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Basin-scale environmental water delivery in the Murray–Darling, Australia: A hydrological perspective

Michael J. Stewardson[1] | **Fiorenzo Guarino**[2]

[1]Department of Infrastructure Engineering, Melbourne School of Engineering, The University of Melbourne, Melbourne, Vic., Australia

[2]Institute for Applied Ecology, The University of Canberra, Canberra, ACT, Australia

Correspondence
Michael J. Stewardson, Department of Infrastructure Engineering, Melbourne School of Engineering, The University of Melbourne, Melbourne, Vic., Australia.
Email: mjstew@unimelb.edu.au

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Abstract

1. A major outstanding challenge for environmental flow management is to move from a single site, reach or river focus to planning and delivering environmental flows across entire river basins. There is a need for case studies of basin-scale environmental water delivery as a first step in understanding and eventually generalising basin-scale responses.
2. The Commonwealth Environmental Water Holder manages a portfolio of water entitlements for protecting and restoring aquatic ecosystems of the Murray–Darling Basin (MDB). This article describes the strategies used by the water holder and the hydrological outcomes of their basin-scale environmental water delivery program.
3. There are five delivery strategies used to enhance benefits achieved with available environmental water. Although the volume of commonwealth environmental water is small relative to mean catchment inflows, improvements in baseflows and freshes are seen across the MDB. Water was also successfully delivered into floodplain wetlands.
4. The case study provides a successful example of implementing a basin-scale program for environmental water delivery. However, there remains a great need to improve the knowledge, governance and planning tools for managing environmental water for a broad range of ecological demands that operate at the basin-scale.

KEYWORDS
environmental flow, flow regime, river basin, river restoration, wetland inundation

1 | INTRODUCTION

The diversion of surface water from rivers for consumptive use, particularly for irrigated agriculture has led to widespread, and sometimes severe, alterations in river streamflow regimes in most of the world's major river basins (Stewardson et al., 2017; Vörösmarty et al., 2010). These alterations include reduced baseflows (Brown, Western, McMahon, & Zhang, 2013), reduced magnitude and frequency of flow pulses including overbank flooding (Mueller et al., 2014), and attenuation or complete reversal of the natural seasonal flow pattern (Biemans et al., 2011). Adverse impacts of these changes for stream ecosystems are well established (Poff et al., 1997). Environmental flows are increasingly considered in programs to address these impacts. Environmental flows refer to the maintenance or restoration of water regimes to protect aquatic and riparian ecosystems (Horne, O'Donnell, & Tharme, 2017; Horne, O'Donnell, Webb, et al., 2017) and their benefits for humans (Dyson, Bergkamp, & Scanlon, 2003). Over the last decades, there has been progress in developing the science and methods required to assess the environmental flow requirements of rivers (Tharme, 2003). In many parts of the world, there are now case studies documenting environmental flow programs including monitoring of environmental outcomes (Olden et al., 2014). Environmental flow management has become a well-accepted component of sustainable water resources management (Horne, O'Donnell, Webb, et al., 2017; Horne, O'Donnell, & Tharme, 2017).

A major outstanding challenge for the application of environmental flows is to move from a single site or river focus, to planning and delivery of environmental flows across entire river basins (Poff & Matthews, 2013) or larger regions that are hydrologically connected via inter-basin transfers. Most published experimental environmental flow studies deal with individual rivers, with many restricted to a single reach downstream of large dams (Olden et al., 2014). These site-scale studies can overlook important connections through river networks that mediate the transport of water, sediment, energy, oxygen, nutrients, contaminants and organisms longitudinally along stream channels, laterally with floodplains and vertically with the hyporheic zone (Brierley et al., 2010; McCluney et al., 2014). There is a strong case for planning river restoration at the basin-scale. In particular, a basin-wide approach is needed to address complex basin-wide ecosystem interactions (McCluney et al., 2014), including those between water resources and other stressors on river ecosystems as well as social, economic and political concerns (Jakeman & Letcher, 2003).

There are examples where environmental flow planning has occurred at the basin-scale, including in the Mekong Basin (Ziv, Baran, Nam, Rodriguez-Iturbe, & Levin, 2012). However, we are not aware of any documented case studies reporting on the outcomes of delivering environmental flows at the basin-scale. To address this gap, this article provides a case study of basin-scale environmental flow delivery, in the MDB, in south-eastern Australia.

This case study focuses on hydrological responses to environmental flow management at the basin-scale. Although hydrological outcomes are rarely an objective of environmental flow programs, they are critical to the achievement of desired ecological outcomes. Importantly, it is not easy to predict hydrological responses to environmental flow delivery, at the basin-scale. Complex trade-offs are required, including prioritising environmental flows for multiple environmental water demands in different locations across the basin, and these are subject to numerous policy and physical constraints. Environmental flow targets are often achieved by delivering water along one or more rivers over long distances with extended and variable delivery times, but flow events are attenuated through the river network by natural and anthropogenic flow inputs and withdrawals. Research, such as this study, is needed to understand complex basin-scale hydrological responses in a managed river basin, including the necessary data inputs and evaluation methods. This is critical for understanding the broader ecological responses to basin-scale environmental flow management.

2 | BACKGROUND TO CASE STUDY

The $1\text{x}10^6$ km^2 MDB supports 50% of Australian irrigated agriculture (A$7.2 billion in 2012–2013) (Hart & Davidson, 2017), dominating production in rice, cotton, fruit and grapes. Ecosystem health of the basin has suffered through a range of human disturbance including irrigation development (Walker & Thoms, 1993). In 2012, after 4 years of planning led by the Murray–Darling Basin Authority, the Commonwealth Government of Australia ratified "the Basin Plan" in legislation. This plan sets sustainable diversion limits (SDLs) for the basin's subcatchments (Hart, 2016a,b). SDLs were based on assessment of environmental flow requirements of "Umbrella Environmental Assets," which were mainly large floodplain wetlands at the downstream end of the basin's major tributaries (Swirepik et al., 2016). It is assumed that meeting the environmental flow demands of these large wetland systems will likely meet the demands of other ecological values in the basin (Swirepik et al., 2016). The Basin Plan SDLs require a reduction on the previous diversion limit (or "Cap") by a volume of 2,750 GL (1 Gl = 10^9 m^3) calculated based on average water withdrawals. This represents ~20% of average total annual water withdrawals (mostly for irrigation) prior to the Basin Plan (Hart, 2016a). Significant progress towards meeting the SDLs has been achieved by recovering water for the environment through purchase of water entitlements from irrigators, combined with water savings achieved through improvements in the efficiency of the irrigation water supply system (Hart & Davidson, 2017).

In this article, we make an important distinction between the terms "environmental water" and "environmental "flow." We use "environmental water" to refer to the volume of water protected for environmental use (Horne, O'Donnell, Webb, et al., 2017; Horne, O'Donnell, & Tharme, 2017). In the MDB, the environmental water provision is the residual in excess of the SDL. Recent water reforms including the Basin Plan have introduced a secure mechanism for protecting some of this environmental water called an environmental water entitlement. The commonwealth government holds all the water licences recovered mostly from irrigators to meet the Basin Plan SDLs as an environmental water entitlement. Additional (and smaller) environmental water entitlements have also been recovered by state governments with jurisdiction in the MDB and non-government environmental organisations. These environmental water entitlements carry the same rights as irrigation entitlements (Horne, O'Donnell, & Tharme, 2017). The establishment of environmental water entitlements marks a significant change in environmental water management from earlier reliance on water withdrawal limits.

We use the term "environmental flow" when referring to enhancements of the flow regime achieved through use of environmental water. There is an important distinction in this study between environmental water (i.e., the volume of water used for environmental benefit) and environmental flows, which is a response to delivery of environmental water investigated in this article. Indeed, new institutions have been established in Australia and elsewhere to deliver environmental water entitlements to improve environmental flow outcomes. In the MDB, the role of Commonwealth Environmental Water Holder (CEWH) was established under the Water Act 2007 to have responsibility for the commonwealth environmental water entitlement. The Commonwealth Environmental Water Office (CEWO) supports the CEWH in managing the portfolio of commonwealth environmental water by delivering environmental flows across the MDB, with the objective of improving and restoring the environmental condition of the basin's rivers.

In the MDB, commonwealth environmental water entitlements are delivered primarily by active management, defined by ongoing decisions regarding when, and how environmental water will be used each water year (O'Donnell & Garrick, 2017). This approach to delivery of environmental flows is consistent with the "designer flows paradigm" approach for assessing environmental flow requirements in heavily regulated river systems (Acreman et al., 2014). With the designer paradigm, components of the flow hydrograph are assembled into a target environmental flow regime that meets a particular set of ecological and social objectives (Acreman et al., 2014). Both the designer paradigm and active management recognise that environmental water must be well targeted to achieve defined ecological outcomes in rivers where water resources are fully or over-allocated.

