Technical Review of the Water Sharing Plan for the Barwon-Darling Unregulated and Alluvial Water Sources 2012

Report prepared by:

Professor Fran Sheldon

Australian Rivers Institute, Griffith University, Brisbane

For:

NSW Natural Resources Commission

August 2019

AUSTRALIAN RIVERS INSTITUTE

Griffith UNIVERSITY

Disclaimer

Fran Sheldon

☏ 07 3735 3914

✉ f.sheldon@griffith.edu.au

https://www.griffith.edu.au/australian-rivers-institute

Report citation

Sheldon, F. 2019. Technical Review of the Water Sharing Plan for the Barwon-Darling Unregulated and Alluvial Water Sources 2012. Advice to the NSW Natural Resources Commission.

Contents

1 Preamble and Analysis

1.1 General: importance of flow in dryland river ecology

(modified from Sheldon, 2017)

Flow pulses have an over-riding influence on both physical structure and ecological responses of all rivers and streams (Poff and Ward 1989; Bunn and Arthington, 2002), such that the variability in the magnitude, frequency, timing, duration and rate of change of flow pulses underpins river ecosystem function and integrity (Walker et al. 1995; Puckridge et al. 1998). This variation occurs over a range of temporal scales (Figure 1) which include (i) individual changes in flow - the flow pulse, (ii) flow history, or antecedent conditions relevant for each flow pulse and (iii) the long-term flow regime, or long-term record of the pattern of flow. Flow pulses, of varying magnitudes, are important for maintaining ecological processes such as nutrient cycling, breeding and spawning responses, and dispersal (Leigh et al. 2010) they are also important for connectivity along river channels (Poff et al. 1997). Flow pulses occurring after extended periods of no flow will elicit a different biotic response to those occurring after a series of similar pulses (Leigh et al. 2010).

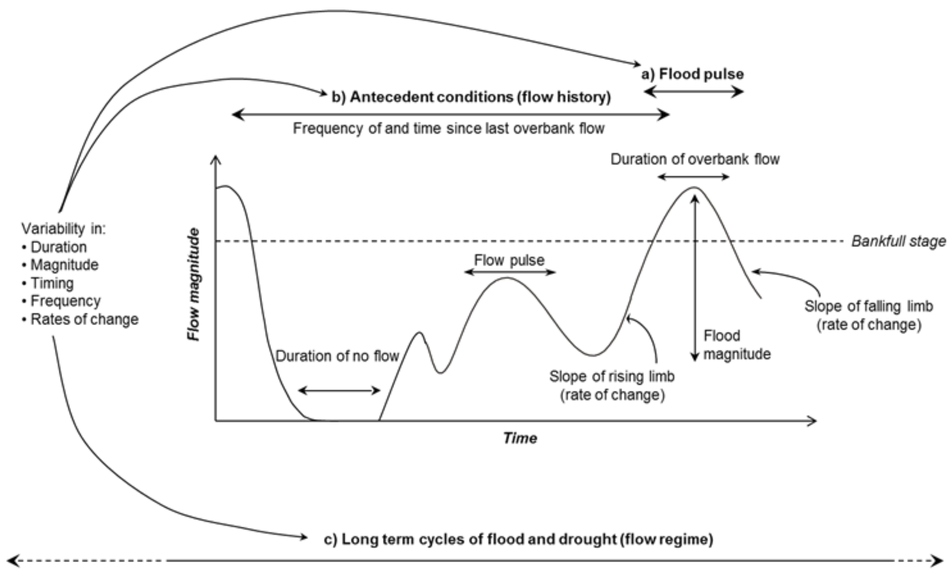


Figure 1: Various features of the (a) flood pulse, (b) flow history and (c) flow regime that have ecological significance. From Leigh et al. (2010), modified from Walker et al. (1995)

All types of flow in rivers are ecologically important (Figure 2). **Baseflows** and **very low flow periods**, including the stable no flow periods where water can remain within the channel (some sections may dry with extensive no flow) are important for maintaining aquatic habitat within the channel, such as inundanted snags and the roots of riparian trees. Small localised flow pulses and no-flow periods are a crucial component of the overall flow-regime. While they are not often associated with large scale reproductive responses in riverine species there is evidence that some fish and freshwater mussels will preferentially reproduce when water levels are low and stable. During periods of extended low flow, declining water quality in any remaining aquatic habitats can be a significant issue for resident biota. Given the hydrological variability of the Barwon-Darling and the associated variable lengths of time between large flow pulses and floods (even under natural flow conditions) remnant aquatic pools and reaches within the river channel network are critical for the maintenance of healthy populations of many aquatic organisms (Sheldon et al. 2010).

Less-frequent **in-channel flow pulses (small and large freshes)** (Figure 2) are important for reconnecting river reaches and moderating water quality in previously disconnected reaches or weir pools, providing opportunities for spawning and recruitment of fish. The increased turbidity and water movement associated with in-channel flows can reduce the concentrations of nuisance algae (green and cyanobacteria) in the water column. These in-channel pulses are also important for increasing habitat availability – also required for spawning and recruitment of fish and invertebrates. NSW DPI (2015) showed the increase in availability of snag habitat and in-channel bench surfaces associated with in-channel flow pulses of different magnitudes. The relatively frequent small flow pulses (Figure 2) are important for maintaining connectivity along river channels and refreshing aspects of water quality in pools and isolated reaches (Poff et al. 1997). These events are often overlooked as important in river systems; however, they play a vital part in the overall hydrological variability of the river. Low flows control the extent of physical aquatic habitat and thereby influence the composition and diversity of biota, trophic structure, and carrying capacity of river systems. Low flows also mediate changes in habitat conditions, which in turn, drive patterns in the distribution and recruitment of biota, they affect the sources and exchange of energy in riverine ecosystems, thereby affecting ecosystem production and biotic composition, and restrict connectivity and diversity of habitat, increase the importance of refugia, and drive multiscale patterns in biotic diversity (Rolls et al. 2012).

In the Barwon-Darling River system flow and flow variability within the main channel have been shown to drive in-channel habitat complexity. The in-channel river environment of the Barwon–Darling, below the floodplain, is ‘complex’; along its length the channel cross-section shows large inset benches as prominent morphological features. These ‘benches’ represent flow pulses of different magnitude and provide surfaces for vegetation growth between flow pulses and habitat for the accumulation of organic matter (Sheldon and Thoms 2006). In-channel flow events are vital for rivers such as the Barwon-Darling, they connect isolated parts of the channel network, assist in maintaining water quality parameters in ranges suitable for aquatic biota, allow dispersal of aquatic organisms and replenishing soil moisture of riparian areas for riparian vegetation health. Given these events are naturally more frequent than the overbank flows they are crucial for maintaining populations of fish, invertebrates and turtles.

Overbank flows drive large scale geomorphic processes and, over time through erosion and deposition, create the billabongs, anabranches and floodplain wetlands of the larger Darling floodplain (Sheldon and Thoms, 2004). Overbank flows also provide water to floodplain wetlands and waterbodies, soil moisture to floodplain vegetation - which can act as a germination and recruitment trigger, and opportunities for landscape scale dispersal of aquatic biota. Inundated floodplain habitats are often focal breeding sites for waterbirds and other terrestrial animals. In the Barwon-Darling system overbank flows provide a number of native fish species with flows sufficient to undertake large-scale migrations, triggered by the extensive connection of riverine habitat. While large overbank flow events in the Barwon-Darling River are not seasonal or regular they trigger spawning in many riverine fish, germination events for riparian and floodplain vegetation (recruitment often requires follow up rains), and waterbird breeding and recruitment in floodplain wetlands. They stimulate zooplankton production (emerging from floodplain soils) which fuel the massive breeding of fish and waterbirds associated with flooding. Many species in dryland river systems have life cycles that ultimately depend on the large overbank flood events, even though they are not seasonal or regular.

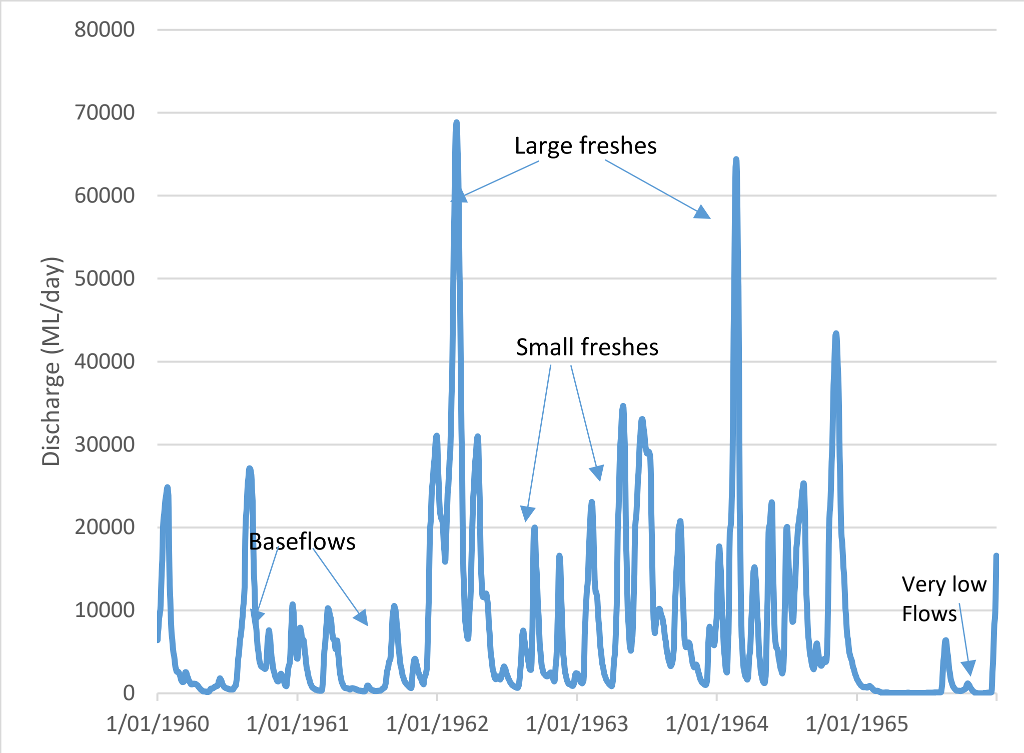


Figure 2: Daily flows (ML/day) for the Darling River at Bourke over a five-year period between 1960 and 1965 modelled without development conditions (from MDBA, 2016). Ecologically relevant flows are mapped onto the hydrograph

The **connection and disconnection dynamics** across all flow levels in riverine systems, through changes in discharge, have been shown to influence the diversity of algal, microinvertebrate, macroinvertebrate and fish assemblages (eg. Boulton and Lake, 1992a; Boulton and Lake 1992b; Boulton et al. 1992; Jenkins and Boulton, 2003; Arthington et al. 2005; McGregor et al. 2005; Marshall et al. 2006). Likewise, the periodic connection and disconnection of aquatic habitats mediate ecosystem function, for example the sequential wetting and drying of stream and floodplain soils can cause pulsed releases of nutrients (Baldwin and Mitchell 2000; McIntyre et al. 2009; Gallo et al. 2014; Woodward et al. 2015) and hot spots of decomposition and microbial activity (Larned et al. 2010).

Alteration to the flow regime of most rivers in the Murray-Darling Basin has been implicated in the establishment and success of several alien fish species. It is difficult to disentangle if this reflects a preference by the invader for the new modified flow regime, or that the modified flow regime has reduced the abundance of native species to such an extent that has allowed the invaders 'room' to move in. The most destructive invader in the Barwon-Darling river system currently is the Common Carp (*Cyprinus carpio*). Carp were first noticed in the river in large numbers in the late 1970's (Gehrke and Harris, 2004). Carp in the Barwon-Darling compete with native species for food and habitat, they are also prone to damaging river banks and making river habitats less preferable for native species. There is a strong association between the increase in carp abundance in the Barwon-Darling and the decline in abundance of native catfish, who are benthic species and whose habitat is disturbed by carp feeding actions.

Given the importance of different kinds of flow events, and therefore flow variability, in the Barwon-Darling, it is important to emphasise that extended periods of no flow are likely detrimental to the long-term viability of native fish and invertebrate populations through (i) the impacts of declining water quality which can directly cause mortality to adults, juveniles or eggs, (ii) reduced availability of habitat for spawning and recruitment and, (iii) in many cases, the absence of triggers for spawning and recruitment. While the impacts of extended periods of low flows on fish have been well documented, relatively little is known about their impacts on invertebrates and especially the larger invertebrates such as the iconic river mussels. River mussels are susceptible to anoxia and poor water quality (Sheldon and Walker 1989), so any declines in water quality from extended periods of no flow could have extremely negative consequences for the viability of freshwater mussel populations. Extended periods without flow also increase the extent of habitat fragmentation and population isolation; isolated populations of organisms are more vulnerable to disturbance events which can cause localised extinctions.

1.2 Data used in this report

All data used in this report were supplied by the NSW Natural Resources Commission unless otherwise referenced.

Flow data were daily flows in ML/day from two sources (Table 1):

1. “actual” flow data downloaded from WaterNSW Real Time Data website at https://realtimedata.waternsw.com.au on 30 April 2019.
2. “modelled” were from a Water NSW model run of "bdent1.sqq". This data is generated by taking a “current conditions” run then switching off all the development, so for example no dams or weirs, no irrigators, no system rules. It is not a true “natural” conditions model run as it does not consider other important factors such as changes in land use such as large-scale clearing. The model components including rainfall-runoff models and flow losses were calibrated to replicate observed responses seen in the last 30-40 years which could be materially different to what was occurring 100 years ago.

Table 1: Summary of the flow data used in this report.

Site	Gauge Number	Modelled	Actual
Collarenebri	422003	1/7/1895 - 30/6/2009	1/11/1980 - 30/4/2019
Walgett	422001	1/7/1895 - 30/6/2009	10/8/1972 - 30/4/2019
Brewarrina	422002	1/7/1895 - 30/6/2009	1/1/1900 - 30/4/2019
Bourke	425003	1/7/1972 - 30/6/2009	1/7/1972 - 30/4/2019
Wilcannia	425008	1/7/1895 - 30/6/2009	18/10/1972 - 30/4/ 2019

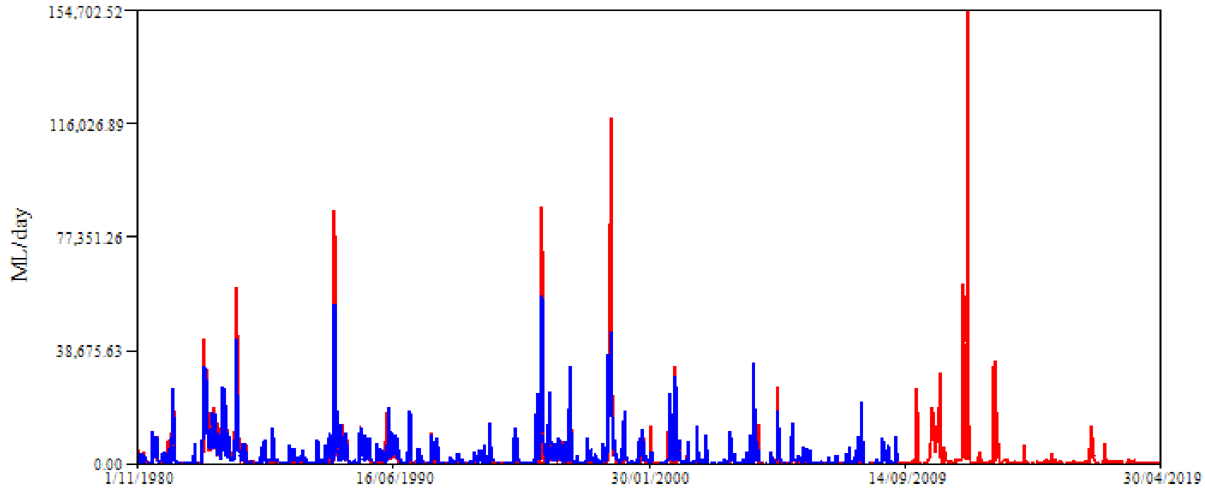
1.3 Flow variability in the Barwon-Darling

1.3.1 Summary of flow variability

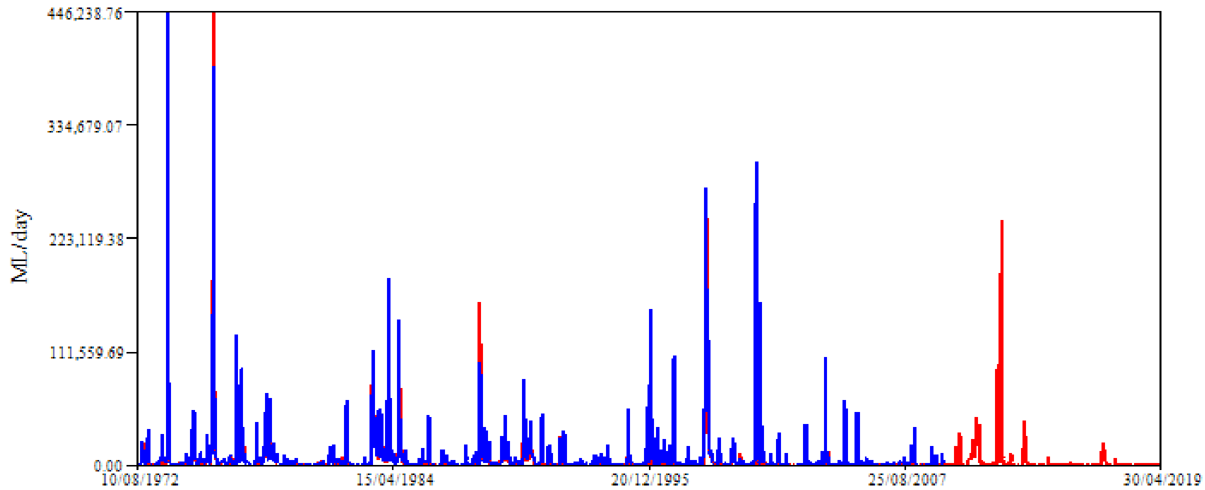
The Barwon-Darling is a hydrologically variable dryland river system. Long-term hydrographs from a series of gauges along the river highlight this variability (Figure 3) which includes periods of extreme high flows interspersed with periods of low flow Table 2.

Table 2: General statistics for daily flow data (ML/day) from five gauges along the Barwon-Darling River: Collarenebri (422003, Walgett (422001), Brewarrina (422002), Bourke (425003) and Wilcannia (425008).

