

ESTABLISHING ENVIRONMENTAL WATER REQUIREMENTS FOR THE MURRAY–
DARLING BASIN, AUSTRALIA'S LARGEST DEVELOPED RIVER SYSTEMJ. L. SWIREPIK^a, I. C. BURNS^b, F. J. DYER^c, I. A. NEAVE^a, M. G. O'BRIEN^{a*}, G. M. PRYDE^a AND R. M. THOMPSON^c^a Murray–Darling Basin Authority, Canberra, ACT, Australia^b The Murray–Darling Freshwater Research Centre, Wodonga, Victoria, Australia^c Institute for Applied Ecology, University of Canberra, Bruce, ACT, Australia

ABSTRACT

There is a global need for management of river flows to be informed by science to protect and restore biodiversity and ecological function while maintaining water supply for human needs. However, a lack of data at large scales presents a substantial challenge to developing a scientifically robust approach to flow management that can be applied at a basin and valley scale. In most large systems, only a small number of aquatic ecosystems have been well enough studied to reliably describe their environmental water requirements. The umbrella environmental asset (UEA) approach uses environmental water requirements developed for information-rich areas to represent the water requirements of a broader river reach or valley. We illustrate this approach in the Murray–Darling Basin (MDB) in eastern Australia, which was recently subject to a substantial revision of water management arrangements. The MDB is more than 1 million km² with 18 main river valleys and many thousands of aquatic ecosystems. Detailed eco-hydrologic assessments of environmental water requirements that focused on the overbank, bankfull and fresh components of the flow regime were undertaken at a total of 24 UEA sites across the MDB. Flow needs (e.g. flow magnitude, duration, frequency and timing) were established for each UEA to meet the needs of key ecosystem components (e.g. vegetation, birds and fish). Those flow needs were then combined with other analyses to determine sustainable diversion limits across the basin. The UEA approach to identifying environmental water requirements is a robust, science-based and fit-for-purpose approach to determining water requirements for large river basins in the absence of complete ecological knowledge. © 2015 The Authors. *River Research and Applications* published by John Wiley & Sons, Ltd.

KEY WORDS: environmental flows; flow management; hydrology; flow restoration; environmental water requirements; umbrella environmental asset; Murray–Darling Basin

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INTRODUCTION

Increasing global population is placing an ever greater demand on global freshwater resources due to the combined effects of abstraction and pollution, driven by demands for potable water and irrigation (Vörösmarty *et al.*, 2000). It is estimated that 80% of the world's population is currently at threat from poor water security and that the majority of the globe's freshwaters are now heavily impacted by human activities (Vörösmarty *et al.*, 2010). River systems affected by abstraction exhibit modification of flow regimes in terms of total volumes and timing of flows, with consequences for hydrologic function, biodiversity values, ecosystem services and recreational uses (Poff *et al.*, 1997). Over-allocation of water resources affects the majority of river systems worldwide (Vörösmarty *et al.*, 2010), and there is currently a socio-political imperative to adjust water allocations to restore a range of different values (Castella *et al.*, 1995;

Arthington *et al.*, 2006; Acreman and Ferguson, 2010) including biodiversity, ecosystem services, recreational activities and cultural and spiritual values. Determining the hydrologic regime required to support these values across large river basins is a significant challenge for water managers worldwide.

Australia is the world's driest inhabited continent, characterized by extreme temporal and spatial variation in rainfall (McMahon and Finlayson, 2003). The Murray–Darling Basin (MDB) in south-eastern Australia comprises the catchment areas of the Murray and Darling rivers and their many tributaries. The MDB is more than 1 million km² in area, covering five states/territories (Figure 1). It includes more than 77 000 km of rivers, creeks and water-courses, and an estimated 30 000 wetlands (Water Act 2007 – Basin Plan, 2012). Despite an extensive catchment, the river system has relatively modest average inflows of 31 600 GL per year with extreme variability (range 6700 to 117 900 GL) (Water Act 2007 – Basin Plan, 2012).

The MDB is the most important agricultural region in Australia, producing almost all of Australia's rice and cotton

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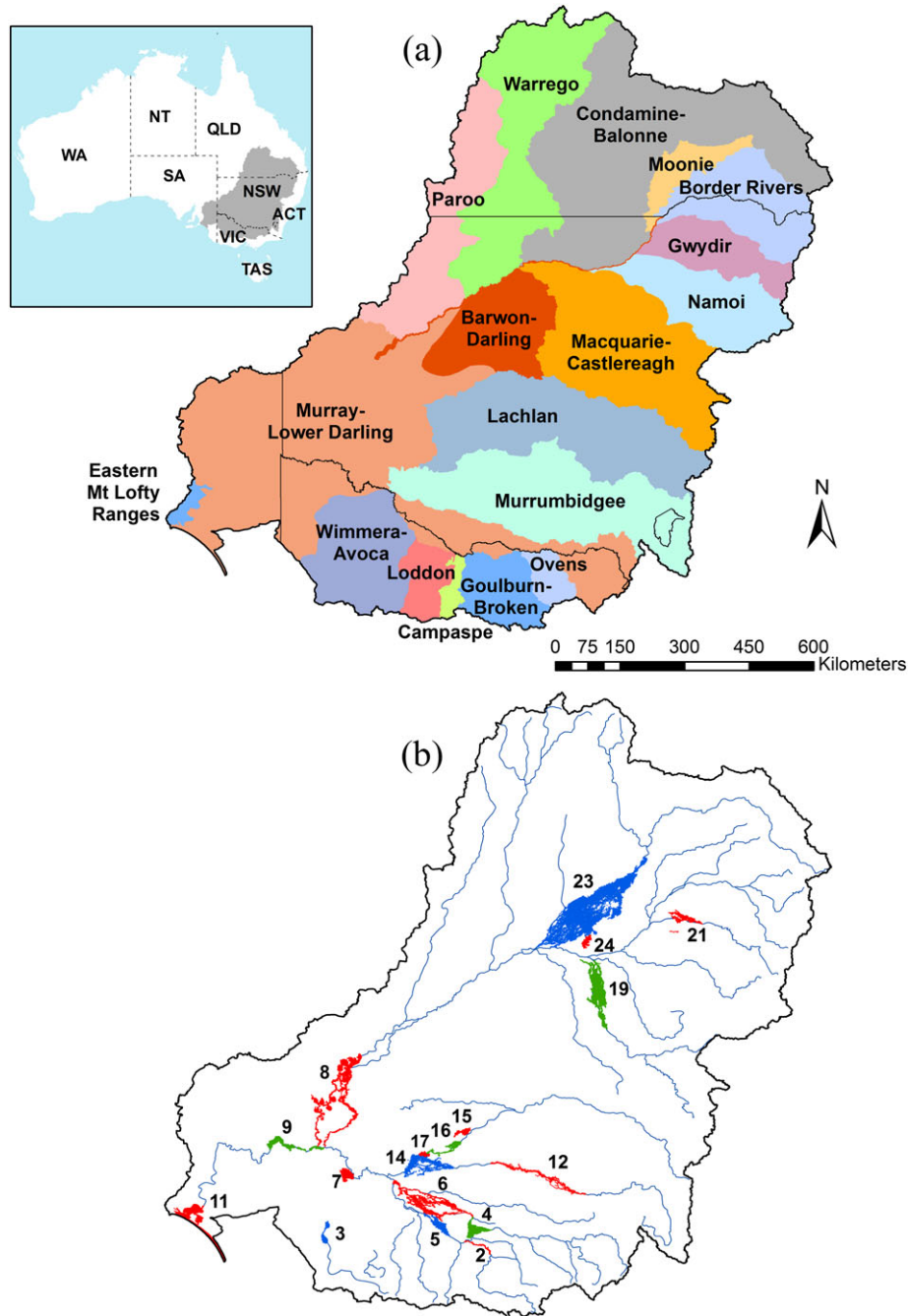


Figure 1. Maps of Murray–Darling Basin showing (a) the 18 major river valleys and (b) the location and extent of the umbrella environmental asset (UEA) sites (numbered—see Table II for site names) used to develop environmental water requirements. In-channel UEAs not shown.

and a high proportion of its broad acre crops, livestock and horticulture (ABS, 2013). In 2011–2012, the gross value of agricultural production in the MDB was \$A19 billion, or around 40% of the total Australian value of agricultural commodities (ABS, 2013). About one-third of the MDB’s annual agricultural production by value is irrigated (ABS, 2013) with

consumptive use prior to the Basin Plan reforms averaging 13 623 GL per year (Water Act 2007 – Basin Plan, 2012).

