Restoring the ecological integrity of a dryland river: why low flows in the Barwon-Darling River must *flow*

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This paper arose from examination of historical flow data which revealed the depths of the crisis the Barwon-Darling River is presently facing, and the choices we can make now to restore it.

Citation:

Mallen-Cooper, M. and Zampatti, B.P. (2020). Restoring the ecological integrity of a dryland river: why low flows in the Barwon-Darling River must *flow*. *Ecological Management and Restoration*. doi: 10.1111/emr.12428

Link to publication:

https://onlinelibrary.wiley.com/doi/10.1111/emr.12428

Summary

For dryland rivers globally, understanding hydro-ecological function is fundamental to informing trade-offs between consumptive water use and aquatic ecosystem integrity. The Barwon-Darling is an Australian dryland river system recognised for its hydrological variability, which is considered a primary driver of the riverine ecosystem. Emphasis has been placed on extremes of zero flow and flood but examining the low flow hydrology and hydraulics - through historical and modern droughts - demonstrates that under natural conditions, the river system also exhibits persistent and predictable flow characteristics. From 1885 to 1950, prior to flow regulation, the Barwon-Darling flowed 92% of the time, and throughout severe droughts (1895–1903 and 1939–1945) the river system was characterised by: near-perennial flows (85% of the time), with lotic (flowing water) habitats; and near-annual, in-channel, flow pulses. Furthermore, evidence of lotic biota are found consistently in Aboriginal middens dating over the past 15,000 years, thus indicating the long-term persistence of lotic conditions.

We propose these consistent hydrological and hydrodynamic features have shaped the ecology of aquatic biota in the Barwon-Darling River but are now experiencing unprecedented change. Flow storage and diversion have increased the frequency and duration of zero flows in some reaches, but arguably the most substantial impacts, along the entire river, are on: i) low flows, which are now frequently below lotic thresholds, and ii) the magnitude of near-annual flow pulses, which are reduced by over 90%. Consequently, in modern droughts, the river becomes predominantly lentic (still-water), an impact that is exacerbated by weirpools which create artificial lentic conditions for approximately 1000 km (40%) of river. The ecological impacts of these changes are increasingly apparent, with the loss of lotic biota and a reduction in biodiversity. An ecohydraulic perspective explains present impacts, provides new directions and some immediate solutions for river management, and clarifies choices for stakeholders.

Implications for managers

Rehabilitation of the Barwon-Darling River ecosystem is reliant on:

- Incorporating hydrodynamics and lotic refugia as explicit objectives in water management;
- Enabling greater continuity and near permanency of low flows of sufficient magnitude to maintain lotic habitats;
- Providing alternative water sources for towns, such as off-stream storages that can harvest from high flows, enabling all low flows to remain in the river;
- Reducing the spatial extent of lentic weirpool habitats, and
- Restoring flow pulses.

Keywords

Darling River, historic, drought, hydrology, ecohydraulics, lotic, regulation, rehabilitation

Introduction

Balancing water security for human needs and the maintenance of aquatic ecosystems is one of the great challenges of modern society (Richter *et al.* 2003; Vörösmarty *et al.* 2010). This task is exacerbated in dryland regions of the world, where human demands for water are high but rainfall and run-off are low and unpredictable (Petts 2017; Chu *et al.* 2018). Rivers in these regions are often characterised by their extreme hydrological variability (Walker *et al.* 1995; Puckridge *et al.* 1998; Young and Kingsford 2006; Arthington and Balcombe 2011), commonly coinciding with intermittency or ephemerality (Tooth 2000).

In dryland rivers, the frequency and duration of flooding and intermittency (periods of zero flow) are key aspects of hydrology that influence ecosystem processes and structure, including the diversity and abundance of biota (Balcombe *et al.* 2007; Leigh *et al*. 2010; Sheldon *et al.* 2010; Webb *et al.* 2012). Yet dryland rivers may also spend long periods of time (months–years) between these extremes, when low flows can prevail (Smakhtin 2001; Thoms *et al.* 2004; Young and Kingsford 2006). These disparate hydrological states mean intermittent dryland rivers can shift back and forth between longitudinally connected lotic (flowing water) systems, and fragmented lentic (still-water) systems (Sheldon *et al.* 2010).

The Barwon-Darling River in South-Eastern Australia is an intermittent dryland river renowned for its hydrological variability (Puckridge *et al.* 1998). Zero flows are a focal point for descriptions of the river; such as, "The Darling River at Menindee ceased to flow 48 times between 1885 and 1960, and . . . did not flow for 364 days in the 1902–3 drought." (Murray-Darling Basin Commission 2004; Blair 2019).

Since the 1960s, the river's hydrology has been substantially modified by flow regulation, in the form of water storages and extraction. The hydrological impacts of regulation have been characterised (Thoms and Sheldon 2000; Australian Academy of Science 2019), but impacts on riverine hydraulics and associated ecological implications remain largely unexplored. Flow regulation in the Barwon-Darling River has been associated with ecological degradation (Thoms and Delong 2018), including, in 1991, the world's longest (~1000 km) riverine cyanobacterial bloom (Bowling and Baker 1996). More recently (2019), the deaths of hundreds of thousands of fish were associated with cyanobacterial blooms followed by deoxygenation of weirpools (Vertessy *et al.* 2019). Both events were associated with months of low or zero flows.

From 2001 to 2009, the Murray-Darling Basin (MDB) experienced the 'Millennium Drought', one of the most severe droughts on record (van Dijk *et al.* 2013) followed by another extensive drought that commenced in 2013 and is ongoing (Vertessy *et al.* 2019). Similar droughts, however, have occurred previously (Freund *et al.* 2017) prior to the development of dams and weirs in the catchment.

Droughts are characterised by low flows that directly affect habitat, hydraulic conditions, water quality, resource flux and riverine connectivity; and in turn regulate the distribution, abundance and diversity of aquatic biota (Rolls *et al*. 2012). Understanding these hydro-ecological relationships is critical to informing trade-offs between consumptive water use and ecosystem integrity (Bunn and Arthington 2002). It is within this context that we examine the low flow hydrology and hydrodynamics (variation in hydraulics over time and space) of the Barwon-Darling River before and after flow regulation, particularly in extreme droughts. Our objectives are to: i) understand the interaction of hydrology and riverine hydraulics, and the dynamics of lotic habitats; ii) integrate these findings with contemporary, historical and paleo-ecological data to provide an ecohydraulic premise for the rehabilitation of the Barwon-Darling River, and iii) use these findings to provide recommendations for water management that sustains aquatic ecosystems and people.

Study Area

In southeast Australia, the Barwon and Darling rivers comprise part of Australia's longest river system, the Murray-Darling (Fig. 1); they drain the northern Murray-Darling Basin (MDB) which is characterised by a mostly semi-arid to arid catchment of 650,000 km^2 (Matheson and Thoms 2018). The Barwon River constitutes the northern reach of the Barwon-Darling, running from the confluence of the Weir River and Macintyre River to the junction with the Culgoa River, where it becomes the Darling River to the junction with the River Murray (Fig. 1). Major and more consistent run-off is derived from the eastern tributaries (Border Rivers, Gwydir, Namoi and Macquarie) that drain the western slopes of the Great Dividing Range, while the northern tributaries (Paroo, Warrego and Culgoa) are arid and more intermittent, providing minor and more variable run-off (Thoms *et al.* 2004).

For over 30,000 years, Aboriginal people have had a cultural connection with the river (Balme 1995). Fish, mussels and snails were an important food source for Aboriginal people (Humphries 2007; Garvey 2017), and some of the world's oldest examples of stone fish-traps are located on the Barwon River at Brewarrina (Mathews 1903). Indeed, fish are integral to the cultural heritage of communities throughout the Barwon-Darling system; they are considered a sentinel of river health; and contribute to recreational fishing and tourism (Koehn 2015).

Like many rivers in Australia's Murray-Darling Basin, modification of the Barwon-Darling river system has been profound (Thoms *et al.* 2004). European settlement of the river commenced in the mid-1800s, but widespread regulation of flow did not commence until the 1960s. There are now eight major headwater dams in the eastern tablelands (Fig. 1), multiple weirs, pumped extraction with off-stream storages, and floodplain water harvesting, which modify the river's hydrology and fragment the riverine ecosystem. Median flows in the mid-reaches of the Darling River are now reduced by over 70% (Thoms and Sheldon 2000).

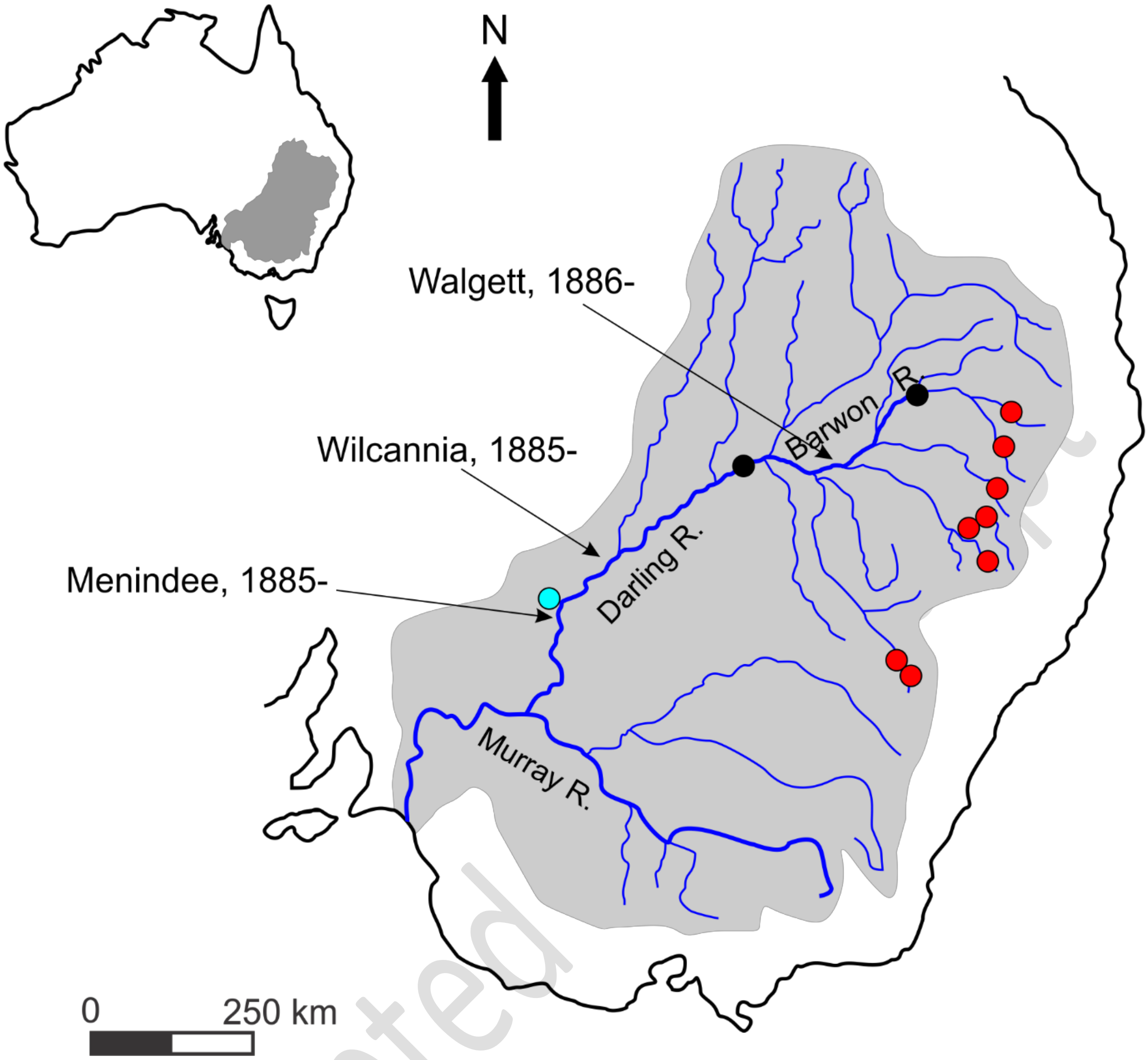


Figure 1. Study area showing: river gauge locations and period of record; major (>100 GL) dams (red symbols); towns (black symbols) mentioned in the text (Bourke to the west and Mungindi to the east).