A smaller proportion of commonwealth environmental water holdings are also delivered using passive environmental water management. A passive management approach refers to activities related to maintaining the legal and policy framework in which environmental water is acquired and managed (and in some instances, may be the legal owner of environmental water) (Horne, O'Donnell, Webb, et al., 2017; Horne, O'Donnell, & Tharme, 2017). Importantly, there is limited or no opportunity for ongoing decisions regarding when, and how environmental water will be used with a passive management approach.

O'Donnell and Garrick (2017) describe how a gradient of passive-to-active environmental flow management roles can exist within a single environmental water management agency. This is the case for the CEWO's use of commonwealth environmental water. In the MDB, active management is possible across the southern MDB and some of the northern rivers where environmental water can be flexibly ordered from a dam. There are also rivers in the northern MDB with little or no water storage capacity and environmental water must be sourced from streamflows delivered from natural catchment run-off. In these systems, environmental flows are triggered when "access-to-take" streamflow thresholds are exceeded. The timing of these events is relatively uncontrolled by the CEWO. This situation is closer to the passive end of the environmental flow management spectrum.

2.1 | Water use strategies

In this article, we examine five strategies used by the CEWO to enhance environmental benefits achieved with commonwealth environmental water. These strategies are primarily used with the active management approach. However, some may also be employed to a limited extent with the passive management approach. These strategies are briefly described here and discussed in detail by Docker and Johnson (2017).

Augmentation is a strategy whereby environmental water is used to augment water released from storages for downstream non-environmental (i.e., consumptive) uses. This is possible where non-environmental water delivery occurs at an environmentally beneficial time. The augmentation approach can be used for targeting both baseflows and freshes also known as pulses or events. In some cases, the CEWO negotiates with non-environmental water users or the water supply agency to modify the timing or magnitude of delivery of water for downstream consumptive use to improve beneficial environmental outcomes. In an extreme case, environmental water may not be required and an environmental flow component may be fully achieved by modifying the delivery of water for downstream consumptive use.

Coordination is a strategy whereby the CEWO coordinates water delivery with other environmental water holders to achieve synergies with their combined water delivery. Effective coordination must accommodate organisations of different legal forms, accountabilities and capabilities, including some non-government organisations (O'Donnell, 2013). As the largest environmental water holder in the basin with broadest spatial coverage, the CEWO has a particularly important role in ensuring effective coordination of environmental water delivery across agencies.

Piggy-backing is a strategy used in some valleys where the CEWO seeks to "piggy-back" environmental releases on unregulated flow pulses to achieve the greatest magnitude or duration of flow pulse with the minimum of environmental water. This strategy is only possible when: (1) releases can be timed to align with the unregulated flow pulse; and (2) the flood risks associated with any higher-than-expected unregulated flows are acceptable. In the Murray River, long travel times between the upstream dams and major tributary inputs make it difficult to use this strategy for short flow freshes but it is feasible to extend a multi-week unregulated fresh using environmental flows (Docker & Johnson, 2017).

Shepherding is a strategy where the CEWO increases the effectiveness of its environmental water holdings using the same "parcel" of water for multiple environmental purposes as it flows downstream (Docker & Johnson, 2017). However, passing environmental flows downstream to the river mouth can be challenging in the MDB. Importantly, many of the water entitlements held for the environment were acquired from irrigators and retain the same legal properties initially intended to support irrigation water use. Under these entitlements, water is considered unused if it is not extracted at the point of use as defined in the entitlement, and may be returned to the consumptive pool to be reallocated for other water users including irrigation (MDBA, 2014). The state of Victoria, which extends across all the valleys south of the Murray River, has enacted legal provisions to allow environmental water to be protected downstream to the basin outlet. In other jurisdictions, such shepherding of environmental water must be negotiated on a case-by-case basis and is not always possible (MDBA, 2017).

Assisted delivery is a strategy where the CEWO uses one or more of a variety of water supply infrastructure to assist with the delivery of environmental water including: adjusting river stage using weirs; redirecting water down anabranch and distributary channels using regulators; pumping water into riparian wetlands; and constructing levees to increase the volume of ponded water held in floodplain wetlands. These strategies are widely applied in the southern MDB using either existing irrigation infrastructure or installing new infrastructure specifically to enhance environmental flow outcomes (Bond et al., 2014). This approach is particularly important for delivering water out of channel when physical and policy constraints prevent the delivery of bankfull flow magnitudes using environmental flow releases.

3 | METHODS

3.1 | Scale of evaluation and environmental flow delivery

This article reports on basin-wide hydrological outcomes of environmental water delivery by the CEWO in the 2014–2015 water year (i.e., 1 July 2014 to 30 June 2015). We focus on this year because it is the first time the CEWO commissioned a basin-scale hydrological evaluation of its program.

To represent spatial variations across the MDB, the analysis of hydrological outcomes is organised into a set of 25 valleys (Figure 1). These valleys are the same as those defined for the Murray–Darling Basin Sustainable Rivers Audit (Davies, Stewardson, Hillman, Roberts, & Thoms, 2012) and based primarily on the catchments of major tributaries of the Murray and Darling Rivers. In addition, the Murray River is divided into five valleys: the Upper, Central and Lower Murray Valleys, a short valley at the river mouth which includes a system of lakes, and a set of anabranch channels called the Edward–Wakool valley. The Darling River is divided into the Lower Darling and the Darling–Barwon system. Out of a total of 27 valleys, this analysis focuses on the 16 valleys where environmental water was delivered by the CEWO in the 2014–2015 year. These valleys include most of the significant freshwater habitats that have been threatened by surface water withdrawals.

The CEWO maintains a record of all the environmental flow events that receive a contribution of commonwealth environmental water. These events are classified as either a *baseflow* event; a *fresh* event which is a flow pulse that remains well below the bankfull level; a *bankfull* event where flow approaches bankfull but remains

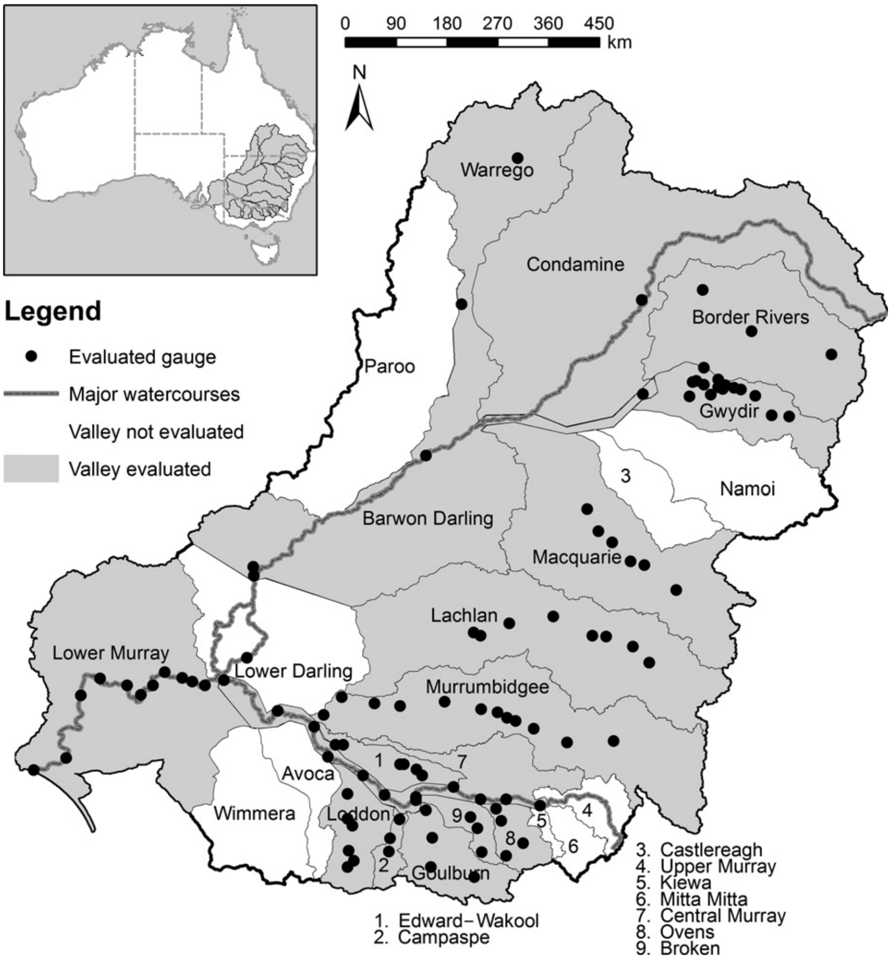

FIGURE 1 The Murray–Darling Basin showing the 16 valleys (of 25) where commonwealth environmental water was delivered to rivers, floodplains and wetlands during the 2014–2015 water year for the purpose of improving or restoring environmental assets and function (shown in grey)

