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

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Abstract. The Murray–Darling Basin Plan was established with the objective of restoring water from irrigation to the environment, thereby conserving wetlands and biodiversity. We examined whether the Plan is achieving this objective by assessing whether environmental watering has helped conserve threatened flow-dependent fauna. Two frog species, two waterbirds and four fishes, were assessed for their conservation status in relation to (1) whether they were targeted in environmental watering plans, (2) whether population monitoring had occurred and (3) evidence of population recovery. We determined indicators of abundance and occurrence of species between 2012–13 and 2018–19 and found widespread inconsistencies in the targeting of environmental watering for these species, including their being overlooked in watering plans and actions in several catchments. Environmental watering had some positive outcomes for some threatened species in some locations on some occasions, but benefits, and their monitoring and reporting, are patchy and inconsistent. Monitoring of temporal trends in distribution, occurrence and abundance of species is inadequate to evaluate success. If the Plan is to achieve its objective and uphold Australia's international environmental treaty obligations, more needs to be done to target and deliver environmental water for threatened species and improve the monitoring and reporting of outcomes.

Keywords: environmental water, biodiversity conservation, water reform, environmental monitoring and reporting, Sloane's froglet, southern bell frog, Australasian bittern, Australian painted snipe, trout cod, Murray hardyhead, silver perch, flathead galaxias.

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Introduction

Freshwater ecosystems are some of the most vulnerable and endangered in the world, facing continued uncertainty in the Anthropocene because of the effects of climate change, diversion of water for consumptive purposes and land-use change (Ramsar Convention on Wetlands 2018). One river system under serious threat is the Murray–Darling Basin (hereafter 'the Basin'), the fourth largest river basin in Australia, covering one-seventh of the land area and containing its longest perennially flowing rivers. The Basin has over 30 000 wetlands covering ~25 000 km^2, including 16 wetlands listed under the Ramsar Convention and over 200 considered of national importance (Environment Australia 2001). Known as 'Australia's food bowl', the Basin produces over 40% of the nation's total agricultural production, largely from irrigation. Diversions for irrigation amount to at least 46% of the average surface water available (CSIRO 2008, p. 32).

The high proportion of surface water diversions, combined with extensive river regulation and the effects of climate change, have resulted in major changes to flow and flood regimes for many rivers and wetlands in the Basin. The volume of outflow to sea at the mouth of the River Murray, on the basis of climate records from 1895 to 2006, is now 40% of that before water resource development commenced. Cessation of flow now occurs for 40% of the time, compared with 1% under previous conditions of natural flows (CSIRO 2008). In the period 1997–2020, the Basin was in drought for a total of 17 years, with the Millennium Drought (1997–2010) being the longest on record and the 2016–2020 drought the most severe (van Dijk *et al.* 2013; Holgate *et al.* 2020). Natural floods (i.e. those driven by rainfall) are now markedly less frequent, of shorter duration, shallower and cover smaller areas than before river regulation and water resource development (Sims *et al.* 2012). Under climate change, these trends are projected to increase, with wetlands in the southern Basin most severely affected under a scenario of +1.6°C in mean annual surface temperature by 2030. Some wetlands are highly likely to undergo transition to dryland ecosystems in coming decades (Colloff *et al.* 2016, fig. 3*d* and table A3 therein).

The rivers and wetlands of the Basin provide habitat and resources for a high diversity of endemic freshwater plants and animals. Each species has its particular set of water requirements for its survival and reproduction (Roberts and Marston 2011; Rogers and Ralph 2011). Those species that have specialist habitat and resource requirements, lack drought-resistant stages in their life cycle or are not highly mobile are particularly susceptible to the effects of altered flow regimes and prolonged drought (Colloff and Baldwin 2010). Of particular vulnerability are those species that occupy temporary floodplain wetlands that are connected to main river channels only during periods of high flows and floods following major rainfall, including upper-to-mid floodplain habitats, anabranches, distributary creeks, billabongs, lakes, ephemeral swamps, claypans and soaks.

Rivers and their catchments in the Basin have been assessed as mostly in poor or very poor condition (Davies *et al.* 2008, 2010, 2012). Poor ecological condition is linked to negative changes in ecosystem functions and loss of biodiversity. The 2016 State of the Environment Report assessed Basin wetlands as having undergone 'widespread loss of ecosystem function', with 'species populations declining' (Argent 2016). Whereas populations of many flow-dependent species in the Basin tend to show declines during droughts and varying degrees of recovery after floods (Colloff *et al.* 2015), population time series provide just one source of evidence on changes in ecological condition of wetlands. Others include the spatial extent of wetlands, availability of suitable habitat, changes in flow and flood regimes, shifts in frequency of occurrence and range of particular species (including local extinctions), alterations in ecosystem functions (such as rates of primary and secondary productivity, nutrient cycling and food-web connectivity), and severity and frequency of occurrence of threatening processes (e.g. droughts, cyanobacterial blooms, blackwater events and bushfires). Many of these changes have been underway well before the rapid rise in irrigation diversions between 1950 and 1980 and pre-date the commencement of most long-term ecological monitoring endeavours (Colloff *et al.* 2015, fig. 1 therein).

Frogs, waterbirds and fishes constitute the majority of the flow-dependent native vertebrate fauna of the Basin, totalling ~156 species (31 frogs, ~80 waterbirds and 45 fishes). Several species of frogs have undergone major contractions in range (Gillespie and Hines 1999; Mahony 1999; Heard *et al.* 2012) and eight species are listed as threatened under biodiversity legislation in New South Wales or nationally (Hunter and Waudby 2017). Threats include habitat loss, altered flow and flood regimes, predation by introduced fish species and the fungal disease chytridiomycosis. Populations of southern bell frog at risk of local extinction on the lower Murrumbidgee floodplain showed some recovery over a 7-year period following environmental watering (Wassens 2010).

Waterbird abundance appears to be in decline across the Basin, down from very high levels recorded in aerial surveys between 1983 and 1985 (Kingsford *et al.* 2014, 2017), although there are differences in statistical significance depending on the statistical model used (Colloff *et al.* 2015; Kingsford *et al.* 2015, 2017). Poor catchment condition and high water diversions have major detrimental effects on waterbird assemblage composition and diversity, with colonial nesting species being associated only with catchments in moderate to good condition (Reid *et al.* 2013). Breeding events of colonial nesting waterbirds are triggered when site-specific flow volume and duration thresholds are exceeded (Arthur *et al.* 2012). Below the thresholds, species do not breed. In wetlands where flow volume has been reduced by irrigation diversions and climate change, thresholds are met less frequently and waterbird breeding has declined (Brandis *et al.* 2018).

Populations of native fishes in the Basin have undergone severe declines and are now estimated at <10% of their total abundance during the mid-19th century (Murray–Darling Basin Commission 2004), although this figure is based on anecdote and expert opinion, not empirical or modelled data. Some 26 species are listed as threatened under State, Territory or Commonwealth legislation (Lintermans 2007, table 1 therein). Some species, such as Murray hardyhead, are now extinct throughout substantial parts of their former range (Ellis *et al.* 2013). The *Native Fish Strategy* (2002–13), recently reprised as the *Native Fish Recovery Strategy* (Murray–Darling Basin Authority 2020*a*), has the objective of restoring populations to 60% of those before European colonisation (Koehn *et al.* 2014*a*).

The conservation of biodiversity is central to Australia's obligations to international environmental treaties. Australia is a signatory to the *Convention on Biological Diversity* (1993), the *Convention on Migratory Species* (1983) and the *Ramsar Convention on Wetlands* (1971), which requires the 'wise use' and the maintenance of the ecological character of all wetlands, with a particular focus on conservation Ramsar-listed wetlands. These international treaties are implemented in Australia in large part through the *Environment Protection and Biodiversity Conservation Act* 1999 (Cth) (hereafter, the *EPBC Act*) and the *Water Act* 2007 (Cth) (hereafter, the *Water Act*). The *Water Act* legislates for conservation of the Basin Ramsar wetlands and enacts this through the Murray–Darling Basin Plan (Commonwealth of Australia 2012) (hereafter 'the Basin Plan'), a statutory instrument under the *Water Act* for returning water to the environment by reducing the amount taken for irrigation and other consumptive uses. The Murray–Darling Basin Authority (MDBA) is responsible for the Basin Plan. Biodiversity in the Basin is also protected by legislation in the four Basin States (Queensland, New South Wales, Victoria and South Australia) and the Australian Capital Territory.

The *Water Act* legislates for the 'environmentally sustainable level of take' (ESLT), and the process for determining it is outlined in the Basin Plan. The ESLT sets a sustainable diversion limit (SDL) for consumptive use of water to ensure that the environmental water requirements of rivers and wetlands are met. The current target for water to be restored to the environment is for a long-term average annual yield of 2075 GL, plus 450 GL of savings by so-called 'efficiency measures' projects by 2024 (Murray–Darling Basin Authority 2017). The Guide to the Basin Plan contains the claim that 'significant environmental benefits will be achieved', including: 'assistance in the recovery of many of the Basin's threatened species of birds, fish, invertebrates mammals and reptiles' (Murray–Darling Basin Authority 2010, p. xxvi). Sections 8.05 and 8.06 of the Basin Plan deal with protecting and restoring water-dependent ecosystems, their functions and biodiversity, including threatened species (Commonwealth of Australia 2012). The Basin-wide Environmental Watering Strategy (Murray–Darling Basin Authority 2014, 2019*a*) provides details of how the environmental objectives of the Basin Plan are to be implemented, including expected outcomes for river flows and connectivity, native vegetation, waterbirds and fishes.

Environmental water to achieve the objectives of the Basin Plan includes water held by the Commonwealth Environmental Water Office (CEWO), New South Wales, Victoria and South Australia and with the MDBA under The Living Murray (TLM) Program, as well as for specified purposes under various water-sharing agreements. The MDBA has a coordination role and holds no TLM entitlements. In Queensland, environmental water is protected in water-resource plans for each river valley by access rules rather than specific allocations. The CEWO partners with States and other water holders in the planning and delivery of environmental water. Monitoring of outcomes has been undertaken by State agencies and the CEWO-funded Long-Term Intervention Monitoring Project (LTIM) from 2013–14 to 2018–19, data from which form the basis for environmental evaluations of the Basin Plan. The LTIM is based on the following seven 'selected areas': the junction of the Warrego and Darling, Gwydir, Lachlan, Murrumbidgee, Edward–Wakool, Goulburn and lower Murray (Gawne *et al.* 2014).