Methods

Hydrology

Firstly, to establish natural patterns of intermittency, we examine flow records from 1885 to 1950, before flow regulation. Secondly, we compare the low flow hydrology and hydrodynamics of extreme droughts before and after flow regulation, using the: Federation Drought (1895–1903), World War II Drought (1939–45), Millennium Drought (2001-2009) and 2013–2019 data for the present ongoing drought (referred hereafter as the 2013–2019 drought). To further assess the effects of water diversion on low flows, we compare gauged data with modelled natural flows in the Millennium Drought. At the time of publication, modelled natural flows for the 2013-2019 drought were unavailable.

We use main-channel records that include data from 1885–86 onwards, from reaches in the upper (Walgett [119 m AHD] from 1886, Gauge 422001), middle (Wilcannia [63 m AHD] from 1885 [Menindee gauge used pre-1913 as it is more accurate and an effective surrogate for Wilcannia prior to the Menindee Lakes Scheme (Academy of Science 2019)], Gauge 425008); and lower Darling River (Menindee [52m AHD] from 1885, Gauge 425012) (Fig. 1). Up to 1950, historical flow data were published as monthly records (minimum, mean and maximum) (Water Conservation and Irrigation Commission 1956) while more recent data (1974 onwards) are daily and available online (www.waterinfo.nsw.gov.au; accessed 15 June 2020).

Modelled natural daily flows were from the MSM–BIGMOD model downstream of Menindee and IQQM model upstream of Menindee (Murray-Darling Basin Authority, unpublished data). Modelled data were available from 1895 to mid-2009 (Murray-Darling Basin Authority, unpubl. data), for the three locations on the Barwon-Darling River: 1) Walgett, 2) Wilcannia, and 3) downstream of Menindee (including downstream of Menindee lakes). Gauged and modelled natural flows were compared using flow duration curves.

Hydrodynamics

We obtained water velocity data from river cross-sections at three hydrographic gauging stations on the Barwon-Darling River: two - Walgett and Wilcannia - were the same as used for hydrological analysis, while the third was downstream of Menindee (Gauge 425048, near the offtake of the Great Darling Anabranch), which ensured all three gauging stations were in comparable free-flowing river reaches, not impacted by backwater from a downstream weir. Water velocity measurements spanned the period 1995–2018 and discharges from zero to flood levels (70,000 ML d^{-1} [megalitres per day]). Mean water velocity versus discharge data were then used to provide an assessment of the duration of lotic and lentic conditions in droughts, acknowledging that mean channel velocity is a surrogate for hydrodynamic diversity in reaches not impacted by backwater from weirs or barriers (Bice *et al*. 2017).

To assess the spatial extent to which weirs in the Barwon-Darling River raise water levels and create lentic pool habitats, we derived weirpool lengths from weir crest heights and assumed the weirpool surface had a flat hydraulic gradient at low flows. These were superimposed on a river channel profile (unpublished data, WaterNSW). Channel survey was available for Mungindi to Weir 32; while the unsurveyed reach from Burtundy to Wentworth weirpool (482km) was assumed to be a consistent gradient.

To provide a context for changes in hydrology and hydrodynamics among historical and contemporary droughts, we examined water management in the Barwon-Darling river system in the 2013–2019 drought. Specifically, we characterised inflows and outflows from headwater storages on major tributaries, and the operation of main channel weirs.

Mussels and Snails

In March 2019, 16 sites (Table 1, Appendix S1) along 1500 km of the Barwon-Darling River were inspected for the presence of River Mussel (*Alathyria jacksoni*) and River Snail (*Notopala sublineata sublineata*). We also re-examined the paleo-record of these biota in Aboriginal middens in the lower Darling River (Balme 1990, 1995) to assess their long-term presence, and how this might reflect past hydraulic conditions.

Results

Intermittency prior to flow regulation

Based on mean monthly flows from 1885–1950, prior to flow regulation, the Barwon-Darling River at Walgett, Wilcannia and Menindee flowed for 95, 94 and 92% of the time, respectively, including continuous flows for up to 19 years. The 65-year period of record includes droughts in 1885, 1888, 1895–1902, 1914–1915, 1919–20, 1923 and 1939–45, which each have months of zero flow. At Menindee, there were 81 events of zero flow in this period: 61 of these were less than one month, 17 were one to six months duration, and three were greater than six months - occurring in 1888 (10 months), 1902 (11 months), and 1919–20 (7 months). In summary, prior to river regulation, the Barwon-Darling River flowed for more than 90% of the time and was characterised by short spells (generally less than one month) of zero flow.

Hydrology of droughts

The four severe droughts we selected - Federation Drought (1895–1903), World War II Drought (1939–45), Millennium Drought (2001–2009) and 2013–2019 – all had comparable rainfall and runoff per annum (Verdon-Kidd and Kiem 2009; Freund *et al.* 2017). All droughts are, however, unique and variation was present with slightly less rainfall in the Barwon-Darling catchment in the World War II Drought compared with the Millennium Drought (Leblanc *et al*. 2012), while 2018 had the second lowest inflows from the eastern tablelands of any year between 1893-2019 (Vertessy *et al*. 2019). Flow duration curves (using mean monthly flow) for the historical droughts and modelled flow for the Millennium Drought show very high levels of consistency between zero and 2,000 ML d^{-1} within a reach (upper, middle and lower river) (Fig. 2). Along the Barwon-Darling River there are different patterns of change in droughts (Fig. 2). In the upper river (Walgett), zero flows are similar in historical droughts and the Millennium Drought – occurring for less than 11% of the time - but increase to 18% of the time in the 2013–2019 drought. In the middle river (Wilcannia), zero flows increase from historical to contemporary droughts, from 15% to 21–23%; while the lower river (Menindee) had less zero flows in contemporary droughts due to regulated flow releases from Menindee Lakes. Modelled natural flow for the Millennium Drought shows less zero flows (i.e. more flow) at Walgett and Wilcannia compared to all droughts, and more zero flow at Menindee.

Baseflows and flow pulses exhibit the greatest differences. In historical droughts, flows exceed 700 ML d^{-1} at Walgett and 1300 ML d^{-1} at Wilcannia and Menindee 50% of the time, compared with 175 ML d^{-1} at Walgett, 70 ML d^{-1} at Wilcannia, and 195 ML d^{-1} at Menindee in contemporary droughts (Fig. 2). Modelled natural flows in the Millennium Drought exhibit a similar pattern to historical droughts, with baseflows of 500 ML d^{-1} exceeded 50% of the time at Walgett and 900 ML d^{-1} at Wilcannia and Menindee (Fig. 2). Wilcannia demonstrates the greatest differences at very low flows, with 40% of flows less than 5 ML d^{-1} in the Millennium Drought, compared with 400 ML d^{-1} for modelled natural flows, 600 ML d^{-1} in the Federation Drought and 1000 ML d^{-1} in the World War II drought (Fig. 2). Consequently, river regulation has fundamentally altered low flows in the Barwon-Darling River.

In the two historical droughts and in modelled natural flows for the Millennium Drought, the Barwon-Darling was characterised by near-annual flow pulses (1.25 ARI, Annual Recurrence Interval) ranging from 8620 to 12,637 ML d^{-1} occurred. Discharge of this magnitude is mainly contained within the river channel (river cross-sections from https://realtimedata.waternsw.com.au/, accessed 8 December 2019) with some reconnection of low-lying wetlands (NSW Department of Primary

Industries 2015). These flows in the unregulated river contrast starkly with the 1.25 ARI flows for the Millennium and 2013–2019 droughts (analysis includes recent peak flows in March 2020), which were 670 and 650 ML d^{-1}, respectively.