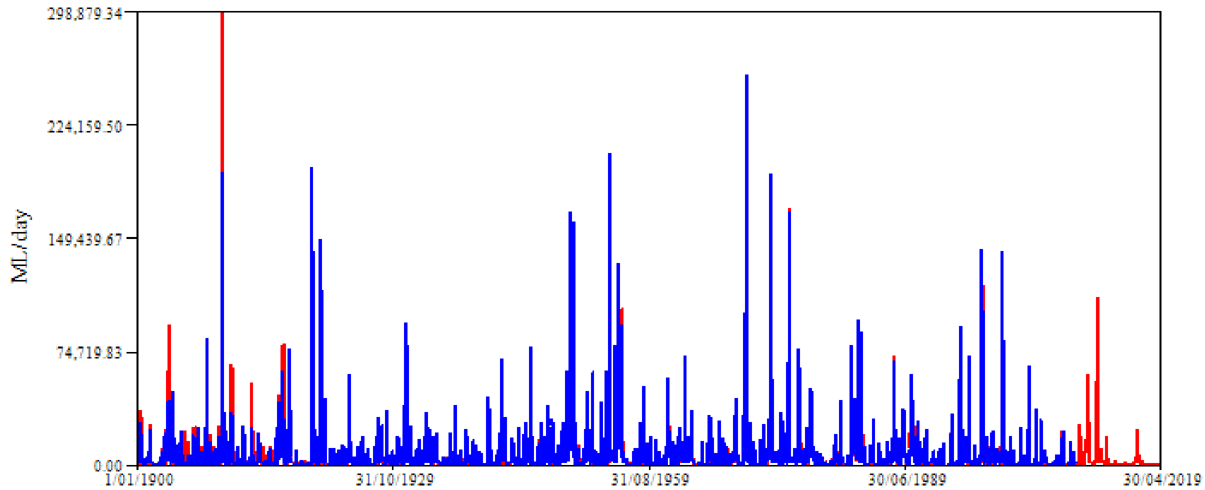
	Collarenebri		Walgett		Brewarrina		Bourke		Wilcannia	
	Actual	Modelled	Actual	Modelled	Actual	Modelled	Actual	Modelled	Actual	Modelled
Min	0	1.79	0	0	0	0	0	0	0	0
Max	118207	57450	446239	455000	298879	258000	500931	384000	68493	62612
Mean	23217	2779	5373	8077	5299	6881	81581	11777	5906	8659
Median	266.7	606	594	1343	1237	1906	11051	2931	1074	3582
CV	2.97	2.05	3.76	3.03	2.29	2.28	3.15	2.32	1.69	1.29



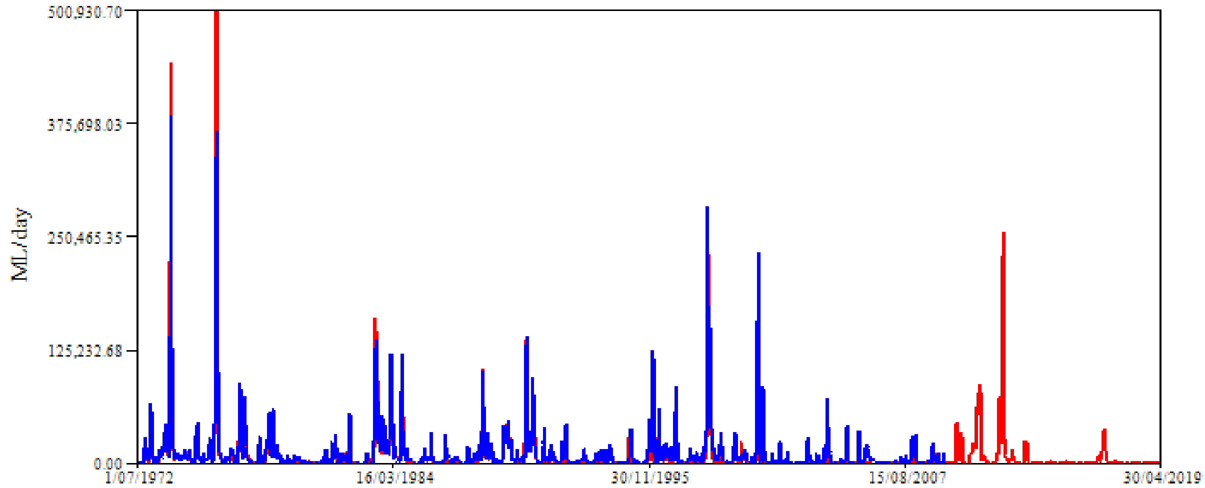
(a)



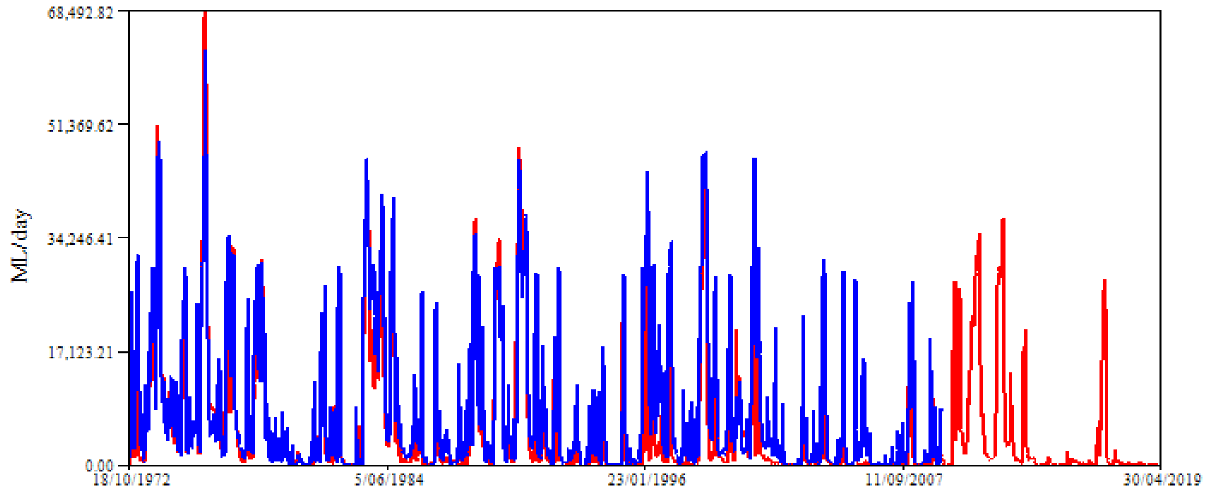
(b)



(c)



(d)



(e)

Figure 3: Daily flow data (ML/day) for gauge stations along the Barwon-Darling River (a) Collarenebri (422003); (b) Walgett (422001); (c) Brewarrina (422002); (d) Bourke (425003) and (e) Wilcannia (425008) - modelled (blue) and actual (red)

1.3.2 Defining flow bands in the Barwon-Darling

The draft Long-Term Water Plan for the Barwon-Darling River system (OEH, 2019) defines a series of ecologically significant flow bands (Figure 4 and Table 3). These bands are defined based on their influence on habitat availability, habitat connectivity, influence on reproduction and recruitment of key flora and fauna and mediation of water quality. Flows within the "Very Low Flow" band occur more than 80 percent of the time under "modelled" pre-development conditions (Table 3; Figure 5). Freshes (small and large) occur a further 22% of the time (Table 4; Figure 5), leaving overbank flows and floods occurring in less than <10% of long-term hydrograph (Table 4; Figure 5).

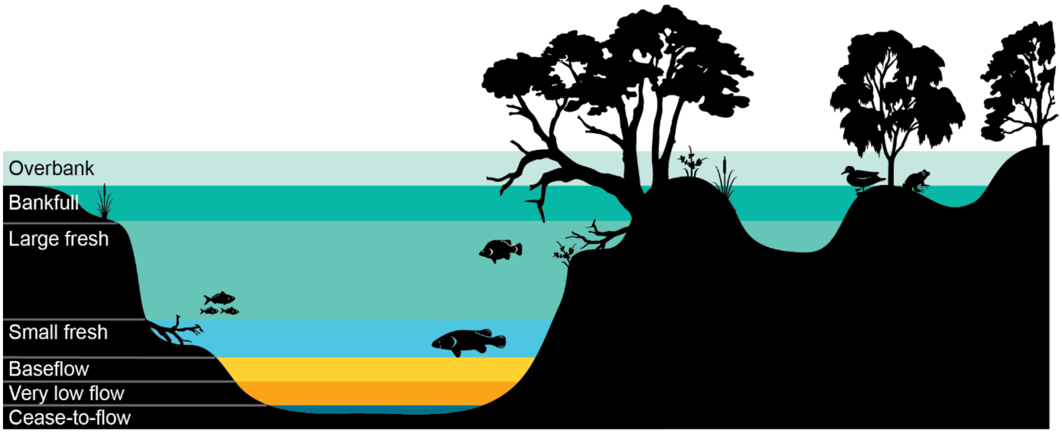


Figure 4: Simplified conceptual model of the ecologically important flow bands in the Barwon-Darling River, from the Long-term Water Plan for the Barwon-Darling system (OEH, 2019).

Table 3: Description of the ecological signifance of each flow band, from the Long-term Water Plan (OEH, 2019) for the Barwon-Darling River system.

Flow component	Description
Overbank / Wetland inundation flow (OB / WL)	Broad scale lateral connectivity with floodplain and wetlands. Supports nutrient, carbon and sediment cycling between floodplain and channel. Promotes large-scale productivity.
Bankfull flow (BK)	Inundates all in-channel habitats and connects many low-lying wetlands. Partial or full longitudinal connectivity. Drown out of most small in-channel barriers (e.g. small weirs).
Large fresh (pulse) (LF)	Inundates benches, snags and inundation-tolerant vegetation higher in the channel. Supports productivity and transfer of nutrients, carbon and sediment. Provides fast-flowing habitat. May connect wetlands and anabranches with low commence-to-flow thresholds.
Small fresh (pulse) (SF)	Improves longitudinal connectivity. Inundates lower banks, bars, snags and in-channel vegetation. Trigger for aquatic animal movement and breeding. Flushes pools. May stimulate productivity/food webs.
Baseflow (BF)	Provides connectivity between pools and riffles and along channels. Provides sufficient depth for fish movement along reaches. In the Barwon-Darling, the baseflow is a long slow event, rather than a permanent baseflow.
Very low flow (VF)	Minimum flow in a channel that prevents a cease-to-flow. Provides hydrological connectivity between some pools.
Cease-to-flow (CF)	Partial or total drying of the channel. Stream contracts to a series of disconnected pools. No surface flows.

Table 4: Flow bands, their equivalent flow (ML/day) from the Long-Term Water Plan (OEH, 2019), along with the approximate “modelled” pre-development percentile flow (1972-2009) for Walgett (422001), Brewarrina (422002), Bourke (425003) and Wilcannia (425008) gauges

Long-Term Water Plan flow bands		Walgett		Brewarrina		Bourke		Wilcannia		
		Flow band (ML/day)	Approximate Percentile (modelled)	Flow band (ML/day)	Approximate Percentile (modelled)	Flow band (ML/day)	Approximate Percentile (modelled)	Flow band (ML/day)	Approximate Percentile (modelled)	Barwon-Darling Water Sharing Plan Flow Class (approximate)
Low flows	Cease to Flow	<35	97th	<45	97th	<25	98th	<30	96th	No Flow Class
	Very Low flows	<326	>79th	<468	>77th	<450	>80th	<200	87th	Low Flow Class
	Baseflows	326-706	79th - 63rd.	468-1008	77th – 63rd	450-972	80th -70th	200-400	87th -80th	
Freshes	Small	706-3111	63rd – 35th	1008-3500	63rd – 47th	972-5400	70th – 38th	400-4000	80th – 47th	A & B Class Extractions
	Large	3111-27000	35th – 6th	3500-32100	47th – 4th	5400-35000	38th- 8th	4000-29000	47th – 10th	B & C Class Extractions
Over-bank	Bankfull	9000-27000		9000-32100		10000-35000		8000-29000		C Class Extractions
	Small	>27000		>32100		>35000		>29000		
	Medium	>60000				>75000				
	Large	>200000		>50000		>220000		>35000		

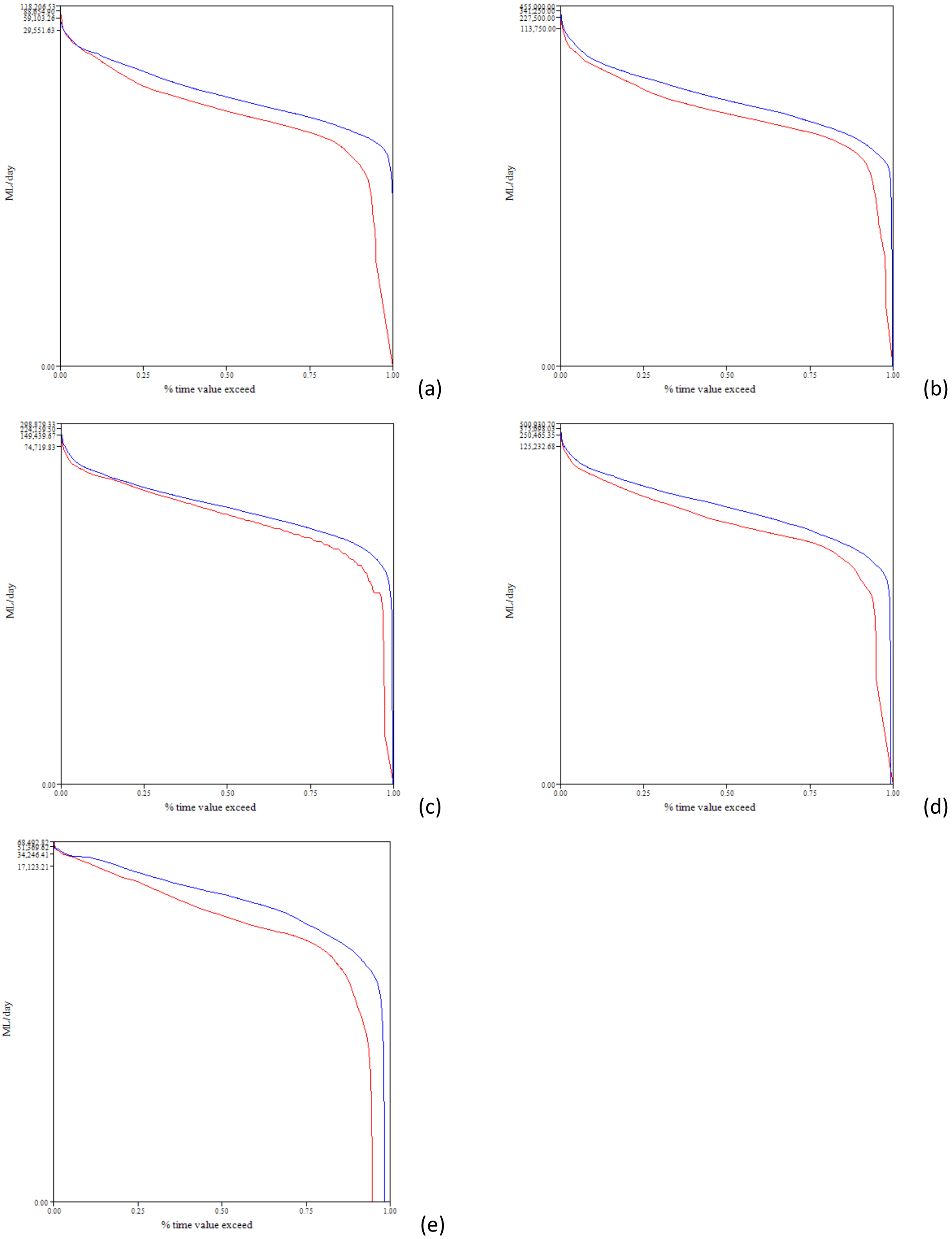


Figure 5: Flow duration curves generated from daily flow data for (a) Collarenebri; (b) Walgett; (c) Brewarrina; (d) Bourke (425003) and (e) Wilcannia (425008) – red line "actual" flows 1972-2019 and blue line "modelled" pre-development flows 1972-2019.

1.4 Water resource development in the Barwon-Darling

1.4.1 Summary of water licences and allocations in the Barwon-Darling WSP area

There are several different licence types for water extraction within the Barwon-Darling water sharing plan; these include:

- Domestic and stock access licences
- Local water utility licences
- Unregulated river access licences (no shares allocated at the start of the plan)
- Unregulated river (A class) access licences
- Unregulated river (B class) access licences
- Unregulated river (C class) access licences
- Aquifer access licences (no shares allocated at the start of the plan)
- Specific purpose access licences
  - Aboriginal environmental access licences (no shares allocated at the start of the plan)
  - Aboriginal cultural access licences (no shares allocated at the start of the plan)
  - Salinity and water table management access licences

Water is also allowed for under basic landholder rights which includes water taken for domestic and stock rights, native title rights and harvestable rights.

Table 4 summarises the licence types from the Water Sharing Plan with the relevant flow band access rules that are applicable within specific management zones with the flow threshold estimates from the Long-Term Water Plan. This shows that all the access rules for “low flows”, “A Class”, “B Class” and “C Class” licences sit within the “Low Flows” and “Freshes” flow bands. Access to water within the Low Flows, A Class and B Class bands occurs within the “very low” and “baseflow” threshold flow bands as defined by the Long-Term Water Plan.

There is a total of 237 water access licences (WALs) in the Barwon Darling, they are owned by 158 licence holders (both individuals and corporations) with a total share component of 196,499 units. Of this total share domestic and stock licences comprise 0.5%, A class licences 5%, B Class licences 67.7% and C Class licences 23.3%. Along the Barwon-Darling River, 72% of the total volume of water across all licence classes, and 79% of the A class licence volume is extracted between Boomera (just upstream of Brewarrina) and Louth (Figure 6 and Figure 7). Discounting any impact of extractions on flows in the Barwon-Darling further upstream in tributaries, the section of the Barwon-Darling river – between Boorooma and Louth – has significant extraction impact on the river below Bourke.

Of the 158 licence holders in the Barwon Darling, 10 control 86% of the total share component in the river and 4 of these holders’ control 75% of the total share component.