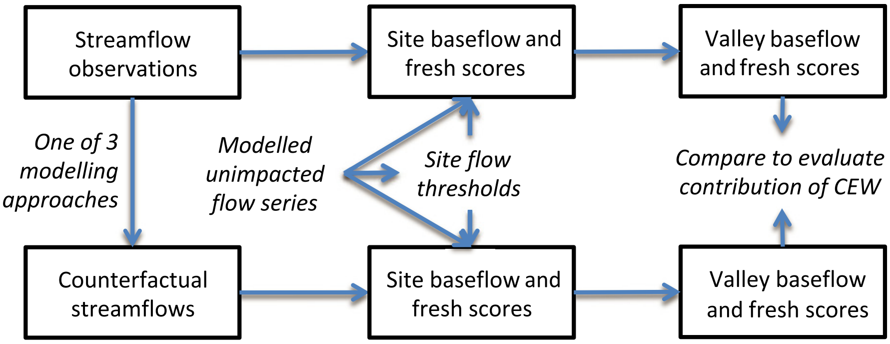

FIGURE 2 Workflow diagram for hydrological analysis used in this study [Colour figure can be viewed at wileyonlinelibrary.com]

in-channel; an *overbank* flow event where flow moves out of the main channel because magnitudes exceed channel capacity; or *wetland inundation* where water is diverted into floodplain wetlands using weirs, regulators, canals or pumps. Each individual event corresponds with an environmental water use decision approved by the CEWO, often in conjunction with other stakeholders. This record of environmental flow events provides a convenient basis for reporting environmental flow management across the MDB. A detailed account of the events in the 2014–2015 years including the timing and duration of each event is provided in Stewardson and Guarino (2016a). In addition, the CEWO maintains a record of its water entitlement volumes in each valley delivered through active (i.e., releases from storages) and passive (i.e., unregulated flows) management.

3.2 | Evaluating baseflows and freshes

The hydrological analysis made use of available data to report on the contribution of commonwealth environmental water to baseflows and freshes. The analysis was primarily based on streamflow records sourced for 109 unique streamflow gauging stations across the MDB for the 2014–2015 water year. Gauging stations were selected to represent locations where streamflows are affected by CEWO environmental water delivery. An uneven distribution of sites across valleys reflects restricted availability of reliable data in some valleys.

The analysis for the hydrological evaluation is shown as a workflow in Figure 2. The contribution of commonwealth environmental water to flow regimes is evaluated based on a comparison of observed streamflow conditions with a hypothetical *counterfactual* scenario where no environmental water was provided. Stewardson and Skinner (2018) demonstrate the usefulness of this counterfactual approach for inferring effects of environmental flows when before-after or control–impact comparisons are not possible. Three methods were used to model streamflows for this counterfactual scenario according to the modelling capability for each valley's river system. These methods are described in Table 1 along with their different limitations.

Direct comparisons of streamflow magnitudes between sites are made difficult by the relative size of the rivers and their catchments. To eliminate the dominant effect of river size, we assess contributions of the CEWO relative to five flow thresholds that scale with channel size (Figure 3). This allows meaningful comparisons to be made across the MDB. Two of the thresholds correspond to baseflows (referred to

TABLE 1 Three methods used to model streamflows for the counterfactual scenario

Method	Description	Limitations
Accounting model	This method tracks the known releases of environmental water from reservoirs, downstream along the river using simple mass balance with fixed travel times to estimate the contribution estimate active environmental water at downstream sites. The environmental flow is assumed to attenuate downstream with agreed loss rates for the valley used in water accounting.	No account for the additional water that would have been available for irrigation releases under the counterfactual case (i.e., the effect of the environmental water recovery program is included in the counterfactual scenario).
Modelling access-to-take trigger	This method is used where environmental water was sourced from stream flows delivered directly from the catchment (i.e., no reservoir). The volume is accounted in accordance with its licence condition, with delivery timed to commence when the access-to-take streamflow threshold is triggered. The environmental flow is assumed to attenuate downstream with agreed loss rates for the valley used in water accounting.	Assumption that irrigation diversion would have commenced as soon as the access-to-take threshold is triggered under the counterfactual scenario.
Water resource model	This method (which is only applied to Murray River sites) employed a rule-based water resource planning model MSM-BigMOD (Close, Mamalai, & Sharma, 2004) to simulate the scenario of water entitlements distributed as they would have been without the program of environmental water recovery for the CEWO.	Requires assumptions concerning operation of the water delivery under the counterfactual scenario that may not be realistic.

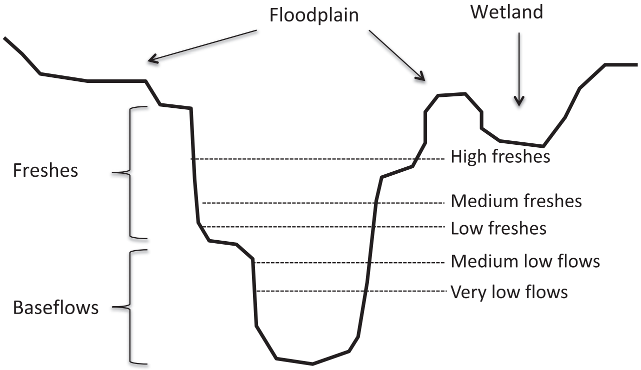

FIGURE 3 Indication of the water stage corresponding to the five flow thresholds used for comparing flow regimes across rivers

as very low and moderately low flow thresholds), and the analysis considered duration of flows below these baseflow thresholds. The other three flow thresholds correspond with flow freshes (referred to as low, medium and high fresh thresholds) and the analysis targeted frequency of flows exceeding these fresh thresholds. These five threshold discharges are defined in Table 2 along with the methods used for their estimation at the 109 study sites.

We calculated a flow regime "score" corresponding to each of the five flow thresholds for each site. The purpose of this score is to provide a simple metric that captured most of the complex hydrological information, but was sufficiently descriptive to report on environmental flow outcomes across the Basin at an annual timescale. This score is a measure of hydrological conditions ranging from 0, very poor conditions, to 1, desirable conditions. The score indicates the "dryness" of the flow regime in 2014–2015, focussing in the flow regime components that may be targeted by environmental flows. Importantly, the evaluation of hydrological outcomes is based on a comparison of the observed and counterfactual scenarios. The target environmental flow condition is not necessarily a perfect score of 1.

TABLE 2 Flow thresholds used for analysis of baseflows and freshes

Flow threshold	Definition	Physical Interpretation	Method of calculation
Very low flow	Flows that fall below the lowest flow in the unimpacted monthly flow series or 2% of mean unimpacted flow, whichever is greater	Exceptionally low flow at the lower end of range that would normally occur in an unimpacted perennial river	The baseflows are estimated based on low flow percentiles in an unimpacted flow series. For this we used a multi-year flow series of monthly flow volumes derived using a model for the scenario of no water resource development (MDBA, 2012). In ephemeral rivers, these low flow percentiles could be zero. For this reason we set a lower limit on each of the baseflow thresholds based on a proportion of the mean unimpacted flow.
Moderately low flow	Flows that fall below the 95th percentile exceedance flow in the unimpacted monthly flow series or 10% of the mean unimpacted flow, whichever is greater	Typical flow used as a minimum flow to maintain low flow habitats	
Low fresh	Flow spells that raise water levels at least one-eighth of the height of the bank above the medium-low flow level	A slight increase in stage above baseflow levels and would be a frequent occurrence in both the dry and wet seasons under unimpacted flow conditions	The fresh thresholds were scaled relative to bankfull discharge estimated as the greater of either: (1) the 5th percentile exceedance in the monthly unimpacted flow (×1.5 as a rough estimate of peak daily flow based on the mean monthly value) (De Rose, Stewardson, & Harman, 2008); and (2) an empirical model derived from data across south-eastern Australia (M15 in Stewardson, Derose, & Harman, 2005) using reach-mean bankfull dimensions previously estimated at nearby sites from airborne LiDAR surveys across the basin (Davies et al., 2012). The estimates of discharge corresponding to the low, median and high freshwater levels (defined above) were based on widely accepted at-a-station hydraulic geometry equations where depth varies with discharge raised to an exponent (Knighton, 1975). In this case we used a discharge exponent value 0.28, which is typical for south-eastern Australia (Stewardson, 2005).[a]
Medium fresh	Flow spells that raise water levels at least one-quarter of the height of the bank above the medium-low flow level	An increase in stage that wets the lower part of the bank and would be a frequent occurrence in an unimpacted regime maintaining moist soils, and is an important component of a variable watering regime for this portion of the channel throughout the year	
High fresh	Flow spells that raise water levels at least half of the height of the bank above the medium-low flow level	Freshes of this magnitude would have occurred in most years in the unimpacted flow regime, and it would be common for freshes to exceed this threshold several times per year	

[a] This method will work best in river channels unmodified by river engineering including weirs. We argue that in engineered channels, such as the Murray River with many weirs, these estimates still provide useful flow thresholds for comparing hydrological outcomes across rivers throughout the Basin, but care is needed with physical interpretation of these flow thresholds.

