

Supplementary material

Flow to nowhere: the disconnect between environmental watering and the conservation of threatened species in the Murray–Darling Basin, Australia

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Table S1. The conservation status of the eight threatened species of flow-dependent fauna in the Murray–Darling Basin according to Commonwealth, State and Territory biodiversity conservation legislation

Data are from Department of Agriculture, Water and Environment (2021). N/A, not applicable, i.e. species does not occur in that State or Territory

Species	New South Wales ^A	Victoria ^B	South Australia ^C	Queensland ^D	Australian Capital Territory ^E	Commonwealth ^F	National recovery plan?
Sloane's froglet	Vulnerable	Not listed	Not listed	N/A	Not listed	Endangered	No
Southern bell frog	Endangered	Threatened [Endangered]	Vulnerable	N/A	Vulnerable	Vulnerable	Yes (2012)
Australasian bittern	Endangered	Threatened [Endangered]	Endangered	Endangered	Endangered	Endangered	Draft
Australian painted snipe	Endangered	Threatened [Critically endangered]	Endangered	Endangered	Endangered	Endangered	Draft
Trout cod	Endangered	Critically endangered	Endangered [Extinct]	N/A	Endangered	Endangered	Yes (1994)
Murray hardyhead	Critically endangered	Endangered [Critically endangered]	Not listed [Critically endangered]	N/A	N/A	Endangered	Yes (2008)
Silver perch	Vulnerable	Threatened [Vulnerable]	Vulnerable [Endangered]	Not listed	Endangered	Critically endangered	No
Flathead galaxias	Critically endangered	Not listed [Vulnerable]	Not listed [Extinct]	N/A	N/A	Critically endangered	No

^AStatus according to the *Biodiversity Conservation Act 2016* (NSW) and the *Fisheries Management Act 1994* (NSW).

^BStatus according to the *Flora and Fauna Guarantee Act 1988* (Vic.). Non-statutory listings in brackets are according to Department of Environment, Land, Water and Planning (2013).

^CStatus according to the *Fisheries Act 1982* (SA) and the *National Parks and Wildlife Act 1972* (SA). Non-statutory listings in brackets are according to Native Fish (SA) Inc. (2009).

^DStatus according to the *Nature Conservation Act 1992* (Qld).

^EStatus according to the *Nature Conservation Act 2014* (ACT).

^FStatus according to the *Environment Protection and Biodiversity Conservation Act 1999* (Cth).

References

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Table S2. Breeding sites of threatened species (based on Fig. 1) for determination of whether environmental flow events met the water requirements of species for breeding

NK, not known; F, freshes (including bankfull); O, overbank; W, wetland

Species and catchment	Known breeding sites	Freshwater habitat	Flow type	Duration	Frequency	Season
Sloane's froglet		Shallow temporary wetlands with emergent vegetation	O, W	3–4 months	1–2 years	Autumn–spring
Central Murray	Albury to Corowa					
Central Murray	Barmah–Millewa Forest					
Goulburn–Broken	Moodies Swamp					
Southern bell frog		Permanent, still waterbodies with emergent vegetation	O, W	3 months	1–2 years	Spring–summer
Mid-Murrumbidgee	Yanco Creek wetlands					
Lower Murrumbidgee	Yanga and Nimmie–Caira					
Lower Murray	Murray Mallee Lakes near Mildura					
Lower Murray	Chowilla Lindsay–Wallpolla					
Lower Murray	Lakes Alexandrina and Albert					
Australasian bittern		Shallow wetlands with tall, dense emergent vegetation	O, W F, O, W	>3 months	NK	Summer
Macquarie	Macquarie Marshes					
Mid-Murrumbidgee	Fivebough and Tuckerbil swamps					
Mid-Murrumbidgee	Yanco Creek wetlands					
Lower Murrumbidgee	Nimmie–Caira					
Lower Murray	Chowilla–Lindsay–Walpolla					
Lower Murray	Lakes Alexandrina and Albert					
Australian painted snipe		Shallow temporary wetlands w. low vegetation, mudflats	O, W	~2 months	2 years	Spring–summer
Gwydir	Gwydir and Mallowa wetlands					
Mid-Murrumbidgee	Fivebough and Tuckerbil swamps					
	Yanco Creek wetlands					
Trout cod		Deep, flowing river channels with large woody debris	F, O	~2 months	1–2 years	Spring–summer
Central Murray	Yarrawonga to Euston					
Goulburn–Broken	Goulburn and Broken channels					
Ovens	Ovens channel and floodplain					
Murray hardyhead		Fresh/saline floodplain lakes with submerged vegetation	O, W	2 months	1 year	Spring–summer
Central Murray	Murray Mallee Lakes near Mildura					
Lower Murray	Riverland (Disher Ck, Berri Evap. Basin)					
Lower Murray	Murray Bridge to Lower Lakes					
Silver perch		Perennially flowing river channels, open water	F, O	~1 month	1 year	Spring–summer
Lower Murrumbidgee	Yanga and Nimmie–Caira					
Edward–Wakool	Edward, Wakool, Niemur rivers					
Goulburn–Broken	Goulburn and Broken channels					
Flathead galaxias		Floodplain wetlands, lagoons & slow-flowing creeks	O, W	~1 month	1 year	Spring
Campaspe	Floodplain wetlands					
Goulburn–Broken	Broken floodplain and wetlands					