Table 5: Flow bands in which the three unregulated river access licences (A, B and C) operate for each river management zone as per the Water Sharing Plan for the Barwon-Darling Unregulated and Alluvial water sources, combined with the flow thresholds of ecological relevance from the Long-term Water Plan for the Barwon-Darling

	Gauge	**Low Flows**						**Freshes**			**Overbank**	
Long-term Water Plan Flow Threshold Estimates		**Cease to Flow**	**Very Low**	**Baseflow**				**Small**	**Large**		**Bankfull**	**Overbank**
Water Sharing Plan Flow Licence Bands					**Low Flow (ML/day)**	**A Class (ML/day)**	**B Class (ML/day)**			**C Class (ML/day)**		
MUNGINDI TO BOOMI RIVER MZ	416001	<30	<300	300-540	> 0 but ≤ 230	> 230	>230	540-5400	5400-13300	>230	6260-13300	>13300
	416050	<15	<135	135-498	> 0 but ≤ 220	> 220 but ≤ 270	> 270 but ≤ 1500	498-2720	2720-9000	> 1500	6490-9010	>9010
BOOMI RIVER to MOGIL MOGIL MZ	416050				> 0 but ≤ 220	> 220 but ≤ 270	> 270			> 270		
	422004	<35	<343	343-723	> 0 but ≤ 190	> 190 but ≤ 230	> 230 but ≤ 1800	723-5190	5190-17800	> 1800	10700-17800	>17800
MOGIL MOGIL TO COLLARENEBRI MZ	422004				> 0 but ≤ 190	> 190 but ≤ 570	> 570			> 570		
	422003	<40	<393	393-525	> 0 but ≤ 165	> 165 but ≤ 500	> 500 but ≤ 2900	525-4199	4199-30000	> 2900	19000-30000	>30000
COLLARENEBRI TO US WALGETT MZ	422003				> 0 but ≤ 165	> 165 but ≤ 500	> 500			> 500		
	422025	<15	<145	145-317	> 0 but ≤ 100	> 100 but ≤ 430	> 430 but ≤ 3050	317-1224	1224-30100	> 3050	9000-30100	>30100
WALGETT WEIR POOL MZ	422001	<35	<326	326-706	> 0 but ≤ 600	> 600 but ≤ 900	> 900 but ≤ 5650	706-3111	3111-27000	>5650	9000-27000	>27000
DS WALGETT TO BOOROOMA MZ	422001				> 0 but ≤ 600	> 600 but ≤ 900	> 900			> 900		
	422026	<30	<318	318-720	> 0 but ≤ 530	> 530 but ≤ 870	> 870 but ≤ 5500	720-3409	3409-17200	> 5500	9620-17200	>17200
BOOROOMA TO BREWARRINA MZ	422026				> 0 but ≤ 530	> 530 but ≤ 870	> 870			> 870		
	422002	<45	<468	468-1008	> 0 but ≤ 460	> 460 but ≤ 840	> 840 but ≤ 6800	1008-3500	3500-32100	> 6800	9000-32100	>32100
BREWARRINA TO CULGOA RIVER MZ	422002				> 0 but ≤ 460	> 460 but ≤ 840	> 840			> 840		
	422028	<50	<469	469-1148	> 0 but ≤ 400	> 400 but ≤ 760	> 760 but ≤ 8250	1148-5687	5687-19400	> 8250	11000-32000	>32000

CULGOA RIVER TO BOURKE MZ	425029	<25	<450	450-972	> 0 but ≤ 400	> 400 but ≤ 1330	> 1300	972-5400	5400-35000	> 1300	10000-35000	>35000
	425003				> 0 but ≤ 350	> 350 but ≤ 1250	> 1250 but ≤ 11000			> 11000		
BOURKE TO LOUTH MZ	425003	<40	<384	384-902	> 0 but ≤ 350	> 350 but ≤ 1250	> 1250	902-5895	5895-35500	> 1250	14000-35500	>35500
	425004				> 0 but ≤ 260	> 260 but ≤ 1130	> 1130 but ≤ 11150			> 11150		
LOUTH TO TILPA MZ	425004	<35	<350	350-845	> 0 but ≤ 260	> 260 but ≤ 1130	> 1130	845-5853	5853-25480	> 1130	14000-25480	>25480
	425900				> 0 but ≤ 215	> 260 but ≤ 1010	> 1010 but ≤ 11000			> 11000		
TILPA TO WILCANNIA MZ	425900	<30	<200	200-400	> 0 but ≤ 215	> 260 but ≤ 1010	> 1010	400-4000	4000-29000	> 1010	8000-29000	>29000
	425008				> 0 but ≤ 123	> 123 but ≤ 850	> 850 but ≤ 12000			> 12000		

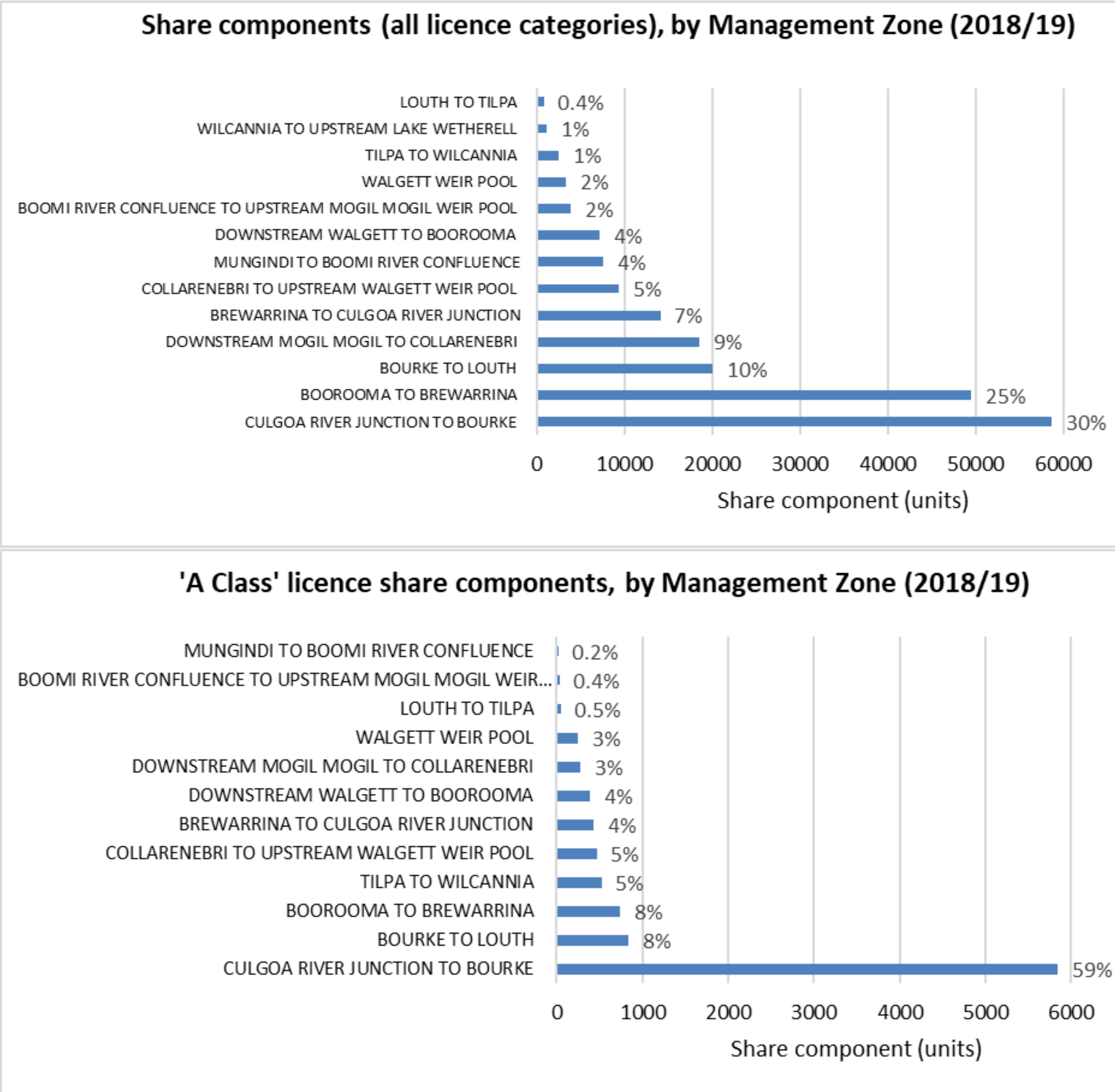


Figure 6: Spatial distribution of all extraction licences (top) and A class licences specifically (bottom).

1.4.2 Changes in discharge within flow bands

Modelled (pre-development) discharge data was compared to “actual” discharge data for the Collarenebri gauge (422003), Walgett gauge (422001), Brewarrina gauge (422002), Bourke gauge (425003) and Wilcannia gauge (425008) for the period 1972-2009. For each discharge series flow bands specified in the Long-Term Water Sharing Plan (OEH, 2019) were turned into percentiles and the corresponding percentile flow under the modelled flow regime and percent change calculated (Table 6). These suggest that across all gauges there has been a 40-60% reduction in very low flows, a 46-70% reduction in baseflows and a 20-50% reduction within the small freshes flow band (Table 6). For the two most downstream locations there has been a greater than 60% reduction in the “Very Low Flow” band (Figure 5; Table 6).

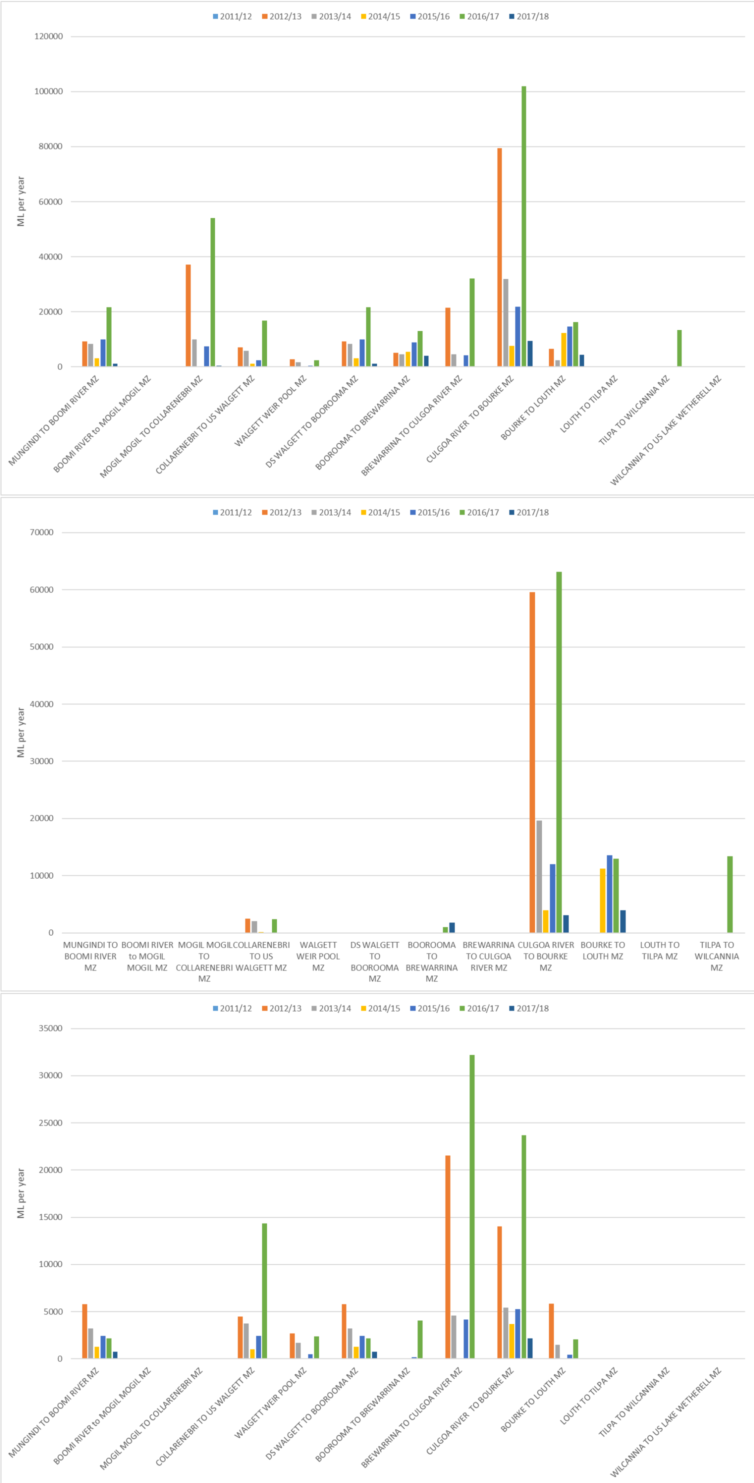


Figure 7: Spatial and temporal (2011-2018) distribution of all extraction licences (top), A class licences specifically (centre) and B Class licences specifically (bottom)

Table 6: Low flow thresholds based on specific low flow percentiles (ML/day) from the 'actual' and 'modelled' times series and the change between "modelled" and "actual" for the Collarenebri gauge (422003), Walgett gauge (422001), Brewarrina gauge (422002), Bourke gauge (425003) and Wilcannia gauge (425008). Data calculated using the Time Series Analysis in the River Analysis Package (Marsh et al. 2003).

						Licence Extraction – relative to Actual Discharge Data			
Gauge	Long-term Water Plan Flow Bands[1]	Actual Flow (ML/day)	Approximate Corresponding Percentile	Modelled Pre-development Flow (ML/day)	Percent change between modelled and actual	Low Flow	A Class Access	B Class Access	C Class Access
Collarenebri	Cease to Flow	<40	83	116.4	-65				
	Very Low Flows	<393	43	845	-53				
	Baseflow	393 - 525	43 -38	845 - 1124	-53				
	Small Freshes	525 - 4199	38 - 14	1124 - 5698	-26				
	Large Freshes	4199 - 30000	14 -1	5698 - 30000	0				
Walgett	Cease to Flow	<30	91	99	-64				
	Very Low Flows	<318	62	766	-57				
	Baseflow	326-720	62-46	766-1643	-57				
	Small Freshes	706-3409	46-23	1643-6176	-49				
	Large Freshes	3111-17200	23-7	6176-25284	-32				
Brewarrina	Cease to Flow	<45	91	155.6	-71				
	Very Low Flows	<468	67	816	-42				
	Baseflow	468-1008	67-53	816-1639	-38				
	Small Freshes	1008-3500	53-32	1639-4364	-20				
	Large Freshes	3500-32100	32-1	4364-41225	-22				
Bourke	Cease to Flow	<25	91	160	-84				
	Very Low Flows	<450	68	1065	-58				
	Baseflow	450-972	68-52	1065-2586	-62				
	Small Freshes	972-5400	52-25	2586-10548	-49				
	Large Freshes	5400-35000	25-5	10548-50543	-31				
Wilcannia	Cease to Flow	<30	87	186	-84				
	Very Low Flows	<200	78	507	-60				
	Baseflow	200-400	78-68	507-1315	-69				
	Small Freshes	400-4000	68-32	1315-8290	-52				
	Large Freshes	4000-29000	32-5	8290-30281	-4				

[1] These flow bands relate to the Actual Flow data, the equivalent "pre-development modelled" flow data is given as a comparison based on equivalent percentile flows

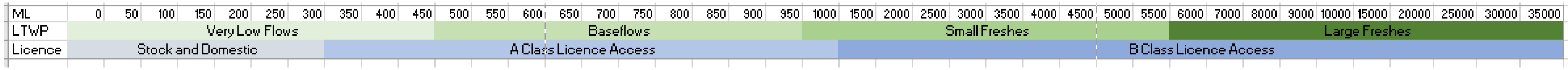
Table 7: Summary of flow bands, their approximate percentile of flow for "actual" and "modelled" pre-development data, combined with the ecological importance of each flow band and the related pumping licence band. Adapted from Sheldon (2017). Percentiles have been derived as per Table 3

Long-term Watering Plan Flow Band (Bourke)	**Flow Band Description from Long Term Watering Plan**	**Flow Band Importance – summary from literature**	**Flow Band related discharges Gauge Station – Discharge ML/day – estimated in literature**					**Licence Bands (Bourke ML/day)**		
			Walgett	Brewarrina	Bourke	Louth	Wilcannia	A Class (350-1250)	B Class (1250-11000)	C Class (<11000)
Cease-to-flow (CF) <25 ML/day	• Partial or total drying of the channel. Stream contracts to a series of disconnected pools. No surface flows	Partial or total drying of the channel. Stream contracts to a series of disconnected pools. No surface flows.	0	0	0	0	0			
Very low flow (VF) <450 ML/day	• Minimum flow in a channel that prevents a cease-to-flow. Provides hydrological connectivity between some pools.	• Flows required to inundate low-level in-channel surfaces and associated habitat that is important for the maintenance of fish and invertebrate populations and water quality mediation (from Carlisle, 2017)	261	346						
Baseflow (BF) 450-972 ML/day	• Provides connectivity between pools and riffles and along channels. Provides sufficient depth for fish movement along reaches. In the Barwon-Darling, the baseflow is a long slow event, rather than a permanent baseflow.	• Flows required to maintain lotic habitat over large spatial scales, required for specialist native fish (eg Murray Cod) (Mallen-Cooper & Zampatti (2015)			500		500			
		• Flows that enhance spawning in low-flow spawning specialist fish, such as olive perchlet (endangered) and other small bodied fish (see Humphries & Walker 2013).	>500		500	350				
		• Critical discharge (ML/day) required to suppress persistent stratification and *Anabaena circinalis* growth in the Barwon-Darling River (Mitrovic et al. 2006; Mitrovic et al. 2010)		510	450		350			

Long-term Watering Plan Flow Band (Bourke)	Flow Band Description from Long Term Watering Plan	Flow Band Importance – summary from literature	Flow Band related discharges Gauge Station – Discharge ML/day – estimated in literature					Licence Bands (Bourke ML/day)		
		• Riparian Flows – minimum flows for reaches to remain connected (DWR, 1992)	700	550	390	280	150			
		• Flows required to inundate low-level in-channel surfaces and associated habitat that is important for the maintenance of fish and invertebrate populations and water quality mediation (from Carlisle, 2017) • Maintains flow for lotic species (eg. river mussels)			440	401	361			
Small fresh (pulse) (SF) 972-5400 ML/day	• Improves longitudinal connectivity. Inundates lower banks, bars, snags and in-channel vegetation. Trigger for aquatic animal movement and breeding. Flushes pools. May stimulate productivity/food webs.	• Flows required to inundate low to mid- level in-channel surfaces and associated habitat – important for within-channel connectivity, fish and invertebrate dispersal, nutrient transfer and water quality mediation (from Thoms et al. 1996)			2500	5500	2000			
		• Threshold flows required for spawning and migration of Golden Perch – duration of flows at this threshold >10 days (Stuart and Sharpe, 2017)		3000						
		• Algal Suppression Flows: Access to uncontrolled/unregulated flows is managed to achieve a flow of at least 2,000ML/day for 5 days at Wilcannia in the period October to April inclusive, unless a flow of at least this size has occurred within the preceding months (DWR, 1992).					2000			
Large fresh (pulse) (LF) 5400-35000 ML/day	• Inundates benches, snags and inundation-tolerant vegetation higher in the channel. Supports productivity and transfer of	• Flows required to inundate mid-high level in-channel surfaces and associated habitat – important for fish and invertebrate breeding, riparian vegetation health, mediate nutrient			9,500	10,500	10,000			

Long-term Watering Plan Flow Band (Bourke)	Flow Band Description from Long Term Watering Plan	Flow Band Importance – summary from literature	Flow Band related discharges Gauge Station – Discharge ML/day – estimated in literature					Licence Bands (Bourke ML/day)		
	nutrients, carbon and sediment. Provides fast-flowing habitat. May connect wetlands and anabranches with low commence-to-flow thresholds.	transfer from unwetted to wetted surfaces (from Thoms et al. 1996)								
		• Fish Migration Flows: Access to uncontrolled/unregulated flows is managed to achieve a target flow of at least 14,000 ML/day at Brewarrina and/or 10,000ML/day at Bourke for 5 days in the months September to February inclusive, unless 2 such flows have occurred within this period (DWR, 1992).		14,000			10,000			
Bankfull flow (BK) 10000-35000 ML/day	• Inundates all in-channel habitats and connects many low-lying wetlands. Partial or full longitudinal connectivity. Drown out of most small in-channel barriers (e.g. small weirs).	Discharge (ML/day) required to inundate 50% of the floodplain wetlands and provide opportunities for large scale waterbird and fish breeding events, maintenance of floodplain vegetation health and large-scale nutrient transfer from unwetted to wetted surfaces (from Cooney 1994).		19,000	30,000		21,000			
Overbank / Wetland inundation flow (OB / WL) >35000	Broad scale lateral connectivity with floodplain and wetlands. Supports nutrient, carbon and sediment cycling between floodplain and channel. Promotes large-scale productivity.									