3.3 | Analysis and calculation of baseflow and freshes

Different analysis methods were applied for calculating scores corresponding to the five thresholds. For the baseflows, the maximum score (of “1”) indicates that the seasonal duration of flows below the baseflow thresholds does not exceed seasonal durations that would have occurred in an average year when the river was not impacted (i.e., prior to water resources development). For this, we use a multi-year unimpacted monthly flow series modelled for the scenario of no water resource development in the basin (MDBA, 2012). Using the two baseflow thresholds allows us to characterise the “dryness” of the full baseflow range. However, for the purposes of reporting a single summary metric, we averaged the two baseflow scores corresponding to the very low and moderately low flow thresholds to calculate a single baseflow score for each site and flow series.

For the freshes, the score relates to the occurrence of freshes. The maximum score (of “1”) was assigned for the low, medium and high fresh scores if a fresh occurred in three, two and one of the calendar seasons, respectively. We did not attempt to adjust these scores based on a comparison with the unimpacted flow regime because the available unimpacted monthly flow series did not provide an adequate estimate of unimpacted fresh frequencies. The three thresholds allow us to evaluate the range of flow freshes relevant to environmental water delivery. However, as with the baseflows, the scores for the three fresh thresholds are combined into a single flow fresh score for the site. In this step, the component scores are weighted according to the ratio 50:30:20 (low: medium: high). Lower freshes are given more weight because they are more often the target of environmental flow recommendations in the MDB. The scores for each site within a valley are averaged to provide a valley baseflow and fresh score. Results are averaged across thresholds and sites to provide a few metrics for clarity of reporting at the basin-scale, but the analysis of multiple thresholds and sites is important to ensuring the summary metrics respond to changes in different aspects of the flow regime and different locations within each valley.

As discussed above, commonwealth environmental water delivery is often coordinated with other environmental water holders to achieve a combined outcome. In such cases, it makes little sense to consider the contribution of the commonwealth environmental water in isolation. For consistency, we have evaluated the aggregate hydrological outcome of all environmental water. To identify the contribution of the commonwealth environmental water, we have developed a simple procedure for sharing any increase in the flow regime scores provided by the combined environmental water delivery as follows.

1. Calculate the total improvement in score (relative to the counterfactual) with all environmental water provided over the water year.
2. Calculate the improvement that would have been achieved if commonwealth environmental water was delivered on its own.
3. Calculate the improvement if the non-commonwealth environmental water had been delivered on its own.
4. Apportion the total improvement (from 1 above) based on the ratio of improvements achieved in 2 and 3 above.

3.4 | Mapping floodplain inundation extents

For this study, a map of maximum inundation extents was compiled by combining data from several different sources. The highest quality data were inundation extents mapped using Landsat satellite imagery using an inundation detection algorithms developed specifically for the MDB wetlands (Thomas et al., 2015). These data were of a high quality but their coverage was limited to the larger wetland systems in New South Wales. Some additional inundation mapping was possible using reports from visual surveys, aerial photography and hydrodynamic modelling (Tuteja & Shaikh, 2009). A national water mapping product (Mueller et al., 2016) was used to fill the remaining data gaps. This national product allowed a comprehensive basin-wide assessment but had some known limitations in its ability to detect inundation where it was obscured by emergent vegetation. Available observations of inundation were accumulated to provide an inundation extent for the full year.

4 | RESULTS

In the 2014–2015 water year, the annual rainfall across the MDB was 412 mm, 88% of the long-term average (BoM, n.d.). The ten valleys in the north of the basin where commonwealth environmental water delivery occurred all experienced average rainfall conditions (Central Murray, Condamine, Upper Darling, Gwydir, Lachlan, Lower Murray, Macquarie, Murrumbidgee and Warrego Rivers and Border River Valleys), while six valleys in the southern basin experienced below average rainfall conditions (Broken, Ovens and Edward–Wakool, Campaspe, Loddon and Goulburn Valleys) (Stewardson & Guarino, 2016b). Rainfall in the later three valleys was very much below average including one region that experienced the lowest rainfall on record.

In 2014–2015, the CEWO delivered 1,014 Gl, which is only 62% of its average annual water allocation of 1,600 Gl (Stewardson & Guarino, 2016b). A total of 1,637 Gl was delivered by all environmental water holders across the basin including the CEWO (BoM, n.d.). This environmental water is only 8% of the total 20,756 Gl inflow to the basin’s rivers that year (BoM, n.d.). In contrast, 35% of inflows were diverted for human consumptive purposes (mostly irrigation) (BoM, n.d.). Only 6% of inflows reached the basin outlet in 2014–2015 (BoM, n.d.). The remaining 59% of inflows (including some environmental water) is lost from reservoirs, rivers and floodplains by evapotranspiration. While our focus in this article is on the contribution of CEWO environmental water delivery, other hydrological fluxes can contribute substantial environmental benefits including irrigation water delivery where it

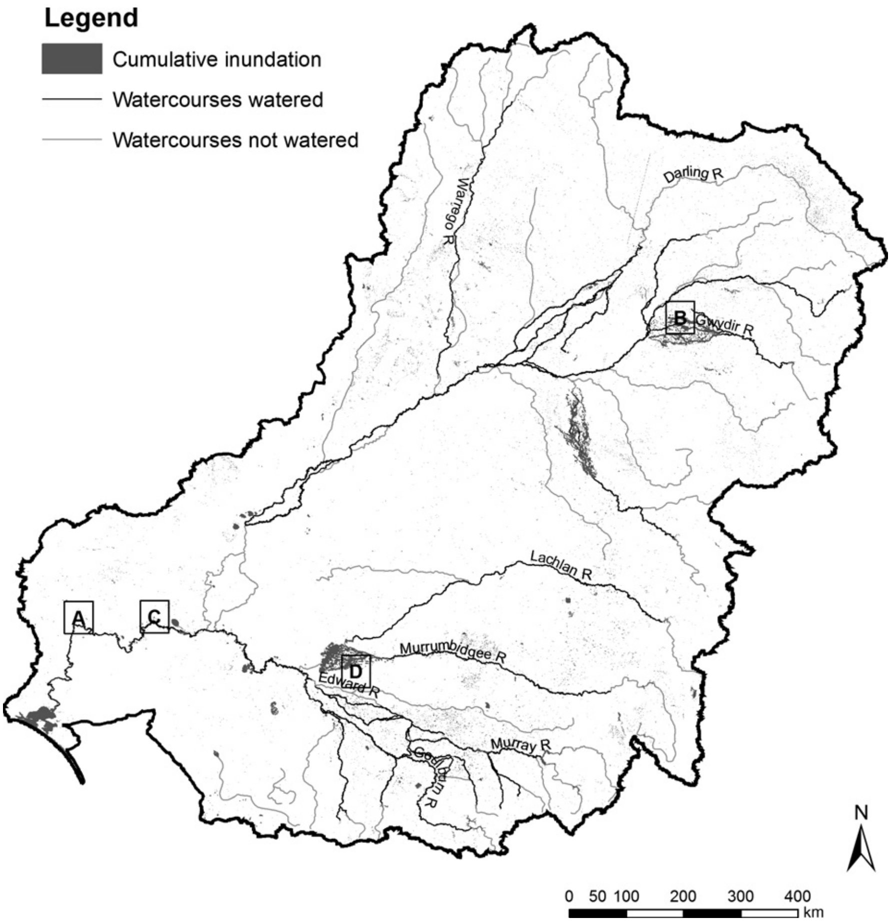

FIGURE 4 Rivers watered (thick grey lines) that received environmental water, including from the CEWO, and areas where active environmental made a contribution to inundation in the Basin during the 2014–2015 water year. Locations A to D indicate examples of different wetland inundation strategies (Figure 7)