High agricultural demands for water in the MDB have generated a long history of competing water use, particularly between the states (Eastburn and Mackay, 1990). In 1995, an audit of water use in the MDB showed increasing

diversions and widespread decline in river health, leading to a cap on diversions. In 2004, state and federal governments agreed to the principle of achieving sustainable water use (National Water Initiative (COAG, 2004)). This led to several major programmes to secure water specifically for the environment. Largest amongst these were The Living Murray programme (500 GL per year, \$A700 million; MDBA, 2011a) and the NSW Rivers Environmental Restoration Program (108 GL per year, \$A181 million; NSW Department of Environment, Climate Change and Water, 2011).

In 2008, the Murray–Darling Basin Authority (MDBA) was established to prepare a Basin Plan to establish environmentally sustainable diversion limits (SDLs) for the MDB (Water Act 2007 – Basin Plan, 2012) (Figure 2). The Basin Plan sought to deliver a ‘healthy working basin’ (Figure 2) with healthy and resilient ecosystems, vibrant and strong regional communities and productive and sustainable water-dependent industries. A range of measures are being implemented including the recovery of an average of 2750 GL per year from consumptive use (20% reduction; Water Act 2007 – Basin Plan, 2012) for increased

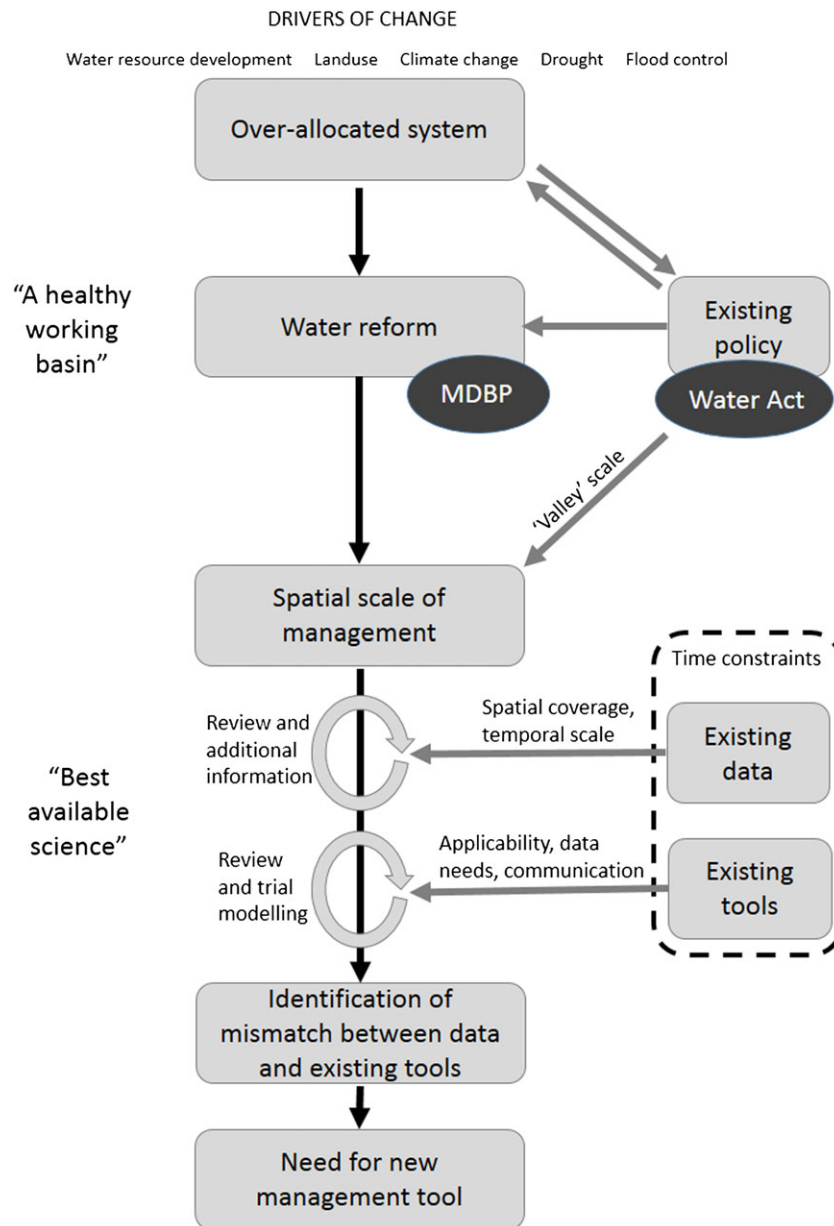


Figure 2. Conceptual diagram illustrating the major drivers of change, policy context, overarching principles (in quotes) and management needs in the Murray–Darling Basin that led to the identification of the need for a new management tool. MDBP indicates the Murray–Darling Basin Plan

environmental flows through a multi-billion dollar investment in modernization of irrigation infrastructure to save water, and purchase of water entitlements.

Determining the amount of water that may be extracted from a river system while protecting environmental values requires multiple lines-of-evidence and taking into account the many needs and constraints involved. These include ecological, hydrological, social and economic assessments. In this paper, we use the eco-hydrological assessment undertaken within the MDB water planning process as a real-world example of how this may be done in the context of imperfect knowledge and limited timeframes.

Alternative approaches to determining environmental water requirements

A large number of frameworks and methods exist for establishing the environmental water requirements of rivers, each with varying degrees of complexity and time and knowledge requirements (Tharme, 2003; Acreman and Dunbar, 2004). In recent years, ecosystem or holistic methods (as defined by Tharme, 2003) have emerged as best practice in environmental flow planning. This recognizes the importance of ecosystem functions for healthy rivers and that all components of the flow regime are important for sustaining function (Poff *et al.*, 1997). Holistic methods draw on elements of ecology, geomorphology and hydrology and can be data and knowledge intensive. This means they have typically been more suited to single rivers or reaches than basin-wide application.

One holistic method, the ecological limits of hydrologic alteration (ELOHA, Poff *et al.*, 2010), is directed at regional scale application and as such is emerging as one of the more commonly applied approaches. The ELOHA framework was designed to capture existing ecological and hydrological information and combine it with hydrological modelling and geomorphic classification to develop reach-based flow-alteration ecological-response relationships. These relationships can then be used to determine the consequences of flow-restoration activities and set environmental flow targets. Central to the regional application of ELOHA is the classification of river reaches (based on similarity of natural flow regime and ecological character) that facilitates the establishment of environmental flow targets for river classes rather than each individual river.