The 2020 Basin Plan evaluation found that the implementation over the previous 7 years was 'having a significant and positive impact on the Basin environment' (Murray–Darling Basin Authority 2020*b*, p. xiii). However, other reports have highlighted a major shortfall in restoring river flows, with average annual volumes 40–60% less than expected (Wentworth Group of Concerned Scientists 2020) and with only 7% of the wetland area in targeted catchments having received effective environmental flows annually between 2014–15 and 2018–19 (Chen *et al.* 2021). In addition, claims for a 'positive impact' on the environment at Basin scale are not supported by some of the findings from environmental monitoring. For example, increased vegetation diversity was recorded at only a few sites and these showed highly variable responses (Capon and Campbell 2017). Moxham *et al.* (2019) found only temporary, local responses by floodplain plant communities to environmental watering. Gawne *et al.* (2020) reported short-term, localised responses, stating that 'the monitoring program is showing promise with short-term responses being observed and long-term patterns being recorded', but presented no evidence for the latter claim.

There has been no comprehensive assessment of the objective in Section 8.05(3) of the Basin Plan for the conservation of threatened species. Syntheses of the conservation status of threatened flow-dependent fauna at Basin scale are limited to fishes (e.g. Koehn *et al.* 2013, 2020; Whiterod *et al.* 2019) and waterbirds (Kingsford *et al.* 2014). Reports containing empirical data on status and trends tend to be species-specific, with a focus on particular regions, for example, Australasian bittern in rice fields in the Riverina of New South Wales (Herring *et al.* 2019), Murray hardyhead in the lower Murray valley (Ellis *et al.* 2013) and Murray cod in the central Murray at Gunbower Creek (Stuart *et al.* 2019).

The 2020 Basin Plan evaluation claims positive outcomes for only two threatened species, both being fish, namely Murray hardyhead and southern pygmy perch in Lakes Alexandrina and Albert, but notes that 'The overall condition of many populations is still, however, considered to be poor and Yarra pygmy perch is considered to be regionally extinct' (Murray–Darling Basin Authority 2020*b*, p. xiii). The LTIM report on fishes found that drought-induced low flows during most of the 5-year monitoring period (except 2016–17, when high flows caused blackwater hypoxia and fish kills in some areas) had 'limited the extent to which inferences can be made about the effects of higher flow conditions' and that 'higher flows are expected to [positively] influence fish populations, but this remains untested in the context of the LTIM program' (King *et al.* 2020). In summer 2018–19, many thousands of Murray cod, a threatened species, were among millions of fishes killed in the Darling River at Menindee, caused by hypoxia-inducing cyanobacterial blooms and low flows due to severe drought and excess upstream irrigation diversions, including floodplain harvesting (Australian Academy of Sciences 2019; Vertessy *et al.* 2019).

The Productivity Commission (2018) 5-year review of the Basin Plan reported major progress in the acquisition and use of environmental water, but poor coordination on reporting of outcomes. McGowan (2017) found that members of rural communities generally supported the Basin Plan's environmental objectives, but poor communication of conservation benefits led to diminished trust in the MDBA. Deficient communication and reporting was also highlighted in the LTIM Project (Hart and Butcher 2018). The Basin Plan involves expenditure of A$13 billion of public funds. Failure to communicate environmental benefits, including for threatened species, risks damaging public trust in the Basin Plan, placing its legitimacy and partnerships for implementation in jeopardy (Colloff and Pittock 2019).

Evaluating the effectiveness of the Basin Plan in conserving threatened species is central to adaptive management under climate change. Winter rainfall in the southern Basin has declined by 12% since 1997, 75% of Basin streamflow gauges show declines since 1970 (over 94% in the northern Basin) and surface temperatures have increased, with the five hottest years having been recorded between 2013–14 and 2019–20 (CSIRO and Bureau of Meteorology 2020). Projections under median-to-dry scenarios are for runoff reductions of 18–46% by 2050 (Zhang *et al.* 2020). Less water in rivers, plus higher temperatures and evaporative losses mean less water to meet environmental needs, as well as higher water requirements for both the environment and irrigated agriculture (Murray–Darling Basin Authority 2019*b*). The effectiveness of current environmental watering on threatened freshwater fauna forms a basis for assessing whether future water availability will be sufficient to achieve the environmental objectives of the Basin Plan.

The lack of a comprehensive assessment of the outcomes of the Basin Plan for threatened species means that it has not been possible to assess whether Australia has upheld its obligations as a signatory to international environmental treaties. Our aims in this paper are to address whether environmental watering under the Basin Plan has helped conserve threatened flow-dependent fauna. We assessed whether eight selected threatened species were included as targets for environmental watering in Commonwealth documents and environmental water-management plans. We then determined whether species were targets for environmental watering events in those catchments in which they occurred and whether monitoring and reporting of outcomes had taken place. Finally, we constructed time series of indicators of the relative abundance and occurrence of each species between 2012–13 and 2018–19 to assess the likelihood of any significant conservation benefits since the implementation of the Basin Plan.

Materials and methods

Species distribution and conservation status

We selected the following eight threatened flow-dependent faunal species: Sloane's froglet (*Crinia sloanei*), southern bell frog (also known as the growling grass frog; *Litoria raniformis*), Australasian bittern (*Botaurus poiciloptilus*), Australian painted snipe (*Rostratula australis*), trout cod (*Maccullochella macquariensis*), Murray hardyhead (*Craterocephalus fluviatilis*), silver perch (*Bidyanus bidyanus*) and flathead galaxias (*Galaxias rostratus*). Selection criteria for species were as follows: (1) they are listed as threatened under the *EPBC Act* and one or more State or Territory acts; (2) they are distributed predominantly (but not exclusively) in the low-lying, regulated catchments of the southern Basin, which is where almost 90% of the volume of environmental water was released between 2012–13 and 2018–19 (Chen *et al.* 2021); species were excluded if their distributions were mainly in upland river valleys above headwater dams; (3) each species is found in floodplain wetlands and river habitats and has particular freshwater requirements for breeding, habitat maintenance and connectivity that can only be met currently by managed environmental flows; (4) there are sufficient distribution records available to determine the likely range of each species and whether that range had changed over time. The species we chose represent a subset of the threatened species in the Basin that match these criteria (4 species of frogs, 6 waterbirds and 14 fishes).

A knowledge of the distribution of each threatened species underpins any assessment of whether environmental watering has helped their conservation. So as to determine in which catchments species were present and whether their distributions had changed over the longer term, we used point-source occurrence records from the Atlas of Living Australia (ALA), from earliest records (1800 for Australasian bittern) to 2020, to construct distribution maps. We differentiated records as before 1990 and after, to detect any expansion or contraction in range. We chose the year 1990 on the premise that if a species had not been recorded in a catchment for 30 years or more, it was unlikely to be considered a target in environmental watering plans. We cross-referenced distributions against published sources for frogs (Pyke 2002; Knight 2013; Anstis 2017), waterbirds (Blakers *et al.* 1984; Barrett *et al.* 2003; Rogers *et al.* 2005) and fishes (Lintermans 2007; Nicol *et al.* 2007), as well as data in national recovery plans for southern bell frog (Clemann and Gillespie 2012), trout cod (Trout Cod Recovery Team 2008; Koehn *et al.* 2013) and Murray hardyhead (Department of Environment, Land, Water and Planning 2017).

Review of environmental watering plans

We reviewed Commonwealth government environmental watering plans to determine whether Commonwealth responsibility for the conservation of the threatened species was reflected in plans for environmental watering. In particular, we examined if threatened species were mentioned in objectives of environmental watering plans, including for the maintenance of critical habitats. Reports reviewed were the Basin-wide Environmental Watering Strategy (Murray–Darling Basin Authority 2014, 2019*a*), the CEWO Water Management Plan (WMP; Commonwealth Environmental Water Office 2020) and CEWO Portfolio Management Plans (PMPs; Commonwealth Environmental Water Office 2019*a*, 2019*b*, 2019*c*, 2019*d*, 2019*e*, 2019*f*, 2019*g*, 2019*h*). This review enabled us to compare the distribution of species with the species and catchments that were included in environmental watering plans. We did not include State water resource plans because some are currently still under review and they are not yet fully operational (Murray–Darling Basin Authority 2020*c*).

Monitoring and reporting of environmental watering outcomes

We assessed environmental watering events and the monitoring and reporting of environmental outcomes from reports of the LTIM Project (Gawne *et al.* 2014) to determine whether threatened species had benefitted from environmental flows and whether the implementation of environmental watering was consistent with MDBA and CEWO plans. We collated references to each threatened species from the final 'Basin-scale evaluation' thematic reports for biodiversity and fishes, covering the 5-year period (2014–15 to 2018–2019) of the LTIM project. The Basin-scale reports are compiled from data from technical monitoring reports for each of the seven 'selected areas' (and other sources; cf. Hale 2017, p. 6, for details) and we scanned these reports for references to the threatened species, as well as the Basin-scale synthesis report (Hale *et al.* 2020*a*), compiled from the Basin-scale thematic reports. We used independent reports (Wentworth Group of Concerned Scientists 2020; Chen *et al.* 2021) to cross-check whether flows and environmental water were delivered as expected under the Basin Plan.

Water requirements of threatened species

Environmental watering and habitat requirements for each species (magnitude of flow or flood, duration, frequency and seasonality) were collated from expert opinion and published sources, including national recovery plans (cf. Department of Agriculture, Water and Environment 2021*a*), conservation advice issued under the *EPBC Act* (Threatened Species Scientific Committee 2013*a*, 2013*b*, 2016, 2019) and State conservation plans (Table S1 of the Supplementary material). We focussed on water requirements for breeding because the objectives of the Basin Plan specify protection and restoration of populations of native biota (Section 8.06(6)(a, b)) 'by ensuring that flow sequences, and inundation and recession events, meet ecological requirements (e.g. cues for migration, germination and breeding) and habitat diversity, extent, condition and connectivity that supports the life cycles of biota of water-dependent ecosystems (e.g. habitats that protect juveniles from predation) is maintained.'

To assess whether water requirements for breeding were being met for each threatened species, we selected those catchments containing a breeding population or known breeding sites, on the basis of recent records (since 2012) collated from the literature (Fig. 1, Table S2 of the Supplementary material) and where that species and catchment had been targeted for environmental watering in the CEWO water management plan (WMP) or portfolio management plans (PMPs; Table 1). We compiled details of all CEWO environmental watering events between 2014–15 and 2018–19 (Gawne *et al.* 2016, 2017; Hale

2019; Hale *et al.* 2018, 2020*a*, appendix A therein) for each catchment and region containing breeding sites and identified all events that matched the CEWO classification of flow types 'fresh' (including 'bankfull'), 'overbank' and 'wetland' (the first two relevant to trout cod and silver perch, the latter two relevant to all other species). For each species, we deleted all records that did not match the criteria for breeding site or flow type and cross-referenced the remainder against reports of events from State water holders and others (e.g. Department of Environment, Water and Natural Resources 2017; Office of Environment and Heritage 2017; Victorian Environmental Water Holder 2017; Murray–Darling Basin Authority 2018). Where CEWO events involved contributions of water from other agencies, we re-assessed each event (supplemented by information from Stewardson and Guarino 2016, 2017, 2018, 2019, 2020) for whether or not the magnitude, frequency, duration and seasonal timing of events matched with the water requirements of each threatened species for breeding.