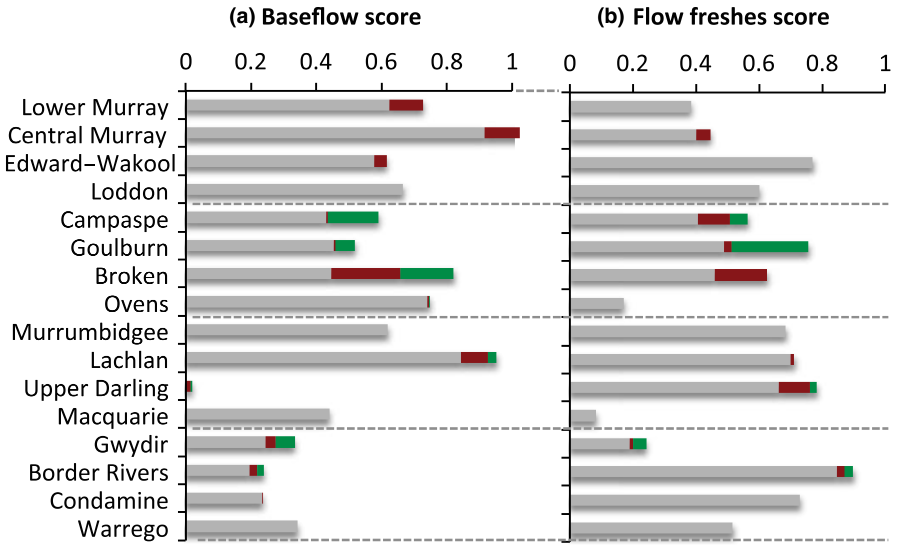

FIGURE 5 Average baseflow and fresh scores for the 16 valleys across the Murray–Darling Basin that received water from the CEWO in the 2014–2015 year. Contributions of CEWO and other environmental water holders to these scores are shown in brown and green, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

coincides with environmental demands and evapotranspiration by native vegetation.

Many of the basin's major rivers received water provided by the CEWO, and there was some minor wetland and floodplain inundation achieved using environmental water (Figure 4). Figure 5 reports on the hydrological outcomes achieved by the CEWO in each valley. To achieve the reported outcomes in 2014–2015, the CEWO undertook 85 watering actions across 16 river valleys over the course of the year. These actions included 13 baseflow events, 25 fresh events, two bankfull events, 42 wetland inundation events and two actions that combined either baseflows and freshes or baseflow and wetland inundation (Table 3).

The CEWO applied each of the five delivery strategies outlined above across multiple valleys in the MDB. The CEWO used: coordination in nine valleys; augmentation in seven valleys, piggy-backing in six valleys; shepherding in eight valleys; and assisted delivery in

TABLE 3 Summary of events achieved by the CEWO in each valley

Valley	Volume of water delivered (Ml)	Baseflow	Fresh	Bankfull	Wetland inundation	Baseflow and fresh
Gwydir	56,639		2		2	
Murrumbidgee	152,560				8	
Lower Murray	592,723	2	1		21	
Central Murray	59,726		1		9	
Border Rivers	3,229		6	2		
Condamine	17,392		2			
Upper Darling	1,761		3			
Warrego	2,542		3			
Lachlan	5,000		1			
Macquarie	10,000				1	
Loddon	2,879		1			
Broken	32,879	3			1[a]	
Goulburn	225,884	4	4		1	
Edward–Wakool	39,562	3[b]				2[c]
Ovens	70	2				
Campaspe	5,791		1			
Total		14	24	2	42	3

[a] This action delivered water for a baseflow in the upper Broken which was then reused for inundating a wetland in the lower Broken.

[b] One of the baseflow actions in the Edward–Wakool Valley augmented a recession for a flow pulse.

[c] These two combined actions in the Edward–Wakool Valley delivered both a baseflow and a fresh.

six valleys (Table 4). There was considerable variation in the contribution of environmental water delivered in each valley (Table 4). In the three valleys where none of the environmental water entitlement can be actively managed (Condamine–Balonne, Barwon–Darling and Warrego), there was little or no improvement in baseflow or fresh scores attributed to the commonwealth environmental water delivery. Commonwealth environmental water delivery achieved the greatest improvements in baseflow score in the Broken, Lower Murray and Central Murray Rivers. In all three of these valleys, the CEWO applied four of the five delivery strategies to improve benefits achieved with the environmental water, and commonwealth environmental water was a relatively large portion of the total actual flow for the year. The greatest improvements in fresh score were achieved in the Campaspe and Broken Rivers both of which included the use of the coordination and augmentation strategies to enhance the magnitude of freshes achieved with commonwealth environmental water.

Commonwealth environmental water contributed to maintaining minimum flows in the Loddon, Campaspe and Goulburn Rivers in northern Victoria, and the Murrumbidgee and Macquarie Rivers in NSW (Figure 5a). It also contributed to enhanced minimum flows in the Lower Murray River, including into the Lower Lakes upstream of the river mouth. The flow fresh regime was enhanced by environmental watering actions in the Lower Murray, Loddon, Campaspe, Goulburn, Lachlan, Macquarie and Gwydir River valleys (Figure 5b). The Commonwealth made a significant contribution in all cases except in the Campaspe River where the Victorian Environmental Water Holder provided most of the environmental water. Medium and high freshes were generally rare across the MDB with environmental flows contributing in the Loddon, Campaspe, Murrumbidgee, Lachlan and Macquarie valleys. Commonwealth environmental water was an important contributor to freshes in all these valleys.

Examples of the specific contributions of environmental flows for individual sites are provided in the Goulburn (Figure 6), Gwydir (Figure 7) and Border Rivers (Figure 8) Valleys. The Goulburn and Gwydir Rivers are examples where commonwealth environmental water is delivered from storages (lake Eildon and Copeton Dam, respectively), allowing active management of environmental water releases to target specific components of the flow regime. The key difference between these two valleys is that the Goulburn is a single channel river for its full length and environmental water is largely targeted within this channel. There is little opportunity to deliver water out of the channel because of practical constraints on river operations. However, environmental flows significantly improved the baseflow regimes with greatest enhancement at McCoy's, the site furthest downstream, producing a baseflow regime that was close to the unimpacted condition. CEWO releases were critical for maintaining low freshes. However, there were no medium or high freshes at any of these sites in the Goulburn Valley. Without environmental releases there would have been just one brief low fresh around July

TABLE 4 Contribution of commonwealth environmental water delivery to flows in each of the MDB valleys, proportion of this water that is actively managed, strategies used by CEWO in water delivery, and consequent improvement in baseflow and fresh scores attributed to commonwealth environmental water

		Increase in . . .			Commonwealth environmental water delivered in 2014–2015[c] as a proportion (%) of . . .	
Valley	Proportion of environmental water entitlement that is actively managed (%)[a]	Baseflow score	Fresh score	Environmental water delivery strategies used in 2014–2015[b]	Total annual actual flow 2014–2015	Natural mean annual flow
Gwydir	82	0.03	0.01	1, 2, 3 and 5	19	5.70
Murrumbidgee	38	0.00	0.00	2 and 5	8	3.64
Central Murray	100	0.11	0.05	1, 2, 3, 4 and 5	13	5.40
Lower Murray	100	0.10	0.00	1, 2, 3, 4 and 5	21	4.40
Lachlan	100	0.08	0.01	3	1	0.35
Macquarie	94	0.00	0.00	2	4.8	0.30
Loddon	100	0.00	0.00	2 and 4	10.4	1.10
Goulburn	100	0.00	0.03	1, 2 and 4	12.2	7.40
Ovens	100	0.00	0.00	1	0.01	0.00
Broken	100	0.21	0.17	1, 2, 4 and 5	38	1.09
Campaspe	100	0.01	0.10	1, 2 and 4	8.2	2.70
Border Rivers[d]	51	0.02	0.03	3	1.2	0.73
Condamine-Balonne	0	0.00	0.00	3	8.2	3.05
Barwon–Darling	0	0.01	0.01	3	0.8	0.19
Warrego	0	0.00	0.00	3 and 5	2.6	3.66

[a] Note this is based on entitlements and may differ from actual environmental water allocations and use in the 2014–2015 year.

[b] Numbers 1–5 in this column refer to the five strategies as follows: augmentation (1), coordination (2), piggy-backing (3), shepherding (4) and assisted delivery (5).

[c] The annual volumes of commonwealth environmental water, actual flow and natural mean annual flow apply at a point in each valley upstream of major irrigation diversions and downstream of major tributary inflows.

[d] Includes Moonie & Nebine Rivers.

2014 (early in the water year). Commonwealth environmental water provided two additional low freshes in spring and a third near the end of the year.

In contrast to the Goulburn River, the lower Gwydir River (downstream of Pallmallawa) is a distributary river system feeding numerous wetlands including the Ramsar listed Gwydir Wetlands located along the lower Gwydir River and Gingham Watercourse (Figure 7). In the Gwydir Valley, the CEWO contributed to four environmental flow events spread over 308 days between September 2014 and March 2015, targeting the distributary river system in the river's lower reaches (Figure 7). Regulating structures downstream of Pallmallawa diverted flows from the Gwydir River into Mehi River, Carole Creek, Lower Gwydir River and Gingham Watercourse (Figure 7). At Millewa on Gwydir River, environmental water contributed 72% of the total streamflow which produced some limited wetland inundation along the lower Gwydir River with a similar result in the Gingham Watercourse.