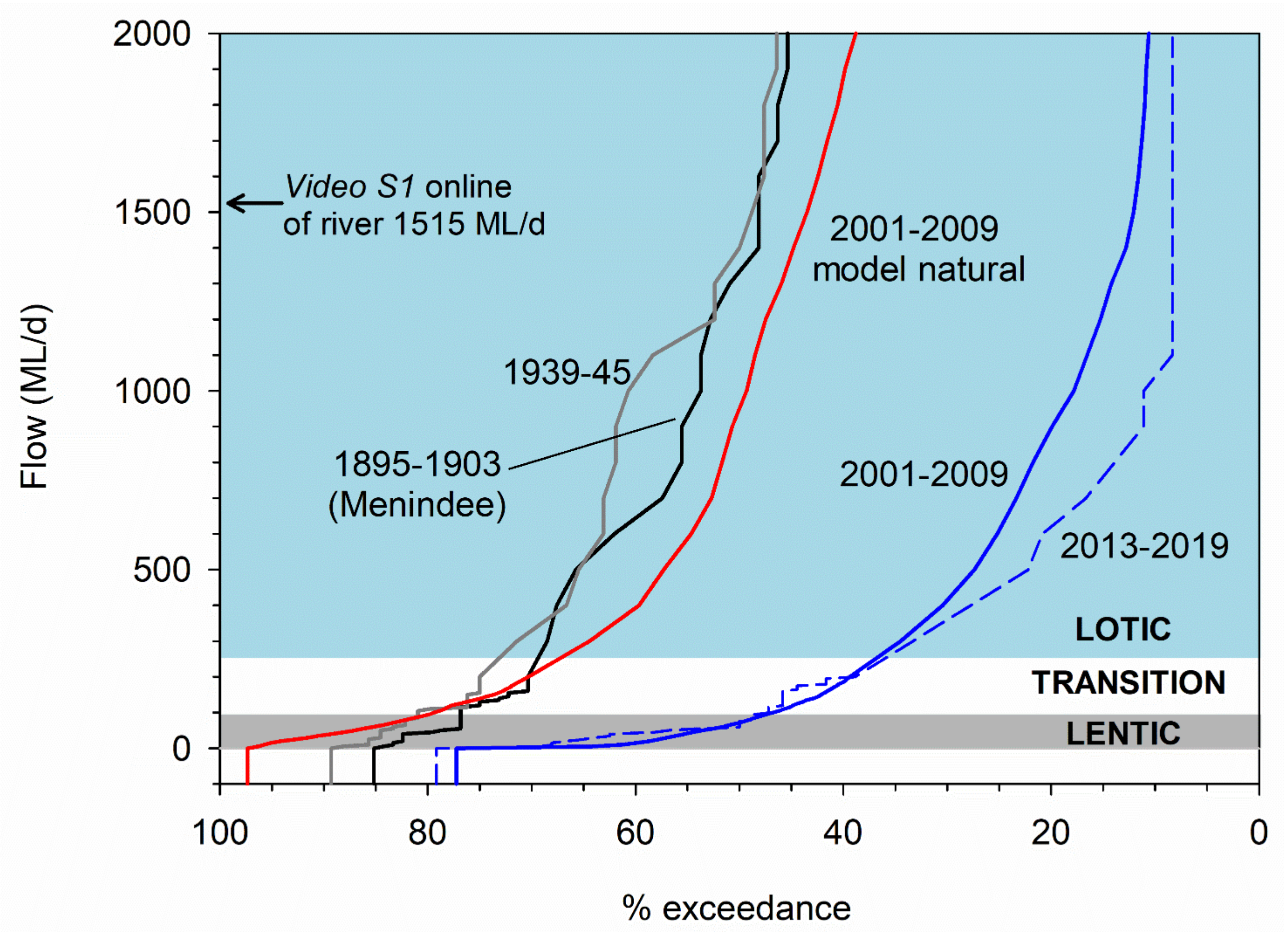


Figure 2. Flow duration curves of droughts pre-regulation (black and grey lines) and post-regulation (blue solid and dashed lines), shown with modelled natural flow for the Millennium Drought (2001-09), for the middle of the Barwon-Darling River (Wilcannia). Lentic (< 0.15 m s^{-1}) and lotic (> 0.3 m s^{-1}) flows, derived from hydrographic data (Fig. 3), are shaded grey and blue, respectively. Upper river (Walgett) and lower river (Menindee) graphs are in Appendix S2 in *Supporting Information* online. Video of river is online in Appendix S3 (link to online video).

Hydrodynamics

Hydrographic data from three cross-sections on the Barwon-Darling River show that mean channel water velocities rapidly increase from zero to 0.2–0.3 m s^{-1} in association with small increases in discharge from zero to 250 ML d^{-1} (Fig. 3). Above 250 ML d^{-1}, water velocities plateau above 0.2 m s^{-1} in the upper river (Walgett), and above 0.3 m s^{-1} in the middle and lower river (Wilcannia and downstream of Menindee). Walgett had two noticeable groups of data, with higher water velocities up to 500 ML d^{-1} for 1974–1999 and lower water velocities for the same discharge for 2000-2018, suggesting some change in channel morphology over this period.

Water velocities for lotic (flowing) and lentic (still-water) habitats - considered applicable for a low gradient river (Mallen-Cooper & Zampatti 2018) - are superimposed on Figure 3. From these data, we approximated thresholds of 100 ML d^{-1} as the upper discharge for lentic habitats and 250 ML d^{-1} as the lower discharge for lotic habitats, while flows in between were considered transitional between the two hydraulic conditions. These thresholds were also superimposed on Figure 2, which then shows the duration of lotic and lentic habitats.

Outside of droughts from 1885–1950, there were continuous lotic conditions (> 250 ML d^{-1} minimum monthly flow) for up to six years. In historical droughts and modelled natural flows for the Millennium Drought, lotic habitats were maintained for more than 69% of the time at all three Barwon-Darling River sites (Fig. 2). In contrast, the gauged flow data for the Millennium and 2013–2019 droughts show lotic conditions are reduced to 37–43% of the time.

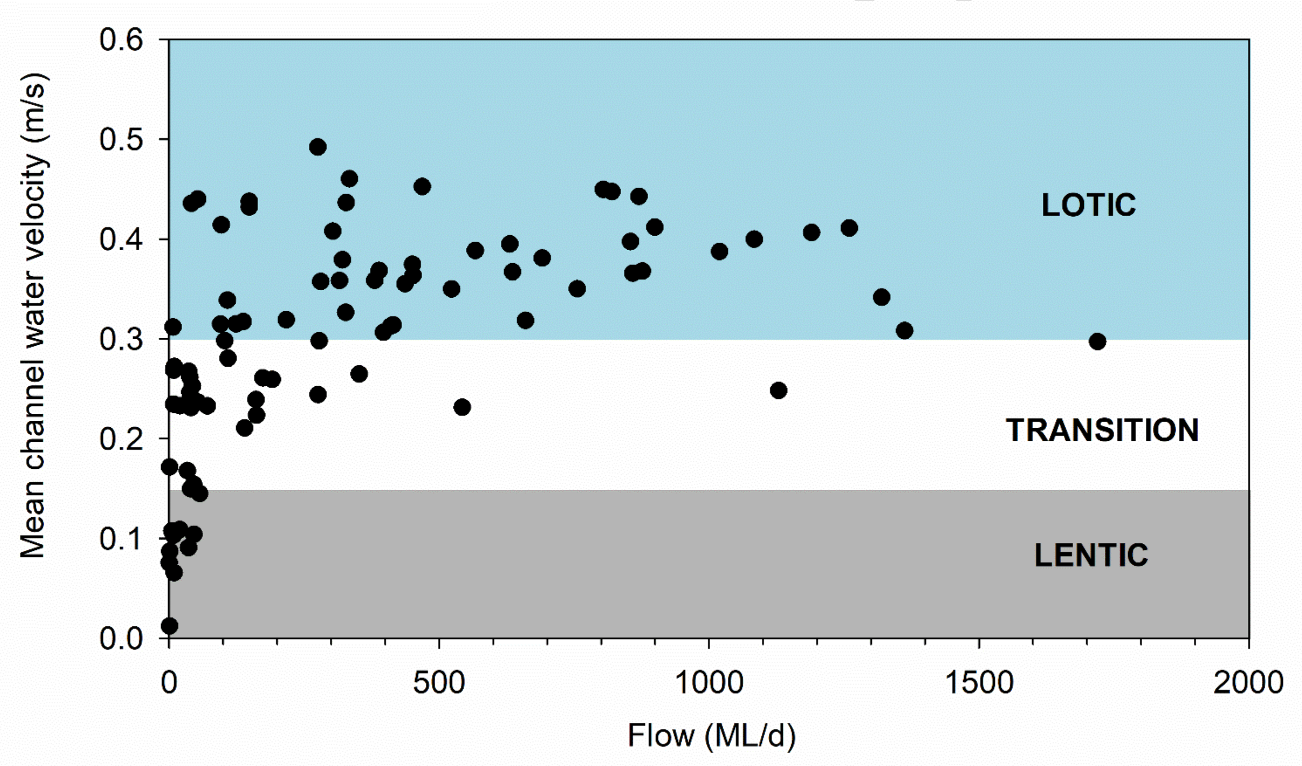


Figure 3. Hydrographic data of mean channel water velocity versus discharge for the middle of the Barwon-Darling River (Wilcannia). Lentic (< 0.15 m s^{-1}) and lotic (> 0.3 m s^{-1}) conditions are based on water velocity and are shaded grey and blue, respectively. Upper river (Walgett) and lower river (downstream of Menindee) graphs are in Appendix S4 in *Supporting Information* online. Lotic conditions for all three sites occur at relatively low discharges > 250 ML d^{-1}.

The duration of lentic periods greater than 3 months has also increased. At Wilcannia, historical droughts and modelled natural flows for the Millennium Drought show lentic periods of 4–9 months except for 12 months in 1902 (Fig. 4). The gauged flows in the Millennium and 2013–2019 droughts, however, have extreme events of 17 months duration in the Millennium Drought and 30 months in the 2013–2019 drought, which are the longest in the 134-year record. It should be noted that: contemporary data are expressed as mean monthly discharge to enable a comparison with the historical data, and; within the 30-month period in 2013–2019 there was 25 individual days with flows greater than 250 ML d^{-1}.