Note: there is overlap between the flow bands categorised through the Long-term Water Plan and the pumping bands for different class licences. The example given here is for the Bourke gauge.



2 Response to the Terms of Reference

2.1 Flow Components and Cease to Pump Classes

2.1.1 TOR 1. *Which of the flow components, of the Long-term Watering Plan for the Barwon-Darling, are critical for meeting essential environmental requirements (flows required to meet native fish movement and dispersal outcomes; providing ecosystem requirements for wader bird species), and what represents the most significant risk if flow components are not met.*

Flow variability plays a vital role in meeting essential environmental requirements along the Barwon-Darling, however, for the system to benefit from the larger flows that fuel ecosystem productivity, we need to protect those flows deemed 'maintenance' flows – the flow bands that maintain ecological functioning within the river between larger flow events. Table 8 summarises the flow classes as per the Long-Term Water Plan, relates these to essential environmental outcomes and then divides these into two broad groups based on their overall essential environmental requirement.

The Barwon-Darling is a dryland river system, in fact it is one of Australia's most hydrologically variable river systems (Puckridge et al. 1998), with periods of low flow and small flow pulses, or freshes, punctuated by large overbank flows that fuel large scale riverine productivity. Recognising the role flow variability plays in the overall productivity of the Barwon-Darling, the flow components in the Long-Term Water Plan can be divided into two broad groups based on their role in fueling ecosystem productivity. One group of flow components could be termed "maintenance" flows – they provide longitudinal connectivity at varying scales along river channels, provide some opportunity for small scale breeding and recruitment events and, most importantly, assist in moderating water quality along reaches, by preventing the establishment of thermal stratification in reaches, flushing algal blooms and reducing conductivity. Higher flow classes could be termed "productivity" flows – these are the flow levels that stimulate mass reproduction and recruitment of a range of organisms, they drive nutrient cycling between the river and floodplain and reset a range of water quality parameters throughout the system. The "maintenance" flow bands are essential for keeping the system in a resilient state allowing it to respond to the larger "productivity" flows when they occur.

Using this ecological framework for grouping flows, those flows within the "maintenance" group are essential for maintaining water levels and water quality in channel reaches, maintaining healthy populations of flora and fauna and providing overall resilience to the ecosystem. The most significant risk is the failure of water management approaches to meet the 'maintenance' flows for the Barwon-Darling, resulting in a loss of ecosystem resilience.

Table 8: Flow bands described in the Long-Term Water Plan (OEH, 2019), their environmental outcomes and a broad description of their role in overall ecosystem functioning.

Flow component Long-Term Water Plan	**Essential environmental outcomes**	**Role in Ecosystem Functioning**
Overbank / Wetland inundation flow (OB / WL)	Overbank flows provide maximum connectivity both longitudinally along the river but also laterally across the floodplain, connecting the river with its floodplain and wetlands. These flows support nutrient, carbon and sediment cycling between floodplain and river channel environments. They provide opportunities for large scale breeding events of many fish species as well as invertebrates and associated predatory fauna (riparian birds). These flows promote large-scale productivity of the riverine ecosystem.	"Productivity" flow events – drive large scale connectivity longitudinally and laterally, fuelling high levels of production, reproduction and recruitment across a broad range of flora and fauna
Bankfull flow (BK)	Bankfull flows provide maximum longitudinal connectivity along the river channel and may inundate low low-lying wetlands and anabranch channels. As these flows drown out most small in-channel barriers (e.g. small weirs) they provide periods of maximum connectivity for fish moving throughout the channel network and are therefore periods of maximum dispersal. Many fish species may take advantage of these flows for breeding events. Without these large connection flows populations can become isolated.	
Large fresh (pulse) (LF)	Large flow pulses longitudinally connect sections of the river channel providing opportunities for regional dispersal of fauna. They will inundate vital in-channel habitat, such as benches, snags and inundation-tolerant vegetation higher in the channel – which increases the complexity of habitat available for spawning and recruitment of juvenile fish.	"Maintenance" flow events, provide connectivity along channels, allow movement and some reproduction and recruitment of aquatic fauna. Moderate and reset water quality parameters
Small fresh (pulse) (SF)	Small freshes can improve longitudinal connectivity regionally, inundate within channel habitats including lower banks, bars, snags and in-channel vegetation. They can moderate water quality by flushing algal blooms, reducing conductivity and breaking down thermal stratification. Small freshes may trigger some aquatic animal movement and breeding.	
Baseflow (BF)	Baseflows are most relevant to the upper portions of the Barwon-Darling covered in the WSP. They provide connectivity between pools and riffles and between reaches along channels. These flows provide sufficient depth for fish movement between pools along reaches. In the Barwon-Darling, the baseflow is a long slow event, rather than a permanent baseflow.	
Very low flow (VF)	Minimum flow in a channel that prevents a cease-to-flow. Provides hydrological connectivity between some pools.	
Cease-to-flow (CF)	Partial or total drying of the channel. Stream contracts to a series of disconnected pools. No surface flows.	

2.1.2 TOR 2. *Following on from Question 1, how do the flow classes in the Long-Term Water Plan for the Barwon-Darling relate to the cease to pump flow classes outlined in the Barwon-Darling Water Sharing Plan*

Table 9 compares the flow classes as outlined in the Long-Term Water Plan with those of the Barwon-Darling Water Sharing Plan and shows how both classifications relate to the broad grouping of flows into either 'maintenance' or 'productivity'. The B Class flow band includes 'maintenance' flows as well as 'productivity' flows.

Table 9: Long-Term Water Plan (OEH, 2019) flow classes and their relationship to the Barwon-Darling Water Sharing Plan Flow Classes and the broad ecological groupings of flow classes (see also Table 2).

<table>
<tr><th>Flow Class Grouping</th><th>Long-Term Water Plan Flow Classes</th><th>Barwon-Darling Water Sharing Plan Flow Class</th><th>Maintenance Flows</th><th>Productivity Flows</th></tr>
<tr><td rowspan="2">Overbank Flows</td><td>Overbank / Wetland inundation flow
(OB / WL)</td><td>A, B and C Class Extractions</td><td></td><td></td></tr>
<tr><td>Bankfull flow
(BK)</td><td rowspan="2">A and B Class Extractions</td><td></td><td></td></tr>
<tr><td rowspan="2">Freshes</td><td>Large fresh (pulse)
(LF)</td><td></td><td></td></tr>
<tr><td>Small fresh (pulse)
(SF)</td><td rowspan="2">A Class Extractions</td><td></td><td></td></tr>
<tr><td rowspan="3">Low Flows</td><td>Baseflow
(BF)</td><td></td><td></td></tr>
<tr><td>Very low flow
(VF)</td><td>Low Flow Class</td><td></td><td></td></tr>
<tr><td>Cease-to-flow
(CF)</td><td>No Flow Class</td><td></td><td></td></tr>
</table>

Three of the flow classes in the Barwon-Darling Water Sharing Plan allow extractable access to flows within the Low Flows and Freshes broad flow class grouping – these flows are considered "maintenance" flows in terms of ecosystem functioning and provide ecosystem resilience.

2.2 Seasonality of Flows

2.2.1 TOR 3: *What is the ecological role of seasonal variability in the Barwon-Darling system?*

In their hydrological classification of Australian rivers and streams Kennard et al. (2010) classified the Barwon-Darling system as “unpredictable summer dominated flows, highly intermittent” suggesting the system has a high variability of flows including periods of zero flow, and floods, which are more likely to occur in the summer months.

The Barwon-Darling River is a mix between a system driven by a high degree of flow variability and an associated “boom” and “bust” ecology, reflecting periods of extreme flooding and drought (Puckridge et al. 1998) and a system with relatively frequent small, and often seasonal, freshes (small and large). For this reason, the flora and fauna of the system is a mix between taxa that can easily respond to the “boom” periods with large, and often multiple, breeding events (eg. bony herring) and those that require seasonal cues for reproduction and recruitment (eg. Murray Cod). For these latter species seasonaility in flows is extremely important, many require flowing habitat during the spring and summer for larval survival and juvenile recruitment (Mallen-Cooper & Zampatti 2015; Mallen-Cooper & Zampatti 2018).

While the ecological role of seasonality of flows is known for many of the fish in the Barwon-Darling system, little is known about the role of seasonality on the reproduction, recruitment and long-term survival of other aquatic fauna. The population genetics of river mussels suggests that, at least in the Barwon-Darling, they spawn and recruit during periods of flow and their population structure is broader than the site scale (in comparison to freshwater mussel populations in the Lake Eyre Basin rivers that show strong population structuring at the site scale – reflective of their disconnected habitat) (Baker et al. 2003; 2004), and globally freshwater mussels tend to spawn seasonally, with those in the lower River Murray known to follow this pattern (Walker 2017).

While there is limited information on the importance of seasonaility of flow for Barwon-Darling ecology, spring and summer freshes (small and large), are likely to be significant in the reproduction, recruitment and survival of many species. Seasonal flows (particularly between October and March) are also important for reducing the frequency and magnitude of toxic algal blooms and persistent stratification of pools. Changes in seasonality, or reductions in the magnitude, frequency and duration of seasonal freshes will therefore impact water quality and the maintenance of healthy populations of flora and fauna.

2.2.2 TOR 4: Has the seasonality of the hydrograph shifted with climate induced changes to rainfall patterns?

A high degree of yearly and decadal variability in long-term flow and rainfall across the northern Murray-Darling Basin means detecting a distinct climate signal outside of background variability is difficult and requires considerable modelling. The annual ranfall anomaly for the Murray-Darling Basin for the period 1900-2019 (Figure 8) highlights both the annual variability but also the decadal variability in rainfall with periods of high rainfall alternating with periods of reduced rainfall.

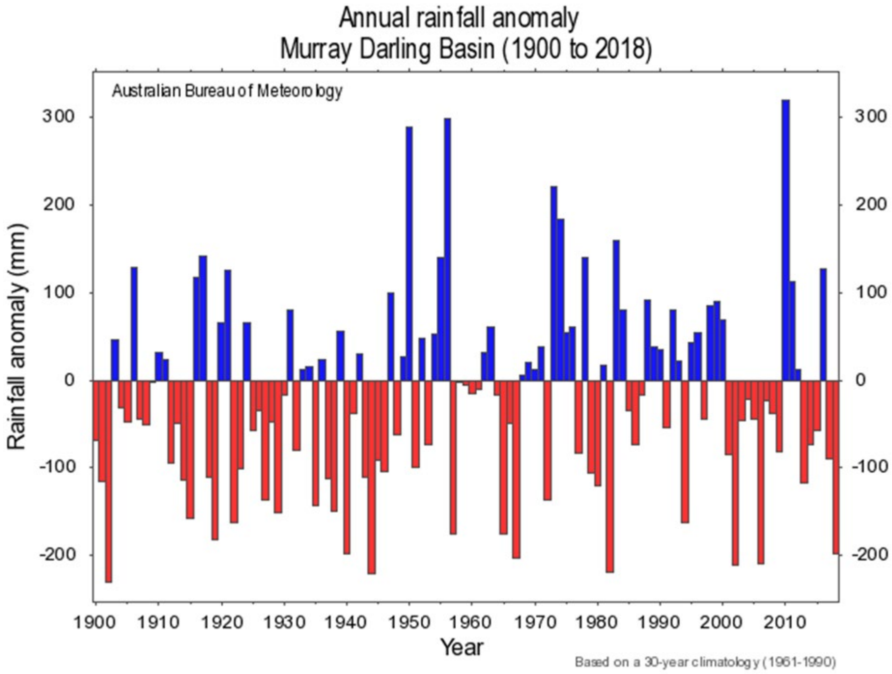


Figure 8: Annual rainfall (mm) anomaly for the Murray-Darling Basin. BOM 2019.

There is currently no easily accessible modelled hydrological data for the Barwon-Darling for the recent period (2010-2019), or a model that allows scenario testing, either water resource development scenarios or climate change scenarios, and this is a severe knowledge gap. However, there has been considerable collaboration between CSIRO, the BOM and the MDBA to understand the impact of a changing climate on the hydrology of the Murray-Darling Basin (https://www.mdba.gov.au/basin-plan-roll-out/climate-change) with a climate change research program established to fill these knowledge gaps.

For this report, however, a multilple lines of evidence approach is presented below which suggests there has been a climate shift in recent decades that will undoubtably influence rainfall and runoff and therefore streamflow. Whether this shift will be sustained or is part of a larger range of decadal rainfall variability (see Figure 8), we do not have the long-term data to definitively say.

Previous studies (eg. Leigh et al. 2010) have shown a correlation between large climate systems (Southern Oscillation Index) and discharge in the Barwon-Darling system, with the correlation becoming stronger further downstream (Figure 9). This correlation is also evident when the average number of dry days per year is explored. From 1989-2000 negative SOI values were associated with an increased number of dry spells (Figure 10), as would be expected under El Niño conditions which tend to be drier than normal, while positive SOI values were associated with fewer dry spells as expected under La Niña conditions (Sheldon, 2017).

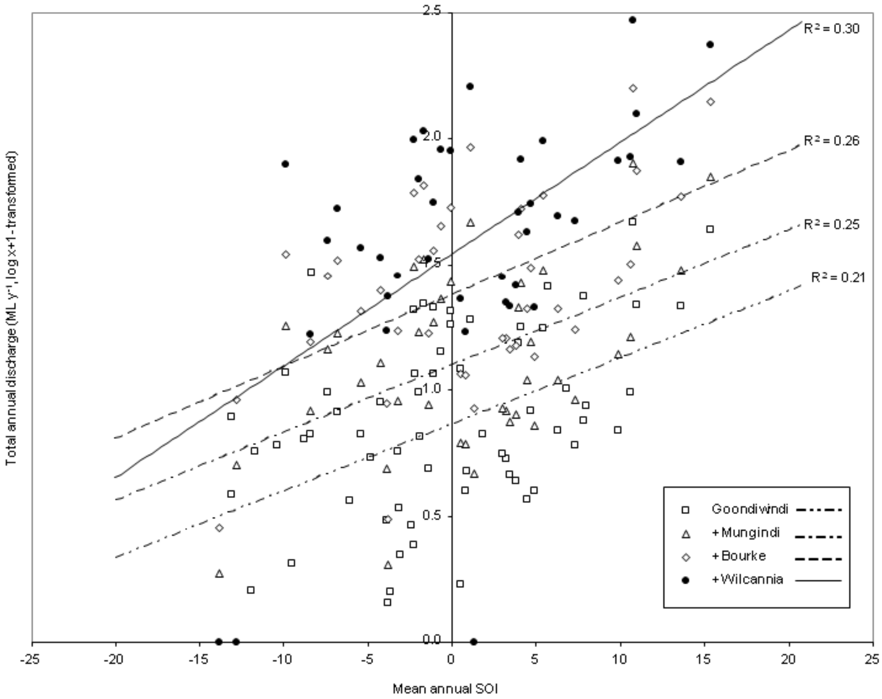


Figure 9: Correlation between mean annual values ofthe Southern Oscillation Index (SOI) and simulated total annual discharge (ML year/1) in the Darling River system under conditions of pre-European settlement (1924–2005), cumulatively combined from upstream gauges to those further downstream (Goondiwindi, Goondiwindi +Mungindi, Goondiwindi + Mungindi + Bourke, Goondiwindi + Mungindi + Bourke + Wilcannia). From Leigh et al. (2010)

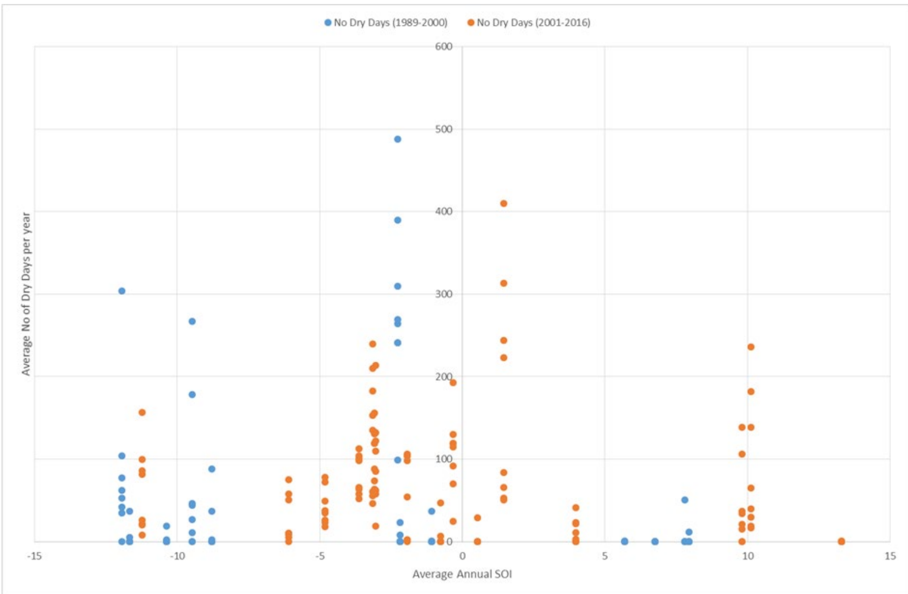


Figure 10: Relationship between the average annual Southern Oscillation Index (SOI) value and the average number of dry spells for gauge locations along the Barwon-Darling River between Mungindi and Wilcannia. From Sheldon (2017)

Broad scale climate data also suggests a warming and drying trend, with the annual mean temperature anomaly for the Murray-Darling Basin being consistently positive since the early 1990's (Figure 11) and the trend in total rainfall and maximum temperature across the Murray-Darling Basin showing decreased rainfall and increased temperatures (Figure 12).