Environmental flows in the Border Rivers were supplied by natural river flows sourced directly from catchment run-off with little or no reservoir storage. These largely unregulated rivers are typical of the valleys in the northern MDB, and represent 35% of the Basin area in total. Nine environmental flow events were provided in the Border Rivers Valley in the 2014–2015 year but with little apparent effect on the valley's flow regime scores.

In the 2014–2015 water year, floodplain inundation was achieved in the Border Rivers, Condamine–Balonne, Warrego, Gwydir, Macquarie, Murrumbidgee, Lachlan, Broken and Lower Murray valleys (Figure 4). Four different methods were used to deliver environmental water for these events. In the mid-Murrumbidgee and Murray Rivers, water was pumped from the main channel to fill wetlands (Figure 9a). In the lower reaches of the Gwydir and Macquarie Rivers overbank flooding was achieved by delivering environmental water into the distributary river system where channel capacities reduce and water spills onto floodplains at relatively low discharges (Figure 9b). In the Murray River, main channel weirs were raised producing an elevated backwater pool that inundated low-lying floodplain habitats including anabranch channels (Figure 9c). In the lower Murrumbidgee River, regulating structures on the main channel were used to divert water into irrigation canals, which can be operated to create a spill into floodplain wetlands (Figure 9d).

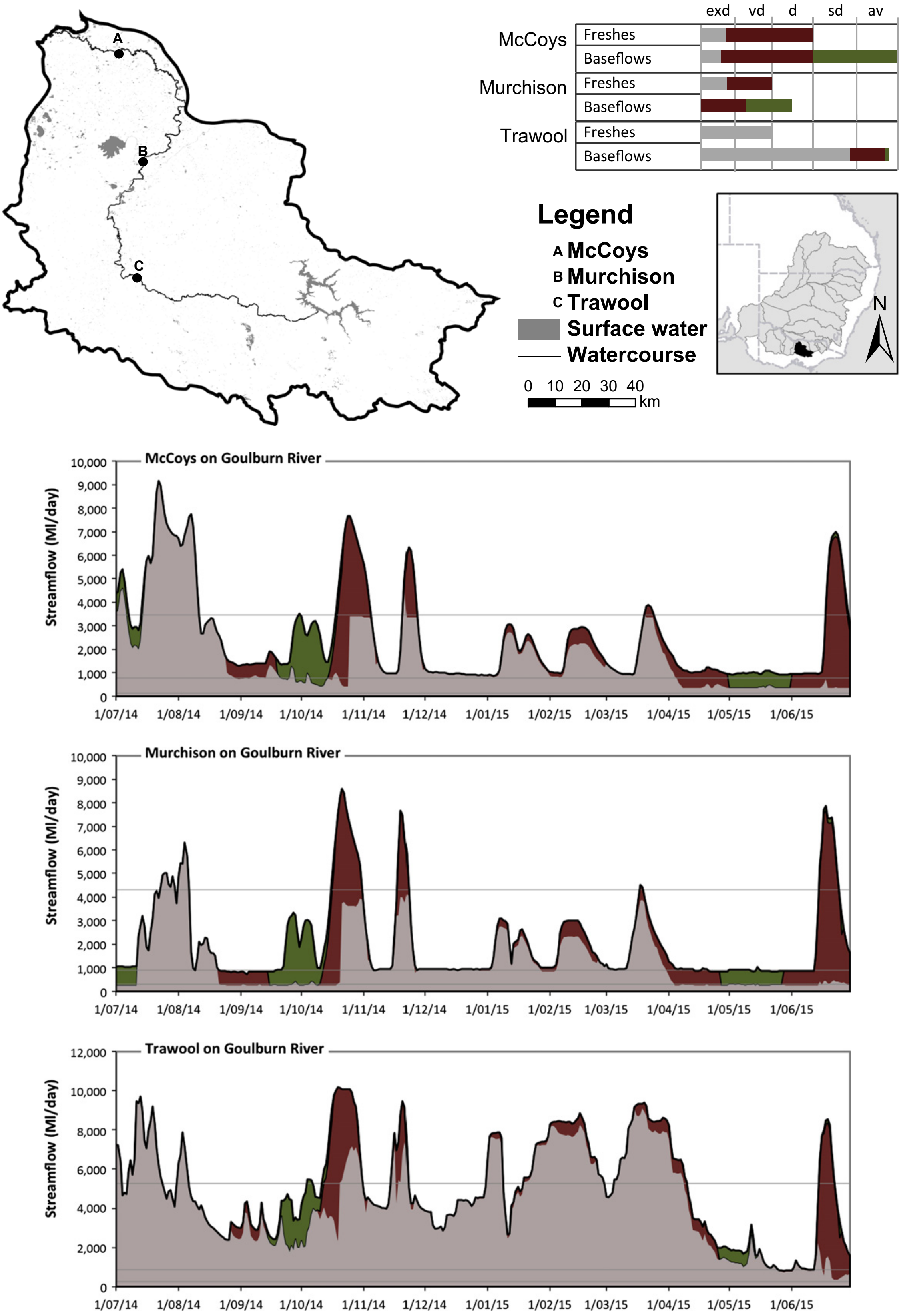

FIGURE 6 Map shows watercourses in the Goulburn valley watered with active environmental water and areas out of the main channel where inundation was detected during the 2014–2015 water year. The contribution of commonwealth environmental water is shown for three sites: (a) McCoys; (b) Murchison; and (c) Trawool. For each of these sites, the bar chart shows scores and the hydrograph shows actual flows recorded at these sites. In these bar charts and hydrographs, the contribution of the commonwealth is shown in brown and the contribution of water delivered by other environmental water holders is shown in green. Letters on the bar charts refer to the dryness score achieved at each site (exd) extremely dry; (vd) very dry; (d) dry; (sd) somewhat dry; and (av) average [Colour figure can be viewed at wileyonlinelibrary.com]