The ELOHA framework, or components of it, has been applied in numerous countries, with the majority of published cases in the USA. The studies that have been published seem to suggest that complete application of the framework is more common in smaller basins (Sanderson *et al.*, 2012; Buchanan *et al.*, 2013; McManamay *et al.*, 2013) with partial application more common at state and national scale (e.g. Kendy *et al.*, 2009; Kennard *et al.*, 2010; Moreno *et al.*, 2014). In the MDB, a review of the

available approaches suggested that a lack of large-scale datasets meant that it was impractical to apply the ELOHA approach across the entire basin. A conceptualization of the policy context, the scale of the management issue and existing tools suggested the need for a new management tool (Figure 2). The approach developed drew on attributes of holistic frameworks, particularly ELOHA, as well as methods that use quantified relationships between hydrological processes and ecological responses.

THE UMBRELLA ENVIRONMENTAL ASSET APPROACH

The approach we outline here addresses the need to make system-wide management decisions, when detailed information is only available for parts of the system. Consistent with the concept of umbrella species in conservation biology (Lambeck, 1997; Roberge and Angelstam, 2004), we use an approach of 'umbrella ecosystems'. Information-rich areas [umbrella environmental assets (UEAs)] are used to develop management interventions, based on the philosophy that the needs of these assets will reflect the needs of a broader set of assets in the system. In the original documentation of the method (MDBA, 2011b), these assets were called hydrologic indicator sites and were sites for which the flow-ecology relationships such as those used in ELOHA were relatively well understood. This approach directly addresses the issue of incomplete information, which is the typical situation in large-scale ecosystem management. The steps in the UEA approach are outlined in Figure 3 and detailed in the succeeding text, using the MDB as a basin example. The approach is then illustrated through application to a single UEA within the basin.

Selection of umbrella environmental assets

In the MDB, identification of UEAs occurred at a large spatial scale that considered different valleys (catchments). Three filters, as listed in Table I, were applied in combination to identify valleys that would be excluded from further analysis to identify UEAs. This resulted in seven valleys being excluded (Table I) and 11 of the 18 main river valleys in the MDB being chosen for a detailed assessment (Table II and Figure 1). Within each of the 11 valleys, the following principles were used to guide the selection of UEAs:

- High ecological value. The MDBA established five criteria to identify high-value water-dependent environmental assets in the basin, based on commonwealth obligations under international agreements and aligning with the National Framework and Guidance for Describing the Ecological Character of Australian Ramsar Wetlands (Department of the Environment, Water, Heritage and

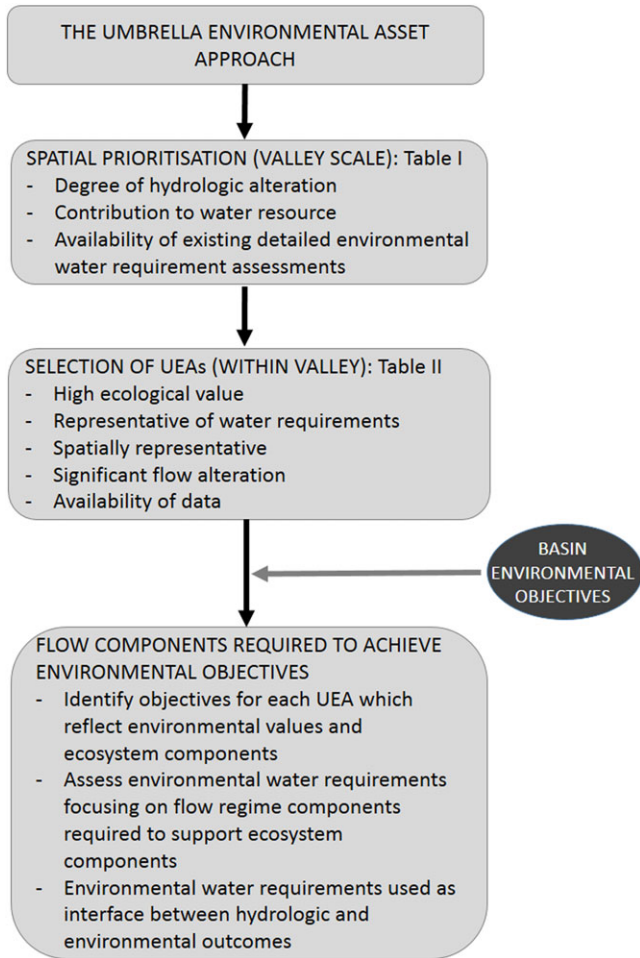


Figure 3. Conceptual overview of the umbrella environmental asset (UEA) approach to determining environmental water requirements in the Murray–Darling Basin

the Arts, 2008) and the draft criteria for identifying High Conservation-Value Aquatic Ecosystems (SKM, 2007).

- Representative of water requirements. The water requirements of the UEA were assumed to represent the water needs of a broader reach of river or an entire river valley. This focussed attention at large, water-dependent ecosystems typically at the downstream end of a river reach or valley. At these sites, flows inundate a broad extent of floodplain, so by inference, these bigger flows provide water to the near-river environment at other parts of the river.
- Spatially representative. The hydrology and geomorphic character of the UEAs needed to be representative of river valleys or large reaches, rather than sites of unusual hydrology or geomorphic character.
- Significant flow alteration. UEAs experienced significant departures from without-development flows in parts of the flow regime. The MDBA considered priority parts of the flow regime were those associated with freshes,

Table I. Valleys within the MDB that do not contain an umbrella environmental asset based on application of three filters: (1) ‘largely unmodified flow regime’, where the modelled end-of-system flow under pre-Basin Plan water sharing arrangements was greater than 80% of without-development flows (i.e. simulated conditions without water resource development); (2) ‘small volume of the surface water resource’ where valleys that contributed less than 1% of the total surface water resource of the MDB and (3) where an ‘existing detailed environmental water requirement assessment’ indicated that relatively small additional volumes of water were required to protect and restore the environment

Valley	Filter		
	Largely unmodified flow regime	Small volume of the surface water resource	Existing detailed environmental water requirement assessment
Campaspe			✓
Eastern Mount	✓	✓	
Lofty Ranges			
Loddon			✓
Moonie		✓	
Ovens	✓		
Paroo	✓		
Warrego	✓		

MDB, Murray–Darling Basin.

bankfull flows and overbank flows as these represent the greatest volumes of water and therefore sensitivity to establishing SDLs (MDBA, 2011b).

- Availability of data. The quality and quantity of hydrological and ecological information associated with the UEA needed to be sufficient to allow a detailed assessment of environmental water requirements.

In total, 24 UEAs across the basin were chosen for detailed eco-hydrological assessment (Table II and Figure 1). The largest of the assets covered 646 378 ha (Lower Balonne River floodplain system), while the smallest was 8866 ha (Lower Goulburn River floodplain). The use of the five principles listed previously meant that the selected UEAs were generally located at or near the bottom of the system (e.g. large terminal wetlands, lowland floodplain complexes) and below major areas of extractive use.

