furthermore, reduced salinity concentrations in the Coorong, likely improved habitat for estuarine biota.

Indicator	One-year evaluation question(s)	Answers to one-year evaluation question(s)
Matter Transport	What did CEW contribute to providing for the dispersal of organic and inorganic material and organisms between river and wetlands?	The modelling suggests that CEW increased the export of dissolved and particulate matter. This was observed through: • Increased salt export from the Murray River Channel and Lower Lakes. Total salt import through the Murray Mouth in 2017-18 was 527,042 tonnes. CEW contributed 2.9 million tonnes of salt export through the Murray Mouth. • Increased transport and exports of nutrients from the Murray River Channel, Lower Lakes and Coorong/Murray Mouth. • Increased transport and exports of phytoplankton biomass from the Murray River Channel, Lower Lakes and Coorong/Murray Mouth. It is important to remember than nutrients are a resource that drive productivity and fuel food webs. The increased transport of dissolved and particulate matter may have provided benefits for the Lower Lakes, Coorong and near-shore marine environment by providing energy to ecosystem productivity, as nutrients and phytoplankton are consumed by higher trophic organisms.
Micro-invertebrates	What did CEW contribute to increased microinvertebrate input from floodplain to the river and thus reducing the reliance of in-stream food webs on autochthonous productivity? What did CEW contribute to increased dispersal of organisms between river and wetlands?	Of ~171 taxa recorded from the LMR main channel in 2017-18, 96 (56%) were not true potamoplankton (plankton of flowing waters), but littoral/epiphytic/epibenthic incursions, flushed into the main channel from floodplain or littoral sources, e.g. Barmah-Millewa return flows. In contrast, 193 (68%) taxa were not true potamoplankton during sampling in 2016-17, when there were overbank flows. No wetland samples were collected in 2017-18 to ascertain CEW dispersal of microinvertebrates from the main channel flows.
Fish (channel)#	Did the length-frequency distribution for Murray cod in the Gorge zone reflect recent recruits, sub-adults and adults?	During autumn 2018, recent recruits (i.e. <300 mm TL, 73%) and sub-adults (i.e. 300–600 mm TL, 28%) were sampled in the Gorge geomorphic zone of the LMR; however, adults (>600 mm TL) were not sampled.

Indicator	One-year evaluation question(s)	Answers to one-year evaluation question(s)
Fish (channel)#	Did a YOY cohort represent >50% of the Murray cod population from the Gorge zone?	Yes. During autumn 2018, a YOY cohort (i.e. <150 mm TL) of Murray cod represented more than 50% (73%) of the population in the Gorge geomorphic zone of the LMR.
	Did the length-frequency distribution for bony herring, Murray rainbowfish and carp gudgeon, include size classes representing YOY in the Gorge zone?	Yes. During autumn 2018, length-frequency distributions indicated YOY were present for bony herring, Murray rainbowfish and carp gudgeon.
	Did the relative abundance of common carp in the Gorge zone increase during the current year, relative to the previous year, whilst the relative abundances of flow-dependent native species decreased?*	For all sites sampled both during autumn 2017 and 2018, there was a decrease in the ratio (total abundance) of common carp to flow-dependant, native species (golden perch and silver perch) in 2018, relative to the previous year. During 2017 the mean site ratio was 19.33 carp (± 4.45 S.E.) to every 1 flow-dependant, native species. In 2018, this ratio decreased to 4.37 carp (± 1.71) to every 1 flow-dependant, native species.
	Did the estimated biomass of common carp in the Gorge zone increase during the current year, relative to the previous year, whilst the estimated biomass of flow-dependent native species decreased?*	In contrast to relative abundance, there was an increase in the ratio (total biomass) of common carp to flow-dependant, native species (golden perch and silver perch) at three of the five sites sampled in autumn 2018, relative to the previous year. During 2017, the mean site ratio was 1.48 kg of carp (± 0.33 S.E.) to every 1 kg of flow-dependant, native species. In 2018, this ratio increased to 4.33 kg of carp (± 1.96) to every 1 kg of flow-dependant, native species.
Fish Spawning and Recruitment	What did CEW contribute to the population age structure of golden perch in the LMR?	CEW delivery in 2017-18 did not contribute to the presence of any new cohorts (age 0+) of golden perch in the LMR, despite spawning during spring–early summer 2017.
	What did CEW contribute to the population age structure of silver perch in the LMR?	CEW delivery in 2017-18 did not contribute to the presence of any new cohorts (age 0+) of silver perch in the LMR. No silver perch spawning was detected in 2017-18.