Table S3. Occurrence of eight threatened species in the Murray–Darling Basin by catchment (river valley), on the basis of records of occurrence pre-1990 and those post-1990 in the Atlas of Living Australia (see Fig. 2)

Green cells indicate where the species was recorded post-1990 but not before and yellow cells where the species was recorded pre-1990 but not after. 1, recorded; 0, not recorded

Catchment	Sloane's froglet		Southern bell frog		Australasian bittern		Australian painted snipe		Trout cod		Murray hardyhead		Silver perch		Flathead galaxias	
	<1990	>1990	<1990	>1990	<1990	>1990	<1990	>1990	<1990	>1990	<1990	>1990	<1990	>1990	<1990	>1990
Paroo	0	0	0	0	1	0	1	0	0	0	0	1	1	0	0	
Warrego	0	0	0	0	0	1	1	1	0	0	0	1	1	0	0	
Condamine–Balonne	0	1	0	0	1	1	1	0	0	0	0	1	1	0	0	
Moonie	0	0	0	0	1	0	1	0	0	0	0	1	0	0	0	
Border Rivers	0	1	0	0	1	1	1	1	0	0	0	1	1	0	0	
Gwydir	0	0	0	0	1	1	1	1	0	0	0	1	1	0	0	
Namoi	0	1	0	0	1	1	1	1	0	0	0	1	1	0	0	
Macquarie	1	1	1	1	1	1	1	1	0	0	0	1	1	1	0	
Barwon–Darling	0	0	0	0	1	1	1	1	0	0	0	1	1	0	0	
Lower Darling	0	0	0	0	1	1	1	1	0	0	0	1	1	0	0	
Lachlan	1	1	1	1	1	1	1	1	0	0	0	1	1	1	0	
Murrumbidgee	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Central Murray ^A	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Ovens	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	
Goulburn–Broken	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	
Campaspe	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	
Loddon	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	
Wimmera–Avoca	0	0	1	1	1	1	1	1	1	0	1	0	1	1	1	
Lower Murray	0	0	1	1	1	1	1	1	1	0	1	1	1	1	0	

^AIncludes Edward–Wakool and upper Murray.

Table S4. Water requirements of eight flow-dependent threatened species in the Murray–Darling Basin for breeding, habitat connectivity and maintenance

Species require flooding, except trout cod and silver perch, which require mid-to-high freshening flows. CEWO, Commonwealth Environmental Water Office; DEE, Department of Environment and Energy; DELWP, Department of Environment, Land, Water and Planning; MDBA, Murray–Darling Basin Authority; TSSC, Threatened Species Scientific Committee; TCRT, Trout Cod Recovery Team