In a separate analysis, additional sites across the basin were selected for the purposes of assessing the environmental water requirements for baseflow components of the flow regime. While these parts of the flow regime are ecologically significant (Rolls *et al.*, 2012), their environmental water requirements are small in terms of volume. Accordingly, effort was strategically focused on high flows that were more critical to the task of establishing SDLs given the revision to arrangements was focussed on the volume of diversions—and managing the pattern of flows could be

Table II. The name, area and valley location of each of the umbrella environmental assets within the Murray–Darling Basin. Map ID numbers refer to Figure 1

Map ID	Umbrella environmental asset	Extent: in-channel (km) floodplain (ha)	Valley
1	Lower Goulburn River (in-channel flows)	407 km	Goulburn–Broken
2	Lower Goulburn River floodplain	8866 ha	
3	Wimmera River terminal wetlands	24 948 ha	Wimmera–Avoca
4	Barmah–Millewa Forest	67 420 ha	Murray
5	Gunbower–Koondrook–Perricoota Forest	54 277 ha	
6	Edward–Wakool River system	131 894 ha	
7	Hattah Lakes	48 111 ha	
8	Lower Darling River system	201 675 ha	
9	Riverland–Chowilla floodplain	68 880 ha	
10	Lower River Murray (in-channel flows)	1989 km	
11	The Coorong, Lower Lakes and Murray Mouth	138 214 ha	
12	Mid-Murrumbidgee River wetlands	47 304 ha	Murrumbidgee
13	Lower Murrumbidgee River (in-channel flows)	1164 km	
14	Lower Murrumbidgee River floodplain	114 664 ha	
15	Booligal Wetlands	15 296 ha	Lachlan
16	Lachlan Swamp	30 422 ha	
17	Great Cumbung Swamp	14 684 ha	
18	Barwon–Darling River	1519 km	Barwon–Darling
19	Macquarie Marshes	208 643 ha	Macquarie–Castlereagh
20	Lower Namoi River (in-channel flows)	493 km	Namoi
21	Gwydir Wetlands	37 786 ha	Gwydir
22	Lower Border Rivers (in-channel flows)	1111 km	Border Rivers
23	Lower Balonne River floodplain system	646 378 ha	Condamine–Balonne
24	Narran Lakes	23 484 ha	

addressed after securing sufficient water for environmental purposes. The baseflow analysis is not further discussed in this paper.

Identifying key flow components required to achieve environmental objectives

The establishment of environmental water requirements across the basin was guided by basin-wide environmental objectives and ecological targets (Water Act 2007 – Basin Plan, 2012). Consistent with these objectives, the environmental water requirements of ecosystem components (i.e. vegetation, fish and waterbird communities and some ecosystem functions) were assessed for each UEA. This required an understanding of the ecological and hydrological characteristics of the site and knowledge of how these components interact. This information was used to determine which parts of the flow regime were in deficit for important ecosystem components and therefore required restoration. The ecosystem components at each UEA, and their flow requirements, were described using all available information, typically from a number of different sources. Relevant aspects of the hydrology of each UEA were described using a combination of observed data, modelled data (Yang, 2010) and available literature.

The assessment of environmental water requirements for each UEA focussed on the components of the flow regime required to meet the known needs of ecosystem components of the site, typically in-channel freshes, bankfull flows and overbank flows. The hydrological metrics used were flow magnitude (threshold or volume), duration, frequency and timing. Flow magnitudes were defined based on known flow–ecology relationships, for example, the flow required to inundate a certain vegetation community. The duration, frequency and timing were based on the known range of requirements of each specific ecosystem component. Often, the frequency and duration may have been less than the natural occurrence but still within the known tolerance range of a community, mimicking other methods like ELOHA.

The condition of ecosystem components varies in response to climatic conditions, even under natural or pre-development conditions (Sheldon, 2005; Leigh *et al.*, 2014). The frequency of flow events, and therefore ecological condition, will be affected by climatic patterns with condition declining during periods of prolonged drought (Thomson *et al.*, 2012). For this reason, the frequency of events required to meet environmental objectives was presented as long-term averages (as opposed to, say, number of events per decade), with climatically driven events

occurring in the model more often in wetter times and less often in drier times. Provision of more frequent inundation in wetter times is expected to increase the resilience of communities, aiding survival during dry times.

There is uncertainty in identifying environmental water requirements for many reasons. Firstly, for many species and ecological communities, the relationship between the provision of water and environmental outcomes is poorly understood (Poff and Zimmerman, 2010). It is likely that there are flow thresholds for many plants and animals beyond which their survival or ability to reproduce is lost. For many ecosystem components, the precise details of those thresholds are unknown, or knowledge is evolving (e.g. for river red-gum communities Bren, 1988; Wen *et al.*, 2009; Roberts and Marston, 2011). Secondly, vegetation communities are located across the floodplain and naturally experience significant variability in their inundation frequency. Thirdly, environmental water requirements vary spatially in response to differences in climate, soil type, access to other water sources and differences in genetic diversity. Consequently, in specifying environmental water requirements, a range in the frequency of flow events required to meet the needs of ecosystem components was specified.

The environmental water requirements of each UEA were based on an amalgam of information as no one study comprehensively described the environmental water requirements at a UEA. Where available, site-specific eco-hydrologic information was used, complemented by observed patterns or relationships from other sites and generic literature on water requirements of flood-dependent biota and ecosystem functions. Once the flow requirements were established, they were assessed against the modelled without-development (~ natural) and current-development (2009) flow patterns.

CASE STUDY—WATERBIRDS AT BARMAH–MILLEWA FOREST

The Barmah–Millewa Forest is a large (67 420 ha), Ramsar-listed water-dependent ecosystem widely recognized as one of the most ecologically valuable sites within the MDB, meeting all five criteria used by the MDBA to identify high environmental value. The forest was one of the 24 UEAs selected for a detailed assessment of environmental water requirements. This case study demonstrates the application of the UEA approach for establishing environmental water requirements for one ecosystem component (waterbirds).

Using the UEA approach, environmental water requirements established for Barmah–Millewa Forest are assumed to be representative of the broader environmental flow needs

of a 425-km reach of the River Murray between a large upstream storage (Hume Dam) and a major tributary (Goulburn River). The location of the forest towards the downstream end of the reach combined with its size and diversity of ecosystem components means that the site can be used to represent the water requirements of upstream flood-dependent ecosystems that have similar ecological character and are more confined on the floodplain.

The Barmah–Millewa Forest has been extensively studied, and the relationship between its hydrology and ecological character is well understood compared with the majority of the MDB's water-dependent environmental assets. The ecological values of the forest have been compromised by several factors, but the main impact has been water resource development (including river regulation) that has caused a decrease in the frequency of medium-sized spring floods. As a result, the average period between beneficial spring–summer floods has approximately doubled (from 1.8 to 3.5 years, (CSIRO, 2008)). Flood volumes have also been greatly reduced; the average annual flood volume is now less than a quarter of the volume under without-development conditions (from 1217 to 291 GL (CSIRO, 2008)).

Protecting and restoring waterbird populations are key elements of the Basin Plan environmental objectives (Water Act 2007 – Basin Plan, 2012). Barmah–Millewa Forest is recognized as providing important habitat for waterbirds and regularly supports >20 000 waterbirds (Victorian Department of Sustainability and Environment, 2008). The flows required to support waterbird habitat and recruitment at Barmah–Millewa Forest have also been the subject of research and analysis (e.g. Leslie, 2001; Overton *et al.*, 2009). Accordingly, waterbirds were selected as one of the ecosystem components to be included in the determination of environmental water requirements for the forest.

Table III provides a summary of the multiple sources and types of eco-hydrological information used to inform environmental water requirements for waterbirds in Barmah–Millewa Forest. It illustrates that environmental water requirements are derived from an amalgam of information. Similar detailed assessments were undertaken using multiple sources of information to derive environmental water requirements for other ecosystem components (vegetation, fish and some ecosystem functions). The UEA water requirements represent the collation of eco-hydrological assessments for all ecosystem components as documented within separate environmental water requirements reports for each UEA (MDBA, 2012a).