Indicators of occurrence and abundance of threatened species

We assessed changes in the annual total count of the number of individuals (as an indicator of relative abundance) and the number of records for each species (as an indicator of frequency of occurrence) within the Basin since the implementation of the Basin Plan in 2012–13 up to 2018–19, using the following three publicly available databases: the ALA (Atlas of Living Australia 2020), the Victorian Biodiversity Atlas (VBA; Department of Environment, Land, Water and Planning 2020) and the New South Wales BioNet Atlas (see http://www.bionet.nsw.gov.au/).

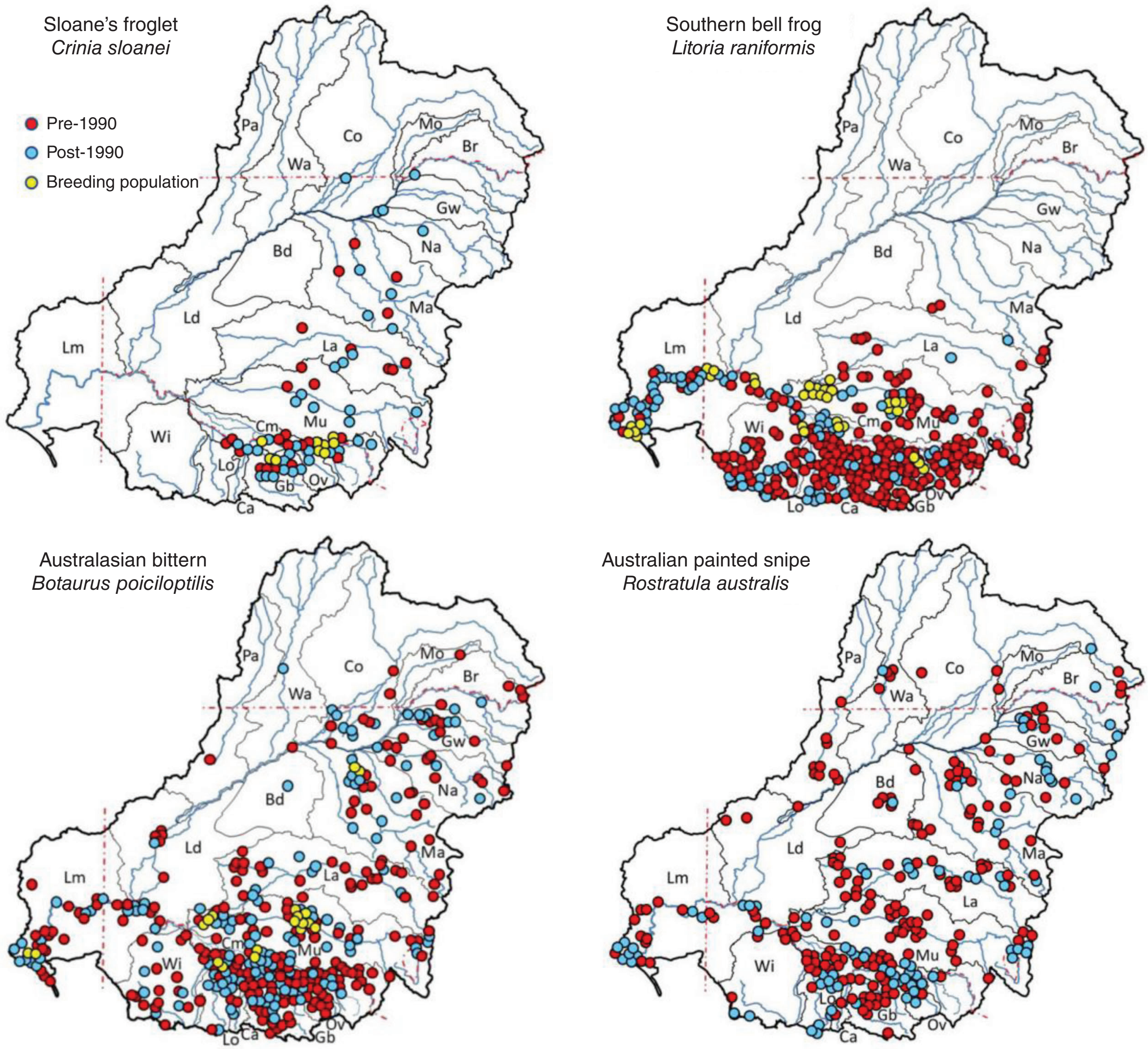

Fig. 1. Distribution of the eight threatened species in the Murry–Darling Basin on the basis of records of occurrence before and after 1990 from the Atlas of Living Australia, as well as known breeding populations or sites (cf. text for details). For explanation of abbreviations of catchments, see Fig. 3.

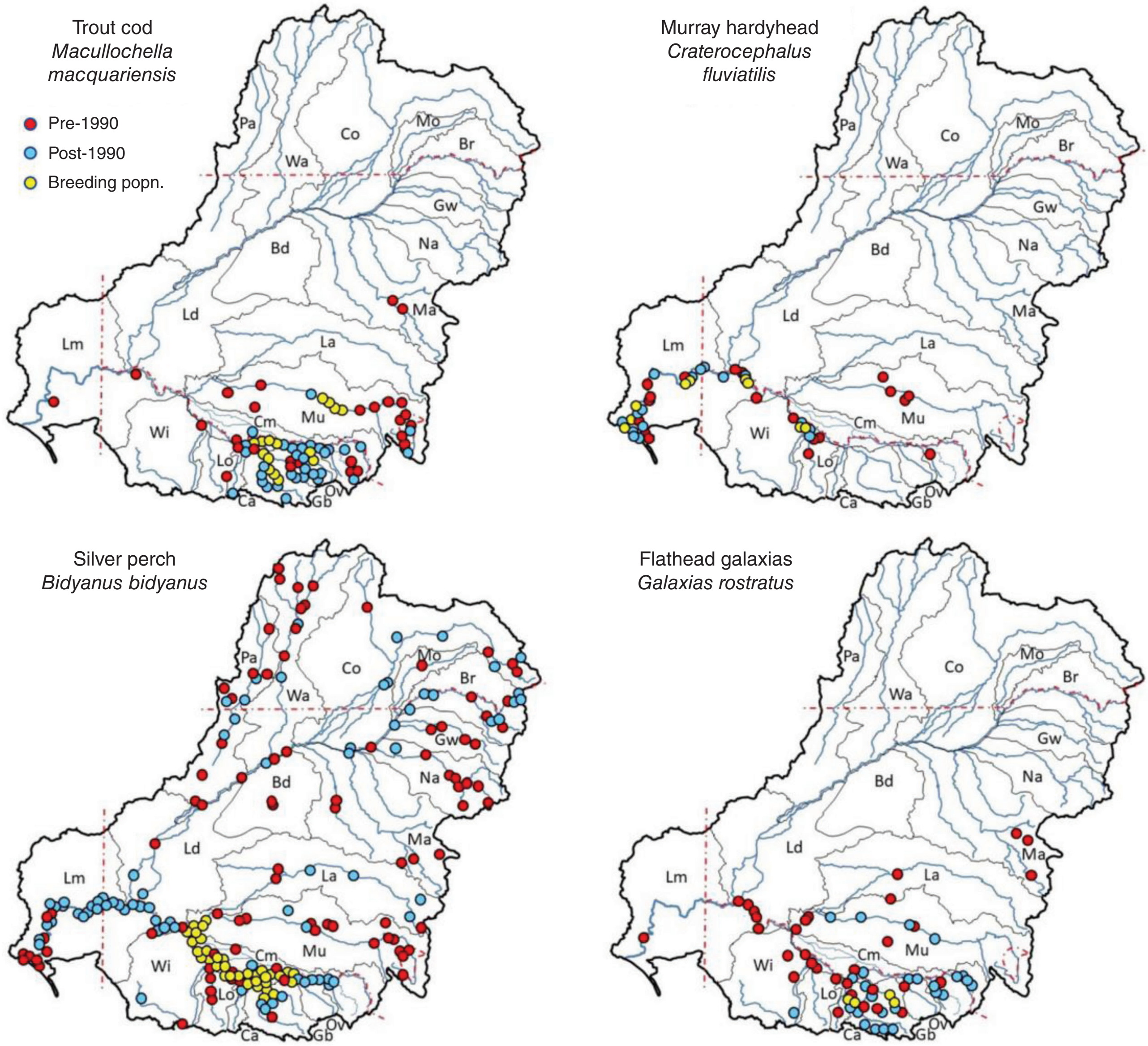

Fig. 1. (*Cont.*)

We checked the Queensland WildNet database, but there were no records of the species within the Basin for the period we examined, and also the Biological Databases of South Australia, but records had been lodged with the ALA. We consulted several agencies about the availability of unpublished data on distribution, abundance and occurrence of the eight threatened species. Most agencies had either uploaded their data to one of the public databases or were unable to make it public at present. Others had only a few relevant records.

We removed duplicate entries from the ALA, VBA and BioNet databases, records from outside the Basin, and those for 2020 (records for the year were incomplete at the time of our compilation) to create a consolidated dataset for the eight threatened species. We mapped records of occurrence to assess which catchments containing threatened species had not been included in environmental watering plans and monitoring reports. A species was judged as having a *likelihood of presence* in a particular catchment if it had been recorded in ALA records after 1990 (cf. methods section on species distribution above) and as *definitely present* if it had been recorded in at least five surveys from 2012–12 to 2018–19. Five records since 2012 were chosen as an arbitrary threshold to reduce the chances of erroneously assigning a species to a catchment because of a misidentification, a chance occurrence or where a species had become recently locally extinct. To measure changes in annual counts of individuals and the number of records of each species, we transformed the data using the natural logarithm of the raw data + 1 to remove zeroes, i.e. $\log_e (n + 1)$. We used reduced

Table 1. Reporting of threatened species targeted for environmental watering in each river valley of the Murray–Darling Basin, based on Commonwealth Environmental Water Office (CEWO) Long-term Intervention Monitoring Project (LTIM) reports

Yellow cells indicate reported benefits from environmental watering for species targeted in the CEWO water management plan (WMP) or portfolio management plans (PMPs). Blue cells indicate the WMP or PMPs included the species as a target for environmental watering but no outcomes were reported (except for silver perch in the Lachlan). Green cells and 'DP' indicate catchments containing species for which there were five or more occurrence records from 2012–13 to 2018–19 (Atlas of Living Australia 2020; Department of Environment, Land, Water and Planning 2020; New South Wales BioNet Atlas, see http://www.bionet.nsw.gov.au/), but species were not mentioned in LTIM reports. Orange cells and 'LP', likelihood of presence based on occurrence records post-1990 in the Atlas of Living Australia (Fig. 1)