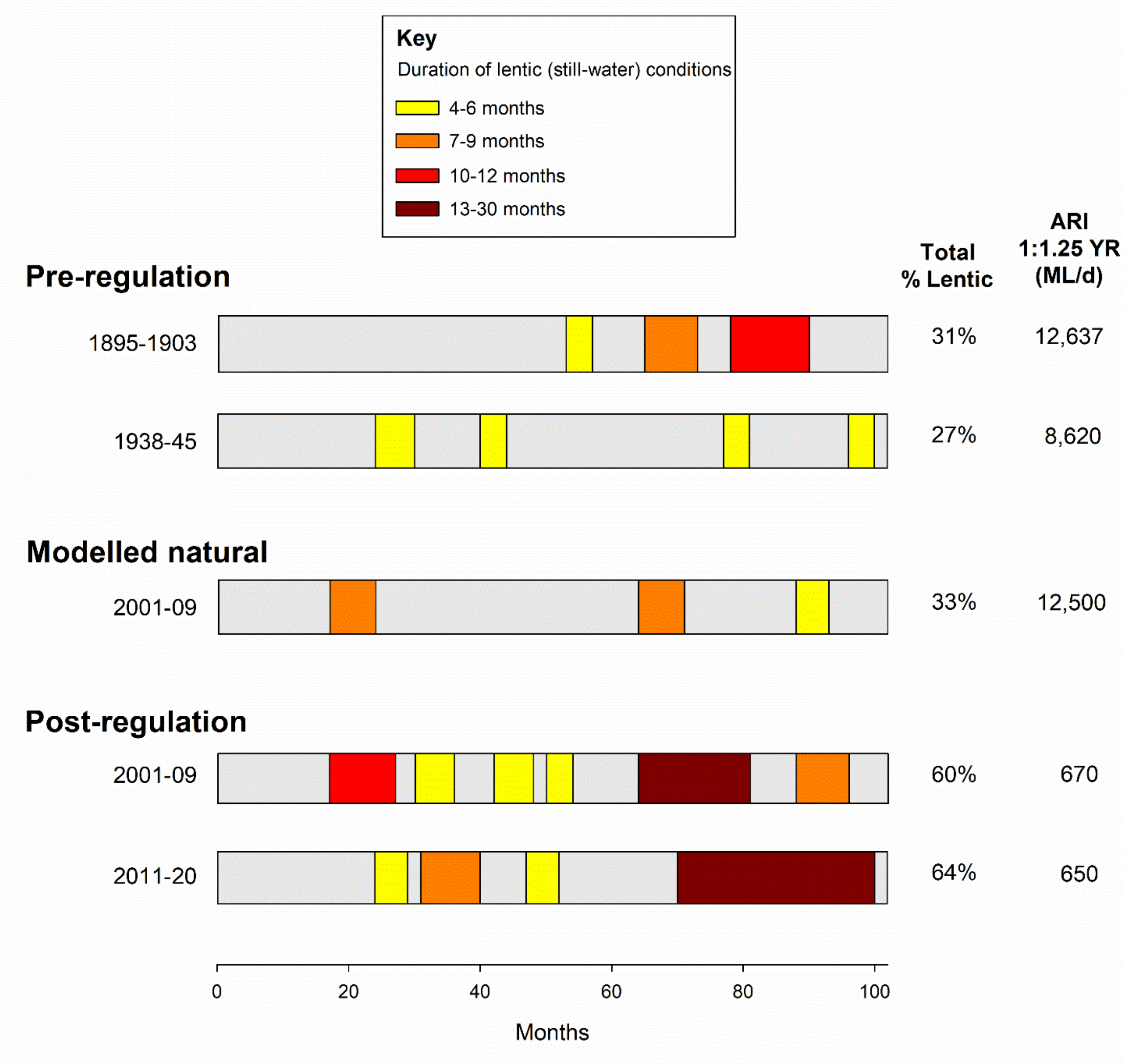


Figure 4. Duration of lentic conditions at Wilcannia >3 months for pre- and post-regulation droughts, and modelled natural flows for the Millennium Drought. Here lentic incorporates flows < 250 ML d^{-1} which includes the transition zone from lentic to lotic (100-250 ML d^{-1}). Also shown are the total percentage of lentic conditions (Fig. 2) and the 1:1.25 ARI flow. In post-regulation droughts, lentic conditions dominate, and lentic events are of greater duration; while the magnitude of flow pulses has reduced by >90%.

The spatial integrity of lotic habitats in the Barwon-Darling River is also fragmented by weirs, especially at low discharges, where 40% of the river channel is potentially comprised of lentic weirpools (Fig. 5). Consequently, under these conditions, the longest reaches with potential lotic habitats are between: 1) Walgett and the upper weirpool limit of Brewarrina (169 km), 2) Brewarrina and the upper weirpool limit of Bourke (117 km), 3) Tilpa and the upper weirpool of Wilcannia (173 km), and 4) Weir 32 and upper weirpool limit of Pooncarie (287 km).

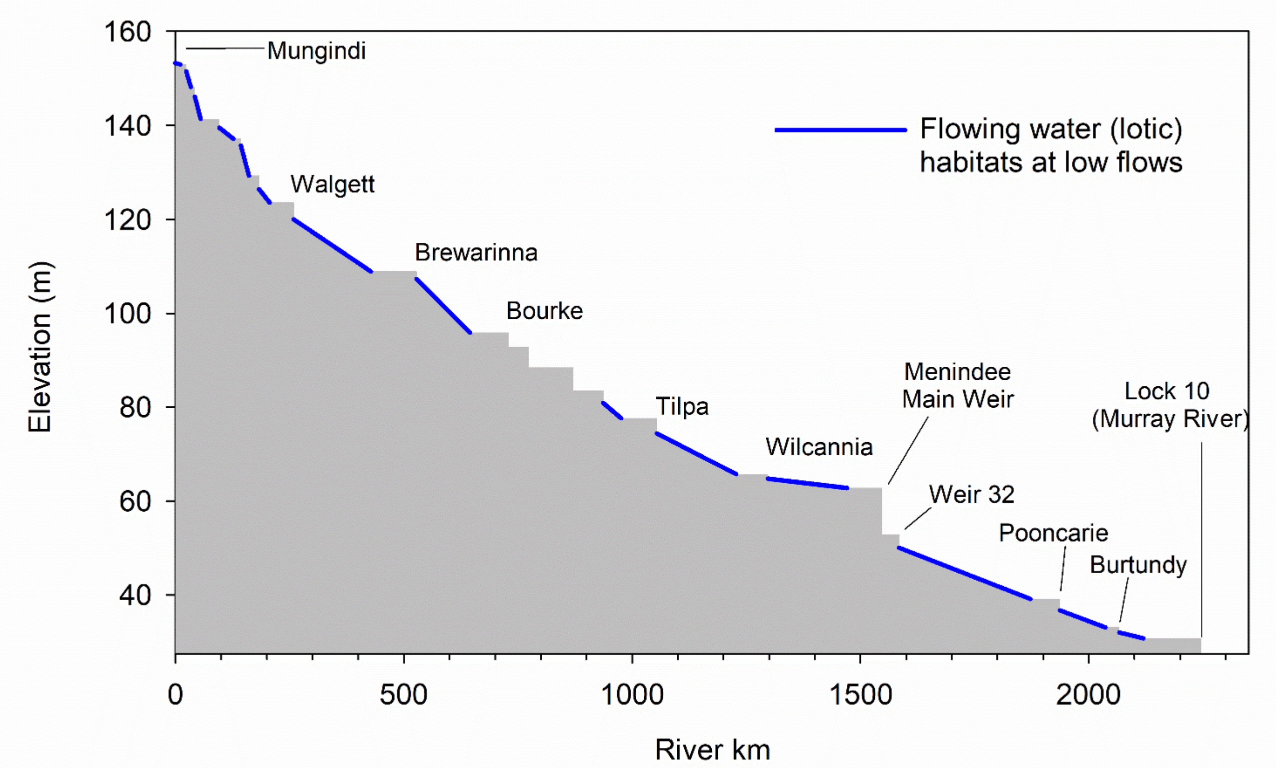


Figure 5. Profile of the Barwon-Darling River, with blue lines showing flowing (lotic) reaches between weirpools at low flows, and fragmentation of a long-distance lotic ecosystem.

In summary, regulation of the Barwon-Darling River has greatly reduced the magnitude of low flows, to the extent that lotic conditions occur for much less time and over far less area, while continuous periods of lentic conditions have increased. In the post-2000 droughts, the temporal extent of lotic habitats was reduced by approximately 50% while the spatial extent was reduced by weir pools. In addition, the pre-regulation hydrograph was characterised by substantial near-annual flow pulses, even during drought, but in contemporary droughts the magnitude of these has decreased by 92–95%. Overall, the Millennium and 2013–2019 drought show a change in the Barwon-Darling River in droughts from a predominantly connected lotic, to a fragmented lentic, river.

Mussels and Snails

The occurrence of mussels and snails in the paleo record provides insights into the past hydrology and hydraulics of the Barwon-Darling River. Balme (1990, 1995) examined 220 Aboriginal middens from a range of geomorphic types in the lower Darling River. The most common aquatic fauna in the middens were River Mussel and Floodplain Mussel (*Velesunio ambiguous*), followed by River Snail. Along the lower Darling River, River Mussel was present in all midden sites associated with river channels, while the Floodplain Mussel was in almost all floodplain midden sites (Balme 1990). Radiocarbon dating of the mussel shells (Balme and Hope 1990) shows the age of sites with River Mussel spanned from 15,250 to 99 years BP, with increments between 100 and 3420 years.

In 2019, deceased River Mussels were ubiquitous at 16 sites inspected along the Barwon-Darling River, while only one site had live individuals. The River Snail, which is presumed extinct in the Barwon-Darling system (NSW Department of Primary Industry 2007), was located at four sites, but all individuals were recently deceased. All dead snails were in desiccated rocky habitats and dead mussels in desiccated runs, both these habitats would have been characterised by lotic conditions under low flows.

Water management in low flows

In 2018-19, there was zero flow in the Darling River at Bourke (Fig. 1) for 433 days (29th August 2018 to 4th November 2019, https://realtimedata.waternsw.com.au/, accessed 25 November 2019). During this period, over 100,000 ML was captured in tributary headwater dams (Burrendong, Keepit, Copeton, Pindari, Glenlyon), which is a typical volume of inflows for a severe drought (Vertessy *et al.* 2019). In the same period, 932,460 ML of storage was released (https://realtimedata.waternsw.com.au/, accessed 8 December 2019), mostly for irrigation, but also for environmental flows (163,577 ML) , with 76% of this allocated to the Macquarie River (https://www.environment.gov.au/water/cewo/catchment/macquarie/history, accessed 1/1/2020). In conjunction, total average storage in the headwater dams decreased from 34% to 4%.

In the same period, a total of 32,671 ML entered the Barwon-Darling River between Mungindi and Bourke from: environmental flow releases from dams (18,095 ML), rainfall/runoff downstream of headwater dams (7194 ML from the Culgoa, Castlereagh and Namoi rivers) and other flows at Mungindi (7382 ML, which were partly a release from upstream dams) (https://realtimedata.waternsw.com.au/, accessed 8 December 2019). Of these flows, 1159 ML was accessible to irrigators with the lowest pumping thresholds (Class A), but this leaves 31,512 ML unaccounted for. Some of this loss of flow is due to evaporation, seepage, rewetting dry channels and filling water holes (Boulton *et al.* 2017). Substantial losses, however, also occur as a result of weirpools, where water levels and volume decrease due to extraction for town water and evaporation (Fig. 6). This creates airspace in weirpools that then captures small flow events, further contributing to the loss of flow downstream. Consequently, in 2018–19, a 433-day period of zero flows in the Darling River at Bourke was not solely the result of rainfall drought but also due to active management of headwater storages and water extraction from the river channel for consumptive use.