The outputs of these investigations for the UEAs were combined in Basin Plan hydrologic modelling, which routes water through all rivers and UEAs in the basin. The hydrologic modelling approach is described in detail in MDBA (2012b) with the intention being to publish this within an upcoming

Table III. Information used to inform desirable environmental water requirements for the Barmah–Millewa Forest waterbirds ecological target. This includes information on vegetation communities that provide foraging and nesting habitats for waterbirds (MDBA, 2012a)

Eco-hydrological relationships and supporting evidence

Spatial extent of inundation (flow magnitude)

General MDB information

- Successful waterbird breeding requires a spatial and temporal mosaic of wetland inundation patterns to support healthy and productive foraging and nesting habitats (Overton *et al.*, 2009).

Barmah–Millewa Forest site-specific information

- A flow magnitude of 18 330 ML/d is required to induce breeding of colonial nesting waterbirds (Leslie, 2001).
- High probability of breeding attempts by ibis, spoonbills, herons and egrets after approximately 50 days of flows greater than 15 000 ML/d (Overton *et al.*, 2009).
- A flow magnitude of 20 000 ML/d is required to induce breeding (Victorian Department of Sustainability and Environment, 2008).
- Flows in the range 10 600–60 000 ML/d inundate key vegetation communities present at the forest (Water Technology, 2009).

Duration of inundation

General MDB information

- For successful fledging, colonial nesting waterbirds require flooding duration of 4–5 months (Overton *et al.*, 2009).
- Roberts and Marston (2011) describe the duration of inundation for flood-dependent vegetation communities, for example, river red-gum (*Eucalyptus camaldulensis*) woodlands require inundation for about 2–4 months.

Barmah–Millewa Forest site-specific information

- MDBC (2006) sets out the flood durations and frequencies of selected vegetation communities that existed before water resource development.

Frequency of inundation (including critical interval between inundations)

General MDB information

- Most waterbirds found in the MDB that use inland wetlands have broad distributions and it is believed that individuals of most species are capable of dispersing across the continent (Overton *et al.*, 2009).
- Roberts and Marston (2011) describe frequency and critical intervals between inundation events for flood-dependent vegetation, for example, about every 2–4 years with a critical interval of 5–7 years for river red-gum woodlands.
- Scott (1997) describes waterbirds as being highly mobile and long lived with a life expectancy ranging generally from 3–8 years.

Barmah–Millewa Forest site-specific information

- MDBC (2006) proposed a target for successful breeding of colonial nesting waterbirds at the forest as at least 3 years out of 10.
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MDB, Murray–Darling Basin.

paper. Fundamentally, the UEA environmental water requirements were used as an interface between hydrologic and environmental outcomes, through two main mechanisms:

- Hydrologic model inputs. Environmental water requirements were used to determine a modelled environmental watering strategy; they defined the magnitude, duration, frequency and timing of flow events to be reinstated under a range of water recovery scenarios.
- Hydrologic model outputs. Environmental water requirements were used to infer environmental outcomes from water recovery model scenarios through assessment of how well the requirements were met. This included considering current operational constraints (e.g. limits to flow because of existing infrastructure), which meant that not all environmental water requirements specified for UEAs could be met (MDBA, 2012b).

Consistent with the concept of a healthy working basin, hydrologic modelling and inferred environmental outcomes were combined with socio-economic assessments to identify the balance between meeting environmental water requirements and the impacts of taking water out of productive use.

Umbrella environmental asset representativeness—scaling up from the umbrella environmental asset to wetlands/ecosystems within the broader reach

A key assumption of the UEA approach is that the provision of adequate flow regimes at the individual assets will support the environmental water requirements of the broader set of water-dependent ecosystems. In the MDB, a review of the UEA approach highlighted that this had not been demonstrated at the time the approach was applied (Young *et al.*, 2011). A lack of the necessary data to scale from small-scale local interventions to whole-of-system management is a feature of river restoration efforts worldwide (Palmer *et al.*, 2005). The UEA approach ideally requires testing of two types of representativeness:

- (1) aquatic ecosystem type – how representative the ecosystem types in the UEA are of the broader suite of ecosystem types in the valley or reach and
- (2) environmental water requirements – how representative the environmental water requirements in the UEA are of the water requirements of the broader suite of environmental assets in the valley or reach.

Assessment of ecosystem type representativeness requires a classification of habitats into classes. A number of aquatic ecosystem classifications and typologies have been developed for the MDB (Thoms and Sheldon, 2002; Cunningham *et al.*, 2013; Brooks *et al.*, 2014; Bunn *et al.*, 2014) allowing initial testing of the assumption that the UEA is representative of a broader suite of ecosystem types.

The ecosystem type representativeness of the Barmah–Millewa Forest UEA has been tested using the Brooks *et al.* (2014) aquatic ecosystem classification. The classification was overlain with two flood inundation extents for the River Murray reach containing the Barmah–Millewa Forest UEA. The 1956 flood is one of the largest recorded in this reach, while a flow of 60 GL/d was the highest environmental water requirement specified for the Forest UEA (Table III). The 1956 flood inundated 50 ecosystem types (i.e. palustrine, lacustrine, riverine and floodplain) in the broader River Murray reach with the 60 GL/d flow inundating 47 types or 94% of these. The results indicate that the 60 GL/d flow specified at the UEA picks up most of the ecosystem types. In addition, across the basin of the 91 aquatic ecosystem types in the MDB, 75 occur in UEAs (82%). The missing types are generally not found on the floodplain or had few examples across the MDB (eight of the 16 missing types had 10 or fewer representatives).

To assess the second type of representativeness (environmental water requirement representativeness) in a systematic and comprehensive way would require knowledge of the environmental water requirements of the broad suite of water-dependent ecosystems. The UEA approach has been adopted because this knowledge is not currently available and therefore it is not feasible to robustly test this representativeness assumption.

DISCUSSION

Imperfect knowledge of flow–ecology relationships is a universal challenge in determining the water needs of aquatic ecosystems (Naiman *et al.*, 2002; Poff and Zimmerman, 2010). We are not aware of any large river basin where high-quality science and hydrological modelling could comprehensively describe the flow regime required to protect and restore each part of the basin. It is generally not possible to explicitly know and understand the water requirements of all ecosystem components in a large basin. The disjunct between the timeframes for large-scale ecological investigations (decades) and the timeframes for policy development and implementation (years) creates the need to draw upon the existing and uneven knowledge base to inform the policy process. The UEA approach enables the integration of existing information for key sites, which are then used to represent environmental water requirements across larger areas.

A range of tools and approaches have been developed to define the water needs of aquatic ecosystems (Tharme, 2003; Acreman and Dunbar, 2004). While many have useful elements, they most often require detailed information that is not available for large river basins. The ELOHA framework (Poff *et al.*, 2010) is most frequently used, yet the scale of application, time constraints and limited available

knowledge prevents it from being applied in many large rivers. Richter *et al.* (2012) identified that in spite of ELOHA being developed to provide a resource-effective method of setting environmental flow standards, the costs and time associated with its application are impediments to implementation. The UEA approach integrates the strengths of ELOHA and other existing methods for establishing water requirements with new and innovative thinking.

The use of ‘umbrella ecosystems’ offers an alternative to establishing water needs for types of rivers or freshwater ecosystems. In large systems such as the MDB (more than 1 million km²), the process of classification alone is a large and time-consuming task, and such baseline information is rarely available at the start of a process of establishing water requirements. The UEA approach assumes that the provision of water to the umbrella ecosystem will concomitantly meet the needs of a broader set of assets within the catchment and attention is then directed at defining the water needs of the UEA, rather than a multitude of river types. This was possible because the method was being used to determine the scale of change in diversions—not to lock in a set of river operating rules. Water recovered for the environment will be actively managed in response to prevailing climatic conditions and evolving knowledge of environmental water requirements.