Species	Breeding				Habitat connectivity and maintenance				References
	Magnitude of flow	Duration	Frequency	Season	Magnitude of flow	Duration	Frequency	Season	
Sloane’s froglet	Sufficient to flood habitat to <0.3-m depth	3–4 months	Every 1–2 years	Mar.–Sep.	Sufficient to inundate and connect wetlands	2–3 months	Annual	Mar.–Sep.	Knight 2013, 2014; Anstis 2017; J. Deretic, pers. comm., Oct. 2020
Southern bell frog	Sufficient to flood temporary wetlands	3 months	Every 1–2 years	Oct.–Feb.	Sufficient to flood temporary wetlands	2–3 months	Annual	Sep.–Feb.	Pyke 2002; Wassens <i>et al.</i> 2007; Mann <i>et al.</i> 2010; Clemann and Gillespie 2012
Australasian bittern	Flood of ≥0.3-m depth	At least 3 months	Not known	Dec.–Feb.	Small flood	Not known	Regular	Sep.–Feb.	TSSC 2019; Herring <i>et al.</i> 2019; CEWO 2019
Australian painted snipe	Shallow flood	~2 months	Every 2 years	Aug.–Feb.	Maintain permanent wetlands	Not known	Regular	Year-round	TSSC 2013a; DEE 2019
Trout cod	High flows	~2 months	Every 1–2 years	Oct.–Dec.	In-channel flow variation	Not known	Regular	Year-round	TCRT 2008; MDBA 2014; CEWO 2019, 2020; Koehn <i>et al.</i> 2020
Murray hardyhead	Enough to raise lake levels and lower salinity	2 months	Annual	Sep.–Mar.	High lake level in spring–summer, drawdown in autumn–winter	Not known	Annual	Sep.–Feb.	Backhouse <i>et al.</i> 2008; Ellis <i>et al.</i> 2013; DELWP 2017; Stoessel <i>et al.</i> 2020; Koehn <i>et al.</i> 2020
Silver perch	High flows	~1 month, after limited flooding	Annual	Oct.–Feb.	In-channel flow variation	Not known	Regular	Year-round	MDBA 2014; TSSC 2013b; CEWO 2020; Koehn <i>et al.</i> 2020
Flathead galaxias	Small flood	~1 month	Annual	Aug.–Sep.	Small flood	Not known	Annual	Year-round	MDBA 2014; TSSC 2016

Table S5. Priorities and sites for environmental flows to increase the distribution (range expansion) of the four threatened species of native fishes listed in the 2019 Murray–Darling Basin Authority Basin-wide Environmental Watering Strategy

Catchment	Trout cod	Murray hardyhead	Silver perch	Flathead galaxias
Paroo			Expand range	
Warrego			Expand range	
Condamine–Balonne			Expand range	
Namoi			Expand range	
Macquarie	Establish additional population(s) within the catchment		Expand range	Candidate catchment for re-introduction
Barwon–Darling			Expand range	
Lower Darling			Expand range and establish additional population in lower Darling	
Lachlan	Establish additional population(s) downstream of Wyangala Dam			Candidate catchment for re-introduction
Murrumbidgee	Downstream expansion of the connected population of the Murrumbidgee–Murray–Edward		Establish additional population(s) in ACT reaches of the Murrumbidgee	Establish additional populations
Central and upper Murray (including Edward–Wakool)	Expand range upstream of Lake Mulwala and into the Kiewa River	Expand range. Establish additional populations in central Murray, including at Kerang Lakes	Establish additional population(s) at Gunbower Creek and Billabong Creek-Yanco Creek system	Expand range. Establish additional populations in Kiewa and Mitta Mitta Rivers and their wetlands
Ovens			Expand upstream of Lake Mulwala and into the Ovens River	
Goulburn–Broken	Establish additional population(s) in the mid-Goulburn River		Increase range up the lower Goulburn River. Establish additional population in Broken Creek	Establish additional populations
Campaspe			Establish additional population in Campaspe River	
Loddon			Establish additional population in lower Loddon	
Lower Murray		Expand range. Establish additional populations		Expand range

Table S6. Reporting on benefits of environmental flows to threatened species by State agencies and others

O, occurrence record; PS, population supported; B, breeding record; PM, population monitoring. Note: there was minimal reporting on environmental outcomes by NSW in 2017–18 and 2018–19. There was no monitoring or reporting at all on flathead galaxias