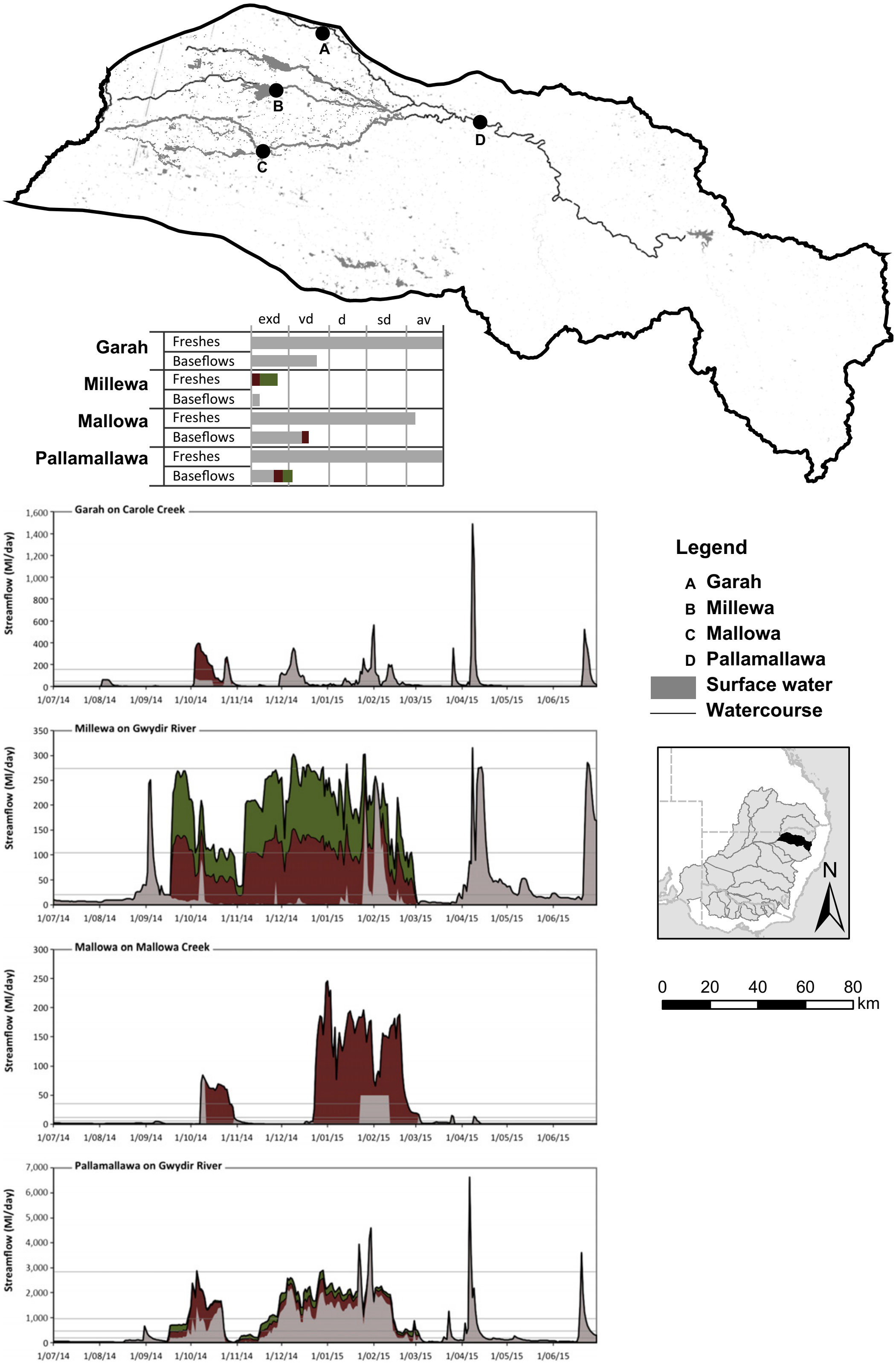

FIGURE 7 Map shows watercourses in the Gwydir valley watered with active environmental water and areas out of the main channel where inundation was detected during the 2014–2015 water year. The contribution of commonwealth environmental water is shown for four sites: (a) Garah; (b) Millewa; (c) Mallowa; and (d) Pallamallawa. For each of these sites, the bar chart shows scores and the hydrograph shows actual flows recorded at these sites. In these bar charts and hydrographs, the contribution of the commonwealth water is shown in brown and the contribution of water delivered by other environmental water holders is shown in green. Letters on the bar charts refer to the dryness score achieved at each site (exd) extremely dry; (vd) very dry; (d) dry; (sd) somewhat dry and (av) average [Colour figure can be viewed at wileyonlinelibrary.com]

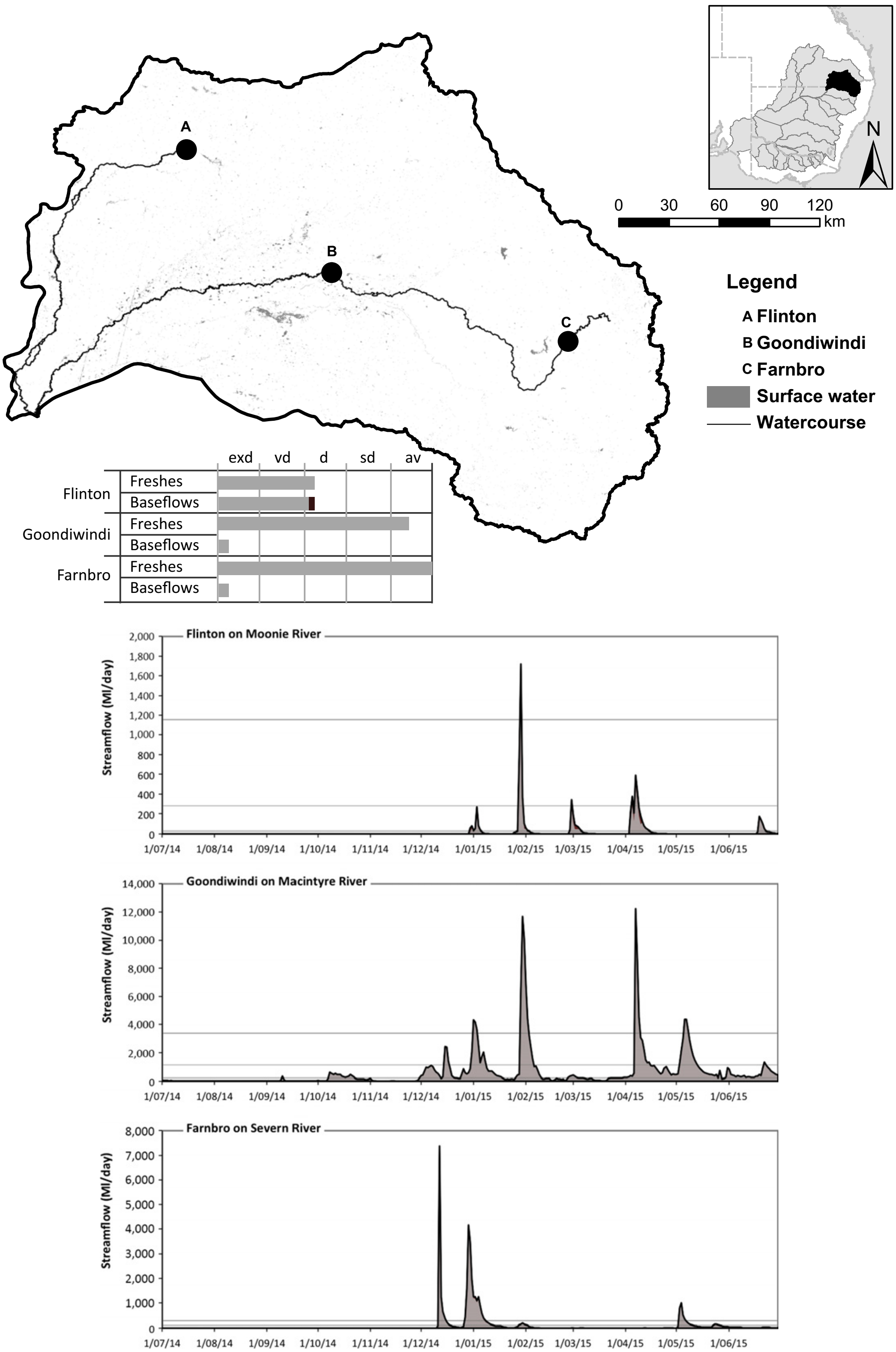

FIGURE 8 Map shows watercourses in the Border Rivers valley watered with active environmental water and areas out of the main channel where inundation was detected during the 2014–2015 water year. The contribution of commonwealth environmental water is shown for three sites: (a) Flinton; (b) Goondiwindi; and (c) Farnbro. For each of these sites, the bar chart shows scores and the hydrograph shows the actual flows recorded at these sites. In these bar charts and hydrographs, the contribution of the commonwealth water is shown in brown and the contribution of water delivered by other environmental water holders is shown in green. Letters on the bar charts refer to the dryness score achieved at each site (exd) extremely dry; (vd) very dry; (d) dry; (sd) somewhat dry; and (av) average [Colour figure can be viewed at wileyonlinelibrary.com]