Both in Australia and globally, there remain significant knowledge gaps in determining flow–ecology relationships. This continues to be a critical barrier to applying many of the more detailed approaches to determining guidelines for flow management (Poff *et al.*, 2010). There is potential to use trait-based approaches in order to provide generic flow–ecology relationships and thus remove the need for detailed data on all taxa, but this research remains in its infancy (Bonada *et al.*, 2007; Merritt *et al.*, 2009). Understanding of flow–ecology relationships is expanding as research in this area continues (Poff and Zimmerman, 2010). Monitoring of environmental watering actions already implemented will add to the understanding of ecosystem responses to flow interventions. One of the significant advantages of the UEA approach is that it allows new data and evidence to be integrated with the existing knowledge base as it becomes available. Ongoing efforts to improve the knowledge base, such as development of inundation models, will allow further assessment of the assumptions that underpin the UEA approach in the MDB. This includes the key assumption that provision of adequate flow regimes at the UEAs will support the environmental water requirements of the broader set of water-dependent ecosystems.

A potential concern with any ‘umbrella’ approach is that management becomes focussed on the umbrella itself, rather than embracing the principle that the umbrella is the management focus in order to accrue benefit to other systems (Roberge and Angelstam, 2004). There is a risk with the

UEA approach that the selected ecosystems are perceived to be iconic in nature and as a result afforded an elevated conservation status compared with other sites. This risk is similar to that seen in conservation management when managing for iconic umbrella or flagship species (Boates and Fenton, 2011). A key part of the UEA approach in the MDB has been a deliberate attempt to build a narrative that clearly articulates the value of the UEAs both in their own right and as representative management foci for broader benefits. The active management of water secured through the MDB reforms provides the opportunity to manage for the full range of outcomes.

Globally, most rivers can be considered 'working rivers', reflecting the fact that at the very least for several decades, a significant proportion of the water has been extracted for human endeavours. It is neither practical nor desirable to return these rivers to a pristine condition in most cases, and in the case of the MDB, the Basin Plan enshrined an objective of a 'healthy working basin'. The assessment of environmental water requirements at UEAs was one of the critical lines of evidence used as a transparent and explicit process to test environmental outcomes for a range of potential policy options. In doing this, the trade-offs associated with different policy options could be explored and communicated to stakeholders.

Increasing global pressures on freshwaters challenges us to manage more river basins at larger scales and with a greater degree of urgency. The establishment of SDLs in the MDB illustrates these challenges. The MDB requires management across jurisdictions, in the face of incomplete knowledge and with an imperative to act. In these aspects, it resembles many of the large river basins worldwide that have existing and emerging over-allocation issues (Vörösmarty *et al.*, 2010). The process of developing flow management strategies in the MDB, and the subsequent decision to create the UEA approach, provides important general learnings for large river management.

- (1) Data are lacking. Despite decades of research into the MDB and review of several thousand scientific studies in the area, there was a lack of data at the appropriate temporal and spatial scales, in key areas, and relating management interventions to ecological outcomes. This is typical of many large river basins worldwide (Hughes, 2001; Nilsson *et al.*, 2005; Campbell, 2007). Aquatic ecological studies are typically at small (kilometre) scales and over short periods (1–3 years), making addressing large-scale management issues using these data particularly difficult (Likens *et al.*, 2009).
- (2) General quantified ecological relationships often do not exist. While there is a broad literature that expresses flow-ecology relationships in conceptual terms and numerous site-specific studies of biota responses to flow

drivers, there are few studies that express general relationships that could be applied at basin scales (Richter *et al.*, 2003). Meta-analyses of published flow-ecology papers are rare but are critical to realistically determining water requirements at management-relevant scales (Poff and Zimmerman, 2010).

- (3) Detailed hydrological data are critical. The physical template against which flow management for ecological outcomes operates is hydrology. High-quality hydrological data and modelling were critical in the development of this process to allow spatial and temporal analysis. However, in many other river basins, these data are lacking despite the clear need for this as a fundamental basis for river management (Richter *et al.*, 1997; Acreman and Dunbar, 2004).
- (4) The 'umbrella species concept' can be applied to water management. The parallels between water management and conservation biology are striking, and the application of the 'umbrella' concept is an example of this. Managing a whole ecosystem where there is uneven knowledge requires using data-rich areas as the basis for making decisions that then benefit the entire system. Here, we adapt the 'umbrella species concept' to an ecosystem level—using sites that have well-defined characteristics as the basis for management decisions.

CONCLUSION

Addressing the immediate challenge of managing for biodiversity and ecosystem function in freshwaters while catering to human needs requires management tools that function at large scales and in the absence of complete information. The UEA approach provides a pragmatic way of establishing environmental water requirements for large systems, relying on detailed knowledge about key representative assets. This approach has utility globally and is compatible with realistic policy settings, which are often time limited.