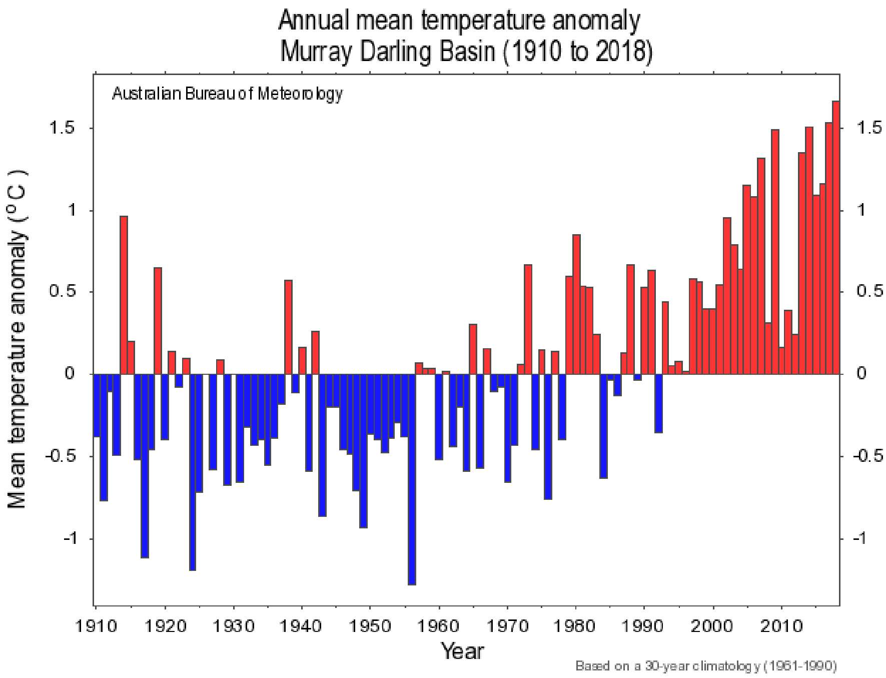


Figure 11: Annual mean temperature anomaly for the Murray-Darling Basin. BOM 2019.

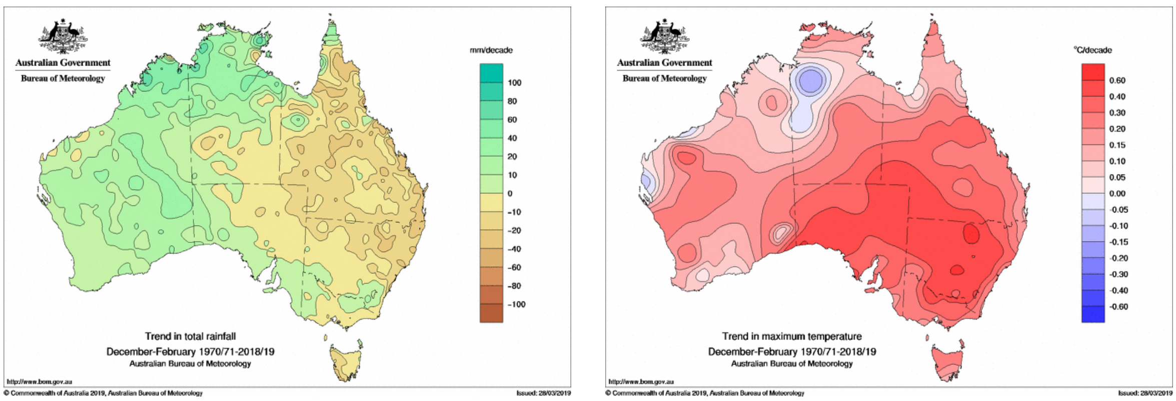


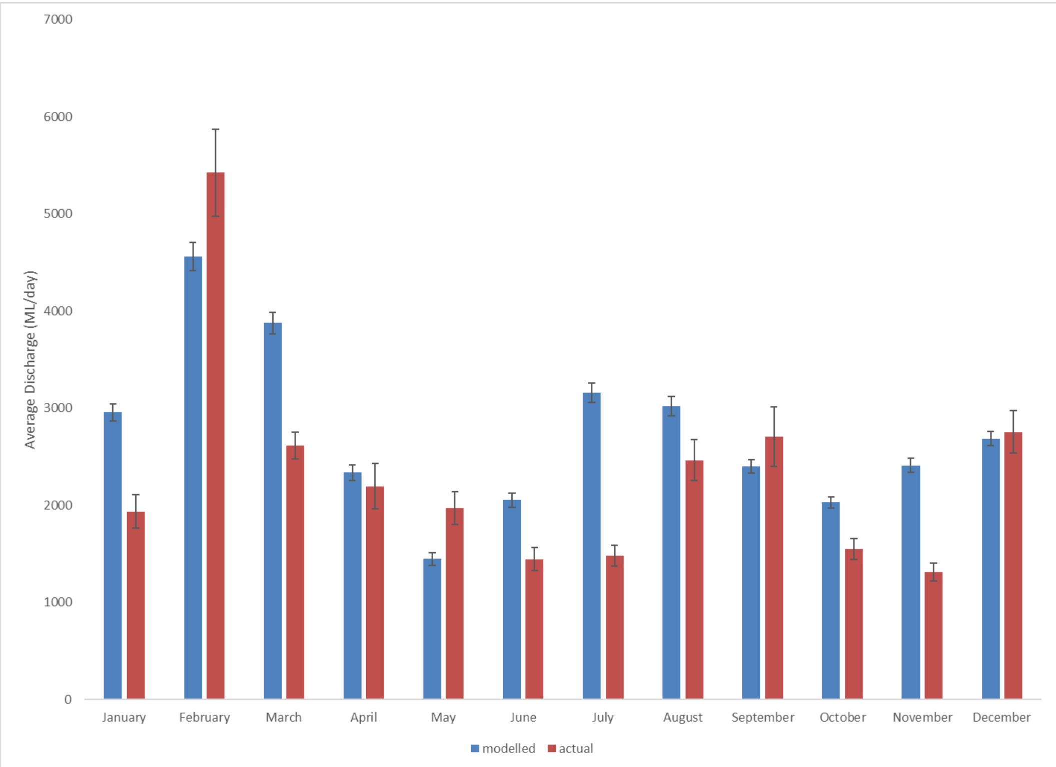
Figure 12: Trend maps for total rainfall and maximum temperature for Australia. BOM 2019.

There is evidence that rainfall and therefore discharge across the northern Murray-Darling Basin is strongly linked to large climate drivers. The trend of reduced rainfall and increases in temperature across the northern Basin will have an impact on discharge totals and discharge variability.

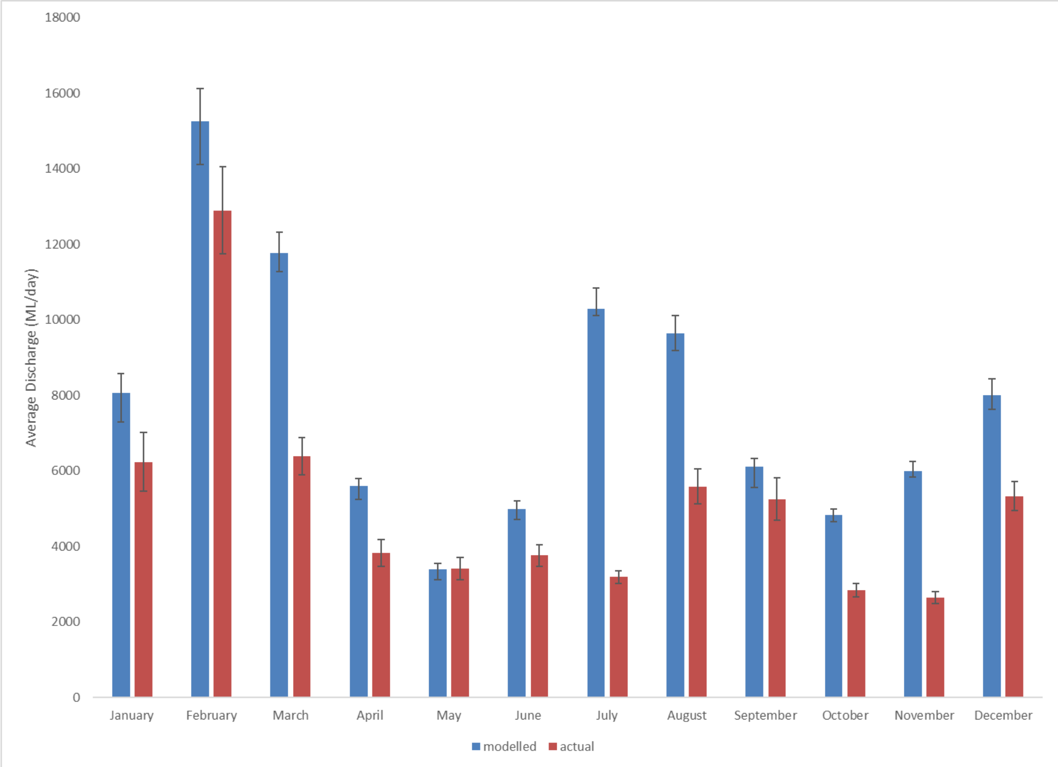
2.2.3 TOR 5: *Has there been a change in the seasonal variability of flows in terms of when water is extracted from upstream tributaries and subsequently made available in the Barwon-Darling system*

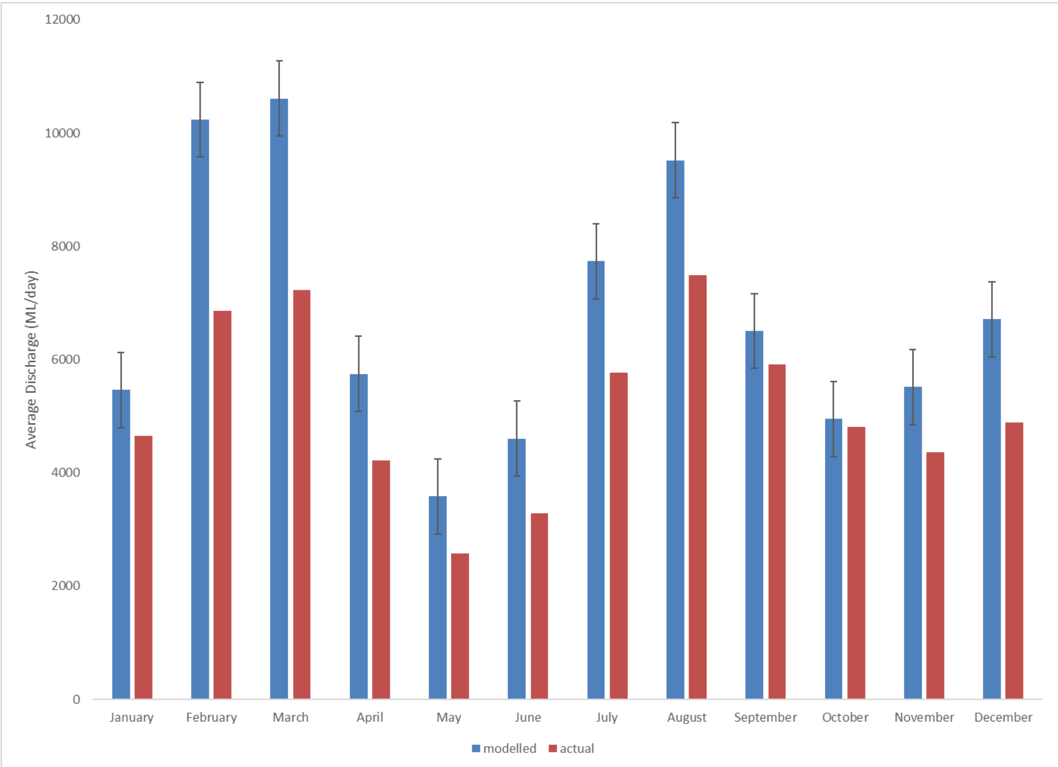
While Kennard et al. (2010) classified the Barwon-Darling system as "unpredictable summer dominated flows, highly intermittent" (see above) there is no strong true seasonal signal in flows across the Barwon-Darling River. To explore potential changes in the timing of flows mean monthly flows for both "actual" and "modelled" (pre-development) data (Table 1) were compared for each gauge, monthly means were calculated for all available data (Figure 13). Variability in monthly discharge across all gauges can be seen with stong decreases in monthly means during the warmer months (November – March) for all gauges apart from Collarenebri.

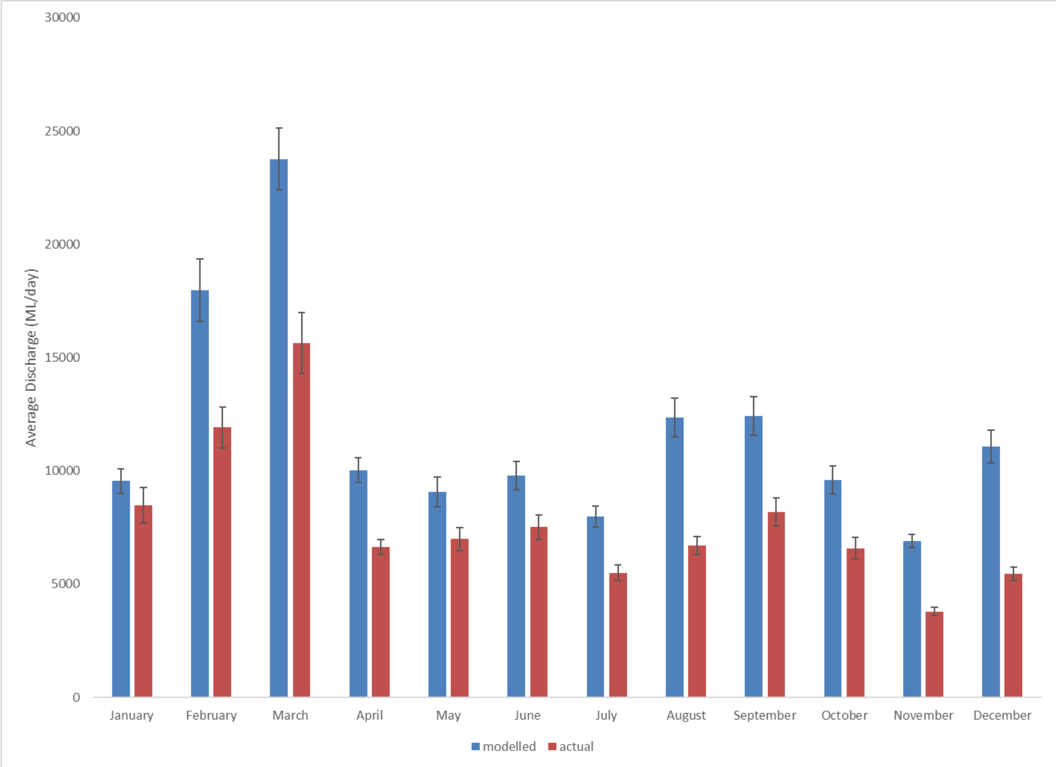
Flows across the Barwon-Darling are not strongly seasonal. Apart from the Collarenebri gauge there has been a decrease in monthly discharge for all gauges across all months with "actual" flows are compared with "modelled" pre-development flows.



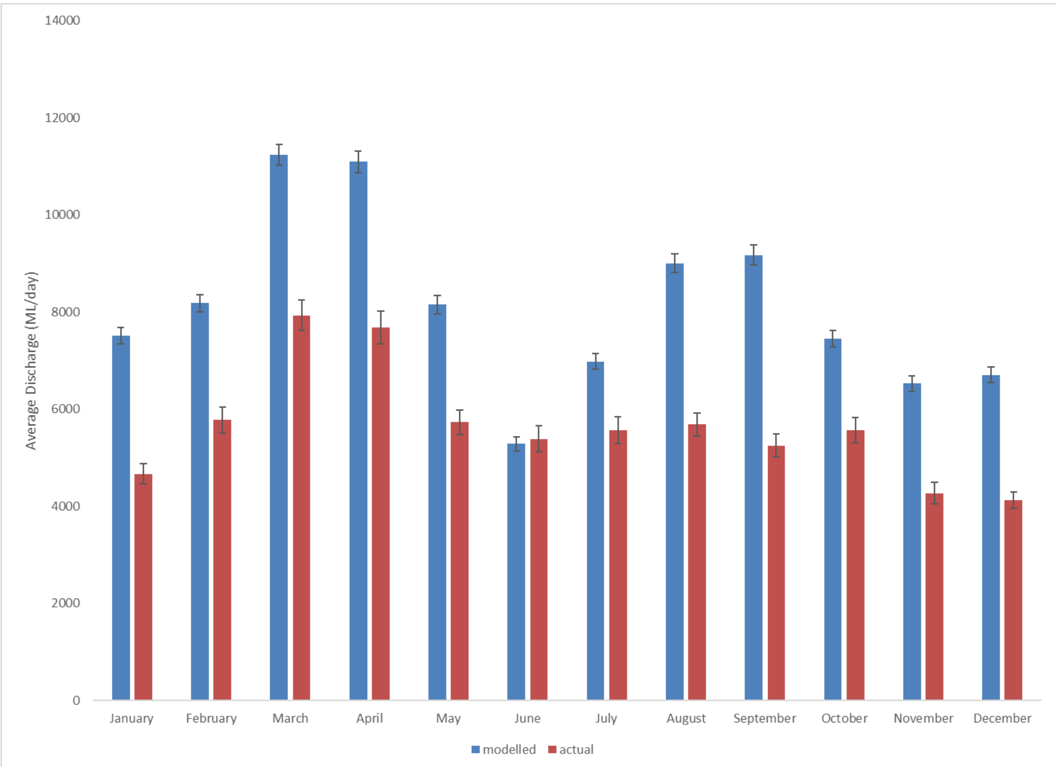
(a)


18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Average Discharge (ML/day)
January
February
March
April
May
June
July
August
September
October
November
December
modelled
actual
(b)


12000
10000
8000
6000
4000
2000
0
Average Discharge (ML/day)
January
February
March
April
May
June
July
August
September
October
November
December
modelled
actual
(c)



(d)



(e)

Figure 13: Mean monthly discharge (ML/day) for all available data (see Table 1) for the (a) Collarenebri (422003), (b) Walgett (422001), (c) Brewarrina (422002), (d) Bourke (425003) and (e) Wilcannia (425008) gauges.

2.2.4 TOR 6: *What does this mean in terms of meeting the flow components outlined in Objective 1 above?*

An increasingly hot and dry northern Murray-Darling Basin, where there is a higher tendency for flows to occur in summer, combined with a concentration of extractions in the Low Flow and Freshes flow bands has likely contributed to the reduction in both median flows and minimum flows during summer months when actual discharge data is compared with the modelled data. There are two aspects to the role of seasonality for specific flows (i) relates to maintenance of the ecosystem and a reduction in ecosystem stress and (ii) relates to the provision of flows to meet life history requirements of biota. The following points summarise the ecological role of seasonality of flows for ecosystem response. A more complete summary of specific seasonal requirements for fish is provided in Appendix 1 (Mallen-Cooper Pers Comm).

(1) Summer freshes (small and large) are vital for maintaining water quality, maintaining water levels in refugial pools and providing connectivity between reaches to allow faunal dispersal and reduce the frequency and magnitude of toxic algal blooms. Increased frequency of reach disconnection and absence of low flows and freshes will increase the risk to the Barwon-Darling of events such as the 2019 fish kills at Menindee (Vertessy et al. 2019).
(2) Spawning and recruitment of native fish require, at a minimum, small freshes (minimum 14 days duration) over the spring and summer months (September – April).
(3) Large freshes are required for fish dispersal and population connectivity, there is evidence that they also contribute to fish health and condition.
(4) Riparian vegetation requires low flows and small freshes for maintenance but requires the larger overbank flows for recruitment and establishment.