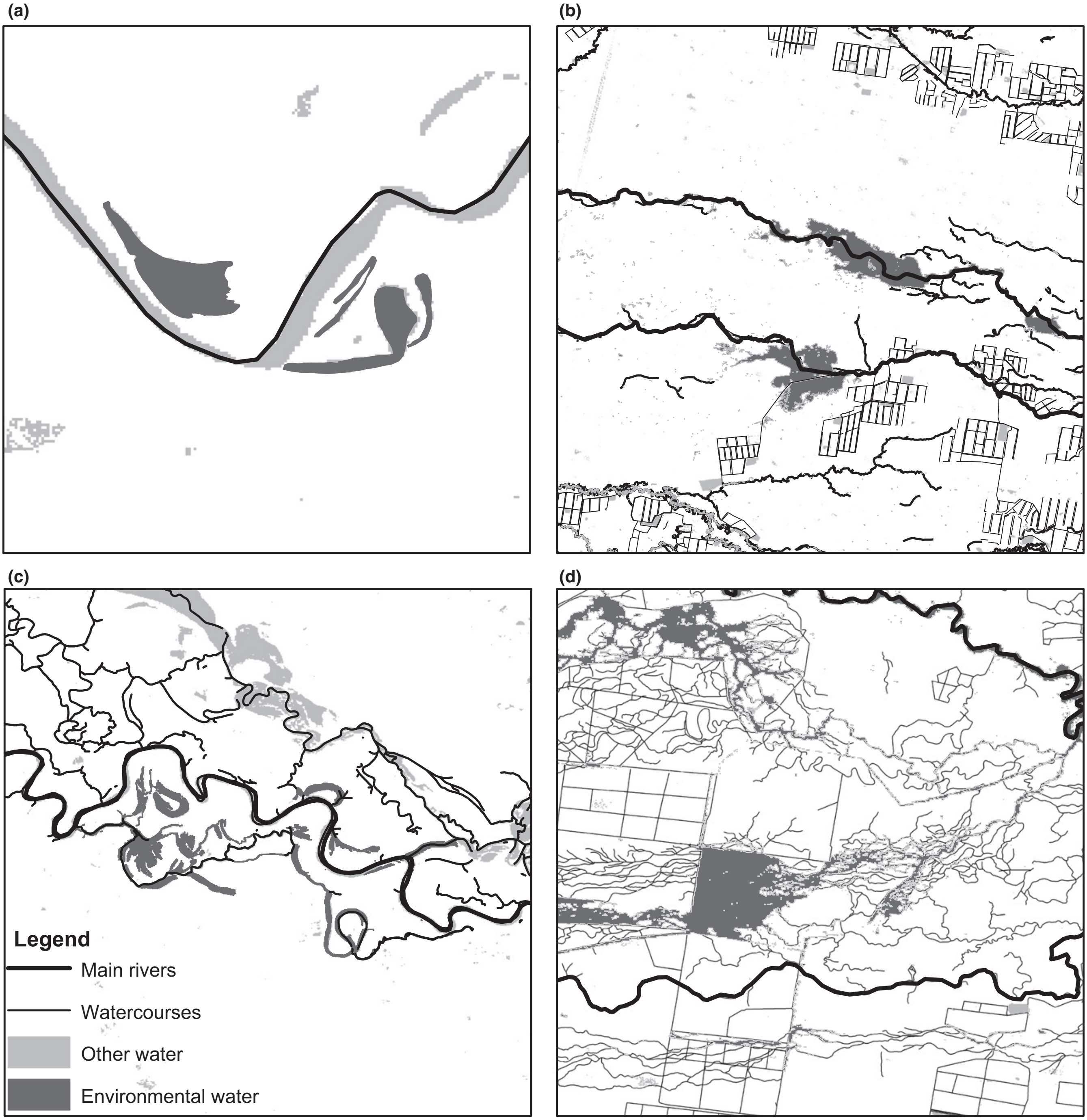

FIGURE 9 Examples of four approaches used to achieve out-of-channel watering using environmental entitlements: (a) pumping water into wetlands is used where overbank flows are impractical or unachievable; (b) overbank flow can be possible particularly where river channel capacity reduces in distributary river systems spilling water onto floodplains at relatively low discharges; (c) raising weir pools can lead to inundation of low-lying floodplain habitats; and (d) channel regulators and irrigation canals and can be used to direct water into floodplain wetlands. Locations of these four sites are showing on Figure 2

5 | DISCUSSION

In 2014–2015, the volume of environmental water delivered in the Murray–Darling Basin was equal to 8% of the total inflows to the river network with commonwealth environmental water making up close to two-thirds of this. By global standards, this represents a very small environmental water provision. In a global analysis, Smakhtin, Revenga, and Döll (2004) estimated that between 20% and 50% of the mean basin run-off is needed to meet environmental water requirements. Despite the small volume of water, the CEWO managed to improve baseflows and freshes across several valleys in the MDB, and also achieved targeted delivery of water into wetlands. In parallel studies, small volumes of environmental water have been associated with ecological responses across the basin. For example, in the

Goulburn River, spring flows contributed to golden perch spawning and movement (Webb et al., 2015). The same flows also helped maintain and improve the abundance and diversity of plants in the riparian zone (Webb et al., 2015). The delivery strategies are discussed here along with identifying some limitations and future challenges.

Richter (2010) included poorly coordinated management of water resources in a list of the six major obstacles to environmental flow management. This obstacle seems to have been overcome to some extent in the MDB with coordination of environmental water contributing to environmental flow outcomes in nine of the 16 MDB valleys considered in this study. The cross-jurisdictional coordination appears to have been particularly effective in the Goulburn, Campaspe and Broken Valleys in the state of Victoria (Figure 3). In these valleys, there were complementary improvements in flow regimes achieved from water delivered by CEWO and the Victorian Environmental Water Holder, and many watering actions included water from both jurisdictions. For example, at McCoys in the Goulburn River, baseflows are maintained by these two agencies in collaboration (Figure 4c).

Augmentation of non-environmental water was also a widespread strategy for enhancing environmental benefits in the MDB including some adjustment of irrigation release schedules to improve co-benefits for the environment. A good example of this is the sequence of three environmental flow pulses delivered in the lower Goulburn River (Murchison and McCoys) between January and March in 2015 (Figure 6). These pulses were almost entirely provided by irrigation water being delivered from the Goulburn River to irrigators further downstream in the Murray River. Environmental water managers negotiated for this transfer of irrigation water to include these three flow pulses. The environmental objective of these environmental flows was to avoid bank erosion likely to be produced if the transfers were delivered at a constant streamflow. This example demonstrates the complexity of isolating ecological effects of environmental water management, when environmental water is delivered to complement non-environmental water delivery that also contributes to the targeted environmental outcomes.

In five valleys of the northern MDB, environmental water was shepherded downstream to achieve environmental targets at more than one site within the same valley. However, water could not be reliably shepherded further downstream from these valleys to achieve environmental targets in the mainstem Barwon–Darling River (Figure 1). The difficulty is that water licences purchased in the northern basin tributaries specify that any unused water passing into the Barwon–Darling may be diverted for consumptive use (MDBA, 2017). State governments in the northern basin are working towards protection of environmental water downstream through the basin to the river mouth. In contrast, the State of Victoria has made provision for protecting environmental water delivered from the basin's southern tributaries into the mainstem Murray River and hence benefitting the Central and Lower Murray River as well as well the Lower Lakes upstream of the river mouth. The lack of such a provision in the northern basin is a serious shortcoming of current environmental water management arrangements that inhibits longitudinal hydrological connectivity through the Barwon–Darling and possibly the lower Darling River valleys.

One of the major constraints on effective use of environmental water in the MDB is the upper streamflow limit imposed on active management of environmental water in many rivers. In particular, this inhibits piggy-backing on natural high-flow events. Any risk of enhancing flood risk is normally judged to be unacceptable, preventing the application of this strategy to top-up unregulated tributary inflows in many cases. However, the MDB sustainable diversion limit was calculated based on the environmental water demands of large floodplain wetlands distributed across the MDB (Swirepik et al., 2016), and many of these demands require sustained high flows in excess of the imposed flow constraints. Achieving many of these environmental flow targets using environmental water will require some reform of current operational rules that constrain delivery of environmental flows (MDBA, 2013). With many riparian landowners concerned about the potential for increased flood risk or other impacts of elevated in-channel flows, removing constraints that have been in place for many decades is problematic. The Murray-Darling Basin Authority is continuing to work with impacted jurisdictions to investigate possible changes to flow height constraints in rivers so that water can get to where it is needed most, while minimising third party impacts.

The results for 2014–2015 demonstrate the success of assisted delivery strategies used by the CEWO to deliver environmental water to wetlands and other floodplain habitats. In many cases, existing irrigation supply infrastructure was repurposed to water floodplain wetlands using significantly less water than would be required to achieve an overbank flood. The use of regulators, weirs and pumps to deliver water onto floodplain habitats has proven effective in watering a restricted set of wetlands in a relatively dry year. There are concerns that this assisted delivery approach fails to support the full range of flood-dependent ecological processes required to sustain healthy river–floodplain systems (Bond et al., 2014). However, it would have been impossible to deliver water to these wetlands by increasing streamflows to bankfull levels in most cases because of limited release capacities, limited environmental water availability, and constraints on managing rivers to deliver high in-channel flows.

The call to develop environmental water programs at the basin-scale (Poff & Matthews, 2013) responds to the notion that a basin-scale approach is required to consider critical ecological processes that operate at this scale (McCluney et al., 2014). There is little evidence yet in the MDB that the CEWO's basin-scale environmental watering actions have successfully targeted such basin-scale processes. However, the program is still in its early stages of delivery, and even earlier stages of monitoring and evaluation. Planning largely focuses on within-valley considerations. Furthermore much, if not all, of the environmental water delivered within many of the valleys, particularly in the northern basin, does not make it to the mainstem river either because of high rates of hydrological loss in the low-gradient distributary river systems or because there is no legal protection for environmental water once it passes out of the valley. In these valleys, there is little possibility environmental flows will promote connectivity through the basin's river network.

The CEWO provides a successful example of implementing a basin-scale program of environmental water delivery. However, there is still much work needed to improve the knowledge, governance and planning tools to manage environmental water so that it effectively, efficiently and appropriately meets ecosystem demands that operate at the basin-scale. Further work should complement this study of hydrological outcomes to basin-scale environmental flows focusing on a broad range of ecological responses at the basin-scale. Fortunately, ecological responses are also being monitored in the MDB but these studies are in their early stages and comprehensive reporting of basin-scale outcomes is not yet possible. However, early reporting at site and area scales is showing early signs of positive ecological responses (e.g., Webb et al., 2015). Hopefully, such basin-scale case studies might eventually provide a solid evidentiary foundation for generalising basin-scale responses to environmental flows.

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ORCID

Michael J. Stewardson http://orcid.org/0000-0003-1356-0472

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