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REFERENCES

- ABS. 2013. Agricultural Census, 2010–11. Australian Bureau of Statistics. URL 7121.0 - Agricultural Commodities, Australia, 2010–11 [accessed 18 June 2015].
- Acreman M, Dunbar MJ. 2004. Defining environmental river flow requirements—a review. *Hydrology and Earth System Sciences* **8**: 861–876. DOI:10.5194/hess-8-861-2004.
- Acreman MC, Ferguson AJD. 2010. Environmental flows and the European Water Framework Directive. *Freshwater Biology* **55**: 32–48. DOI:10.1111/j.1365-2427.2009.02181.x.
- Arthington AH, Bunn SE, Poff NL, Naiman RJ. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* **16**: 1311–1318. DOI:10.1890/1051-0761(2006)016[1311:tcopelj]2.0.co;2.
- Boates JS, Fenton MB. 2011. Flagship species—flagship problems: recovery of species at risk and the conservation of biodiversity in Canada. *Canadian Journal of Zoology* **89**: 369–370. DOI:10.1139/z11-020.
- Bonada N, Rieradevall M, Prat N. 2007. Macroinvertebrate community structure and biological traits related to flow permanence in a Mediterranean river network. *Hydrobiologia* **589**: 91–106. DOI:10.1007/s10750-007-0723-5.
- Bren LJ. 1988. Effects of river regulation on flooding of a riparian red gum forest on the River Murray, Australia. *Regulated Rivers: Research & Management* **2**: 65–77. DOI:10.1002/rrr.3450020202.
- Brooks S, Cottingham P, Butcher R, Hale J. 2014. Murray–Darling Basin aquatic ecosystem classification: stage 2 report. Peter Cottingham & Associates report to the Commonwealth Environmental Water Office and Murray–Darling Basin Authority, Canberra. <http://www.environment.gov.au/system/files/resources/d6a98692-cd31-49f8-bfc9-0012408daf01/files/interim-classification-aquatic-ecosystems-mdb.pdf> [accessed 12 March 2015].
- Buchanan C, Moltz HLN, Haywood HC, Palmer JB, Griggs AN. 2013. A test of the ecological limits of hydrologic alteration (ELOHA) method for determining environmental flows in the Potomac River basin, U.S.A. *Freshwater Biology* **58**: 2632–2647. DOI:10.1111/fwb.12240.
- Bunn SE, Bond NR, Davis JA, Gawne B, Kennard MJ, King AJ, Kingsford RT, Koehn JD, Linke S, Olley JM, Peterson EE, Pollino CA, Sheldon F, Sims NC, Thompson RM, Ward D, Watts RJ. 2014. Ecological responses to altered flow regimes. Synthesis Report. CSIRO Water for a Healthy Country, Clayton, Melbourne. 62p. <https://publications.csiro.au/rpt/download?pid=csiro:EP148472&dsid=DS4> [accessed 17 June 2015].
- Campbell IC. 2007. Perceptions, data, and river management: lessons from the Mekong River. *Water Resources Research* **43**: W02407. DOI:10.1029/2006wr005130.
- Castella E, Bickerton MA, Armitage PD, Petts GE. 1995. The effects of water abstractions on invertebrate communities in UK streams. *Hydrobiologia* **308**: 167–182. DOI:10.1007/bf00006869.
- COAG. 2004. Intergovernmental agreement on a National Water Initiative. <http://www.environment.gov.au/topics/water/australian-government-water-leadership/national-water-initiative> [accessed 12 March 2015].
- CSIRO. 2008. Water availability in the Murray. A report to the Australian Government from the CSIRO Murray–Darling Basin Sustainable Yields Project. CSIRO, Australia. <http://www.csiro.au/Organisation-Structure/Flagships/Water-for-a-Healthy-Country-Flagship/Sustainable-Yields-Projects/MurrayReportMDBSY.aspx> [accessed 12 March 2015].
- Cunningham SC, White M, Griffioen P, Newell G, Mac Nally R. 2013. Mapping floodplain vegetation types across the Murray–Darling Basin using remote sensing. Report prepared for the Murray–Darling Basin Authority, Canberra. [http://www.mdba.gov.au/kid/files/Cunningham et al Floodplain Veg Types Report Nov 2013 REVISION.docx](http://www.mdba.gov.au/kid/files/Cunningham%20et%20al%20Floodplain%20Veg%20Types%20Report%20Nov%202013%20REVISION.docx) [accessed 18 June 2015].
- Department of the Environment, Water, Heritage and the Arts. 2008. National framework and guidance for describing the ecological character of Australian Ramsar wetlands. Module 2 of the national guidelines for Ramsar wetlands — implementing the Ramsar Convention in Australia. <http://www.environment.gov.au/system/files/resources/6d7408dc-2519-4294-9820-f7b2284816dd/files/module-2-framework.pdf> [accessed 12 March 2015].
- Eastburn DR, Mackay N. 1990. In *The Murray*, Mackay N, Eastburn D (eds). Murray Darling Basin Commission: Canberra.
- Hughes DA. 2001. Providing hydrological information and data analysis tools for the determination of ecological instream flow requirements for South African rivers. *Journal of Hydrology* **241**: 140–151. DOI:10.1016/S0022-1694(00)00378-4.
- Kendy E, Sanderson JS, Olden JD, Apse CD, DePhilip MM, Haney JA, Zimmerman JKH. 2009. Applications of the ecological limits of hydrologic alteration (ELOHA) in the United States. In *Proceedings from the International Conference on Implementing Environmental Water Allocations, Port Elizabeth, South Africa*, pp. 23–26. https://services.oregon.gov/owrd/docs/SB839/2009_Kendy_ELOHA_apps.pdf [accessed 18 June 2015].
- Kennard MJ, Pusey BJ, Olden JD, MacKay SJ, Stein JL, Marsh N. 2010. Classification of natural flow regimes in Australia to support environmental flow management. *Freshwater Biology* **55**: 171–193. DOI:10.1111/j.1365-2427.2009.02307.x.
- Lambeck RJ. 1997. Focal species: a multi-species umbrella for nature conservation. *Conservation Biology* **11**: 849–856. DOI:10.1046/j.1523-1739.1997.96319.x.
- Leigh C, Bush A, Harrison ET, Ho SS, Luke L, Rolls RJ, Ledger ME. 2014. Ecological effects of extreme climatic events on riverine ecosystems: insights from Australia. *Freshwater Biology*. DOI:10.1111/fwb.12515.
- Leslie DJ. 2001. Effect of river management on colonially-nesting waterbirds in the Barmah–Millewa Forest, South-Eastern Australia. *Regulated Rivers: Research and Management* **17**: 21–36. DOI:10.1002/1099-1646(200101)02.
- Likens GE, Walker KF, Davies PE, Brookes J, Olley J, Young WJ, Thoms MC, Lake PS, Gawne B, Davis J, Arthington AH, Thompson R, Oliver RL. 2009. Ecosystem science: toward a new paradigm for managing Australia's inland aquatic ecosystems. *Marine and Freshwater Research* **60**: 271–279. DOI:10.1071/mf08188.
- McMahon TA, Finlayson BL. 2003. Droughts and anti-droughts: the low flow hydrology of Australian rivers. *Freshwater Biology* **48**: 1147–1160. DOI:10.1046/j.1365-2427.2003.01098.x.
- McManamay RA, Orth DJ, Dolloff CA, Mathews DC. 2013. Application of the ELOHA framework to regulated rivers in the Upper Tennessee River Basin: a case study. *Environmental Management* **51**: 1210–1235. DOI:10.1007/s00267-013-0055-3.
- MDBA. 2011a. The Living Murray story—one of Australia's largest river restoration projects, MDBA publication no: 157/11, Murray–Darling Basin Authority, Canberra. <http://www.mdba.gov.au/sites/default/files/pubs/The-Living-Murray-story-One-of-Australias-largest-river-restoration-projects.pdf> [accessed 12 March 2015].
- MDBA. 2011b. The proposed environmentally sustainable level of take for surface water of the Murray–Darling Basin: methods and outcomes, MDBA publication no: 226/11, Murray–Darling Basin Authority, Canberra. http://www.mdba.gov.au/sites/default/files/archived/proposed/ESLT_MDBA_report.pdf [accessed 12 March 2015].