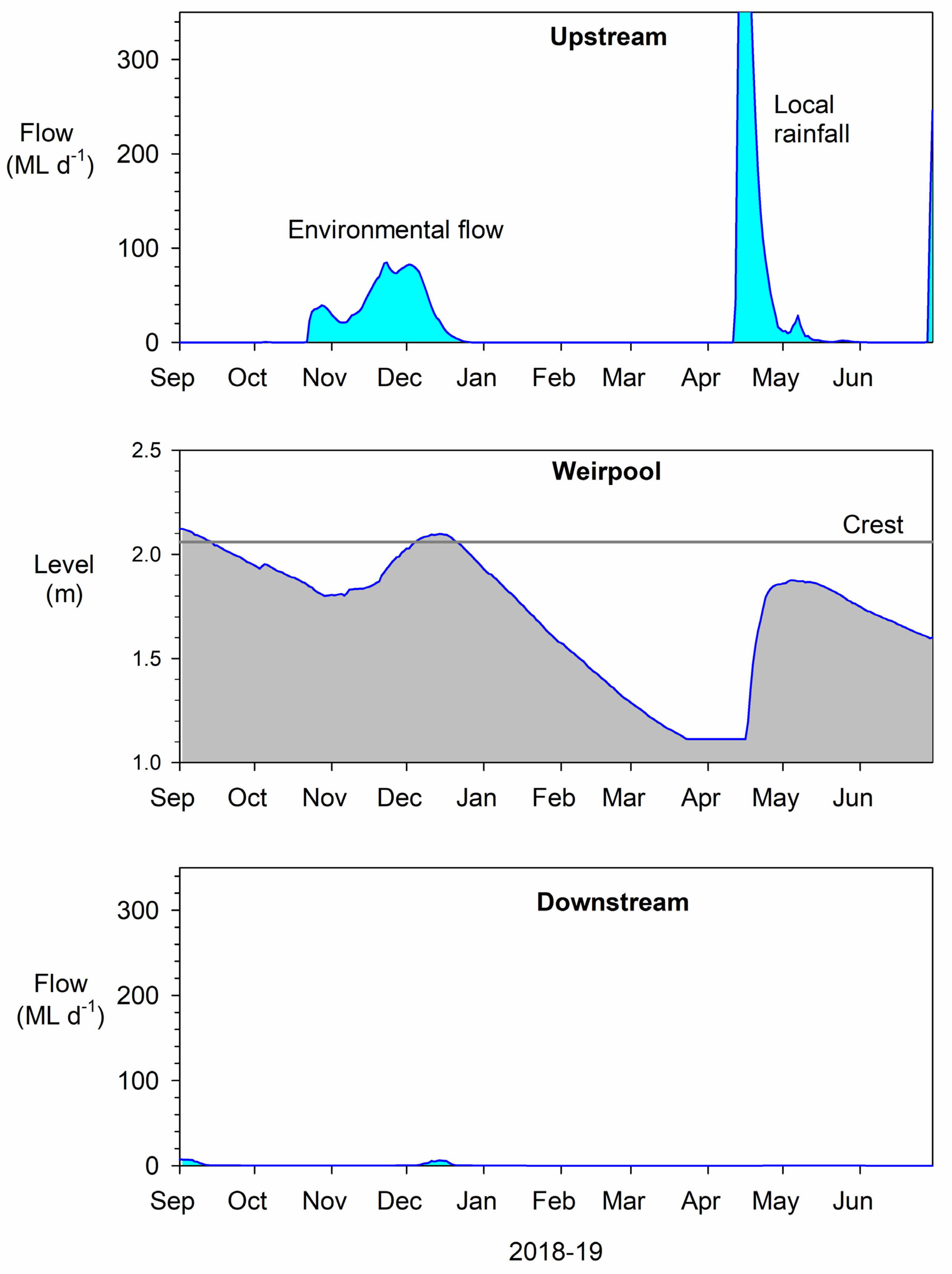


Figure 6. Example of flow capture in a weirpool (Brewarrina) during low flows in the Barwon-Darling River: a) flow approximately 100 km upstream (Gauge 422027), b) weirpool level (Gauge 42202), and c) flow passing weir downstream (Gauge 42202).

Discussion

The Barwon-Darling river system has been categorised as having one of the most variable and unpredictable hydrological regimes in the world (Puckridge *et al.* 1998; Thoms and Sheldon 2000). An emphasis on variability, however, overshadows three persistent features of pre-regulation hydrology and hydrodynamics: 1) near-perennial flows; 2) lotic (flowing water) habitats associated with these flows; and 3) frequent (e.g. every 15 months) flow pulses that provided large-scale (100s-1000s km), contiguous lotic conditions. We propose it is these features that have shaped the ecology of riverine biota in the Barwon-Darling; and which are now experiencing unprecedented change. We suggest an ecohydraulic perspective presents a critical and quantitative path forward for rehabilitating this highly modified river system and provides clear choices for stakeholders and river management.

Hydrology

The pre-regulation period of record used in the study (1885–1950) provides an indication of the natural hydrology of the Barwon-Darling River. Although 65 years is short in comparison to paleo timescales, it does include the drought-dominated regime between 1895 and 1946 (Mills *et al.* 2013), so these data are representative of a dry climate and are unlikely to significantly overestimate flows compared with data post-1950. From 1885–1950, the Barwon-Darling River exhibited a near-perennial hydrology, flowing continuously for up to 19 years and for more than 85% of the time through the worst recorded droughts. The persistent nature of this flow regime is further supported by the paleo-climate record that suggests the Federation Drought - with high baseflows and near-annual flow pulses - was the most severe drought in the Murray Basin in 400 years (Freund *et al*. 2017).

During the 2013–2019 drought, in the upper and middle reaches of the Barwon-Darling at Walgett and Wilcannia, flow intermittency increased in comparison to historical droughts. These zero flow periods could be attributed to diminished inflows caused by rainfall deficiency and climate change (Delworth and Zeng 2014). Nevertheless, our analysis shows that, in 2018–2019, capture and diversion of flow, firstly in headwater dams and secondly for town water supplies, contributed to 433 days of zero flow at Bourke, which is the longest in the 134-year record. Modelled natural flows for the Millennium Drought also indicate more flow and less intermittency than gauged (actual) flows.

Although the duration and frequency of zero flows in the Barwon-Darling River have increased, these events also occurred prior to flow regulation and are indeed considered part of the natural hydrology of the river. What is unnatural, however, is the impact of regulation on low flows and flow pulses, and the associated change in river hydraulics from lotic to lentic.

Hydrodynamics

Despite the extremely low gradient of the Barwon-Darling River (1:20,000, Matheson and Thoms 2018), lotic habitats are consistently present at low flows ($\geq$ 250 ML d^{-1}), and *lotic refugia* (semi-permanent regions of flowing water) likely remain present at very low flows (>100 ML d^{-1}). Prior to 1950, flows greater than 100 ML d^{-1} could be present continuously for years, and even in extreme droughts were present most of the time (75%). Hence, lotic habitats were a dominant natural feature of the Barwon-Darling, underpinning ecosystem processes and determining species composition. This perenniality and hydrodynamic diversity is in contrast to the concept of intermittency and persistence of lentic refugia (waterholes) being key drivers of the function and form of dryland rivers (Sheldon 2005); both are applicable, but this disparity demonstrates the broad hydrological and hydraulic spectrum in dryland rivers.

Hydrological measures (i.e. discharge) remain prime descriptors of dryland rivers, with timing and duration of intermittence often used as defining characters (Costigan *et al.* 2017). Nevertheless, if flow is present, but insufficient to generate lotic conditions, there can be an ecohydraulic impact that is overlooked. We suggest that identifying hydraulic thresholds and using *lentic (or lotic) duration, timing, frequency and spatial integrity* can help quantify and ameliorate ecohydraulic impacts in these rivers. In this study, using 250 ML d^{-1} as a discharge threshold revealed the substantial loss of lotic habitats in the Millennium and 2013–2019 droughts, due to abstraction of flow and low inflows across the catchment. Exacerbating this impact are weirpools, which at low flows, back water up for approximately 1000 km (>40%) of the Barwon-Darling; further reducing lotic habitats and fragmenting the spatial integrity of lotic reaches.

Considering these impacts, the Barwon-Darling River is at risk of transformation from a near-perennial, connected, primarily lotic ecosystem to an artificially intermittent, fragmented, lentic-dominated ecosystem. This is a global issue, with biodiversity in many perennial, dryland rivers impacted by artificial intermittency driven by anthropogenic modification of flow regimes (Kingsford *et al*. 2006; Datry *et al.* 2014).

Flow pulses

Flow data from historical droughts and modelled natural flow for the Millennium Drought indicate that, without storage and diversion of flow, a flow pulse greater than 9,000 ML d^{-1} – typically an increase in river level of two metres – would have occurred every 15 months. These reliable flow pulses are analogous to the annual spring flow pulses that characterised the unregulated flow regime of the adjacent River Murray (Mallen-Cooper and Zampatti 2018). In the Barwon-Darling and elsewhere, these regular hydrological events shape the life histories of riverine biota, consequently influencing ecosystem structure (Mims and Olden 2013). Flow pulses also provide essential carbon inputs to the riverine ecosystem in the periods between less frequent overbank floods (Sheldon and Thoms 2006), and they promote reliable and contiguous lotic habitats over large spatial scales (100s–1000s km) for biota to exploit. Not surprisingly, these events are associated with spawning and strong regional age-classes of Golden Perch (*Macquaria ambigua*) (Sharpe 2011; Zampatti *et al.* 2019), a species characterised by pelagic (drifting) eggs and larvae and flow-related episodic recruitment (Zampatti and Leigh 2013).

Paleo-ecohydraulics

The paleo-record of mussels and snails in Aboriginal middens provides further evidence for the persistence of low flows and lotic conditions in the Barwon-Darling River. River Mussel and River Snail are characteristic of lotic ecosystems and do not persist in lentic habitats and intermittent rivers with long periods of zero flow (Walker 1996; Walker *et al.* 2001; Ponder and Walker 2003). Both these lotic species are present in middens across a time span from the wet early Holocene (11,700 years before present) to the drier later Holocene (Balme 1990, 1995; Stanley and De Deckker 2002) indicating that flowing-water habitats were enduring and that periods of zero flow were sufficiently short to not impact population persistence.

Deaths of fish, mussels and snails

In the summer of 2018–19, hundreds of thousands to over a million fish died in a 30km reach of the lower Darling River, which was attributed to a combination of low flows, high water temperatures, cyanobacteria, thermal stratification and deoxygenation (Vertessy *et al.* 2019). The fish deaths attracted global attention (Normile 2019; Remeikis 2019), but less recognised were extensive mortalities of River Mussel and River Snail, across the Barwon-Darling river system. River Mussel deaths extended from

Menindee to the Queensland border (1500km) and four recently discovered populations of River Snail between Tilpa and the Queensland border were all dead, placing this species at high risk of extinction. It is likely that these mortalities were a result of the extended duration of zero flow and loss of lotic habitats, in association with high temperatures. Continuous periods in which daily maximum air temperatures exceeded 40°C have occurred in other droughts – notably 11 days in the World War II Drought and 22 days in the Federation Drought, which included 13 days above 45°C (Bureau of Meteorology data, www.bom.gov.au, accessed 16/06/2019). Nevertheless, these events coincided with discharges in the Barwon-Darling River (Wilcannia, Menindee) of greater than 500 ML d^{-1} (Water Conservation and Irrigation Commission 1956), which would have protected fish, mussels (Walker 1981) and other riverine biota, while mitigating thermal stratification and risk of cyanobacterial blooms (Mitrovic *et al.* 2010).

Climate change

Climate change is predicted to make south-eastern Australia hotter and drier (Cai and Cowan 2008; Whetton 2011) causing dryland rivers to become more intermittent (Larkin *et al*. 2020). In the Barwon-Darling River, however, a focus on the influence of climate change and drought on the river's flow regime potentially overshadows the dominant impacts of flow storage and diversions. Under present conditions dams and weirs can, and do, capture up to 100% of inflows in droughts. By 2030, climate change may alter runoff in the Barwon-Darling catchment by -10% (range: -29 to +12%) (CSIRO, 2012). In conjunction with current flow management, this would lead to longer periods of zero flows and lentic conditions; but the predominant cause would remain storage and diversion.