Catchment (river valley)	Sloane's froglet	Southern bell frog	Australasian bittern	Australian painted snipe	Trout cod	Murray hardyhead	Silver perch	Flathead galaxias
Warrego			LP	LP			CEWO 2019*c*, 2020	
Condamine–Balonne	LP		CEWO 2019*c*, 2020[A]	CEWO 2019*c*, 2020[A]			CEWO 2019*c*, 2020	
Moonie			LP	LP				
Border Rivers	LP		CEWO 2019*e*[A], 2020[B]	CEWO 2019*e*[A], 2020[B]			Hale *et al.* 2018	
Gwydir			Hale *et al.* 2020*b*	Hale *et al.* 2020*b*			LP	
Namoi	LP		LP	LP			CEWO 2019*d*, 2020	
Macquarie–Castlereagh		LP	Hale *et al.* 2020*b*	Hale *et al.* 2020*b*	CEWO 2019*f*		CEWO 2019*f*	
Barwon-Darling			Hale *et al.* 2020*b*	LP			LP	
Lower Darling			LP	LP			Hale 2018	
Lachlan	LP	Hale 2017	LP	DP			CEWO 2019*g*	
Murrumbidgee	LP	Hale 2019	Hale *et al.* 2020*b*	CEWO 2020	Hale 2017		Stoffels *et al.* 2016	LP
Central Murray	DP	DP	Hale 2019	Hale *et al.* 2020*b*	Hale *et al.* 2020*b*	CEWO 2019*a*	Hale *et al.* 2020*b*	CEWO 2019*a*
Edward Wakool		LP	DP	LP	King *et al.* 2020		King *et al.* 2020	
Ovens	DP	CEWO 2020	CEWO 2020	DP	CEWO 2020		LP	LP
Goulburn	LP	LP	Hale 2017	LP	King *et al.* 2020		Hale *et al.* 2018	LP
Broken	LP	LP	CEWO 2019*h*, 2020	LP	LP		CEWO 2019*h*, 2020	LP
Campaspe	LP	LP	LP	LP	LP		CEWO 2019*h*, 2020	
Loddon		DP	DP	LP	LP		CEWO 2019*h*, 2020	
Wimmera–Avoca		LP	LP	LP			DP	
Lower Murray		Hale 2019	Hale *et al.* 2020*b*	Hale 2017		Hale 2017	King *et al.* 2020	

[A]'Maintain foraging, roosting and breeding habitats at targeted sites on the floodplain to support waterbirds' (CEWO 2019*c*, p. 9, 2019*e*, p. 7, 2020, p. 40).
[B]'Contribute to suitable flow regimes to support refuges, feeding resources and breeding opportunities for waterbirds including listed migratory and threatened species' (CEWO 2020, p. 32).

major axis regression, with analysis of variance to test for the statistical significance of the regression line in each time series (Fowler *et al.* 1998).

To validate the data and address the issue of bias owing to uneven sampling effort in the atlas databases, we compared our time series with those available from field-based monitoring in which survey effort had been standardised and which covered the same period as did our time series. For those species for which comparator time series were not available, we examined the consolidated dataset for evidence of multiple records within each year, collected from the same locality, at the same time and by the same collectors (i.e. records generated from detailed, intensive surveys by staff from State environmental agencies). We then treated these records as a single occurrence, took the mean of the counts of individuals and re-ran the statistical model to detect any significant change in the regression line compared with the original.

Results

Species distribution and conservation status

All species are listed under the various conservation acts nationally and in New South Wales and one or more other jurisdictions (Table S1). Differences in conservation status among the Commonwealth, States and the Australian Capital Territory highlights not only distribution of species by State and Territory but also the variation in rules for listing under eight separate pieces of legislation. The conservation status of the eight threatened species includes the listing of silver perch and flathead galaxias as critically endangered under the *EPBC Act*, but neither has a national recovery plan. In fact, plans are in place only for southern bell frog, trout cod and Murray hardyhead. It is of particular note that the species with the broadest distributions, covering all Basin States (Australasian bittern, Australian painted snipe and silver perch), lack a coordinated national approach under the *EPBC Act* for their conservation and recovery.

Distribution mapping gives some indication of changes in range since 1990. Known breeding populations and key breeding sites for many species are now fragmented and isolated (Fig. 1). The range of seven species appears to have contracted. Only the range of Australasian bittern has not changed markedly since 1990, although breeding is now centred on the Riverina, particularly rice fields, attracting an estimated 40% of the global population in most years (Herring *et al.* 2019), with there being breeding records also from the lower Murrumbidgee (Hayter 2021), Barmah–Millewa Forest (K. Ward, pers. comm., 2 February 2021), Lakes Alexandrina and Albert, Macquarie Marshes and Fivebough and Tuckerbil swamps (Silcocks *et al.* 2014, p. 24). Males were heard calling at Gwydir Wetlands in 2018–19 but no breeding events were recorded (Department of Planning, Industry and Environment 2019).

Changes in the range of Sloane's froglet are uncertain, although it may have decreased in the western Lachlan and Murrumbidgee catchments and the upper Lachlan (Fig. 1). The distribution is incompletely known because the species was first described only in 1958. Up until 1990, it had been recorded only 13 times from New South Wales; post-1990 records are mostly from several intensive surveys along the River Murray from Echuca to Albury between 2010 and 2013 (Knight 2013, pp. 7, 13). Some of the atlas records for the more northern localities may be misidentifications of other species of *Crinia*. However, Knight (2013, p. 6) cited records of a small population on the Barwon floodplain near Walgett and another at Toorale Station near Bourke. Of the northern New South Wales records, those in the ALA from Goodooga on the Culgoa River, Nyngan on the Bogan River and Gilgandra on Marthaguy Creek are based on voucher specimens in the Australian Museum Herpetology collection and are unlikely to be misidentifications. Other northern records are from a 1998 fauna survey at Mungindi Airport near the Barwon River and Rocky Creek in the Pilliga Forest, south-west of Narrabri. Breeding populations are likely to be centred on peri-urban wetlands around Albury and Corowa (Knight 2013), at Moodies Swamp near Shepparton (J. Deretic, pers. comm., 13 October 2020) and at Barmah Forest (K. Ward, pers. comm., 2 February 2021).

There are only two post-1990 locality records of the southern bell frog from the Lachlan and Macquarie and none from the south-eastern slopes (Fig. 1). Known breeding sites include Lakes Alexandrina and Albert (Mason and Hillyard 2011), Lake Victoria, the lower Murrumbidgee, Coleambally and Yanco Creek (Clemann and Gillespie 2012, pp. 6, 7; Mann *et al.* 2010), Chowilla Lindsay–Wallpolla (Murray–Darling Basin Commission 2011) and Kings Billabong near Mildura (K. Ward, pers. comm., 2 February 2021). The species was recorded at only 30% of some 37 temporary wetlands on the South Australian River Murray between Murtho and Morgan, in low numbers, with evidence of recruitment at only two sites (Hoffmann 2018).

There are no post-1990 records of Australian painted snipe in the western lower Darling and Paroo. We found no records of sites with recent and regular breeding (thus no breeding sites are recorded for the species in Fig. 1). The most recent breeding records in the Basin are from 2010–11 following the breaking of the Millennium Drought (Purnell *et al.* 2014, fig. 3 therein), which we used as a basis to infer spatially diffuse and temporarily sporadic breeding in the Macquarie, Murrumbidgee and Murray catchments for the purposes of estimating whether environmental flows delivered in these catchments would meet the water requirements for breeding (cf. *Water requirements of threatened species* below and Table 2).

The records of 15 breeding sites in the southern Basin listed by Rogers *et al.* (2005) are mostly historical, with the most recent in the series from 1984 at Weimby in the lower Murrumbidgee and Gunbar in the Lower Lachlan. Rice crops and wetlands in the southern Riverina provide habitat for the species (Herring and Silcocks 2014), but are not breeding sites. The species was recorded at Gwydir wetlands in 2017–18, but no evidence of breeding was observed (Hale *et al.* 2020*b*, p. 24).

The range of trout cod has declined to a core distribution in the Central Murray, Goulburn-Broken and Ovens (Nicol *et al.* 2007; Koehn *et al.* 2013). Distribution of silver perch has contracted from the eastern slopes, with its core breeding population centred on the River Murray between Yarrawonga Weir and Euston (Tonkin *et al.* 2017) and also in the Edward–Wakool anabranch system.

Murray hardyhead is now likely to be absent from the Ovens and Murrumbidgee, as well as sites of other pre-1990 records on the Murray and lower Loddon. Wood (2017) reported locations of remnant breeding populations of this species (and attempted re-introductions), based on four main clusters along the River Murray (Kerang Lakes, Murray Mallee Lakes near Mildura, wetlands in the Riverland of South Australia and the lower Murray river between Mypolonga and Lakes Alexandrina and Albert). A more recent assessment of the distribution of the species indicated that it is considered extremely rare in New South Wales and extinct in 9 of 13 historically known sites in Victoria, and with only four likely core breeding populations in South Australia (Department of Environment, Land, Water and Planning 2017).

Flathead galaxias is now likely to be absent from the Macquarie, Lachlan and lower Murray. Breeding populations may exist in the Campaspe catchment at Compton and Wanalta creeks (Atlas of Living Australia 2020) and in the Goulburn–Broken catchment (Threatened Species Scientific Committee 2016), but locations of confirmed breeding populations are not precisely known.

Distributions of species by catchment (Table S3 of the Supplementary material) indicated only five catchments in which species were recorded post-1990 but not earlier, namely, Australasian bittern in the Warrego, trout cod in the Ovens and Sloane's froglet in the Condamine–Balonne, Border Rivers and Namoi (cf. details of distribution records in these catchments above). By contrast, there are 15 examples of catchments in which species were present before 1990 but have not been recorded since, of which five are for flathead galaxias (Macquarie, Lachlan, Campaspe, Loddon and lower Murray) and three are for painted snipe (Paroo, Condamine–Balonne and Moonie), two each for trout cod (Wimmera–Avoca and lower Murray) and Murray hardyhead (Wimmera–Avoca and Murrumbidgee) and one for silver perch (Moonie).

Six of the eight threatened species depend on flooding for habitat maintenance and breeding, whereas silver perch and trout cod rely on appropriately timed in-channel freshing flows and the maintenance of lotic habitats. From our review of national recovery plans, other Commonwealth and State government documents and independent research, there was adequate data available on water requirements for all species (Table S4 of the Supplementary material). However, there was limited information on duration of flows for maintenance of suitable habitat.

Review of environmental watering plans

The Basin-wide Environmental Watering Strategy contains overarching guidelines that relate to the objective to 'protect and improve existing populations of threatened species' and includes all four species of fishes considered herein among those targeted for environmental watering (Murray–Darling Basin Authority 2019*a*, p. 68, and appendix 5 therein). It also details links between life history and flow requirements and lists 'priorities for increasing the distribution of native fish', including details of priority sites and objectives for use of environmental flows to expand ranges and establish additional populations of species (Table S5 of the Supplementary material). No threatened species of frogs or waterbirds are listed as targets in the Strategy.