- MDBA. 2012a. Assessment of environmental water requirements for the proposed Basin Plan. Series of 24 reports, Murray-Darling Basin Authority, Canberra. <http://www.mdba.gov.au/what-we-do/basin-plan/development/bp-science/assessing-environmental-water-requirements> [accessed 12 March 2015].
- MDBA. 2012b. Hydrologic modelling to inform the proposed Basin Plan: methods and results. MDBA publication no: 17/12 Murray-Darling Basin Authority, Canberra. <http://www.mdba.gov.au/what-we-do/basin-plan/development/bp-science> [accessed 12 March 2015].
- MDBC. 2006. The Barmah-Millewa Forest icon site environmental management plan 2006–2007, MDBC publication no: 30/06, Murray-Darling Basin Commission, Canberra. http://www.mdba.gov.au/sites/default/files/archived/mdbc-tlm-reports/2083_Env_Man_Plan_Barmah_Millewa_2006-07.pdf [accessed 12 March 2015].
- Merritt DM, Scott ML, Poff NL, Auble GT, Lytle DA. 2009. Theory, methods and tools for determining environmental flows for riparian vegetation: riparian vegetation-flow response guilds. *Freshwater Biology* **55**: 206–225. DOI:10.1111/j.1365-2427.2009.02206.x.
- Moreno JA, Cardenas EG, Gonzalez F, Cardona CA, Obregon N, Dominguez EA, Walschburger T. 2014. Stream classification and assessment of hydrologic alteration towards an environmental flow appraisal of the Magdalena-Cauca River basin (Colombia) *10th International Symposium on Ecohydraulics Trondheim Norway June 23–27th 2014*. [http://www.researchgate.net/publication/263614080_Stream_classification_and_assessment_of_hydrologic_alterations_towards_an_environmental_flow_appraisal_of_the_Magdalena-Cauca_River_basin_\(Colombia\)](http://www.researchgate.net/publication/263614080_Stream_classification_and_assessment_of_hydrologic_alterations_towards_an_environmental_flow_appraisal_of_the_Magdalena-Cauca_River_basin_(Colombia)) [accessed 18 June 2015].
- Naiman RJ, Bunn SE, Nilsson C, Petts GE, Pinay G, Thompson LC. 2002. Legitimizing fluvial ecosystems as users of water: an overview. *Environmental Management* **30**: 455–467. DOI:10.1007/s00267-002-2734-3.
- Nilsson C, Reidy CA, Dynesius M, Revenga C. 2005. Fragmentation and flow regulation of the world's large river systems. *Science* **308**: 405–408. DOI:10.1126/science.1107887.
- NSW Department of Environment, Climate Change and Water. 2011. NSW Rivers Environmental Restoration Program: final report. <https://www.environment.gov.au/system/files/pages/4cfd9575-598c-4a54-bfc8-d5ee30f62233/files/nsw-rivers-environmental-restoration-program.pdf> [accessed 13 October 2015].
- Overton IC, Colloff MJ, Doody TM, Henderson B, Cuddy SM (eds). 2009. Ecological outcomes of flow regimes in the Murray-Darling Basin. Report prepared for the National Water Commission by CSIRO Water for a Healthy Country Flagship, CSIRO, Canberra. <https://publications.csiro.au/rpr/download?pid=csiro:EP10048&dsid=DS6> [accessed 12 March 2015].
- Palmer MA, Bernhardt ES, Allan JD, Lake PS, Alexander G, Brooks S, Carr J, Clayton S, Dahm CN, Follstad Shah J, Galat DL, Loss SG, Goodwin P, Hart DD, Hassett B, Jenkinson R, Kondolf GM, Lave R, Meyer JL, O'Donnell TK, Pagano L, Sudduth E. 2005. Standards for ecologically successful river restoration. *Journal of Applied Ecology* **42**: 208–217. DOI:10.1111/j.1365-2664.2005.01004.x.
- Poff NL, Allan JD, Bain MB, Karr JR, Prestegard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime: a paradigm for river conservation and restoration. *Bioscience* **47**: 769–784. DOI:10.2307/1313099.
- Poff NL, Richter BD, Arthington AH, Bunn SE, Naiman RJ, Kendy E, Acreman M, Apse C, Bledsoe BP, Freeman MC, Henriksen J, Jacobson RB, Kennen JG, Merritt DM, O'Keeffe JH, Olden JD, Rogers K, Tharme RE, Warner A. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology* **55**: 147–170. DOI:10.1111/j.1365-2427.2009.02204.x.
- Poff NL, Zimmerman JKH. 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology* **55**: 194–205. DOI:10.1111/j.1365-2427.2009.02272.x.
- Richter BD, Baumgartner JV, Wigington R, Braun DP. 1997. How much water does a river need? *Freshwater Biology* **37**: 231–249. DOI:10.1046/j.1365-2427.1997.00153.x.
- Richter BD, Davis M, Apse C, Konrad C. 2012. A presumptive standard for environmental flow protection. *River Research and Applications* **28**: 1312–1321. DOI:10.1002/rra.1511.
- Richter BD, Mathews R, Wigington R. 2003. Ecologically sustainable water management: managing river flows for ecological integrity. *Ecological Applications* **13**: 206–224. DOI:10.1890/1051-0761(2003)013[0206:eswmmr]2.0.co;2.
- Roberge J-M, Angelstam P. 2004. Usefulness of the umbrella species concept as a conservation tool. *Conservation Biology* **18**: 76–85. DOI:10.1111/j.1523-1739.2004.00450.x.
- Roberts J, Marston F. 2011. Water regime for wetland and floodplain plants. A source book for the Murray-Darling Basin. National Water Commission, Canberra. http://archive.nwc.gov.au/_data/assets/pdf_file/0007/11230/Wetlands_full_document.pdf [accessed 12 March 2015].
- Rolls RJ, Leigh C, Sheldon F. 2012. Mechanistic effects of low-flow hydrology on riverine ecosystems: ecological principles and consequences of alteration. *Freshwater Science* **31**: 1163–1186. DOI:10.1899/12-002.1.
- Sanderson J, Bledsoe B, Poff NL, Wilding T, Fey N. 2012. Yampa-White Basin Roundtable Watershed Flow Evaluation Tool Study. Prepared by CDM Smith for The Nature Conservancy. <https://www.conservationgateway.org/Files/Pages/yampawhitewfet.aspx> [accessed 18 June 2015].
- Scott A. 1997. Relationships between waterbird ecology and river flows in the Murray-Darling Basin. CSIRO Land and Water technical report no: 5/97, Canberra. <http://www.clw.csiro.au/publications/technical97/tr5-97.pdf> [accessed 12 March 2015].
- Sheldon F. 2005. Incorporating natural variability into the assessment of ecological health in Australian dryland rivers. *Hydrobiologia* **552**: 45–56. DOI:10.1007/210750-005-1504-7.
- SKM. 2007. High Conservation Value Aquatic Ecosystems project—identifying, categorising and managing HCVAE, final report. <http://www.environment.gov.au/system/files/resources/d66f4d88-325a-474f-b0ec-2fc691f7cee7/files/hcvae.pdf> [accessed 12 March 2015].
- Tharme RE. 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* **19**: 397–441. DOI:10.1002/rra.736.
- Thoms M, Sheldon F. 2002. An ecosystem approach for determining environmental water allocations in Australian dryland river systems: the role of geomorphology. *Geomorphology* **47**: 153–168. DOI:10.1016/s0169-555x(02)00085-5.
- Thomson JR, Bond NR, Cunningham SC, Metzeling L, Reich P, Thompson RM, Mac Nally R. 2012. The influences of climatic variation and vegetation on stream biota: lessons from the Big Dry in southeastern Australia. *Global Change Biology* **18**: 1582–1596. DOI:10.1111/j.1365-2486.2011.02609.x.
- Victorian Department of Sustainability and Environment. 2008. Barmah Forest Ramsar site ecological character description, Victorian Department of Sustainability and Environment, Melbourne.
- Vörösmarty CJ, Green P, Salisbury J, Lammers R. 2000. Global water resources: vulnerability from climate change and population growth. *Science* **289**: 284–288. DOI:10.1126/science.289.5477.284.
- Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Glidden S, Bunn SE, Sullivan CA, Liermann CR, Davies PM. 2010. Global threats to human water security and river biodiversity. *Nature* **467**: 555–561. DOI:10.1038/nature09440.
- Water Act 2007 – Basin Plan. 2012. Prepared by the Murray-Darling Basin Authority. <http://www.comlaw.gov.au/Details/F2012L02240> [accessed 12 March 2015].
- Water Technology. 2009. Barmah-Millewa hydrodynamic modelling model recalibration. A report for the Goulburn-Broken Catchment

- Management Authority. http://www.gbcma.vic.gov.au/downloads/Wetlands/Barmah-Millewa_hydrodynamic_modelling_report_optimized.pdf [accessed 12 March 2015].
- Wen L, Ling J, Saintilan N, Rogers K. 2009. An investigation of the hydrological requirements of River Red Gum (*Eucalyptus camaldulensis*) Forest, using classification and regression tree modelling. *Ecohydrology* 2: 143–155. DOI:10.1002/eco.46.
- Yang A. 2010. The integrated river system modelling framework. A report to the Murray-Darling Basin Authority from the CSIRO Water for a Healthy Country Flagship. http://www.mdba.gov.au/sites/default/files/archived/proposed/CSIRO_ESLT_Science_Review.pdf [accessed 13 March 2015].
- Young WJ, Bond N, Brookes J, Gawne B, Jones GJ. 2011. Science review of the estimation of an environmentally sustainable level of take for the Murray–Darling Basin. Final Report to the Murray-Darling Basin Authority from the CSIRO Water for a Healthy Country Flagship. http://www.mdba.gov.au/sites/default/files/archived/proposed/CSIRO_ESLT_Science_Review.pdf [accessed 13 March 2015].