Implications for management

An ecohydraulic premise for the Barwon Darling River

Our study indicates that the riverine ecosystem of the Barwon-Darling has been shaped by a near-perennial hydrological regime and consistency of lotic habitats; arguably as much as the hydrological extremes of zero flow and flood. In the Barwon-Darling River, a focus on hydrological variability overlooks the influence of persistent hydrodynamic features, such as flowing water, in shaping ecological processes and patterns, particularly during low flow periods.

Lotic habitats throughout the MDB support a suite of specific biota, including biofilms, snails, mussels, aquatic insects, crustacea and fish (e.g. Sheldon and Walker 1989, Whiterod and Zubowski 2019). Indeed, the hydrological and hydraulic template of the Barwon-Darling supports a fish assemblage more akin to the adjacent perennial River Murray (Mallen-Cooper and Zampatti 2018), which has permanent lotic habitats, than the ephemeral northern tributaries of the Barwon-Darling catchment, which have long periods of zero flow and lentic conditions (Balcombe *et al.* 2006). Hence, management of the Barwon-Darling as a primarily intermittent river system, that dries to a series of lentic *refuge* water holes, will threaten this lotic ecosystem, with subsequent loss of biodiversity. Such an approach also disadvantages consumptive users of water in the lower catchment, and undermines the public and cultural amenity provided by a near-perennial, lotic ecosystem.

In contemporary droughts in the Barwon-Darling River, two impacts on hydrology and hydraulics stand out: 1) the loss of low flows and associated lotic conditions, and 2) a reduction in regular flow pulses. All aquatic species in the Barwon-Darling can survive temporary periods of zero flow and lentic conditions, but historically, these were dispersed within long periods (month–years) of continuous lotic conditions, enabling populations of uniquely lotic biota to persist. Very low flows, below lotic thresholds, may meet historical metrics of intermittence but do not support a lotic riverine ecosystem.

Making low flows *flow*

Managing low flows in droughts to meet societal and environmental needs is complex and contentious. This is partly because of compartmentalised water management between sub-catchments, which are all upstream of the Barwon-Darling; and trying to meet all objectives when water is at its scarcest. The objectives are not, however, mutually exclusive and are highly achievable. There are four elements to rehabilitating this lotic ecosystem, and making low flows *flow* in the Barwon-Darling River:

1) Incorporating hydrodynamic objectives in water management

Water volumes and discharge are the universal currency of flow management. From an ecological perspective, however, volume and discharge are ultimately surrogates for spatio-temporal hydraulics (hydrodynamics), including depth, velocity, turbulence; that is, the physical environment in which aquatic biota exist (Lancaster and Downes 2010). In the Murray Darling Basin, volume and discharge are fundamental to water policy and management (e.g. Commonwealth (*Water Act 2007*), New South Wales (*Water Management Act 2000*)) but concepts of hydrodynamics are absent. With some modification, however, hydrodynamics can be integrated into contemporary water management. Discharge would remain as the main management lever with hydrodynamics as the primary objective. In the present study, preliminary hydrodynamic-hydrological thresholds have been identified, but to provide spatial detail of ecohydraulic habitats, a comprehensive hydraulic model of the river is required (e.g. Mallen-Cooper and Zampatti 2018).

2) Enabling greater continuity and near permanency of low flows from headwater dams

Applying a low flow regime in the Barwon-Darling requires alternative water management in tributaries. Currently, catchment specific Water Sharing Plans operate largely independently and have little or no requirement to pass water from upstream storage dams to the Barwon-Darling River (e.g. Water Sharing Plan for the Gwydir Regulated River Water Source 2016, https://legislation.nsw.gov.au/#/view/regulation/2015/629, accessed 3 January 2020). The impacts of this compartmentalised water management are exaggerated in a system like the Barwon-Darling which receives 99% of its water from tributaries (Murray-Darling Basin Authority 2018). Linking operation of storage dams and tributaries so they contribute to low flows in the Barwon-Darling is a key to the future health of the river.

3) Providing alternative water sources for towns to prevent extraction at low flows

The present study has shown that water abstraction from weirpools for consumptive use has a profound impact on low flows in the Barwon-Darling. Hence, we suggest the third key component of providing low flows – and preventing ecologically detrimental periods of zero flow – is to provide alternative water supplies for towns and individual landholders on the Barwon-Darling River. One option is off-stream storage, which can be filled during periods of elevated flow, thus decoupling the competing needs of people and the environment at low flows, especially in droughts. The feasibility of this approach has been demonstrated by the NSW Government which built a 500 ML storage for $8.2 million on a tributary of the Barwon-Darling River at Nyngan (NSW Treasury 2019). Groundwater is also an alternative and there may be scope for recharging underground aquifers and using these for storage (Ward and Dillon 2012).

4) Reducing the extent of weirpools

In the Barwon-Darling River, most weirs were built from 1949 to 1980 to provide water supplies for towns during droughts (Thoms *et al.* 1996). The weirpools also provide social and recreational amenity.

Some weirs, however, are remote and support only a few users that could feasibly be accommodated with off-stream storage. Presently, weirs on the Barwon-Darling are being rationalised under the 'western weirs' project (*Water Supply (Critical Needs) Act 2019*). This project presents the opportunity to reduce the number of weirs and recover lotic habitats that have been impacted by weirpools; effectively gaining considerable reaches of lotic habitats. The alternative, of more and/or higher weirs, thus exacerbating the impact of weirpools, would further compromise the integrity of the river ecosystem.

Conclusion

A common premise for the Barwon-Darling River is a highly variable hydrology with long periods of zero flow. Yet, reviewing hydrological and hydraulic data, particularly during severe droughts, reveals that within this variability there is also consistency, with: persistent baseflows supporting lotic habitats; and near-annual, landscape-scale flow pulses. This realisation presents a significant opportunity to improve ecosystem integrity by recovering these key ecohydraulic facets of the natural flow regime through integrated water management, alternative sources of water for consumptive use during low flows, and weir rationalisation. The past provides insight into a Barwon-Darling River ecosystem that supported lotic biota and people for millennia, even with low inflows in extreme droughts. This context enables an ecohydraulic perspective of the river that helps explain present impacts, provides new directions for river management, and clarifies choices for stakeholders.

Acknowledgements

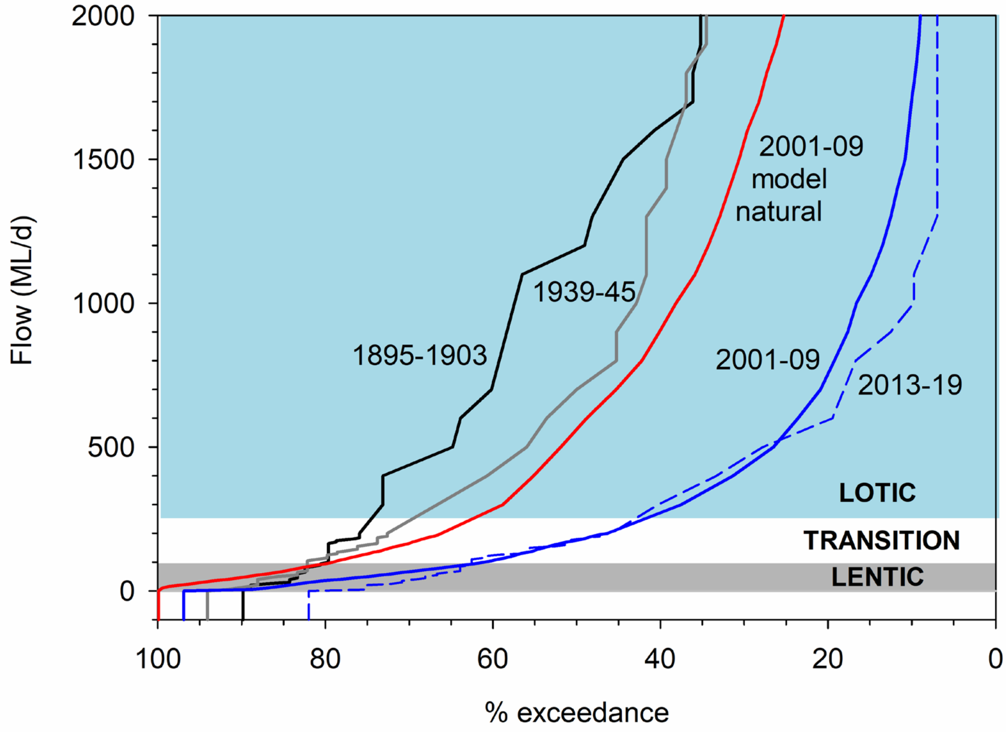
We would like to thank Chris Bice, Terry Hillman and Paul Simpson for insightful comments on the manuscript; the Murray-Darling Basin Authority for providing extensive modelled and gauged hydrological data; WaterNSW for hydrographic data; and John Koehn and two anonymous referees for helpful comments that improved the final manuscript.

Supporting Information

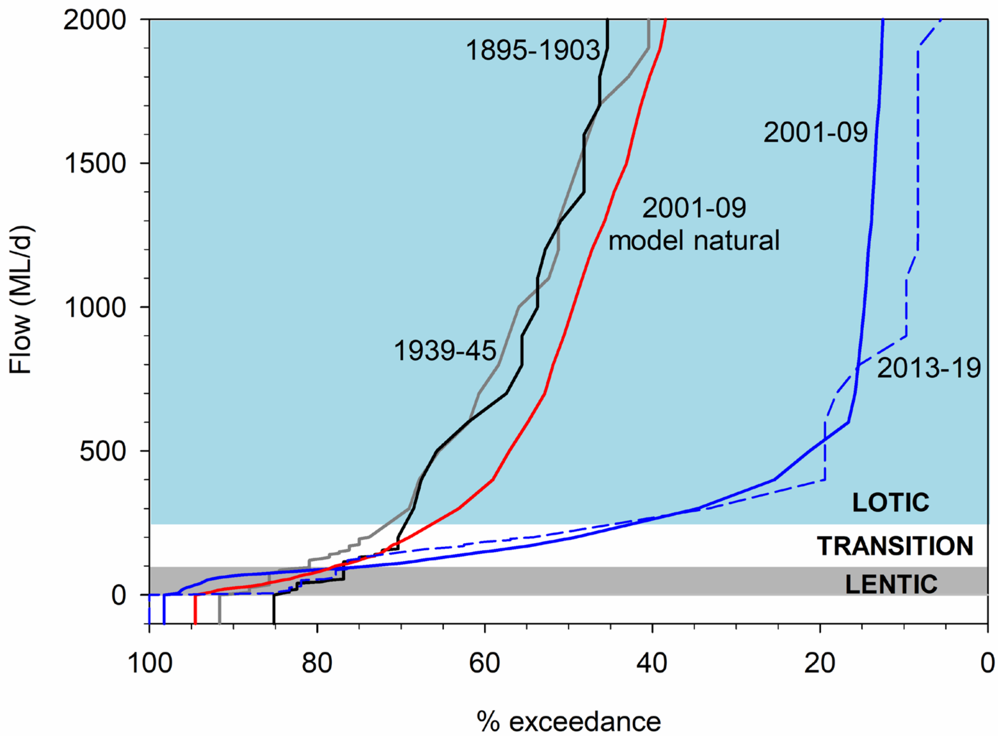
Additional supporting information is online in the Supporting Information section at the end of the article (https://onlinelibrary.wiley.com/doi/10.1111/emr.12428).