In the CEWO environmental watering plans (WMP and PMPs; Commonwealth Environmental Water Office 2019*a*, 2019*b*, 2019*c*, 2019*d*, 2019*e*, 2019*f*, 2019*g*, 2019*h*, 2020), all species except Sloane's froglet were mentioned as targets for environmental watering (blue and yellow cells in Table 1). Every catchment except Wimmera–Avoca and Moonie had at least one target species, ranging from one (Warrego, Barwon–Darling, Lower Darling, Namoi, Campaspe, Loddon) to five (Murrumbidgee, lower Murray). There was a statistically significant positive correlation ($R^2 = 0.78$, $F = 50.7$ with 1,14 d.f.; $P < 0.00001$, corrected for two outliers) between the number of target species in each catchment and the volume of Commonwealth environmental water delivered to the catchment from 2013–14 and 2018–19 ($\log_{10}$-transformed data; cf. Chen *et al.* 2021, table S1 therein), which is positively correlated, in turn, with mean annual discharge (as end-of-system flow) $\log_{10}$-transformed data; CSIRO 2008, appendix A therein; $R^2 = 0.57$, $F = 17.5$ with 1,13 d.f.; $P < 0.002$, corrected for one outlier; Fig. S1 of the Supplementary material).

The WMP and PMPs frequently mention general conservation goals for a particular threatened species, such as maintenance of wetland condition. For example, the 2018–19 Murrumbidgee PMP (Commonwealth Environmental Water Office 2018) stated that environmental water will be provided for habitat and recruitment opportunities for a range of threatened species, including Australasian bittern. We interpret this as a commitment to deliver environmental water within the Murrumbidgee catchment in line with the water requirements for breeding and habitat maintenance of this species.

Flathead galaxias are targets for environmental watering only in the central Murray, although there is a likelihood of occurrence in the Murrumbidgee, Ovens and Goulburn–Broken (Fig. 1, Table S3). The 2019–20 PMP for the Murrumbidgee lists 'improving the core range [of flathead galaxias] in additional locations, including the Murrumbidgee' but the species is considered out-of-scope for Commonwealth environmental water 'until a population is established' (Commonwealth Environmental Water Office 2019*b*, p. 30). The ALA contains five records of flathead galaxias from 1990–2020 on the Murrumbidgee between Wagga Wagga and Hay. By contrast, silver perch is mentioned in the WMP and every PMP (except for the Ovens in the Victorian Rivers PMP) as being in-scope for Commonwealth environmental water (Table 1), reflecting its broad distribution within the Basin.

Monitoring and reporting of environmental watering outcomes

Our review of LTIM reports found that reported effects of environmental watering fell into the following two categories: generalised accounts of environmental watering of sites where threatened species occurred and those containing empirical data on breeding, recruitment or abundance of particular species.

In the former category, a report of annual occurrence of southern bell frog in wetlands in the Murrumbidgee catchment (2014–15 to 2018–19) concluded that the species was supported by environmental flows (Hale *et al.* 2020*b*, p. 26). This conclusion was based on a report in the latter category, with individuals being counted at 2 of 12 wetlands in the lower Murrumbidgee (7 of 12 sites based on frog calls but not sightings), in 2 of 5 years at one site and in 3 of 5 years at the other site, with no trend in abundance at either of these sites (Wassens *et al.* 2020, pp. 105, 114). Evidence of breeding (tadpoles or juveniles) was detected at three sites. The authors concluded that 'Commonwealth environmental water has been used successfully over the five year period to maintain and grow these key populations' (Wassens *et al.* 2020, p. 118). Although the data suggested that population maintenance was likely, no evidence of population increase was provided. No data were presented on occurrence or abundance in the mid-Murrumbidgee, although the report by Hale *et al.* (2020*b*, p. 12) contained no such qualification, stating that 'The nationally listed vulnerable southern bell frog was recorded in wetlands in the Murrumbidgee system at sites that received Commonwealth environmental water, with evidence of breeding.'

Although both categories of report have been interpreted and reported as evidence of beneficial outcomes by both CEWO and the MDBA (e.g. Hale *et al.* 2020*a*, 2020*b*; Murray–Darling Basin

Authority 2020*b*), generalised reports tend to assume that the presence of a species at a site that had received environmental water is causally linked with the watering event. However, as the example above shows, such claims are also made in empirical reports without the data to support them.

As an additional complication, Basin-scale evaluation reports contained data from sites that received Commonwealth environmental water but were monitored by programs other than the LTIM Project. For example, Hale (2017, p. 15) reported that Murray hardyhead populations in the Mallee Wetlands of the lower Murray catchment showed increased abundance after several environmental watering events, suggesting a causal link between abundance and environmental flows. The data were based on an annual monitoring program conducted on behalf of the Mallee Catchment Authority by the then Murray–Darling Freshwater Research Centre (Ellis and Wood 2015; Huntley 2016; Wood 2017), and, subsequently, by Aquasave–Nature Glenelg Trust (Whiterod *et al.* 2019). Annual population data are spread over several reports, of which only that by Whiterod *et al.* (2019), containing data for a single year, is available online. Accordingly, the claim that 'the endangered Murray hardyhead has undoubtedly benefited from environmental water' (Hale 2017, p. 26) cannot be independently verified from publicly available data (cf. also Table S6 of the Supplementary material and associated references).

Table 1 shows the reporting of benefits from environmental watering by species and catchment, based on LTIM Basin-scale reports and also where species were listed as targets for environmental watering but no outcomes were reported. Also shown in Table 1 are the catchments where species occurred between 2012–13 and 2018–19 according to the combined atlas databases (cf. also Fig. 1, Table S3), and between 1990 and 2010 according to the ALA (Fig. 1), but where species were not mentioned in the WMP, PMPs or LTIM reports. LTIM Basin-scale reports of benefits were available for 57% of the catchments where species were listed as targets, 47% when the catchments where species occurred from 2012–13 to 2018–19 were added, but only 26% when catchments in which species occurred since 1990 were added.

Given that the LTIM project involved the monitoring of only seven priority monitoring areas of the Basin, and that State monitoring is also focussed on relatively few major wetland systems, it is inevitable that responses to environmental watering for some species in some catchments will not be monitored. From monitoring data in the LTIM technical reports for selected areas, only three species (southern bell frog, Australasian bittern and silver perch in the Edward–Wakool and Goulburn) were found to have benefitted from environmental watering, with no benefit apparent for Australasian painted snipe, trout cod and silver perch in the Gwydir, Lachlan, Murrumbidgee and lower Murray (Table 3). Sloane's froglet, Murray hardyhead and flathead galaxias were not monitored during the LTIM project.

Water requirements of threatened species

Environmental watering events were likely to meet water requirements for breeding some of the threatened species in some of the catchments in which breeding populations or sites are known to occur (Table S2), but the pattern is variable spatially and temporally (Table 2). For example, silver perch is likely to have its watering requirement met in most years in the Edward–Wakool, Goulburn–Broken and Campaspe catchments, but only one-in-three watering events was likely to have been adequate in the lower Murrumbidgee, and with an average return interval (ARI) for adequate watering of 1-in-2.5 years. Likewise, trout cod is likely to have received adequate environmental watering in the Central Murray and Goulburn–Broken, but less so in the Ovens, a site of major restoration activities for the species (Raymond *et al.* 2019), and with an ARI of 1-in-5 years. Sloane's froglet received adequate watering in 60% of watering events in the Central Murray but only a single, 1-in-5 years event in the Goulburn–Broken. Southern bell frog was likely to have received adequate watering in Murrumbidgee and lower Murray catchments, less so in the Lachlan, with an ARI of only every 2.5 years, but not in the Ovens (ARI 1-in-5 years). Both bird species and Murray hardyhead probably received their water requirements, but only every 1-in-2.5 years for Australasian bittern at the Macquarie Marshes. By contrast, environmental watering in the Campaspe and Goulburn–Broken was unlikely to have met the water requirements of flathead galaxias, with ARIs of 1-in-2.5 years and 1-in-5 years respectively.

In summary, of the 22 species–catchment combinations we assessed, 15 were likely to have been beneficial. However, when considered in the context of the proportion of water requirements of the six flood-dependent species at catchment-scale, only four catchments (Gwydir, Macquarie, Murrumbidgee and Central Murray) received more than 5% of the total volume of environmental water released as floods or wetland watering events (Chen *et al.* 2021). The overwhelming volume of environmental water released in the Lachlan, Ovens, Goulburn–Broken, Campaspe and lower Murray was in-channel flows, likely to be of no benefit to four of the six flood-dependent species. All catchments in Table 2 received lower total flows than expected between 2012–13 and 2019–20 under the Basin Plan, except for the Loddon (Wentworth Group of Concerned Scientists 2020).

Indicators of occurrence and abundance of threatened species

Annual counts of the number of individuals (as an indicator of relative abundance) and the number of records (as an indicator of frequency of occurrence) from 2012–13 to 2018–19 show reasonable fidelity (Fig. 2; cf. Table S7 for raw data). Two species, southern bell frog and Murray hardyhead, were corrected for sampling effort bias. There were statistically significant increasing trends in both indicators for southern bell frog ($F_{\text{counts}} = 22.1$, $P < 0.01$; $F_{\text{records}} = 32.8$, $P < 0.01$) and trout cod in counts only ($F = 12.2$, $P < 0.05$) and a significantly declining trend for Australian painted snipe in counts only ($F = 7.2$, $P < 0.05$; 1,6 d,f. in all cases). All other time series showed no statistically significant trends and are therefore considered stationary (in the statistical sense), but fluctuating. The time series showed increases in 2016 or 2017, which coincided with very high river inflows during the wet year of 2016–17 (Bureau of Meteorology 2021). For this period, there is an increase in both counts of individuals and the number of records for Australian painted snipe, trout cod and silver perch and counts only for Murray hardyhead and southern bell frog.