Indicator	One-year evaluation question(s)	Answers to one-year evaluation question(s)
Fish Spawning and Recruitment	Did CEW contribute to a YOY or age 1+ cohort that represented >30% of the golden perch population in the LMR? Did CEW contribute to a YOY or age 1+ cohort that represented >30% of the silver perch population in the LMR?	No. Age 0+ (2017-18) and 1+ (2016-17) cohorts represented <30% of the golden perch population in the LMR during autumn 2018. In 2017-18, there was spawning of golden perch, but negligible recruitment. One age 1+ (2016-17 cohort) silver perch was detected during electrofishing in the LMR during autumn/winter 2017. Due to a low sample size (*n* = 2), this cohort represented 50 % of the silver perch population in the LMR. A larger sample size will provide a more reliable indication of the relative abundance of YOY and age 1+ silver perch in the LMR.

Fish (Channel) data have been consolidated to evaluate a number of fish targets of DEW's LTWP. These questions and answers do not relate to evaluation of flow or CEW. Furthermore, the LTIM Fish monitoring program is not designed to determine what is facilitating changes in population dynamics of fish species for DEW's LTWP evaluation questions, e.g. spawning and recruitment of Murray cod or common carp.

* To remove sampling season bias, only sites sampled during autumn 2017 were used in carp ratio comparisons against 2018. Site ratios of common carp to flow-dependant, native species were calculated by dividing the total biomass or number of individuals (abundance) of carp for that site by the total biomass or number of individuals (abundance) of golden perch and silver perch for the same site, respectively. The mean site ratio for a particular year was calculated by averaging the site ratios. Common carp were not weighed as part of the Fish (channel) sampling, so biomass was estimated by converting fork lengths to weights based on a FL–mass equation in Vilizzi and Walker (1999).

8 ACRONYMS

AHD	Australian Height Datum
CEW	Commonwealth environmental water
CEWO	Commonwealth Environmental Water Office
DEW	Department for Environment and Water
DOC	Dissolved organic carbon
ENP	Ecosystem net production
ER	Ecosystem respiration
GPP	Gross primary production
LMR	Lower Murray River (South Australian section of the Murray River).
LTIM	Long-Term Intervention Monitoring
M&E	Monitoring and Evaluation
MDB	Murray–Darling Basin
MDBA	Murray–Darling Basin Authority
NPL	Normal pool level
NSW OEH	New South Wales Office of Environment and Heritage
PSU	Practical salinity units
RMIF	River Murray Increased Flows
TL	Total length
TLM	The Living Murray
VEWH	Victorian Environmental Water Holder
YOY	Young-of-year

9 GLOSSARY

Allochthonous	Refers to foreign or outside sources. For example, organic matter of an allochthonous source is that which has been produced outside of the river channel, e.g. terrestrial or floodplain material.
Autochthonous	Refers to local sources. For example, organic matter of an autochthonous source is that which has been produced within the river channel.
Base flow	Flows that are confined to the low flow part of the river channel.
Biofilm	A collection of microorganisms (e.g. bacteria) attached as a 'film' on living (e.g. tree root) and non-living (e.g. wooden pylon) surfaces.
Flood or flooding	Refers to flows that are overbank. In South Australia, this is deemed to be above bankfull flow (45,000 ML/d).
Freshes (flow)	Flows greater than base flow but below bank level.
Epibenthic	Organisms living on the surface of sediment.
Epiphytic	Organisms that are attached to plants.
Heleoplankton	Plankton derived from billabongs and other floodplain still, generally-vegetated, waters.
In situ	Used to describe monitoring *in* the field.
Lentic	Refers to slower water velocities associated with 'pool water' habitat in highly regulated systems, typically median velocities of approximately ≤0.3 m/s.
Littoral	The margin along the bank of the river.
Lotic	Refers to flowing water, typically median velocities of approximately >0.3 m/s.
Pulse (flow)	A description given to the shape of a hydrograph that is characterised by an increase in discharge, followed by a decrease in discharge, often of similar slope.
Recruitment (reproduction)	Refers to individuals passing the critical stages of early life (e.g. larval) and becoming juveniles in a population, described here as age 0+ years.
Respiration (ecosystem)	Ecosystem respiration is the measure of oxygen depletion in water by respiring animals.
RMIF	River Murray Increased Flows: a type of environmental water. Water entitlements recovered under the Snowy Water Initiative (established in 2002) via infrastructure upgrades and water purchase, which receive annual allocations and are used to supply environmental water to the Snowy River (Snowy River Increased Flows, SRIF) and River Murray (RMIF).
Primary productivity	The rate at which energy is converted to organic substances by autotrophs (e.g. algae and plants) during photosynthesis.
Unregulated flows	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.
Weir pool	Stretch of river between two weirs.