Appendix S1. Locations of sites along the Barwon-Darling River inspected for River Mussel and River Snail. (https://onlinelibrary.wiley.com/doi/10.1111/emr.12428)

a) Upper river
(Walgett)

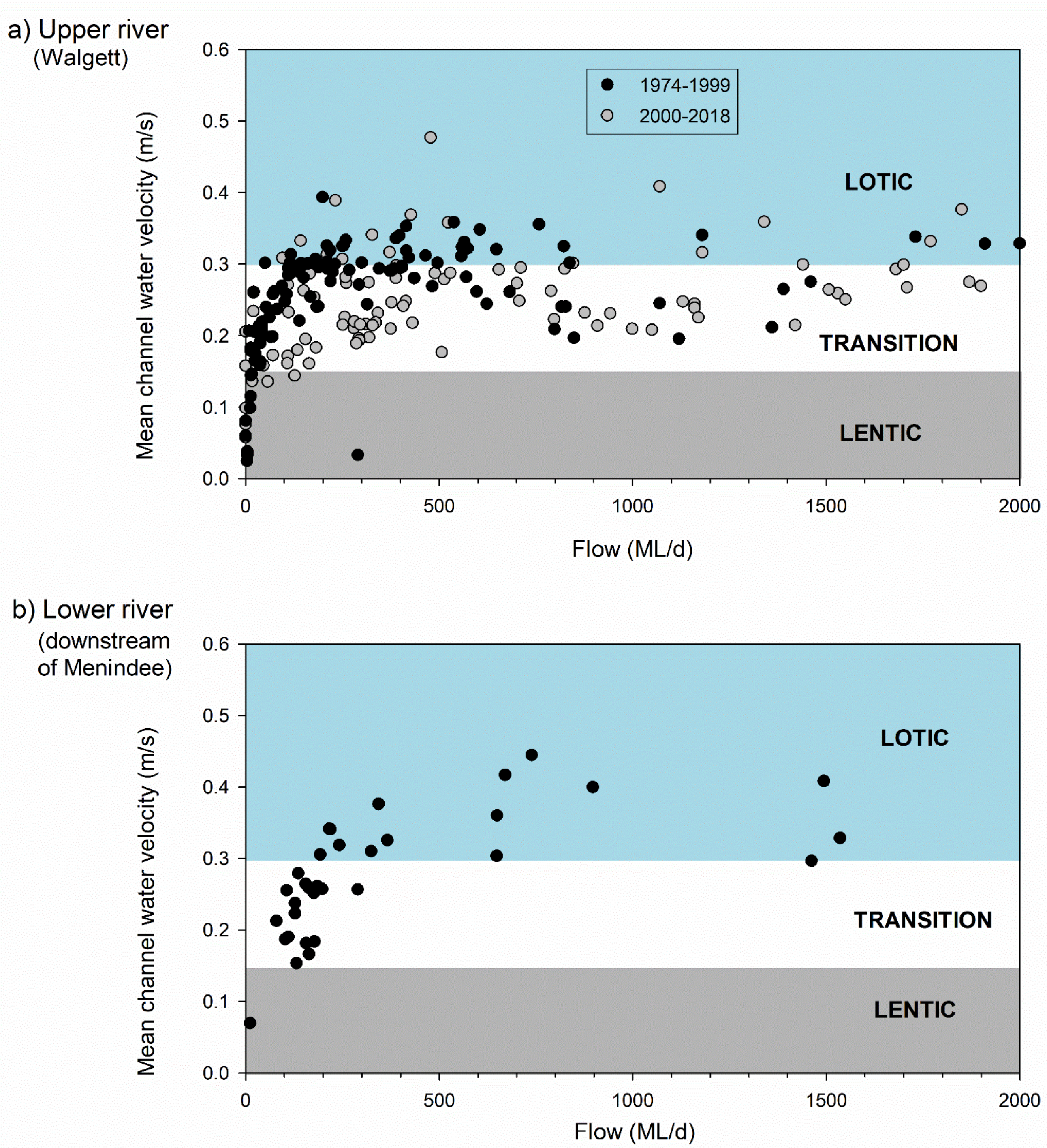


b) Lower river
(Menindee)



Appendix S2. Additional data for Figure 2: flow duration curves of droughts pre-regulation (black and grey lines) and post-regulation (blue solid and dashed lines), shown with modelled natural flow for the Millennium Drought (2001-09), for the upper (Walgett) and lower (Menindee) reaches of the Barwon-Darling River. Lentic (< 0.15 m s^{-1}) and lotic (> 0.3 m s^{-1}) flows, derived from hydrographic data (Fig. 3), are shaded grey and blue, respectively. Middle river (Wilcannia) data in Fig. 2.

Appendix S3. Video of the Barwon-Darling River upstream of Wilcannia weirpool, passing 1515 ML/d on 27 May 2020. Video shows lotic (flowing water) conditions, with rocky habitat in the foreground and large woody debris in the background (link to online video).



Appendix S4. Additional data for Figure 3: hydrographic data of mean channel water velocity versus discharge for the upper (Walgett) and lower (downstream of Menindee) reaches of the Barwon-Darling River. Lentic (< 0.15 m s^{-1}) and lotic (> 0.3 m s^{-1}) conditions are based on water velocity and are shaded grey and blue, respectively. Middle river (Wilcannia) data in Fig. 3. Lotic conditions for all three sites occur at relatively low discharges > 250 ML d^{-1}.

References

Arthington, A.H., and Balcombe, S.R. (2011) Extreme flow variability and the 'boom and bust'ecology of fish in arid-zone floodplain rivers: a case history with implications for environmental flows, conservation and management. *Ecohydrology* **4**(5), 708-720.

Australian Academy of Science (2019) Investigation of the causes of mass fish kills in the Menindee Region NSW over the summer of 2018–2019.

Balcombe, S.R., Arthington, A.H., Foster, N.D., Thoms, M.C., Wilson, G.A., and Bunn, S.E. (2006) Fish assemblages of an Australian dryland river: abundance, assemblage structure and recruitment patterns in the Warrego River, Murray–Darling Basin. *Marine and Freshwater Research* **57**(6), 619-633.

Balcombe, S.R., Bunn, S., Arthington, A., Fawcett, J., McKenzie-Smith, F.J., and Wright, A. (2007) Fish larvae, growth and biomass relationships in an Australian arid zone river: links between floodplains and waterholes. *Freshwater Biology* **52**(12), 2385-2398.

Balme, J. (1990) A Pleistocene tradition: Aboriginal fishery on the Lower Darling River, western NSW. PhD thesis, Research School of Pacific Studies, Australian National University, 256 p.

Balme, J. (1995) 30,000 years of fishery in western New South Wales. *Archaeology in Oceania* **30**(1), 1-21.

Balme, J., and Hope, J. (1990) Radiocarbon dates from midden sites in the lower Darling River area of western New South Wales. *Archaeology in Oceania* **25**(3), 85-101.

Bice, C.M., Gibbs, M.S., Kilsby, N.N., Mallen-Cooper, M., and Zampatti, B.P. (2017) Putting the "river" back into the Lower River Murray: quantifying the hydraulic impact of river regulation to guide ecological restoration. *Transactions of the Royal Society of South Australia* **141**(2), 108-131.

Blair, T. (2019) It's often boom or bust. In The Daily Telegraph. pp. 14. (News Corp Australia: Surry Hills)

Boulton, A.J., Rolls, R.J., Jaeger, K.L., and Datry, T. (2017) Hydrological connectivity in intermittent rivers and ephemeral streams. In: Intermittent rivers and ephemeral streams (eds T. Datry, N. Bonada, A. Boulton). pp. 79-108. Elsevier, London.

Bowling, L.C., and Baker, P.D. (1996) Major cyanobacteria bloom in the Barwon-Darling River, Australia, in 1991, and underlying limnological conditions. *Marine and Freshwater Research* **47**, 643-657.

Bunn S.E., and Arthington, A.H. (2002) Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. *Environmental Management* **30**, 492-507.

Cai, W., and Cowan, T. (2008) Evidence of impacts from rising temperature on inflows to the Murray-Darling Basin. *Geophysical research letters* **35**(7).

Chu, L., Grafton, R.Q., and Stewardson, M. (2018) Resilience, Decision-making, and Environmental Water Releases. *Earth's Future* **6**(6), 777-792.

Costigan, K.H., Kennard, M.J., Leigh, C., Sauquet, E., Datry, T., and Boulton, A.J. (2017) Flow regimes in intermittent rivers and ephemeral streams. In: Intermittent Rivers and Ephemeral Streams (eds T. Datry, N. Bonada, A. Boulton). pp. 51-78. Elsevier, London.

CSIRO (2012) Climate and water availability in south-eastern Australia: A synthesis of findings from Phase 2 of the South Eastern Australian Climate Initiative (SEACI), CSIRO, Australia.

Datry, T., Larned, S.T. and Tockner, K. (2014) Intermittent rivers: a challenge for freshwater ecology. *BioScience* **64**(3), 229-235.

Delworth, T.L., and Zeng, F. (2014) Regional rainfall decline in Australia attributed to anthropogenic greenhouse gases and ozone levels. *Nature Geoscience* **7**(8), 583-587.

Freund, M., Henley, B.J., Karoly, D.J., Allen, K.J., and Baker, P.J. (2017) Multi-century cool-and warm-season rainfall reconstructions for Australia's major climatic regions. *Climate of the Past* **13**, 1751-1770.

Garvey, J. (2017) Australian Aboriginal freshwater shell middens from late Quaternary northwest Victoria: Prey choice, economic variability and exploitation. *Quaternary International* **427**, 85-102.

Humphries, P. (2007) Historical Indigenous use of aquatic resources in Australia's Murray-Darling Basin, and its implications for river management. *Ecological Management & Restoration* **8**(2), 106-113.

Kingsford, R.T., Lemly, A.D. and Thompson, J.R. (2006) Impacts of dams, river management and diversions on desert rivers. In: Ecology of Desert Rivers (ed R.T. Kingsford) pp 203-247. Cambridge University Press, Cambridge.