Table 2. Environmental watering events likely to benefit breeding of eight threatened species in catchments containing breeding sites or populations in the Murray–Darling Basin, 2014–15 to 2018–19, based on water requirements of each species in Table 3

Total events for trout cod and silver perch are based on freshing flows and overbank flow events and for all other species are based on overbank flow and wetland watering events (plus in-channel flows for the Lachlan and Macquarie catchments)

	2014–15		2015–16		2016–17		2017–18		2018–19		Total		Total	
Catchment and species	Beneficial events	Total events	Beneficial events	Total events	Beneficial events	Total events	Beneficial events	Total events	Beneficial events	Total events	Beneficial events	Total events	Proportion beneficial events	Frequency (years) beneficial events
Sloane's froglet														
Central Murray	0	0	2	4	1	1	2	2	1	3	6	10	0.6	1.25
Goulburn	1	1	0	0	0	0	0	1	0	0	1	2	0.5	5
Southern bell frog														
Lachlan	0	0	0	0	1	1	0	0	1	2	2	3	0.67	2.5
Murrumbidgee	3	6	5	10	5	10	2	12	10	14	25	52	0.48	1.0
Ovens	0	0	0	0	0	0	1	2	0	0	1	2	0.5	5.0
Lower Murray	1	1	4	4	1	1	1	2	1	1	8	9	0.89	1.0
Australasian bittern														
Macquarie	0	1	0	0	0	6	1	1	1	1	2	8	0.25	2.5
Murrumbidgee	3	6	5	10	4	10	1	12	11	14	24	52	0.46	1.0
Lower Murray	1	1	1	1	1	1	1	2	0	5	4	10	0.4	1.25
Australian painted snipe														
Gwydir	2	2	1	2	1	1	0	1	3	3	7	9	0.78	1.25
Mid-Murrumbidgee	1	2	1	2	1	1	1	4	5	5	9	14	0.64	1.0
Trout cod														
Central Murray	0	1	3	4	2	2	1	1	2	4	8	12	0.67	1.25
Goulburn	1	4	0	1	0	2	1	8	1	3	3	18	0.17	1.7
Ovens	0	0	0	0	0	1	0	0	0	0	1	2	0.5	5
Murray hardyhead														
Central Murray	2	2	1	1	1	1	1	1	5	5	10	0	0.67	1.0
Lower Murray	1	1	3	3	1	1	1	2	1	3	7	10	0.7	1.0
Silver perch														
Lower Murrumbidgee	0	0	0	0	1	2	0	0	1	1	1	3	0.3	2.5
Edward–Wakool	2	2	4	4	4	4	2	2	1	3	13	15	0.87	1.0
Goulburn–Broken	2	4	0	1	0	2	3	8	2	3	7	18	0.4	1.7
Campaspe	1	1	2	2	0	0	1	1	1	1	5	5	1.0	1.25
Flathead galaxias														
Campaspe	0	0	1	1	0	1	0	0	0	0	1	2	0.5	5
Goulburn	1	1	1	1	0	0	0	0	0	1	2	3	0.67	2.5

Table 3. Reporting of threatened species targeted for environmental watering in the Murray–Darling Basin, based on Commonwealth Environmental Water Office (CEWO) Long-term Intervention Monitoring Project (LTIM) technical reports for selected areas (2014–15 to 2018–19)

LTIM technical reports for selected areas: junction of Warrego and Darling, Eco Logical Australia 2019*a*; Gwydir, Eco Logical Australia 2019*b*; Lachlan, Dyer *et al.* (2020); Murrumbidgee, Wassens *et al.* (2020); Edward–Wakool, Watts *et al.* (2019); Goulburn, Webb *et al.* (2019); lower Murray, Ye *et al.* (2020). Note, fishes were the only faunal group monitored in all seven selected areas. Frogs were monitored only in the Murrumbidgee (along with turtles) and Warrego and Darling and waterbirds only in the Warrego and Darling, Gwydir and Murrumbidgee. N/A, species does not occur within the selected area; no monitoring data, the species was mentioned in the report (typically, its threatened species status or prior occurrence) but without additional monitoring data; green fill, benefit from environmental watering likely; yellow fill, no benefit apparent; red fill, not mentioned or no monitoring data

Selected area	Sloane's froglet	Southern bell frog	Australasian bittern	Australian painted snipe	Trout cod	Murray hardyhead	Silver perch	Flathead galaxias
Warrego and Darling	N/A	N/A	Not mentioned	Not mentioned	N/A	N/A	No monitoring data	N/A
Gwydir	N/A	N/A	No monitoring data	Abundance (max. 3 individuals in 5 years)	N/A	N/A	Abundance (1 individual in 5 years)	N/A
Lachlan	No monitoring data	Not mentioned	Not mentioned	No monitoring data	N/A	N/A	Abundance (4 individuals in 5 years)	N/A
Murrumbidgee	N/A	Occurrence, abundance (time series – increasing trend but not significant), breeding	Occurrence – annual observations, abundance (5 individuals in 5 years), breeding	Not mentioned	N/A	N/A	Abundance (16 adult individuals in 5 years; time series for eggs and larvae – no trend). Spawning, no recruitment detected	'Considered locally extinct'
Edward–Wakool	N/A	No monitoring data	Not mentioned	N/A	Occurrence. No breeding or recruitment	N/A	Breeding and recruitment (time series), improved dispersal	N/A
Goulburn	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Abundance (time series – no trend) Breeding, no recruitment	N/A	Abundance (time series). Spawning and some evidence of recruitment	Not mentioned
Lower Murray	N/A	Not mentioned	Not mentioned	Not mentioned	N/A	Not mentioned	Abundance (time series – no trend). No spawning or recruitment	N/A

In attempting to verify whether the patterns in our time series were similar to those in empirically derived, field-based datasets in which sampling effort had been standardised, we found that the pattern for abundance of silver perch in the Goulburn River from 2014–15 to 2018–19 (Webb *et al.* 2019, p. 151) was almost identical to that for the same period in our data (Fig. 2). Likewise, there was a similar pattern for juvenile and adult silver perch in the Edward–Wakool (Watts *et al.* 2019, p. 142). Occurrence of southern bell frog increased (Wassens *et al.* 2020, fig. 4-55 therein) from 2014–15 to 2018–19, with the greatest rate of increase occurring between 2016–17 and 2017–18, as we found. Population time series of Murray hardyhead at the Mallee Lakes (Ellis *et al.* 2014) showed a pattern of population boom-and-bust similar to that we recorded (Fig. 2) and populations of trout cod in the Ovens River (Raymond *et al.* 2019) increased in line with the trend we observed. The declining trend in counts of Australian painted snipe matches the long-term decline in the reporting rate of this species (Rogers *et al.* 2005; Purnell *et al.* 2014). We found no published population time series based on field surveys for Sloane's froglet, Australasian bittern and flathead galaxias.

Discussion

Our findings indicated two markedly different interpretations of the success of the Basin Plan in conserving threatened species and, thus, meeting Australia's obligations as a signatory of international treaties on biodiversity and the environment. If the focus is only on a narrow selection of species in a limited number of catchments, then one reading of the available monitoring reports indicates that the Basin Plan has largely achieved its objective of using environmental flows to maintain and conserve populations of threatened species. This interpretation is based largely on reports of ecological outcomes from environmental flows published by the CEWO LTIM project (Hale *et al.* 2020*a*, 2020*b*) and the MDBA, based on LTIM findings (Murray–Darling Basin Authority 2020*b*). These reports present the narrative that threatened species have been carefully considered and targeted in the planning and management of environmental watering at the Basin scale, and have responded by increasing in range, breeding frequency, population recruitment, occurrence and abundance. These responses were detected through comprehensive, long-term and systematic Basin-wide monitoring and reporting.

However, the reality is quite different when considered in the context of the broader number of threatened, flow-dependent fauna and all catchments in the Basin, as well as in relation to the requirements of the *EPBC Act*. Based on our analyses, which included the total number of catchments in which each of the threatened species considered herein are likely to occur, only a quarter of the 97 species–catchment combinations (i.e. the number of catchments in which each species occurred post-1990) have been monitored and environmental watering outcomes reported (Table 1). Of those that have, only limited reporting has been based on data collected by systematic, long-term monitoring. In fact, most of the threatened species were not monitored in most of the seven LTIM selected areas (Table 1). Monitoring has focussed disproportionately on some species (e.g. silver perch and trout cod) and ignored others (e.g. Sloane's froglet, flathead galaxias). The lack of clarity and consistency in reporting of environmental watering outcomes for threatened species makes it difficult to determine a causal link between environmental flows and positive conservation outcomes. Under this interpretation, the evidence base for the success of the Basin plan in conserving threatened species is patchy and poor.

By their very nature, threatened species can be difficult to monitor, with fragmented distributions, low abundance, poorly known habitat preferences and cryptic habits. For example, the monitoring of breeding events by Australian painted snipe requires substantial effort to detect both adults and nests (Jaensch 2009). However, such difficulties do not provide a justification for ignoring a species or failing to detect it through the use of inappropriate monitoring methods or sampling localities. Rather, targeted, specialist approaches may be required if we are to have any hope of improving the monitoring of the conservation status of threatened species, even if such monitoring incurs additional costs, effort and resources.

Regarding these deficiencies in monitoring and reporting, it is important to note that despite the expenditure of A$13 billion on Basin water reforms, when the Basin Plan was adopted, State governments withdrew their financial support for environmental monitoring and, in 2013, the Commonwealth government abolished the whole-of-Basin Sustainable Rivers Audit, a collaborative and systematic monitoring activity between the MDBA and State environmental agencies (Davies *et al.* 2010). It was left to CEWO to attempt to construct a monitoring program out of nothing by allocating some of their funding to monitoring outcomes in some of the river valleys where they hold and manage environmental water. However, there remains a compelling need for a comprehensive, properly funded and fully coordinated whole-of-Basin environmental monitoring system, with data that are publicly accessible and open to scrutiny in order to provide a basis for evaluation of progress in achieving environmental objectives against a backdrop of climate change and high variability in river inflows (Colloff and Pittock 2019).

While most of the threatened species in the catchments we assessed are likely to be receiving some environmental water that matches some of their requirements at some wetland locations, this finding appears less optimistic when considered in relation to reported lower-than-expected river flows (having accounted for drought) since the Basin Plan commenced (Wentworth Group of Concerned Scientists 2020), the low proportion of total wetland area inundated with environmental water (Chen *et al.* 2021) and the prospect of less water being available for the environment under climate change (Colloff *et al.* 2016; Zhang *et al.* 2020).