Extraction rules that allow reductions in the frequency, duration and magnitude of very low flows, baseflows, small and large freshes in the Spring, Summer and Autumn will disproportionately impact ecosystem maintenance and the life history strategies of flora and fauna.

2.2.5 TOR 7: *What needs to be considered to account for seasonal variability in flows in the system?*

As outlined in TOR 3, very little is known about the influence of seasonal flows on fauna other than fish in the Barwon-Darling system. Mallen-Cooper & Zampatti (2015; 2018) have highlighted the role of seasonaly flowing habitat in the successful spawning and recruitment of several fish species within the Barwon-Darling River and it is likely that seasonal flows are also important for the reproduction and recruitment of other significant aquatic species, such as river mussels.

In the unregulated section of the Barwon-Darling it is impossible to deliver flows of a particular magnitude and duration at specific times of the year (compared with the way seasonal flows can be managed in the Southern Basin and parts of the Northern Basin tributaries). Therefore, within the context of natural flow variability it is important to protect the low flows and baseflows that do occur within the system.

One option that could be considered is an adjustment in the thresholds of commence to pump flows for the different licences to include a seasonality component, the aim of this would be to provide greater protection of very low flows, baseflows and freshes (small and large) during the warmer summer months.

Most importantly adjustments should be made to better protect the low flows and baseflow (maintenance flows) at whatever time of year they occur by raising the Cease-to-Pump (CTP) level for A Class licences. As outlined in Table 7 the threshold baseflows for ecological outcomes, as recognised by several studies, at Bourke are in the order of 500 ML/day – so raising the CTP level from 350 to 500 ML/day at Bourke (and likewise at other gauge stations and associated management zones) would protect a greater proportion of the critical low and baseflows.

Globally, the most commonly used methods for providing minimum environmental flows for the maintenance of species and ecosystem health are the 'hydraulic rating methods' which seek to define the relationship between flow volume (discharge) and the amount of habitat provided during flow along a stream or river (see Gippel and Stewardson, 1998; Arthington, 2012). While there are more than 20 different 'hydraulic rating' methods, some quite detailed, the basic approach uses the 'wetted perimeter or area' of a river that is covered by a specific discharge. Using this relationship, the discharge required to inundate ecologically critical habitats is determined. This hydraulic habitat method was employed by OEH to determine the flow bands that have been described within the Long-Term Watering Plan (OEH 2019). Each flow band was matched to the discharges required for inundation of specific habitat (see Figure 4).

Flows of 500 ML/day at Bourke have been shown to maintain lotic habitat important for native fish, reduce stratification and therefore algal blooms in channel reaches, and provide connection along the section of the Barwon-Darling below Bourke (Table 7). 500 ML/day at Bourke occurs within the lower 10% of the baseflow band as determined by the Long-Term Water Plan. If the aim is to protect the most critical habitat from the impacts of flow diversions, then the Cease-to-Pump levels for A Class licences need to be set at a point that reflects critical habitat inundation. Based on the literature, the Baseflow "flow band" from the Long-Term Watering Plan was seen as the most critical for long term ecosystem health and maintenance, therefore the goal should be to protect a portion of the Baseflow.

An examination of current CTP for A Class licences shows they are nearly all below the Baseflow band, sitting within the Very Low Flows (see Table 4). To protect the lower end of the Baseflow a 10% of Baseflow protection could be applied at each gauge to determine the CTP for A Class licences. When this is applied across the different sites the recommended increase in CTP for A Class licences can be seen in Table 10.

Table 10: Summary of current and proposed A Class licence CTP threshold based on protecting the lower 10% of the Baseflow band as determined in the Long-Term Water Plan (OEH, 2019). Two values are given, an Initial value based on the Long-Term Water Plan flow bands used in this report (DRAFT Flow Bands) and a second estimate based on updated Long-Term Water Plan flow bands, as of August 2019.

			Initial Long-Term Water Plan Flow Bands			Updated Long-Term Water Plan Flow Bands		
Site	Gauge No	Current A Class CTP	Baseflow Band (ML/day)	10% of Baseflow Band (ML/day)	Updated A Class CTP (ML/day)	Updated Baseflow Band (ML/day)	10% of Baseflow Band (ML/day)	Updated A Class CTP (ML/day)
Collarenebri	422003	**165**	393-525	13.2	**406**	280-650	37	**317**
Walgett Weir	422001	**600**	326-706	38	**364**	320-700	38	**358**
Brewarrina	422002	**460**	468-1008	54	**522**	500-1000	50	**550**
Bourke	425003	**350**	450-972	52.2	**502**	500-1550	105	**605**
Louth	425004	**260**	384-902	51.8	**436**	450-1500	105	**555**
Wilcannia	425008	**123**	200-400	20	**220**	350-1400	105	**455**

The other extraction issue associated with A Class licences that impacts low flows is the ability to utilise carryover water from previous years. Given the obvious impact of A Class licence extraction in the low flow, base-flow and small freshes flow bands a higher cease to pump for access to carryover water could be considered. For example, at Bourke the A Class carryover cease-to-pump could be set at 1000 ML/day – this would ensure a greater volume of baseflows pass through the system at Bourke.

The importance of low flows and freshes during the summer months needs to be considered, both within the context of water extractions and the delivery of environmental water. Raising the Cease-to-Pump level for A Class licences to protect the Very Low Flows and the lower 10th percentile of the Baseflows would be a consistent approach for ensuring a minimum environmental flow.

2.2.6 TOR 8: *Would changes to cease to pump rules / or what flexibility in plan rules would be required to manage extraction to account for this seasonal variability?*

See also Discussion in TOR 12. To maintain seasonal variability in flows and provide the required flows in the vital spring and summer months, changes to cease to pump rules and IDELs will be required. These changes will need to be flexible to not only protect spring and summer flows in the low flow and freshes flow bands, but also protect the first flush flows after a dry period, regardless of season.

One of the options to allow seasonality in flows is to build seasonality into the rules around IDELs and TDELs, these rules could also include long-term flow variability. IDEL rules, particularly in the low flow and freshes flow bands could be built to account for the seasonal environmental requirements of major faunal groups.

So, a better mechanism to protect the low flows (maintenance) at whatever time of year they occur would be to raise the Cease-to-pump level for A Class licences

To maintain seasonal variability in flows and provide the required flows in the vital spring and summer months, changes to cease to pump rules and IDELs will be required.

2.2.7 TOR 9: *Are rules that apply on an annual / ongoing basis sufficient? Or do rules need to somehow apply on a multiyear basis?*

Flows in the Barwon-Darling are highly variable, within a year, between years and between decades. Annual based rules make no sense in this context of flow regime variability. **At a minimum, rules should apply on a multi-year basis and have flexibility with respect to background hydrological conditions – to protect ecosystems as they move into drought.** These rules should not only apply to the Barwon-Darling but also the tributaries that contribute flow to the Barwon-Darling. Extractions in these tributaries influence the "freshes" flow band in the Barwon-Darling.

2.3 Impacts within flow bands related to specific classes of Licences

2.3.1 TOR 10: What has been the likely impact of A class licence extraction on availability of water to meet environmental requirements, availability of water for town water supply and basic landholder rights (water used for stock and domestic purposes) downstream?

Comparison of actual flow data with modelled (natural) flow data highlights the impact of upstream water extraction (all Classes) on the low flows and freshes flow bands, with between 40-80% reduction in flows that would be regarded as 'maintenance flows' (Table 9) (noting that the modelled data at very low flows is less reliable) (Table 6). While attributing these overall flow reductions specifically to A Class licences is difficult, when the number of spells above the A Class commence to pump threshold for 5 gauges along the Barwon-Darling over successive 10 year periods commencing in 1970 is compared (Figure 14), there is a trend of a reduced number of spells and reduced duration of each spell (Figure 15) between 1970 and 2019. Admittedly, there is decadal variability within the data, such as the extremely wet period of the 1970s and the millennium drought in the 2000s. The pattern, however, is particularly evident at the Brewarrina and Bourke gauging stations, the locations of the greatest volume of extractions within the A Class licence band.

This pattern is also seen in Table 6, where a comparison of "actual" flow data with "modelled" pre-development flow data (1972-2009) suggests there has been an approximate 50% reduction in flows in the A Class flow band at Collarenebri and Walgett, an approximate 40% reduction at Brewarrina, but a 60% reduction at Bourke and Wilcannia, and this comparison is before the 2012 Water Sharing Plan changes, as it uses a comparison between modelled and actual data from between 1970 and 2009.

The volume of water extracted under the A Class Licence rules has increased since 2012 due to changes in access arrangements made in 2012, with a marked increase in the volume between 2014-2017 (Figure 16). In these three years (2014-2017) 66,000 ML was extracted from the A Class licence flow band. A survey of the reaches below Walgett suggested the total volume of pools between Walgett and Wilcannia is approximately 15,440 ML, with the volume below Brewarrina where the concentration of A class licence extractions occurs being 12,825 ML (Table 11). The volume extracted was enough to ensure maintenance of water levels and some connectivity along the Darling River below Bourke in the years 2014-2017.

Extraction patterns that occur in the low flows and baseflows are most severe when they intersect with larger climate phenomena, such as the onset of El Nino conditions. The northern Murray-Darling Basin is currently (2019) experiencing a hydrological drought with meteorological drought conditions (reduced rainfall) occurring over the past 3 years (Figure 17). Using multiple lines of evidence that includes the rainfall deficiencies in the three years to 2019, the volumes of water extracted within the A class band from 2015 and the knowledge regarding the onset of hydrological drought conditions, the likely scenario regarding the changed extraction rules post 2012, is that these extractions from the baseflow band could have essentially pushed the Barwon-Darling system below Bourke into very low flow conditions three years earlier than the river upstream (Figure 18). This statement is in recognition that the onset of hydrological drought conditions (extremely reduced flows in rivers and streams) generally lags the onset of meterological drought (a sustained reduction in rainfall) and the lag-time reflects the size and responsiveness of the associated catchment Figure 18; Lake, 2011; Yang et al. 2017). A large river basin, such as the Barwon-Darling, will – in the absence of abstraction – retain baseflows for an extended period downstream even after the onset of meteorological drought in the upstream catchments. However, it is important to stress that this is based on a multiple lines of evidence approach and in the absence of modelled hydrological data for the period 2012 to 2019 it is difficult to completely quantify the impact of A Class extractions on low flow and freshes bands throughout 2017-2019, however a reduction in flows below Bourke for these years can be seen in Figure 19.

A Class licence extractions currently occur within the very low flow band. To protect the low flows the Cease-to-Pump levels need to be raised into the Baseflow bands. The impact of changes in pumping rules since 2012 can only be determined using updated "modelled" pre-development flow data. It is recommended that the pre-development hydrological model be updated with data from 2010 to 2019 so impacts of recent changes can be properly scrutinised.

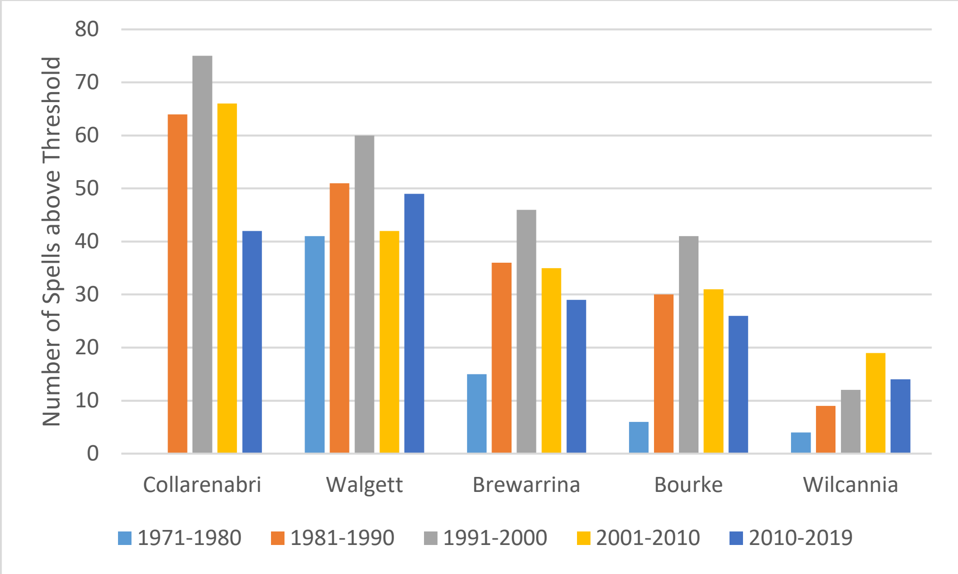


Figure 14: Number of spells above the A Class Commence to Pump threshold for 5 gauge stations along the Barwon-Darling for successive 10 year periods.

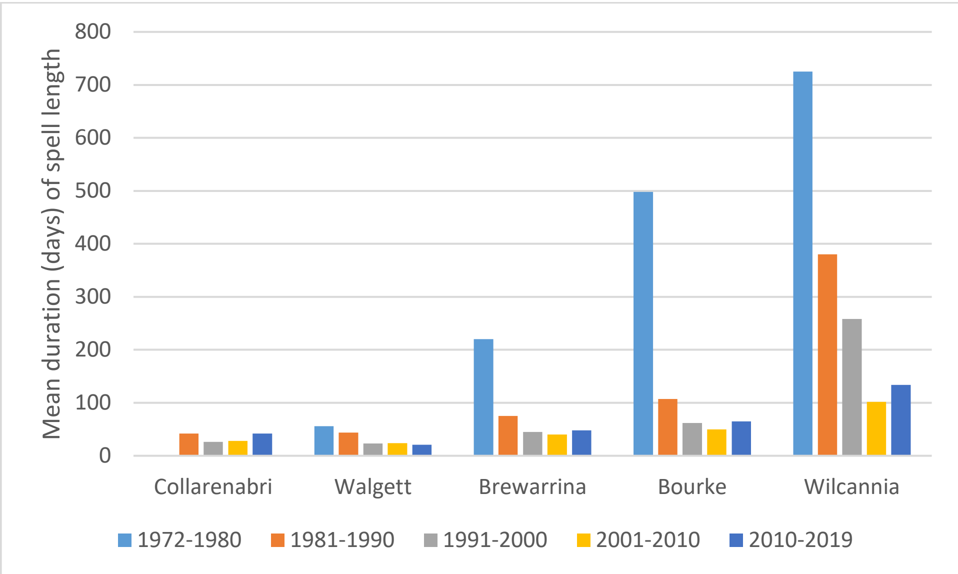


Figure 15: Mean spells duration (days) above the A Class Commence to Pump threshold for 5 gauge stations along the Barwon-Darling for successive 10 year periods.

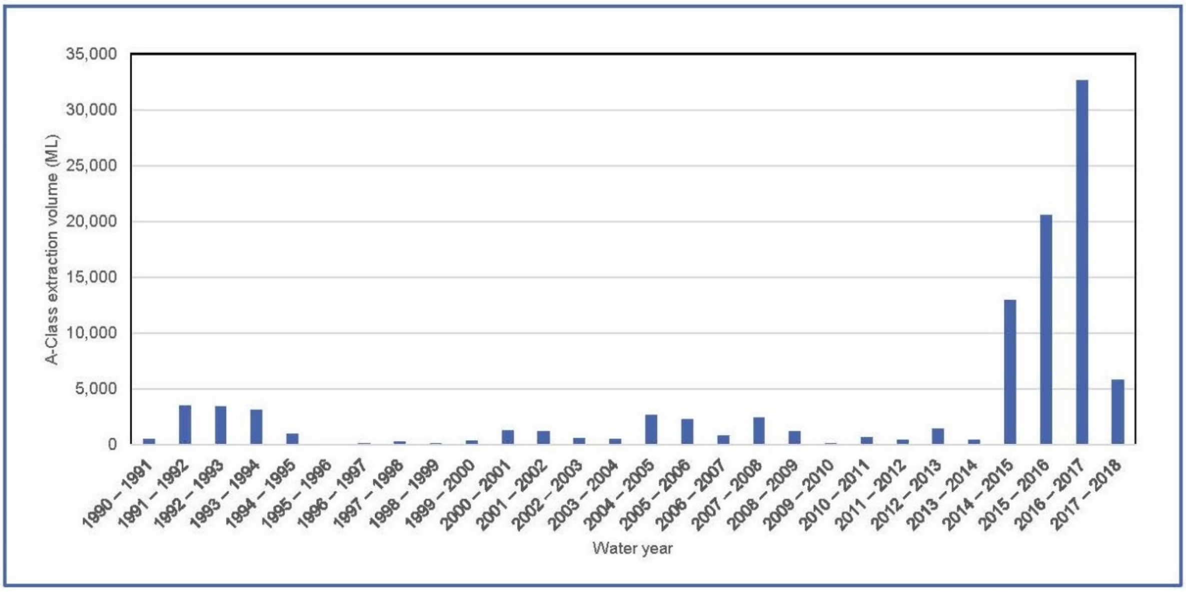


Figure 16: Annual volumes of A-class license water extractions in the Barwon-Darling over the last 28 years (Source: MDBA, using data from NSW DPI and NSW Water Register). From Vertessy et al. (2019)

Table 11: Total number of refuge pools recorded between Walgett and Wilcannia (from NSW DPI 2015).