Koehn, J. (2015) Managing people, water, food and fish in the Murray–Darling Basin, south-eastern Australia. *Fisheries Management and Ecology* **22**(1), 25-32.

Lancaster, J., and Downes, B.J. (2010) Linking the hydraulic world of individual organisms to ecological processes: putting ecology into ecohydraulics. *River Research and Applications* **26**(4), 385-403.

Larkin, Z.T., Ralph, T.J., Tooth, S., Fryirs, K.A. and Carthey, A.J.R. (2020) Identifying threshold responses of Australian dryland rivers to future hydroclimatic change. *Scientific reports* **10**(1), 1-15.

Leblanc M., Tweed S., Van Dijk A. and Timbal B. (2012) A review of historic and future hydrological changes in the Murray-Darling Basin. *Global and planetary change* **80**, 226-246.

Leigh, C., Sheldon, F., Kingsford, R.T., and Arthington, A.H. (2010) Sequential floods drive'booms' and wetland persistence in dryland rivers: a synthesis. *Marine and Freshwater Research* **61**(8), 896-908.

Mallen-Cooper, M., and Zampatti, B.P. (2018) History, hydrology and hydraulics: Rethinking the ecological management of large rivers. *Ecohydrology* **11**(5), e1965.

Matheson, A., and Thoms, M. (2018) The spatial pattern of large wood in a large low gradient river: the Barwon–Darling River. *International journal of river basin management* **16**(1), 21-33.

Mathews, R.H. (1903) The Aboriginal Fisheries at Brewarrina. *Proceedings of the Royal Society of New South Wales* **37**, 146-156.

Mills, K., Gell, P., Hesse, P.P., Jones, R., Kershaw, P., Drysdale, R., and McDonald, J. (2013) Paleoclimate studies and natural-resource management in the Murray-Darling Basin I: past, present and future climates. *Australian Journal of Earth Sciences* **60**(5), 547-560.

Mims, M.C., and Olden, J.D. (2013) Fish assemblages respond to altered flow regimes via ecological filtering of life history strategies. *Freshwater Biology* **58**(1), 50-62.

Mitrovic, S.M., Hardwick, L., and Dorani, F. (2010) Use of flow management to mitigate cyanobacterial blooms in the Lower Darling River, Australia. *Journal of Plankton Research* **33**(2), 229-241.

Murray-Darling Basin Commission (2004) The Living Murray Information Paper no. 10: Menindee lakes, the Lower Darling River and Darling Anabranch. 15 p. Murray-Darling Basin Authority (2018) Observed Flows in the Barwon–Darling 1990-2017: A Hydrologic Investigation. Murray-Darling Basin Authority. 160 p. Murray-Darling Basin Authority, Canberra, Australia.

Normile, D. (2019) Massive fish die-off sparks outcry in Australia. (American Association for the Advancement of Science)

NSW Department of Primary Industries (2007) Recovery plan for the endangered river snail (*Notopala sublineata*). (NSW Department of Primary Industries: Orange.) 28 p.

NSW Department of Primary Industries (2015) Fish and Flows in the Northern Basin: responses of fish to changes in flow in the Northern Murray-Darling Basin - Reach Scale Report. Final Report prepared for the Murray-Darling Basin Authority. (NSW Department of Primary Industries: Tamworth.) 102 p.

NSW Treasury (2019) NSW Budget 2019-20 Half-Yearly Review. NSW Government, Sydney.

Petts, G. (2017) Perspective: river science for dryland river regulation. *Transactions of the Royal Society of South Australia* **141**(2), 230-236.

Ponder, W.F., and Walker, K.F. (2003) From Mound Springs to Mighty Rivers: The conservation Status of Freshwater Molluscs in Australia. *Aquatic Ecosystem Health & Management* **6**(1), 19-28.

Puckridge, J., Sheldon, F., Walker, K.F., and Boulton, A. (1998) Flow variability and the ecology of large rivers. *Marine and freshwater research* **49**(1), 55-72.

Remeikis, A. (2019) Michael McCormack makes first visit to Menindee since fish kill: 'We're all experts in hindsight'; Nationals leader, who had earlier blamed mass deaths on lack of rain, defends irrigators and plays down climate change. In Guardian [London, England]. (Guardian Newspapers Limited: Kings Place, 90 York Way, London, United Kingdom)

Richter, B.D., Mathews, R., Harrison, D.L., and Wigington, R. (2003) Ecologically sustainable water management: managing river flows for ecological integrity. *Ecological Applications* **13**(1), 206-224.

Rolls R.J., Leigh C., and Sheldon F. (2012) Mechanistic effects of low-flow hydrology on riverine ecosystems: ecological principles and consequences of alteration. *Freshwater Science* **31**, 1163-1186.

Sharpe, C.P. (2011) Spawning and recruitment ecology of golden perch (*Macquaria ambigua* Richardson 1845) in the Murray and Darling rivers. PhD Thesis, Griffith University.

Sheldon, F. (2005) Incorporating natural variability into the assessment of ecological health in Australian dryland rivers. *Hydrobiologia* **552**(1), 45-56.

Sheldon, F., Bunn, S.E., Hughes, J.M., Arthington, A.H., Balcombe, S.R., and Fellows, C.S. (2010) Ecological roles and threats to aquatic refugia in arid landscapes: dryland river waterholes. *Marine and Freshwater Research* **61**(8), 885-895.

Sheldon, F., and Walker, K. (1989) Effects of hypoxia on oxygen consumption by two species of freshwater mussel (Unionacea: Hyriidae) from the River Murray. *Marine and Freshwater Research* **40**(5), 491-499.

Smakhtin, V.U. (2001) Low flow hydrology: a review. *Journal of hydrology* **240**(3-4), 147-186.

Stanley, S., and De Deckker, P. (2002) A Holocene record of allochthonous, aeolian mineral grains in an Australian alpine lake; implications for the history of climate change in southeastern Australia. *Journal of Paleolimnology* **27**(2), 207-219.

Thoms, M., and Delong, M. (2018) Ecosystem responses to water resource developments in a large dryland river. *Water Resources Research* **54**(9), 6643-6655.

Thoms, M.C., and Sheldon, F. (2000) Water resource development and hydrological change in a large dryland river: the Barwon-Darling River, Australia. *Journal of Hydrology* **228**, 10-21.

Thoms, M.C., Sheldon, F., and Crabb, P. (2004) The hydrology of rivers in the Darling Basin. In The Darling. (Eds. R Breckwodt, R Boden and J Andrew) pp. 78-92. (Murray-Darling Basin Commission: Canberra)

Thoms, M.C., Sheldon, F., Roberts, J., Harris, J.H., and Hillman, T.J. (1996) Scientific panel assessment of environmental flows for the Barwon-Darling River. A report to the Technical Services Division of the New South Wales Department of Land and Water Conservation.

Tonkin, Z., King, A., Mahoney, J., and Morrongiello, J. (2007) Diel and spatial drifting patterns of silver perch *Bidyanus bidyanus* eggs in an Australian lowland river. *Journal of Fish Biology* **70**(1), 313-317.

Tooth, S. (2000) Process, form and change in dryland rivers: a review of recent research. *Earth-Science Reviews* **51**(1), 67-107.

van Dijk, A.I., Beck, H.E., Crosbie, R.S., Jeu, R.A., Liu, Y.Y., Podger, G.M., Timbal, B., and Viney, N.R. (2013) The Millennium Drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy, and society. *Water Resources Research*.

Verdon-Kidd, D.C., and Kiem, A.S. (2009) Nature and causes of protracted droughts in southeast Australia: Comparison between the Federation, WWII, and Big Dry droughts. *Geophysical Research Letters* **36**(22), L22707.

Vertessy, R., Barma, D., Baumgartner, L., Mitrovic, S., and Sheldon, F. (2019) Independent Assessment of the 2018-19 fish deaths in the lower Darling. Report to the Federal Government of Australia. 99p.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R., and Davies, P.M. (2010) Global threats to human water security and river biodiversity. *Nature* **467**(7315), 555-561.

Walker, K.F. (1981) Ecology of Freshwater Mussels in the River Murray. *Australian Water Resources Council Technical Paper* **63**, 119 p.

Walker, K. (1996) The river snail *Notopala hanleyi*: an endangered pest. *Xanthopus (Nat Conserv Soc SA), March*, 1-5.

Walker, K., Byrne, M., Hickey, C., and Roper, D. (2001) Freshwater Mussels (Hyriidae) of Australasia. In: Ecology and Evolution of the Freshwater Mussels Unionoida. Ecological Studies, Vol. 145. Eds. G. Bauer and K. Wächtler) pp. 5-31. Springer-Verlag, Berlin Heidelberg.

Walker, K.F., Sheldon, F., and Puckridge, J.T. (1995) A perspective on dryland river ecosystems. *Regulated Rivers: Research and Management* **11**, 85-104.

Ward, J., and Dillon, P. (2012) Principles to coordinate managed aquifer recharge with natural resource management policies in Australia. *Hydrogeology Journal* **20**(5), 943-956.

Water Conservation and Irrigation Commission (1956) Surface Water Supply of New South Wales. Stream Flow Records Period to 31st December 1950. Volume 1. Darling River Basin. V.C.N Blight, Government Printer, Sydney.

Webb, M., Thoms, M., and Reid, M. (2012) Determining the ecohydrological character of aquatic refugia in a dryland river system: the importance of temporal scale. *Ecohydrology & Hydrobiology* **12**(1), 21-33.

Whetton, P. (2011) Future Australian climate scenarios. *Climate change: science and solutions for Australia*, 35-44.

Whiterod, N.S., and Zukowski, S. (2019) It's not there, but it could be: a renewed case for reintroduction of a keystone species into the Lower River Murray. *Transactions of the Royal Society of South Australia* **143**(1), 51-66.

Young, W.J., and Kingsford, R.T. (2006) Flow variability in large unregulated dryland rivers. In: Ecology of Desert Rivers. (ed. R.T. Kingsford) pp. 11-46. Cambridge University Press, Cambridge.

Zampatti, B. P., and Leigh, S. J. (2013) Within-channel flows promote spawning and recruitment of golden perch, *Macquaria ambigua ambigua* – implications for environmental flow management in the River Murray, Australia. *Marine and Freshwater Research* **64**(7), 618-630.

Zampatti, B., Fanson, B., Strawbridge, A., Tonkin, Z., Thiem, J., Butler, G., Balcombe, S., Koster, W., King, A., Crook, D., Woods, R., Brooks, S., Lyon, J., Baumgartner, L., and Doyle, K. (2019). Basin-scale population dynamics of Golden Perch and Murray Cod: relating flow to provenance, movement and recruitment in the Murray–Darling Basin. In Murray–Darling Basin Environmental Water Knowledge and Research Project — Fish Theme Research Report. (Eds A. Price, S. Balcombe, P. Humphries, A. King, and B. Zampatti). Pp 42. Centre for Freshwater Ecology, La Trobe University, Wodonga, Victoria