Species and catchment	2014–15	2015–16	2016–17	2017–18	2018–19	Details	References
Sloane's froglet							
Goulburn–Broken			O			2016–17: first record, Doctors Swamp	VEWH 2017, p. 64
Southern bell frog							
Lachlan	O	PS				2014–15: first record, Lower Lachlan since 1980s. 2015–16: habitat maintained Noonamah–L. Bullogal	OEH 2015, p. 12, 2017a, p. 17
Central Murray	O					2014–15: first record, central Murray since 1990s	OEH 2015, p. 26
Murrumbidgee			PM			2016–17: widespread in Nimmie–Caira, >100 individuals at Nap Nap Swamp	OEH 2017b, p. 19
Edward–Wakool	O	O	O			2014–15: at Jimaringle, Cockran and Gwynnes creeks 2015–16: records from Cliffhouse Wetland, Andruco Lagoon, Brechin Swamp. 2016–17: recorded at multiple locations	OEH 2015, p. 26, 2017a, p. 28, 2017b, p. 23
Ovens		O				2015–16: abundant in lower Ovens and wetlands and in the King River upstream of Cheshunt	VEWH 2016, p. 88
Loddon				O	PS	2017–18: first record at Wirra-Lo Wetlands since 2008. Support breeding, Wirra-Lo, Sep.–Dec. 2018	VEWH 2019, p. 46, 2020, p. 57
Lower Murray	O		O		O	2014–15, 2016–17: Chowilla, L. Alexandrina. 2015–15: 4 sites in the Lower Lakes – Wellington East, Dunns Lagoon, Murrundi Wetland and Clayton Bay. 2018–19: Overland Corner, Chowilla, Templeton	DEWNR 2016, p. 20; Durbridge 2016; DEW 2018, p. 34, 2020, pp. 24, 26, 34
Australasian bittern							
Macquarie		O				Macquarie Marshes, June 2016	OEH 2016, p. 13
Central Murray	O	B	PM	PM		Recorded Barmah Forest after natural floods, July 2014. Breeding, Johnson Swamp, 2015. Several sighted, Central Murray Wetlands, Autumn 2017 and Barmah Forest. 2015–16: 73 males recorded, Millewa Forest. 2017–18: 50 males recorded, Millewa Forest	VEWH 2015, p. 55, 2016, p. 74, 2017, p. 67; OEH 2017a, p. 29; Borrell <i>et al.</i> 2017; Borrell 2018, p. 12
Goulburn	O	O				First record from Moodies swamp, Sep. 2014. Second record, May 2015	VEWH 2015, p. 41, 2016, p. 70
Loddon				PM		Records, Hird Swamp and Lake Cullen, Feb.–June 2018	VEWH 2019, p. 47
Lower Murray				O		2017–18: recorded Tolderol Wetland. 2018–19 recorded Milang Snipe Sanctuary, Lower Lakes	DEW 2018, p. 31, 2020, p. 36
Australian painted snipe							
Macquarie		O				Macquarie Marshes, June 2016	OEH 2017a, p. 13
Lower Murray				O		In flooded black box woodland, Hattah Lakes, spring 2017	Wood <i>et al.</i> 2018, p. 62
Trout cod							
Ovens		O				Recorded in King River as far up as Whitfield	VEWH 2017a, p. 88
Murray hardyhead							
Central Murray		O, PM	PS	PM		Recorded, Round Lake; re-introduction, L. Elizabeth 2016. Habitat maintained, Round L. and L. Elizabeth, 2016–17. Survey, L. Elizabeth, Apr. 2018. Habitat maintained Round L. and L. Elizabeth, 2018	VEWH 2016, p. 93, 2017, p. 67, 2018, p. 44, 2019, pp. 21, 56
Lower Murray	PS	PM	PM	PM	PM	Translocation 2500 individual, Brickworks Billabong, 2014. 500 individual records, Brickworks Billabong 2015–16. Large numbers recorded at Disher Creek and Berri Evaporation Basin, 2014–15, also monitored 2017–18, 2018–19. 2016–17: recorded Lakes Alexandrina and Albert. 2018–19: Lyrup Lagoon	VEWH 2015, p. 49, 2016, p. 76; DEWNR 2017a, p. 82, 2017b, 2018, p. 36
Silver perch							
Central Murray		B	B			Spawning, Millewa Forest, 2015; Barmah Forest, 2016	VEWH 2017, p. 79; OEH 2016, p. 29
Lower Murray	PS, PM	O, PM	O, PM	PM	PS, PM	Watering provided connectivity, Hattah Lakes, 2014. Population monitoring, Hattah Lakes (2007–8 to 2017–18). Recorded Lindsay-Walpolla, 2015. Re-stock, Horseshoe Lagoon, Walpolla Island, 2018–19	VEWH 2015, p. 52, 2016, 2019b, p. 62; Wood <i>et al.</i> 2018, p. 54; DEWNR 2016, p. 13
Goulburn–Broken	O		B			Lower Broken Creek, 2014. Spawning, Lower Goulburn, following natural high flows, Nov. 2016	VEWH 2015, p. 45, 2017, p. 61
Loddon			PM			Good numbers at Kerang Weir and Kow Swamp	VEWH 2017, p. 71
Campaspe			PM	O		2016–17: large numbers in Campaspe for first time in 10 years. 2017–18: migrating from Murray	VEWH 2017, pp. 59, 65, 2019a, p. 4