Zone	Zone Length (km's)	Total number	Total surface area (Ha)	Mean depth (m)	Average Pool Size (ML)
Walgett - Brewarrina	279	297	51.5	5.1	8.8
Brewarrina - Bourke	207	216	55.9	4.5	11.7
Bourke - Tilpa	355	374	157	4.7	19.7
Tilpa - Wilcannia	275	182	65.1	4.5	16.1

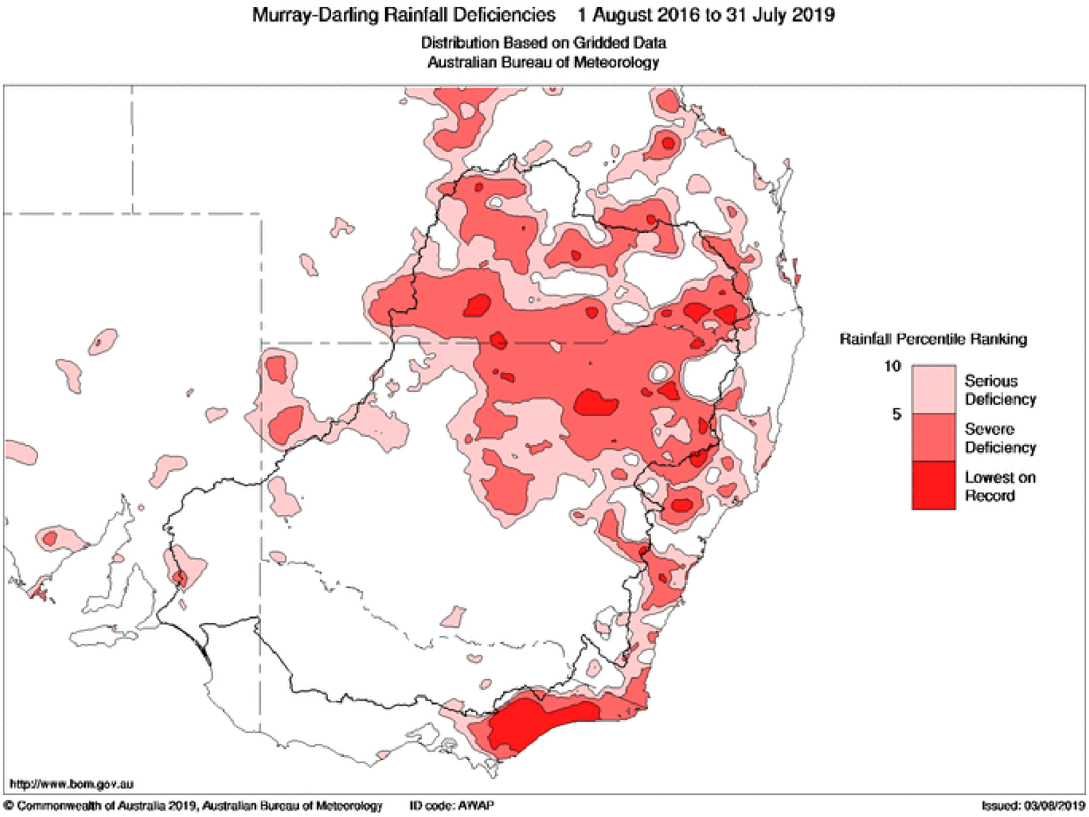


Figure 17: Rainfall deficiency map for the Murray-Darling Basin for the 36-month period leading to August 2019 showing the extreme rainfall deficiency for the headwares of the Barwon-Darling River system (sourced from bom.gov.au)

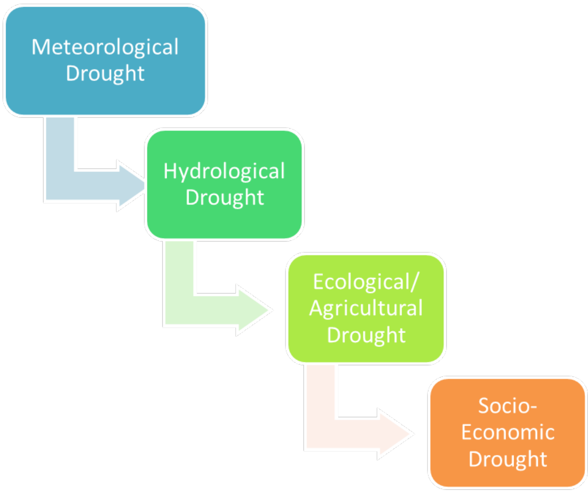
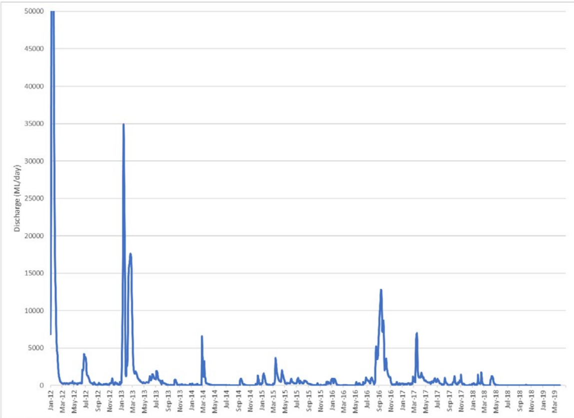
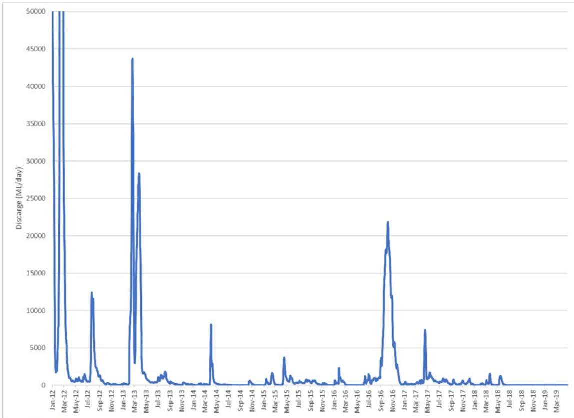


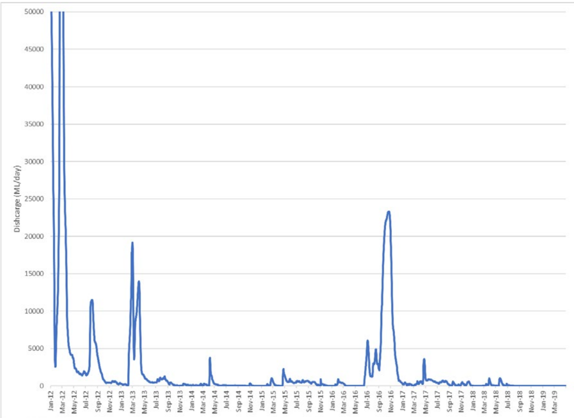
Figure 18: Sequence of drought with severity increasing as the drought moves from a meteorological drought to a socio-economic drought (from Lake, 2011).



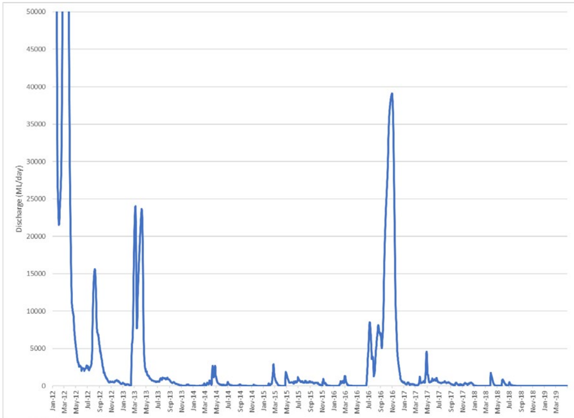
(a)



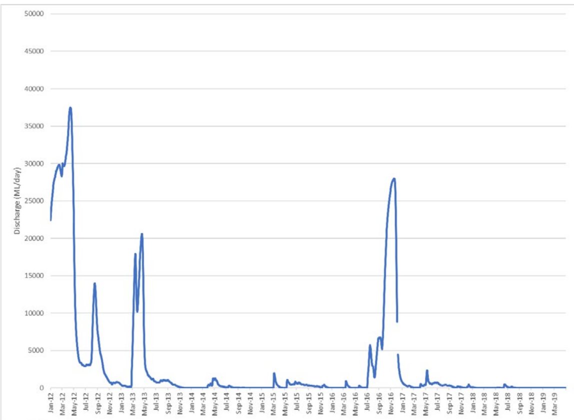
(b)



(c)



(d)



(e)

Figure 19: Hydrographs (actual discharge data for the period 1/1/2012 until 30/4/2019 for the (a) Collarenebri gauge (422003), (b) Walgett gauge (422001), (c) Brewarrina gauge (422002), (d) Bourke gauge (425003) and (e) Wilcannia gauge (425008).

2.3.2 TOR 11: Are there any risks to flow components that need to be looked at in relation to rules that allow for B class licence extraction?

The number of spells above the B Class commence to pump threshold for 5 gauges along the Barwon-Darling over successive 10-year periods commencing in 1970 was compared (Figure 20). Again, like the pattern seen for A Class licences, there was a trend of a reduced number of spells between 1970 and 2019. This was evident at all gauging stations. The same pattern was also evident for the number of spells above the C Class commence to pump threshold (Figure 21). The pattern can also be seen in Table 6; where a comparison of "actual" flow data with "modelled" pre-development flow data (1972-2009) suggests has been an approximate 50% reduction in flows in the B Class flow band at Collarenebri and Walgett, an approximate 20-40% reduction at Brewarrina, but a 50% reduction at Bourke and Wilcannia.

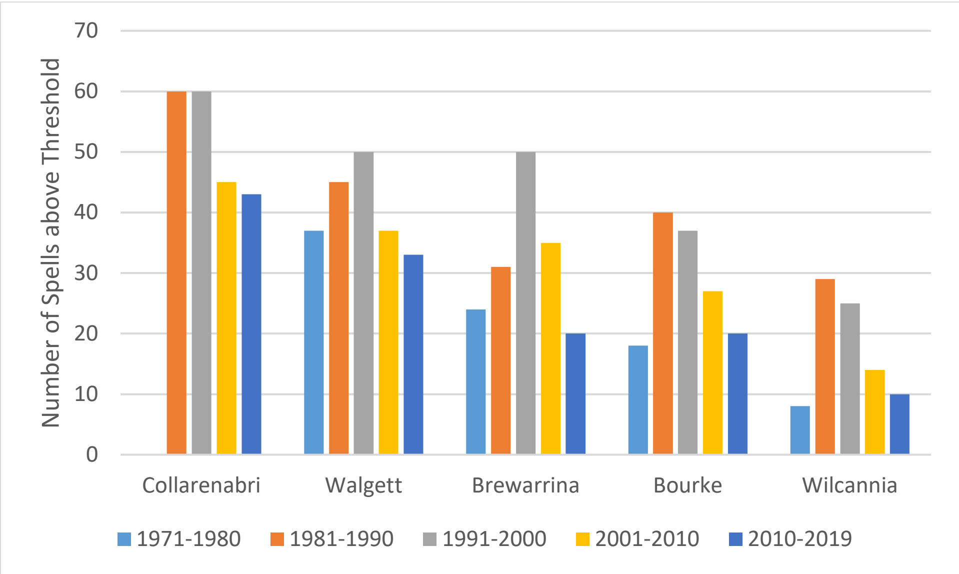


Figure 20: Number of Spells above the B Class Commence to Pump Threshold for 5 gauging stations along the Barwon-Darling for successive 10-year periods.

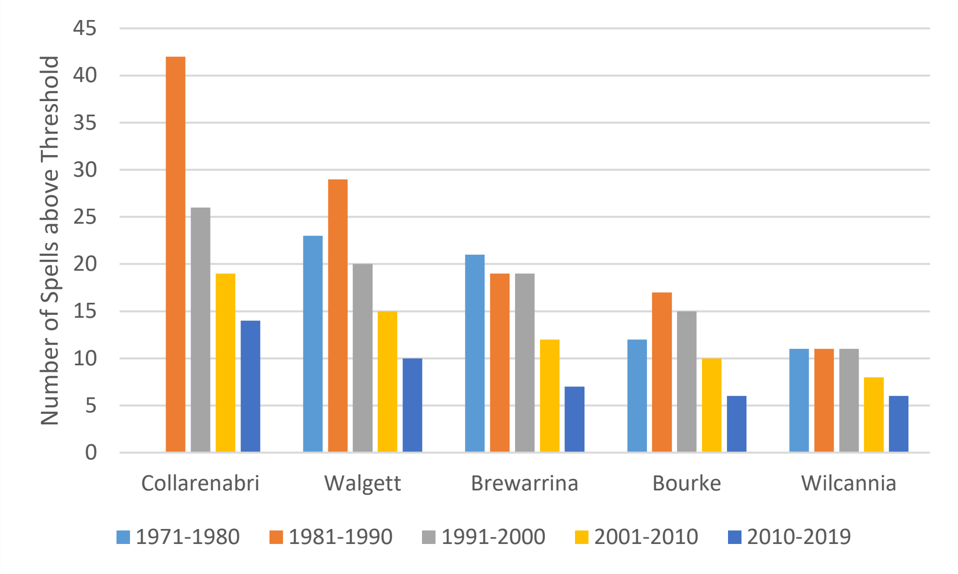


Figure 21: Number of flow spells above the C Class Commence to Pump Threshold for 5 gauging stations along the Barwon-Darling for successive 10 year periods.

There is a trend of reduced number of flow spells above both the B Class commence to pump and the C Class licence commence to pump between 1970-2019. This data suggests there are risks to flow components within the B Class licence extraction bands, particularly under a drying climate regime.

2.3.3 TOR 12: To what extent will Individual daily extraction limits (IDELs) protect the priority ecological flows outlined in Objective 1?

The Water Sharing Plan enables daily extraction limits (IDELs) to be implemented. Implementation of IDELS can assist with protecting flows in the low flow and freshes band, may assist in protecting first flushes as well as maintaining connectivity flows along the lower section of the Barwon-Darling. Six options were investigated for changing IDEL access rules by the NSW Department of Industry. If viewing these options through the lens of protecting the low flow and freshes flow bands then their impacts on A Class and B Class extractions needs to be considered, and particularly changes in the distribution of licences within management zones that might disproportionately impact the lower management zones of the Barwon-Darling. Using the Options Paper provided by the NSW Department of Industry where Option 4 (*distributing IDELs across each licence class within each management zone*) and Option 6 (*WSP rules with redistribution of extinguished IDELs based on trades which have occurred*) were considered to have the most favourable impact on flows in the A and B Class licence bands. IDELs were considered to only be able to protect the priority ecological flows within the low flow and freshes band, if

(a) There are more flexible rules around IDELs, rather than set daily volumes, this flexibility could include:
    a. reduced IDELs for A and B Class licences during first flush flows
    b. reduced IDELs during Spring and Summer to allow spawning and recruitment of fauna

(b) Fixed IDELs (and thus TDELs) are of a volume that does not allow extraction of complete events in the low flow and A Class flow bands
(c) IDELs could be developed to allow protection of seasonal flows that are important for spawning and recruitment of vulnerable taxa
(d) after extended periods of low flow, when climate triggers suggest the commencement of a drying period, IDELs could be adjusted to allow low flows and freshes through the Barwon-Darling.

The NSW Department of Industry suggested four scenarios based on the time since a particular flow has been received at Wilcannia that could be used to influence the implementation of IDELs; these scenarios are:

- 20 days since a flow of 90ML/day at Wicannia
- 20 days since a flow of 400ML/day at Wicannia
- 90 days since a flow of 90ML/day at Wicannia
- 90 days since a flow of 400ML/day at Wicannia

For interest the difference in these flows at Wilcannia between "modelled" pre-development data and "actual" data suggest "modelled" pre-development flows of both 90 ML/day and 400 ML/day occurred more frequently and for longer durations than currently (Table 12).

Table 12: Comparison between "actual" flow data and "modelled" pre-development data at the Wilcannia gauge (425008) for two flow thresholds 90 ML/day and 400 ML/day.

	Actual	Modelled
Flow (ML/day)	90	90
Mean Duration of Flow (days)	335.121	507.875
Mean period Between Flows (days)	73.312	52.87
Flow (ML/day)	400	400
Mean Duration of Flow (days)	117.133	207.843
Mean period Between Flows (days)	62.432	56.1

IDELs could be used to protect low flows, baseflows and freshes flow bands but would need to be developed and implemented with respect to natural flow seasonality and climate variability. Set IDELs that are implemented regardless of seasonal environmental requirements or with not context associated with background variability will continue to place hydrological pressure on the lower management zones in the Barwon-Darling.

2.4 Knowledge Gaps and Evidence

2.4.1 TOR 13: What are the knowledge gaps that continue to exist within the Barwon-Darling plan area?

Hydrology: While there is good hydrological data for several gauges along the Barwon-Darling, this data is not currently linked to either realtime extractions of water for agriculture or a robust modelling framework that allows scenario testing. The following knowledge gaps exist:

- The discharge data for gauges along the Barwon-Darling is good, however, to fully understand the impacts of flow extractions there needs to be a **whole of system model** for the northern Murray-Darling Basin in which pre-development, and other development threshold scenarios, can be run – for a minimum of a 40 year period to account for decadal flow variability. The pre-development model should be run annually so this information is available for decision making.
- Need a greater understanding of the influence of end-of-system tributary flows on flows in the Barwon-Darling
- Need a greater understanding of the impacts tributary extractions and tributary floodplain harvesting have on the freshes (small and large) flow band in the Barwon-Darling.
- Needs better links between the discharge data and the extraction data so impacts on the hydrograph, both locally, and at a management reach scale can be understood.
- The model for pre-development disharges should be tested under low-flow scenarios, as the current model is less reliable at low flows, making detecting impacts of extraction in these flow bands difficult.

Ecology: For the Barwon-Darling plan area there is relatively good information on the ecology of fish and the flows required to reduce algal blooms, however, below is a list of general knowledge gaps that severely impact our understanding of the flow-ecology relationships in the Barwon-Darling.

- Very little is known about the flows required by fauna other than fish
- No knowledge on the spawning cues for the river mussels, a significant aquatic species (cultural and ecological).
- No data on the role of low flows and small freshes in the ecology of the Barwon-Darling
- No knowedge on the host fish species for river mussel glochidia (larvae)
- No knowedge on the role of flow (frequency, variability, seasonality) in structuring the macroinvertebrate assemblages of the Barwon-Darling.
- No knowledge on the broad food-web linkages for the Barwon-Darling river system – this includes the role of the river in riparian foodwebs (riparian birds and mammals).
- Limited knowledge on the role of floods (frequency and duration) on the recruitment and survival of riparian and flooplain vegetation communities.

2.4.2 TOR 14: Provide comment on the strength of evidence the Commission is using to make recommendations

The Commission has good site based hydrological data for nodes within the Barwon-Darling plan area and each of the associated management zones. However, there is limited scenario modelling of this data, so it is difficult to determine impacts from flow changes due to water resource development. This is a severe knowledge gap when trying to determine any impact of water resource development and make ongoing recommendations.

There is limited consistent monitoring of ecosystem health outcomes across the Barwon-Darling plan area. This lack of background ecological data makes detecting impacts of flow change on the ecosystem difficult. A robust monitoring program with indicators aligned to flow change would provide a framework for understand ecosystem responses to flow change, both change from increased, or changed, extractions or flow change resulting from increases in environmental water.

2.4.3 TOR 15: Provide comment on the timeframes required to revisit any changes made to plan rules to see whether things are working, including the evidence required to make that assessment?

Given the natural background variability in discharge, a long-term adaptive management approach needs to be taken to understand the impacts of changes to plan rules. This must include comprehensive hydrological modelling and monitoring combined with a robust ecosystem health monitoring plan that includes indicators that are responsive to changes in flow and can be used to assess flow specific changes and not just general ecosystem health.

3 References

Arthington, A.H. 2012. Environmental Flows: Saving Rivers in the Third Millennium. Unversity of California Press. 421pp.

Arthington, A. H., S. R. Balcombe, G. A. Wilson, M. C. Thoms, and J. C. Marshall. 2005. Spatial and temporal variation in fish assemblage structure in isolated waterholes during the 2001 dry season of an arid-zone floodplain river, Cooper Creek, Australia. Marine and Freshwater Research 56:1-11.