Species conservation status, monitoring and the EPBC Act

The *EPBC Act* is the Commonwealth legislation through which Australia's obligations under the Ramsar Convention are enacted, in large part, and thus also the conservation requirements of the Basin Plan. Of the threatened species we considered here, only three, namely, southern bell frog, trout cod and Murray hardyhead, have national recovery plans in place under the *EPBC Act* (Table S1). There appears to be a lack of co-ordination among agencies charged with the implementation of the Basin Plan regarding how they will contribute to conservation of threatened species and who is responsible for the outcomes. This confusion is highlighted by the following justification by the Department of Agriculture, Water and the Environment for why a national

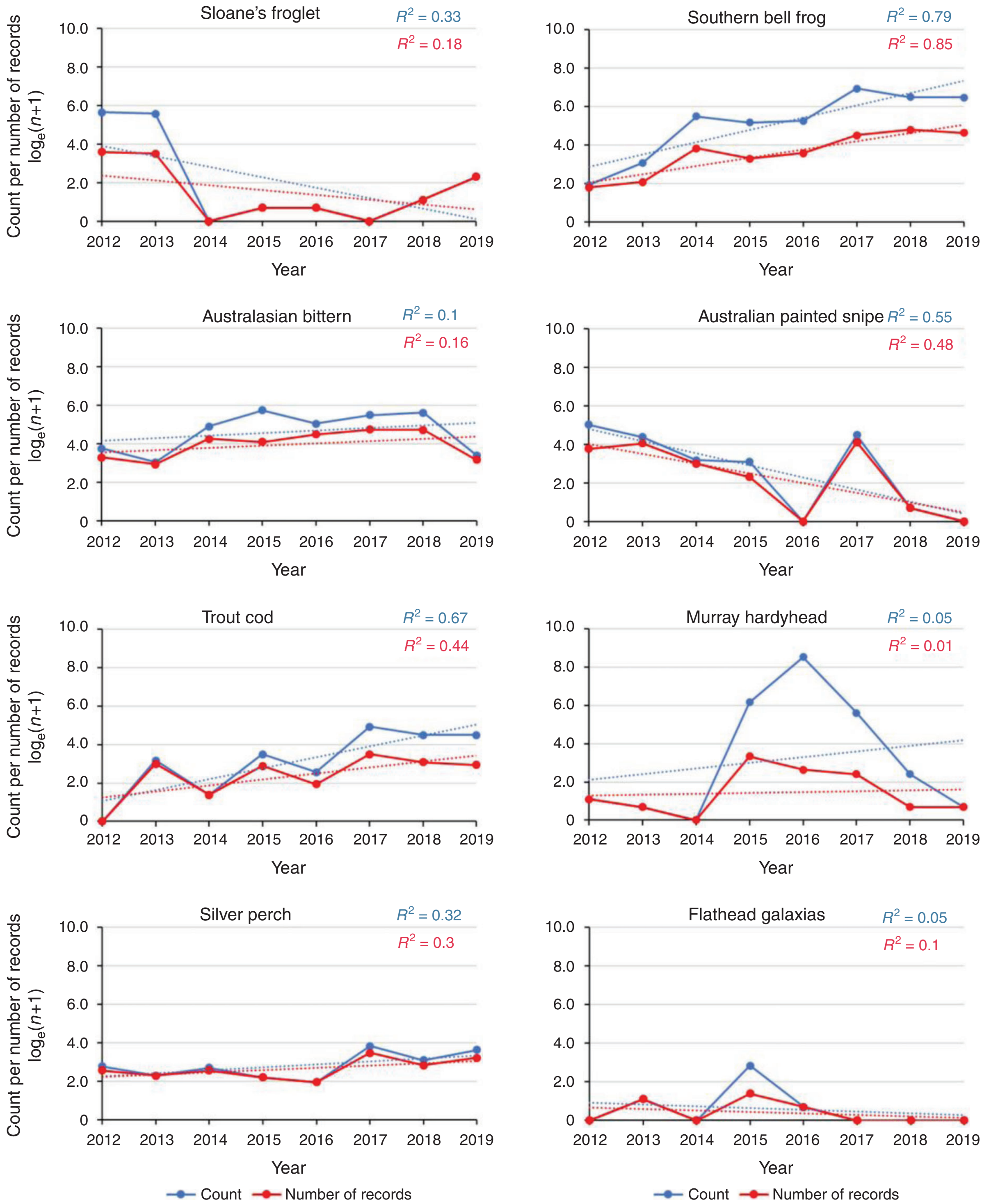

Fig. 2. Annual counts of the number of individuals and the number of records of the eight species from locations in Fig. 3, transformed with $\log_e(n + 1)$, with lines of best fit and coefficients of determination. Data for southern bell frog corrected for sampling effort (Table S7).

recovery plan for flathead galaxias is not required under the *EPBC Act*:

> Actions and mechanisms that are being implemented through a variety of other existing programs (including in other species recovery plans, water management plans, actions being undertaken by relevant catchment management authorities) are likely to be of benefit to this species. In particular, with regard to the threat posed by river regulation

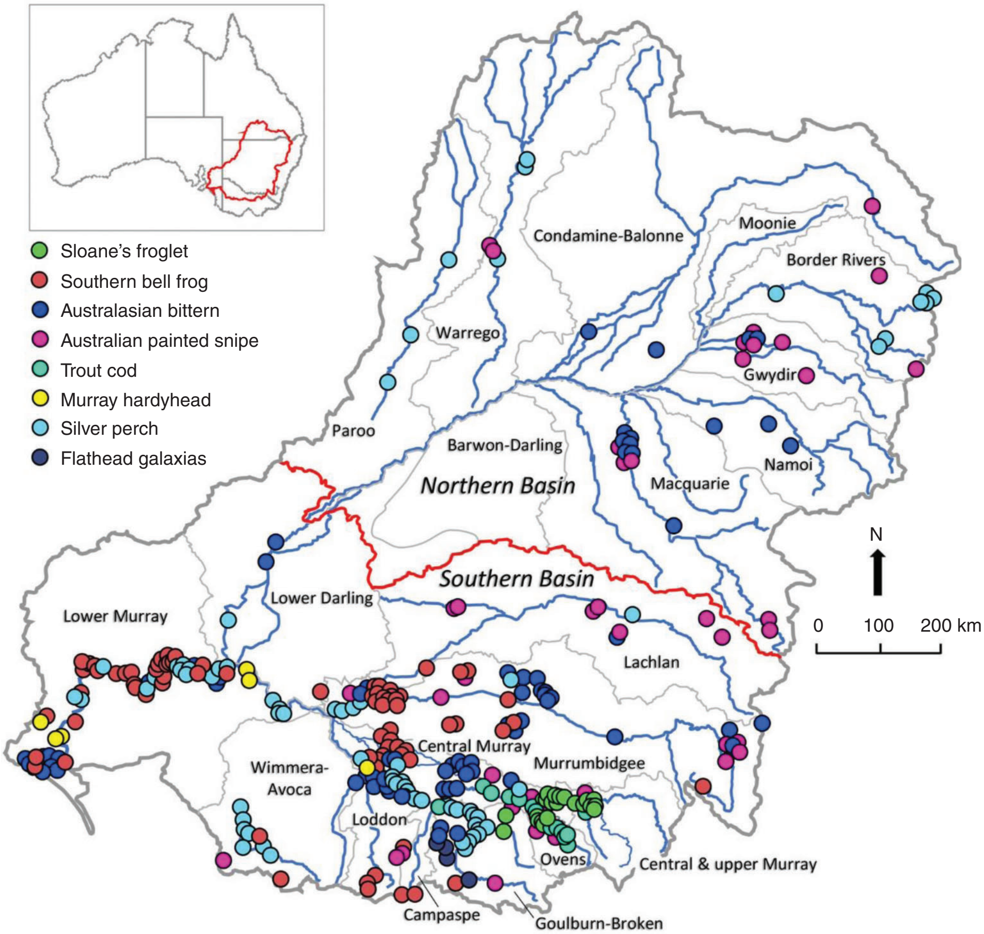

Fig. 3. Locations where data were available for annual counts of individuals and number of records for eight threatened species in the Murray–Darling Basin between 2012–13 and 2018–19 inclusive, on the basis of data from Atlas of Living Australia (2020), Department of Environment, Land, Water and Planning (2020) and the New South Wales BioNet Atlas (see http://www.bionet.nsw.gov.au/).

> and its associated negative impact on lateral connectivity, an objective of the Basin Plan 2012 (paragraph 8.06(3)(b)) is 'to protect and restore connectivity within and between water-dependent ecosystems, including by ensuring that ecological processes dependent on hydrologic connectivity laterally between watercourses and their floodplains (and associated wetlands)'…Given that the threats to the species are poorly understood, prioritisation of recovery actions under a recovery plan to address these threats may be a little premature until there is a greater understanding of the species, which can be gained from targeted research that can be undertaken outside the confines of a species-specific recovery plan (2/05/2016). [Department of Agriculture, Water and Environment 2021*b*]

In other words, the messages are 'the Basin Plan will fix it' and 'more research is needed'. As we found, flathead galaxias were not reported on in the LTIM Basin-wide report (Hale 2019) because they had not been monitored, even though the species was a priority target for Commonwealth watering in the central Murray (Table 1). We found 'actions being undertaken' were unlikely to be of benefit to this species. By way of contrast, the national action plan for trout cod has led to the establishment of a dedicated task force, co-ordination and collaboration among researchers and has stimulated not only monitoring but also basic research on the biology and ecology of the species, as well as a synthesis of the lessons learned for future management of environmental flows (Koehn *et al.* 2013, 2014*b*). As a result, trout cod populations are showing some signs of recovery. For flathead galaxias, such an approach might result, for example, in determining whether there *are* any remnant populations extant in the Murrumbidgee catchment through targeted and intensive sampling, such as was conducted in wetlands in the central and upper Murray (which found no individuals; Pearce *et al.* 2018), instead of making the assumption that the species is 'considered locally extinct' (Wassens *et al.* 2020, p. 173).

Monitoring and reporting of environmental watering outcomes

Reporting on the responses of threatened species to environmental watering is fragmentary, piecemeal and not clearly and systematically supported by empirical evidence. Although the LTIM Basin-wide reports include at least some indication of outcomes for most threatened species considered herein (except Sloane's froglet and flathead galaxias; Table 1), the reported benefits often take the form of merely a mention that a species was recorded at a site that received Commonwealth environmental water. For example, no casual evidence is presented of any relationship between the delivery of environmental flows to Macquarie Marshes in 2017–18 and the recorded presence of Australasian bittern and Australian painted snipe (Hale 2019, p. 21), or trout cod and silver perch at Barmah–Millewa Forest in 2018–19 (Hale *et al.* 2020*b*, p. 18). Occasionally, causal examples of benefits are reported, such as evidence of breeding by southern bell frog after environmental flows in the Murrumbidgee (Hale *et al.* 2020*b*, p 26, based on Wassens *et al.* 2020) and in-channel freshes supporting silver perch movement between the Murray and the Goulburn (Hale *et al.* 2020*a*, p. 50, based on Webb *et al.* 2019); but benefits from environmental flows tend to be assumed rather than demonstrated.

The assumption that the co-occurrence of a species and an environmental watering event is evidence of a benefit in terms of population maintenance or growth is not supported by our data. On the contrary, we found, for example, that despite multiple environmental watering events in the Murrumbidgee, only half of them resulted in the inundation of Australasian bittern habitats sufficient to meet its water requirements for breeding, despite the assertion that 'there is very good evidence that Commonwealth environmental water is contributing to maintaining populations of Australasian bittern with over 10% of the estimated population of the species recorded at the Barmah–Millewa Forest sites.' (Hale *et al.* 2020*b*, p. 40). No supporting evidence for this statement was provided, i.e. data on breeding events, nor was there any qualifying statement that 40% of the population of Australasian bittern breeds in rice fields in the southern Riverina, the region adjacent to the Barmah–Millewa Forest (Herring and Silcocks 2014; Herring *et al.* 2019) which, of course, receive no environmental water and consist of highly simplified habitat in both structure and function. It is difficult to reconcile these basic facts of the ecology of Australasian bittern with the claim that positive outcomes from Commonwealth environmental water 'are undoubtedly being achieved' and this water is supporting 'critical habitat' for the species. Hale *et al.* (2020*b*, p. 40) at least conceded 'it is possible that some species occur largely at sites that do not benefit from Commonwealth environmental water.' An obvious policy response would be for Commonwealth agencies to figure out how they can best help rice farmers support the core breeding population of this nationally endangered species (Bitterns in Rice Project 2021).