Table S7. Annual count of individuals and total number of records of eight endangered species in the Murray–Darling Basin, 2012–2019 analysis due to being an incomplete year

Figures in parentheses are corrected for sampling effort bias (see Materials and methods). Data from Atlas of Living Australia (2020), Department of Environment, Land, Water and Planning (2020) and Office of Environment and Heritage (2020) (references cited in main text)

Species	2012	2013	2014	2015	2016	2017	2018	2019
	Annual count							
Sloane’s froglet	280	262	0	1	1	0	2	9
Southern bell frog	6	21	244	203 (177)	193	1039	745 (662)	906 (656)
Australasian bittern	42	20	134	312	154	245	278	29
Australian painted snipe	150	78	23	21	0	88	1	0
Trout cod	0	23	3	32	12	136	88	88
Murray hardyhead	2	1	0	476 (473)	8336 (5046)	270	10	1
Silver perch	15	9	14	8	6	45	21	37
Flathead galaxias	0	2	0	16	1	0	0	0
	Number of records							
Sloane’s froglet	35	32	0	1	1	0	2	9
Southern bell frog	5	7	45	52 (26)	35	90	203 (120)	353 (103)
Australasian bittern	26	18	70	60	89	115	113	23
Australian painted snipe	42	57	19	9	0	60	1	0
Trout cod	0	19	3	17	6	32	21	18
Murray hardyhead	2	1	0	74 (27)	52 (13)	10	1	1
Silver perch	12	9	12	8	6	31	16	24
Flathead galaxias	0	2	0	3	1	0	0	0

Monitoring reports used to compile Table S4 and Table S6

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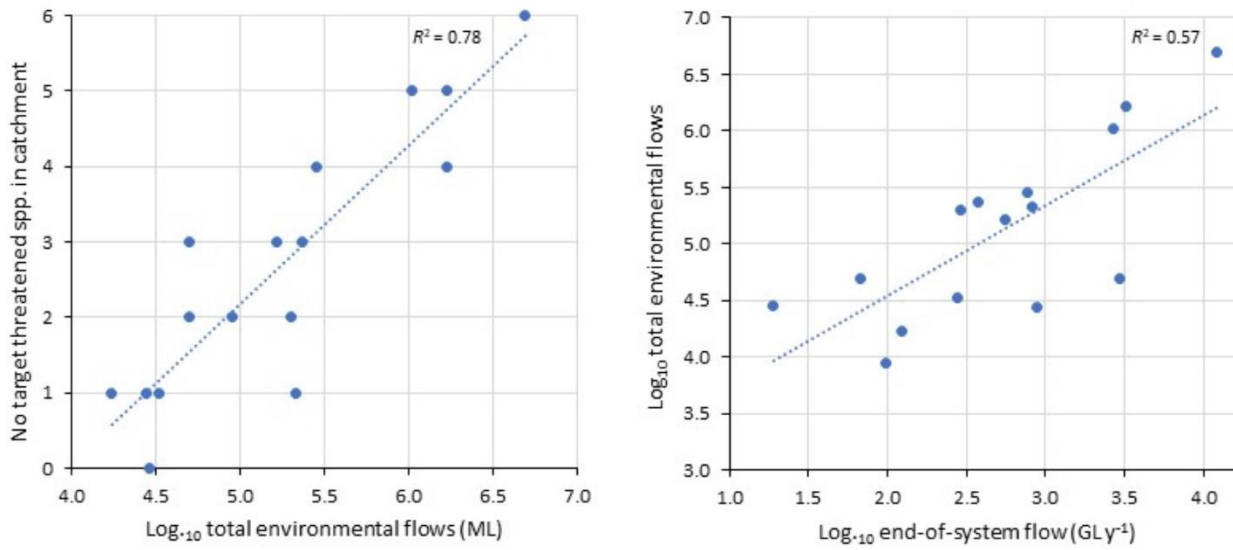


Fig. S1. Relationship between number of threatened species that are targets for environmental flows in CEWO environmental watering plans and portfolio management plans and the volume of Commonwealth environmental water delivered to the catchment from 2013–14 and 2018–19, and also between this latter variable and mean annual discharge (as end-of-system flow) for each catchment.