Baker, A. M., C. Bartlett, S. E. Bunn, K. Goudkamp, F. Sheldon, and J. M. Hughes. 2003. Cryptic species and morphological plasticity in long-lived bivalves (Unionoida: Hyriidae) from inland Australia. Molecular Ecology 12:2707-2717.

Baker, A. M., F. Sheldon, J. Somerville, K. F. Walker, and J. M. Hughes. 2004. Mitochondrial DNA phylogenetic structuring suggests similarity between two morphologically plastic genera of Australian freshwater mussels (Unionoida: Hyriidae). Molecular Phylogenetics and Evolution 32:902-912.

Baldwin, D. S., and A. M. Mitchell. 2000. The effects of drying and re-flooding on the sediment and soil nutrient dynamics of lowland river–floodplain systems: a synthesis. Regulated Rivers: Research and Management 16:457-467.

Boulton, A. J., and P. S. Lake. 1992a. The ecology of two intermittent streams in Victoria, Australia. II Comparisons of faunal composition between habitats, rivers and years. Freshwat. Biol. 27:99-121.

Boulton, A. J., and P. S. Lake. 1992b. The ecology of two intermittent streams in Victoria, Australia. III Temporal changes in faunal composition. Freshwat. Biol. 27:123-138.

Boulton, A. J., C. G. Peterson, N. B. Grimm, and S. G. Fisher. 1992. Stability of an aquatic macroinvertebrate community in a multiyear hydrologic disturbance regime. Ecology 73:2192-2207.

Bunn, S. E., and A. H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environmental Management 30:492-207.

Carlisle, P. 2017. Hydrological impacts of water management arrangements on low flows in the Barwon Darling River system. Advice to the Commonwealth Environmental Water Office.

Cooney, T. 1994. Barwon Darling River Riparian Health Report: Wetlands Inundation. NSW Department of Water Resouces, Sydney.

DWR. 1992. Interim unregulated flow management plan for the North-West. Department of Water Resources, Parramatta

Gallo, E. L., K. A. Lohse, C. M. Ferlin, T. Meixner, and P. D. Brooks. 2014. Physical and biological controls on trace gas fluxes in semi-arid urban ephemeral waterways. Biogeochemistry 121:189-207.

Gehrke, P., and J. H. Harris. 2004. Fish in the Darling River System. Pages 260-277 in R. Breckwoldt, R. Boden, and J. Andrew, editors. The Darling. Murray-Darling Basin Commission, Canberra.

Gippel, C.J. and M.J. Stewardson. 1998. Use of wetted perimeter in defining minimum environmental flows. Regulated Rivers: Research and Management 14: 53-67.

Humphries, P. and K.F. Walker (2013). Ecology of Australian Freshwater Fishes. CSIRO Publishing.

Jenkins, K. M., and A. J. Boulton. 2003. Connectivity in a dryland river: short-term aquatic microinvertebrate recruitment following floodplain inundation. Ecology 84:2708-2723.

Kennard, M., B. Pusey, J. D. Olden, S. J. Mackay, J. L. Stein, and N. Marsh. 2010. Classification of natural flow regimes in Australia to support environmental flow management. Freshwater Biology 55:171-193.

Lake. P.S. 2011. Drought and Aquatic Ecosystems: Effects and Responses. Wiley-Blackwell. 400 pages.

Larned, S. T., T. Datry, D. B. Arscott, and K. Tockner. 2010. Emerging concepts in temporary-river ecology. Freshwater Biology 55:717-738.

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

Mallen-Cooper, M. and Zampatti, B.P. 2015. Background Paper: Use of life history conceptual models of fish in flow management in the Murray-Darling Basin. Report to the Murray-Darling Basin Authority

Mallen-Cooper, Martin & P. Zampatti, Brenton. 2018. History, hydrology and hydraulics: Rethinking the ecological management of large rivers. Ecohydrology. 11. e1965. 10.1002/eco.1965.

Marsh, N. A. Stewardson M. J. Kennard, M. J. (2003) River Analysis Package, Cooperative Research Centre for Catchment Hydrology, Monash University Melbourne.

Marshall, J. C., F. Sheldon, M. Thoms, and S. Choy. 2006. The macroinvertebrate fauna of an Australian dryland river: spatial and temporal patterns and environmental relationships. Marine and Freshwater Research 57:61-74.

McGregor, G. B., J. C. Marshall, and M. C. Thoms. 2005. Spatial and temporal variation in algal-assemblage structure in isolated dryland river waterholes, Cooper Creek and Warrego River, Australia. Marine and Freshwater Research 57:453-466.

McIntyre, R. E. S., M. A. Adams, and P. F. Grierson. 2009. Nitrogen mineralization potential in rewetted soils from a semi-arid stream landscape, north-west Australia. Journal of Arid Environments 73:48-54.

MDBA 2019. Climate change and the Murray–Darling Basin Plan. Murray–Darling Basin Authority Canberra, 2019. CC BY 4.0

Mitrovic, S. M., B. C. Chessman, L. C. Bowling, and R. H. Cooke. 2006. Modelling suppression of cyanobacterial blooms by flow management in a lowland river. River Research and Applications 22:109-114.

Mitrovic, S, 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, 229-242.

NSW DPI 2015, Fish and flows in the Northern Basin: responses of fish to changes in flows in the Northern Murray–Darling Basin, report prepared for MDBA by the NSW Department of Primary Industries, Tamworth

OEH 2019. Draft Long Term Water Plan – excerpt shared by the Commission for the purpose of this review

Poff, N. L., and J. V. Ward. 1989. Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. Can. J. Fish. Aquat. Sci 46:1805-1818.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime: A paradigm for river conservation and restoration. BioScience 47:769-784.

Puckridge, J., F. Sheldon, K. Walker, and A. Boulton. 1998. Flow variability and the ecology of large rivers. Marine and Freshwater Research 49:55-72.

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

Sheldon, F. 2017. Characterising the ecological effects of changes in the 'low-flow hydrology' of the Barwon-Darling River. Advice to the Commonwealth Environmental Water Holder Office, October 2017.

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

Sheldon, F., and M. C. Thoms. 2004. The Darling River corridors.in R. Breckwoldt, R. Boden, and J. Andrew, editors. The Darling. Murray-Darling Basin Commission, Canberra.

Sheldon, F., and M. C. Thoms. 2006. Geomorphic in-channel complexity: the key to organic matter retention in large dryland rivers? Geomorphology 77:270-285.

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

Stuart, I. and C. Sharpe. 2017. Towards a southern connected basin flow plan: connecting rivers to recover native fish communities. Kingfisher Research and CPS Enviro report to the Murray-Darling Basin Authority.

Thoms, M. C., F. Sheldon, and P. Crabb. 2004. A hydrological perspective on the Darling River. Pages 332-347 in R. Breckwoldt, R. Boden, and J. Andrew, editors. The Darling. Murray-Darling Basin Commission, Canberra.

Vertessy, R., Barma, D., Baumgartner, L., Mitrovic, S., Sheldon, F. and Bond, N. (2019). Independent assessment of the 2018-19 fish deaths in the lower darling. Murray-Darling Basin Authority.

Walker, K. F., F. Sheldon, and J. T. Puckridge. 1995. A perspective on dryland river ecosystems. Regul. Riv. 11:85-104.

Walker,K.F. 2017. Reproductive phenology of river and lake populations of freshwater mussels (Unionida: Hyriidae) in the River Murray. Molluscan Research 37: 31-44

Woodward, K. B., C. S. Fellows, S. M. Mitrovic, and F. Sheldon. 2015. Patterns and bioavailability of soil nutrients and carbon across a gradient of inundation frequencies in a lowland river channel, Murray–Darling Basin, Australia. Agriculture, Ecosystems and Environment 205:1-8.

Yang, Y., T. R. McVicar, R. J. Donohue, Y. Zhang, M. L. Roderick, F. H. S. Chiew, L. Zhang, and J. Zhang. 2017. Lags in hydrologic recovery following an extreme drought: Assessing the roles of climate and catchment characteristics. Water Resources Research 53:4821-4837.

Appendix 1: Notes from Martin Mallen-Cooper on the Barwon-Darling Water Sharing Plan.

ISSUE CLARIFICATION								ACTIONS FOR NRC REVIEW			
Issue	**Is this issue primarily flow related?**	**Background to flow requirements**	**Flow requirement** **(seasonal hydrodynamic and hydrological)**	**Is the issue meeting the objectives of Water Management Act?**	**Existing data to confirm/ inform issue**	**Is existing data sufficient to confirm issue?**	**Data needed to confirm/ clarify/ quantify issue**	**Data needed to assess impacts of WSP on flow regimes that directly affect issue,** **and assess where changes could improve issue**	**Part of B-D WSP that affects issue**	**Recommended modification of B-D WSP to partly restore values (social, environmental, cultural) to socially/culturally acceptable levels**	**Intended industry response**
Environment											
Fish											
Specialist native fish[1] that require flowing (lotic) water habitats[2] over moderate spatial scales (10s km), have declined. The only example in the B-D is Murray cod. [1] see Mallen-Cooper & Zampatti (2015) [2] e.g. mean channel velocity > 0.3 m/s, (Mallen-Cooper & Zampatti, 2018)	Yes. Note: other habitat features, especially large woody debris, enhance fish response.	Require flowing water (lotic, 0.3 m/s) over moderate spatial scales (10s km), i) in spring for survival of larvae, and ii) for most of the year for survival of young fish Note: spawning occurs in a range of habitats, but larval survival is high in flowing water	**Spring** Maintain >0.3 m/s [mean channel velocity] over 10s km; > 2 m depth in pools; Typically 400-500 ML/d in B-D Typically, this is 80-90%ile of modelled natural. **Summer/Autumn** Maintain flowing conditions in summer for survival of young. Typically, 150-250 ML/d (~95%ile of natural)	No	Sustainable Rivers Audit	Yes	None required	Daily model of hydrology and preferably hydrodynamics (use existing cross-sections of gauges in free-flowing reaches) and water level[3] of the last 40 years, which would include wet and dry decades Model to include: i) with and without the following Classes (No flow, low flow, Class A) ii) End -of-system flow of NSW tributaries with modelled natural. This will determine if managing 3 lowest flow classes in B-D has a measurable benefit, or low flows are mainly determined by inflows outside B-D WSP [3] Daily data needed to assess seasonality, and water level needed to assess sudden decreases [e.g. 0.5 m over 5 days]).	Classes: No flow, low flow, Class A	If modelling shows significant impacts of low-flow Classes (No flow, low flow, Class A) in B-D WSP then change rules to enable them to store water off-stream when flows are higher If modelling shows tribs are the major impact on low flows, highly recommend that end-of system flows in each catchment be linked to low flow hydrodynamic and hydrological objectives for the B-D.	Greater off-stream storage; more pumping at higher flows
Specialist native fish that require flowing (lotic) water habitats over large spatial scales (100s km), have declined. These comprise golden perch and silver perch.	Yes. Free migration over long distances also essential	ii) requiring flowing water over large spatial scales (100s km) in spring or summer. Adult fish migrate upstream 100s km and larvae drift downstream 100s km in major	1 year ARI or higher of modelled natural (duration may be 3 to 5%ile of modelled natural). To maintain minimum populations of these species in a regulated system like the	No	Sustainable Rivers Audit	Yes	None required	Assess impacts of B-D WSP on 1 Year ARI (natural) using: Daily model of flow and water level[3] of the last 40 years, which would include wet and dry decades i) with and without the following Classes (Class B & C)	Pumping regime of Class B and C Floodplain harvesting	Env should act as the first license? Env needs a spatial scale criterion with end of reach threshold	Floodplain harvesting quantified, regulated. "Shepherding" becomes an embedded part of the WSP with

ISSUE CLARIFICATION								ACTIONS FOR NRC REVIEW			
Issue	**Is this issue primarily flow related?**	**Background to flow requirements**	**Flow requirement** **(seasonal hydrodynamic and hydrological)**	**Is the issue meeting the objectives of Water Manageme nt Act?**	**Existing data to confirm/ inform issue**	**Is existing data sufficien t to confirm issue?**	**Data needed to confirm/ clarify/ quantify issue**	**Data needed to assess impacts of WSP on flow regimes that directly affect issue,** **and assess where changes could improve issue**	**Part of B-D WSP that affects issue**	**Recommended modification of B-D WSP to partly restore values (social, environmental, cultural) to socially/culturally acceptable levels**	**Intended industry response**
		in-channel pulses of flow, or floods The only two examples in the B-D are golden perch and silver perch.	Barwon-Darling the 1 year ARI (natural) should be Young golden perch (fry and fingerlings) will thrive in off-channel lakes (stillwater) and the main channel (flowing water) Young silver perch appear to mainly thrive in main channel habitats with flowing water, although a population in the Warrego.					ii) End -of-system flow of NSW tributaries with modelled natural and current. iii) with and without floodplain harvesting (licensed and rough estimates of unlicensed) This will determine if managing Class B & C and floodplain harvesting in B-D has a measurable benefit, or flows are mainly determined by inflows outside B-D WSP			the env as first user in each Class
<u>Large-bodied native fish that build and guard nests have declined</u> Only example is freshwater catfish	Evidence is equivocal. Fish will abandon nests if there is sudden decrease in water level Known to spawn in artificial pools. Known to use wetlands adjoining main channel habitats; these have declined with flow diversions.										
Notes: 1) These *<u>specialists</u>* are large-bodied fish species that are key cultural species for Aboriginal people and key recreational species											

ISSUE CLARIFICATION								ACTIONS FOR NRC REVIEW			
Issue	**Is this issue primarily flow related?**	**Background to flow requirements**	**Flow requirement (seasonal hydrodynamic and hydrological)**	**Is the issue meeting the objectives of Water Manageme nt Act?**	**Existing data to confirm/ inform issue**	**Is existing data sufficien t to confirm issue?**	**Data needed to confirm/ clarify/ quantify issue**	**Data needed to assess impacts of WSP on flow regimes that directly affect issue, and assess where changes could improve issue**	**Part of B-D WSP that affects issue**	**Recommended modification of B-D WSP to partly restore values (social, environmental, cultural) to socially/culturally acceptable levels**	**Intended industry response**
2) *Generalist* native fish species that can spawn and recruit in any flow conditions (zero to high flows), remain relatively abundant. E.g. bony herring (or bony bream), Australian smelt. 3) It is a well-documented phenomenon that in rivers with regulated flow, *generalist* biota thrive and *specialists* decline. Declining specialist biota are a key indicator of declining river health.											
Mussels and Snails											
Major decline in river mussels	Yes	Require near permanent flowing water over small spatial scales (e.g. 100m)	Maintain >0.3 m/s [mean channel velocity] over 10s km; min. depth possibly 0.3 m Typically, 150-250 ML/d (~95%ile of natural). Max. duration of velocity < 0.1 m/s is probably 3 months based on historical flows but no data *in situ*.	No	Well known but not well-reported	??	??	Above modelling of hydrology and hydrodynamics i) with and without the following Classes (No flow, low flow, Class A) ii) End -of-system flow of NSW tributaries with modelled natural.	Classes: No flow, low flow, Class A	If modelling shows significant impacts of low-flow Classes (No flow, low flow, Class A) in B-D WSP then change rules to enable them to store water off-stream when flows are higher If modelling shows tribs are the major impact on low flows, highly recommend that end-of system flows in each catchment be linked to low flow hydrodynamic and hydrological objectives for the B-D.	Greater off-stream storage; more pumping at higher flows
Major decline (almost extinct) in river snails	Evidence is strong that flowing	Require near permanent	Maintain >0.3 m/s [mean channel	No	Yes	Yes	None required	As above for mussels	As above	As above	A above

ISSUE CLARIFICATION								ACTIONS FOR NRC REVIEW			
Issue	**Is this issue primarily flow related?**	**Background to flow requirements**	**Flow requirement** **(seasonal hydrodynamic and hydrological)**	**Is the issue meeting the objectives of Water Management Act?**	**Existing data to confirm/ inform issue**	**Is existing data sufficient to confirm issue?**	**Data needed to confirm/ clarify/ quantify issue**	**Data needed to assess impacts of WSP on flow regimes that directly affect issue,** **and assess where changes could improve issue**	**Part of B-D WSP that affects issue**	**Recommended modification of B-D WSP to partly restore values (social, environmental, cultural) to socially/culturally acceptable levels**	**Intended industry response**
	water habitats are necessary. However, few sites left to confirm.	flowing water over small spatial scales (e.g. 100m), possibly over hard substrates such as rocks	velocity] over 10s km; min. depth possibly 0.3 m, but no data *in situ*. Typically, 150-250 ML/d (~95%ile of natural). Max. duration of velocity < 0.1 m/s is probably 3 months based on historical flows but no data *in situ*.								
Risk from blue-green algae and fish kills increasing	There are four interrelated factors, including flow: i) reduced low flows which: a) reduces water velocity (more stagnant), b) increases risk of weirpool stratification; ii) increased nutrients, iii) weirpools (deeper than natural pools) which increase depth and risk of stratification at low and zero flow. Overlaid on these factors is increased	Maximise low flows to maximise water velocity (e.g. > 0.1 m/s) and minimise stratification.	Apply min. water velocity in hot weather.	No	Donnelly *et al*. 1997, Mitrovic 2003, 2007. Vertessy 2019, Academy of Science 2019	Yes	Non required	Hydrodynamic model of weir pools and river channel to asses discharge required to maintain low water velocities. Model to include: i) with and without the following Classes (No flow, low flow, Class A) ii) End -of-system flow of NSW tributaries with modelled natural. **<u>NOTE: not practical within NRC review timeframe.</u>** Vertessy 2019 may recommend to Federal Government.	Classes: No flow, low flow, Class A	More low flows required for the river to minimise risk of B-G algae. If modelling shows significant impacts of low-flow Classes (No flow, low flow, Class A) in B-D WSP then change rules to enable them to store water off-stream when flows are higher If modelling shows tribs are the major impact on low flows, highly recommend that end-of system flows in each	Greater off-stream storage; more pumping at higher flows

ISSUE CLARIFICATION								ACTIONS FOR NRC REVIEW			
Issue	**Is this issue primarily flow related?**	**Background to flow requirements**	**Flow requirement (seasonal hydrodynamic and hydrological)**	**Is the issue meeting the objectives of Water Management Act?**	**Existing data to confirm/ inform issue**	**Is existing data sufficient to confirm issue?**	**Data needed to confirm/ clarify/ quantify issue**	**Data needed to assess impacts of WSP on flow regimes that directly affect issue, and assess where changes could improve issue**	**Part of B-D WSP that affects issue**	**Recommended modification of B-D WSP to partly restore values (social, environmental, cultural) to socially/culturally acceptable levels**	**Intended industry response**
	temperature from climate change/variability which favours B-G algae (cyanobacteria), through increasing risk of water stratification in pools and provides more favourable conditions for growth.									catchment be linked to low flow hydrodynamic and hydrological objectives for the B-D.	
Cultural											
Aquatic biota have strong cultural significance for aboriginal people. Fish, mussels and snails were a fundamental source of food and are an inherent cultural value; different fish are totems for different groups (Balme 1983, Humphries 2007).											