Gaps in the reporting of environmental watering outcomes for threatened species are evident Basin wide. Reports were available for only a quarter of the 97 species–catchment combinations and for only half of those where a threatened species was targeted for environmental watering. This finding indicates a failure of the agencies responsible for the implementation of the Basin Plan to uphold important responsibilities for threatened species conservation monitoring and reporting under the *EPBC Act*. Furthermore, it was clear from our findings that far more effort goes into the monitoring of large, charismatic species or ones that are relatively easy to locate, identify and count. Thus, large-bodied fishes, such as trout cod and silver perch, are being monitored but the small-bodied flathead galaxias and Murray hardyhead receive far less attention. A similar situation prevails for southern bell frog compared with Sloane's froglet.

A failure to monitor and detect translates into a failure to prioritise species in environmental watering plans. The lack of monitoring for Sloane's froglet and flathead galaxias is in accord with the fact that no review of threatened, flow-dependent species in the Basin has been undertaken before or since the implementation of the Basin Plan. Yet Sloane's froglet has been shown to benefit from localised environmental watering, with the Goulburn–Broken Catchment Management Authority recording positive responses of populations after multiple environmental watering events at Moodies Swamp and Doctors Swamp near Shepparton (J. Deretic, pers. comm., 13 October 2020). Flathead galaxias have fewest records of occurrence for any species we assessed, with only 31 records in the combined atlas database since 2012. It might be assumed the agencies responsible for the Basin Plan would place far greater priority on a threatened species with such a restricted range and low population size. Without greater priority, flathead galaxias could well be the first species to become extinct under the Basin Plan.

It has been a complex, time-consuming process to assemble and collate the multiple reports of monitoring outcomes that are available for the eight threatened species in the various catchments and to try and associate statements of benefits with a clear evidence base. A comprehensive survey of all reported outcomes across all threatened flow-dependent fauna in the Basin is beyond the scope of the present work. Of major concern was the complexity we found in the reporting, whereby LTIM Basin-wide reports contained information based on data from monitoring programs unrelated to the LTIM Project, such as those undertaken on behalf of catchment management authorities or other clients. We have not undertaken a full assessment of which reports of outcomes can be attributed to which monitoring programs, which is beyond our scope, but suffice it to say, in the reporting of environmental outcomes of the Basin Plan, the lack of clear attribution to publicly available sources of monitoring data undermines confidence in any claims of success.

Indicators of occurrence and abundance of threatened species

We found statistically significant increasing trends in annual counts of individuals and the number of records for southern bell frog and in annual counts for trout cod, but a significantly declining trend in counts for Australian painted snipe, which accords with a sharp decline in reporting rate since 1980 in the Basin, where occurrence is closely related to frequency of flooding of wetlands (Purnell *et al.* 2014). All other species showed no change over time, indicating that environmental flows *may* have contributed to population maintenance, thus potentially forestalling risk of any decline. However, there was no *overall* beneficial effect in terms of population increase of threatened species from environmental watering under the Basin Plan.

Both southern bell frog and trout cod are the subjects of national recovery plans, commenced in 2012 and 1994 respectively. Southern bell frog accounted for by far the largest number of records in the combined atlas database. In removing records from outside the Basin, we noted a very large number of records from Werribee Ponds, where much of Melbourne's sewage is treated, as well as at Bendigo sewage treatment works (inside the Basin). Southern bell frog appears to be a species that can thrive in artificial wetlands and heavily modified ecosystems in urban and peri-urban areas, whereas in its natural habitat it is susceptible to alterations in flow and flood regimes and degradation of protective fringing vegetation habitat by grazing, slashing or burning (Wassens 2010).

For trout cod, considerable effort has gone into re-stocking and translocation, restrictions on angling, as well as ecological restoration, including re-snagging river reaches with woody debris to provide appropriate habitat for spawning, recruitment and growth, restoration of riparian vegetation, fencing out livestock, controlling riparian weeds, removal of weirs and installation of fishways (Koehn *et al.* 2013; Raymond *et al.* 2019). Environmental flows are only part of the reason that populations of trout cod appear to have increased and have extended their range in some river reaches under the three iterations of the recovery plan (Koehn *et al.* 2013). These gains have required a concerted and persistent effort by dedicated agency staff over nearly two decades.

A lesson from the trout cod example is that environmental flows are not enough on their own to ensure the survival of threatened species. They may be an important contributing factor, as in the case of recent reports of breeding success of Australasian bittern, with up to 20 nests at Yanga National Park in the lower Murrumbidgee following delivery of ~200 GL of environmental flows since spring 2020 (Hayter 2021). However, conservation efforts for Australasian bittern, with an estimated national population of ~1200–1500 individuals, have been driven largely through building trusting, long-term partnerships between conservationists and rice farmers in the Riverina, on whose properties the bulk of the bittern population breeds, and developing bittern-friendly rice-farming approaches (Herring *et al.* 2019; Bitterns in Rice Project 2021).

Use of data from the biodiversity atlases to construct time series has some limitations relating to sampling bias and the uncertainty of whether counts of individuals are accurate and consistent. Accordingly, we sought to verify the time series by using empirical data from field surveys based on standardised sampling protocols. Also, we have been cautious in referring to total annual counts of individuals of each species and the annual number of records for each species as *indicators*, but not measures, of relative abundance and rate of occurrence. However, what we have managed to assemble represent some of the best-available (and, in several cases, the only) time series that indicate population status of these threatened species.

Given the considerable effort that has gone into monitoring environmental outcomes of the Basin Plan since its commencement in 2012–13, and the expenditure of tens of millions of dollars of public funds on the LTIM project since 2014–15, it is remarkable that there are so few datasets available for this period that show changes in population size over time, not only for threatened species, but for *any* species. Anyone attempting a synthesis of the benefits of environmental watering for the biota of the Basin faces the prospect of having to make sense of a miscellany of anecdotes and assertions in a plethora of fragmented monitoring reports, many of which are not available for public scrutiny (cf. Table S6). It is possible that a more positive picture may have emerged from our analyses if *all* monitoring results had been publicly available. If a key objective of the Basin Plan is that 'representative populations and communities of native biota are protected and, if necessary, restored' (Commonwealth of Australia 2012, Section 8.05(3)), and a central tenet of the *Water Act* is that the Basin Plan be implemented using the 'best *available* science' (i.e. science that can be freely and independently checked and verified), then without such data, it is hard to envisage the circumstances under which it could reasonably be claimed that this objective had been achieved. The same applies to a central objective of the Ramsar Convention, namely, to maintain the ecological condition of Ramsar wetlands. All monitoring data should be open to public scrutiny as a basic principle of scientific integrity.

It is a matter of considerable public policy concern that so much time, effort and money has been expended on generating so much monitoring data that appear to be of little predictive value in assessing whether or not the Basin Plan is achieving its environmental objectives of protecting flow-dependent ecosystems, their biodiversity and threatened species. The recent review of the *EPBC Act* concluded that 'the current environmental trajectory [of decline] is unsustainable' and that 'good outcomes for the environment…cannot be achieved under the current laws', but also, and overwhelmingly, 'Australians care deeply about our iconic places and unique environment' (Samuel 2020, p. 1).

We suggest the findings of the Samuel Review present an opportunity for a major re-think of how environmental water can be used differently and more effectively for the protection of threatened species. Such an approach would involve a shift from top-down planning and implementation of priorities based on assumptions derived from monitoring and ecohydrological modelling of questionable quality. Instead, we suggest an approach based on Commonwealth and State agencies building meaningful, trusting partnerships with landholders, NGOs, Indigenous groups, local agencies and communities to achieve bottom-up-led habitat restoration, public education and engagement and local-scale monitoring and reporting that can realise better targeted environmental water and a culture of environmental responsibility and commitment. There have been some past examples containing elements of this approach, such as the Water for Nature Program (Jensen 2016) and the work of the Murray–Darling Wetlands Working Group (Nias *et al.* 2003; Nias 2005) involving partnerships with CEWO, and the Nimmie–Caira project, led by Traditional Owners and The Nature Conservancy in partnership with NSW Department of Planning, Industry and Environment (The Nature Conservancy 2021). The opportunity to build on these initiatives has never been more urgent. If government agencies cannot or will not engage in such partnerships, it leaves Australians who care deeply about their environment little choice but to do what they can without the support of governments.

Conclusions

A major objective underpinning the establishment of the A$13 billion Basin Plan was to uphold Australia's obligations to international conservation treaties through the restoration of ecological processes and conservation of threatened species. We assessed whether environmental water has helped conserve threatened flow-dependent fauna under the Basin Plan and found that although some conservation benefits are evident for some species at some locations some of the time, there is a lack of consistent monitoring and reporting on status and trends of threatened species across the Basin. Environmental water management plans, which are intended to outline environmental water targets for threatened species, appear to focus disproportionately on a selected few charismatic species at the expense of lesser-known species. Monitoring and reporting on environmental watering outcomes accounted for only a fraction of the catchments and species for which monitoring could and should have been undertaken.

A major re-think of environmental watering and monitoring of outcomes for threatened species is required. As part of this process, consideration should be given to the issue of ecological trade-offs. For example, in-channel water requirements for successful breeding of trout cod or silver perch may represent an opportunity cost, in terms of the volume of environmental water forgone, to the detriment of threatened biota that require overbank flows for habitat maintenance and breeding. Better understanding of the details of these trade-offs, and potential synergies, is essential for improved and targeted management. With more detailed knowledge of habitat and breeding requirements gained from strategic adaptive management, certain localities (e.g. well established, long-term breeding sites) could be designated for environmental flows for particular species, rather than attempting to benefit everything everywhere. In this regard, the MDBA has prioritised updates to the Basin-wide environmental watering strategy (due in 2022), including 'additional expected environmental outcomes so that the overall environmental objectives for water-dependent ecosystems can be comprehensively assessed (e.g. threatened species)' (Murray–Darling Basin Authority 2019*c*, p. 22).

Identifying Basin-wide population trends for threatened species since implementation of the Basin Plan in 2012–13 is impeded by a lack of consistent, good-quality data on species distribution, occurrence and abundance. If the Basin Plan is to achieve the conservation of threatened species and meet Australia's international environmental treaty obligations, it is a priority to put in place long-term monitoring and reporting programs in conjunction with restoration and recovery initiatives. In such initiatives, environmental watering plans would be integrated into broader sets of activities involving habitat restoration, public education and building meaningful and lasting partnerships with landholders, local agencies and other stakeholders. The approach to conservation in the Basin that is characterised by the expression 'just add water' is unlikely to be successful in the long term without more sophisticated and strategic management.

Conflicts of interest

Jamie Pittock is a member and Matt Colloff an associate of the Wentworth Group of Concerned Scientists. The authors declare that they have no other conflicts of interest.

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