



# Transforming Environmental Water Management to Adapt to a Changing Climate

Samantha J. Capon<sup>1,2\*</sup>, Catherine Leigh<sup>1,2,3</sup>, Wade L. Hadwen<sup>1,4</sup>, Amy George<sup>1</sup>,  
Joe M. McMahon<sup>1</sup>, Simon Linke<sup>1</sup>, Vanessa Reis<sup>1</sup>, Leigh Gould<sup>1</sup> and Angela H. Arthington<sup>1</sup>

<sup>1</sup> Australian Rivers Institute, Griffith University, Nathan, QLD, Australia, <sup>2</sup> Griffith School of Environment and Science, Griffith University, Nathan, QLD, Australia, <sup>3</sup> Science and Engineering Faculty, Queensland University of Technology, Brisbane, QLD, Australia, <sup>4</sup> Griffith Climate Change Response Program, Griffith University, Gold Coast, QLD, Australia

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### \*Correspondence:

Samantha J. Capon  
s.capon@griffith.edu.au

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Environmental water management has become a global imperative in response to environmental degradation and the growing recognition that human well-being and livelihoods are critically dependent on freshwater ecosystems and the ecological functions and services they provide. Although a wide range of techniques and strategies for planning and implementing environmental flows has developed, many remain based on assumptions of hydrologic stationarity, typically focusing on restoring freshwater ecosystems to pre-development or “natural” conditions. Climate change raises major challenges to this conventional approach, in part because of increasing uncertainties in patterns of water supply and demand. In such a rapidly changing world, the implementation of, and capacity of water managers to deliver flow regimes resembling historical hydrological patterns may be both unfeasible and undesirable. Additionally, as emphasis shifts from species-focused water allocation plans toward a greater appreciation of freshwater ecological functions and services, many of which will be influenced by climate change, a thorough re-evaluation of the conventional objectives, planning, delivery and monitoring of environmental water, including its role in the broader context of water and environmental management, is essential. Here, we identify the major challenges posed by climate change to environmental water management and discuss key adaptations and research needed to meet these challenges to achieve environmental and societal benefits and avoid maladaptation.

**Keywords:** adaptation, climate change, environmental flows, hydrology, water resources, wetlands

## INTRODUCTION

Environmental water management (EWM) has become a global imperative in response to environmental degradation and the growing recognition that human well-being and livelihoods are critically dependent on freshwater ecosystems (Capon et al., 2013; Horne et al., 2017a). Considerable research has underpinned the development of a wide range of approaches and tools to support decision-making regarding the acquisition and delivery of environmental water (Table 1; Arthington, 2012). For the most part, however, EWM remains grounded in assumptions of hydrologic stationarity and typically focuses on restoring freshwater water systems to pre-development or “natural” conditions (Milly et al., 2008; Poff and Matthews, 2013; Poff, 2018).

Recent developments in ecological science and natural resources management have prompted a need to expand the spatial and temporal scales of EWM (McCluney et al., 2014) and to broaden consideration of its human context (e.g., Finn and Jackson, 2011; Adams et al., 2017; Capon and Capon, 2017). Climate change in particular necessitates a revision of EWM, especially as it represents, in itself, an important strategy in society's broader adaptation to climate change by promoting the protection and augmentation of increasingly critical ecosystem services (Capon and Bunn, 2015).

Here, we discuss major challenges to environmental flows and EWM under a changing climate as well as the adaptations needed to meet these for both environmental and societal benefit. We use the familiar term "environmental flows" to denote the quantity and spatio-temporal distribution of water delivered, or deemed necessary, to support ecological and societal objectives for rivers, wetlands, and groundwater-dependent ecosystems (Dyson et al., 2003; Arthington, 2012), whereas "EWM" conveys the broader context of environmental water research policy, planning and management (Horne et al., 2017a,b). We begin by outlining the main implications of climate change for EWM. We then consider how conventional approaches to setting objectives and targets, planning and prioritization, delivery, monitoring and evaluation of environmental water might be adapted so that such barriers may be overcome and opportunities for transformation capitalized upon. Finally, we identify key knowledge needs required to support such adaptation.

## CLIMATE CHANGE CHALLENGES FOR EWM

In addition to increasing levels of uncertainty and unpredictability, climate change poses four main challenges for EWM, the first two of which concern the supply of environmental water while the latter two affect demand for its application. First, climate change is driving shifts in patterns of water supply globally with increasing water scarcity and risks to water security anticipated in many places (Vörösmarty et al., 2010; Grey et al., 2013). Both surface and ground water hydrology are highly sensitive to the altered precipitation, warming, increased evaporation, sea level rise and altered snow melt projected under many climate change scenarios (Milly et al., 2005; Döll and Schmied, 2012; IPCC, 2012, 2014; Leigh et al., 2015), with small changes in climatic drivers potentially causing large changes in flow regimes (Capon et al., 2013; Acreman et al., 2014a). Concurrent shifts in water quality are also widely expected (e.g., Döll and Schmied, 2012; Ledger and Milner, 2015). Second, human water demands, especially for agriculture, are simultaneously expected to rise including those related to climate change mitigation and adaptation actions in other sectors, e.g., generation of hydroelectricity or plantations for carbon sequestration (Capon and Bunn, 2015), placing further pressure on already limited environmental water allocations.

Third, freshwater ecosystems, their biota, functions and services, are highly vulnerable to climate change due to high levels of exposure and sensitivity to projected changes and

extreme events (Capon et al., 2013; Leigh et al., 2015; Peirson et al., 2015). Ecological responses to climate change will be complex, dynamic and variable and are very likely to involve shifts in the composition and structure of freshwater ecosystems which, in turn, will affect the ecological functions, goods and services these provide (Capon et al., 2013; Datry et al., 2017). In particular, significant shifts in the distribution of freshwater taxa can be expected in response to projected climatic changes (James et al., 2017). Ecological responses to hydrology are also likely to change. Warmer temperatures, for instance, may make ecosystems and biota "thirstier" and potentially less tolerant of past drying regimes (Leigh et al., 2015, 2016). Shifts in ecological functions and ecosystem services can be similarly anticipated. The capacity of freshwater ecosystems to retain flood waters, for example, may become more variable in space and time (Capon et al., 2013; Datry et al., 2017). Freshwater ecosystems will furthermore be sensitive to climate change effects in the surrounding landscape which may exacerbate direct impacts (Capon et al., 2013; Hadwen and Capon, 2014). Finally, the demand for and importance of many water ecosystem goods (e.g., fish) and services (e.g., flood mitigation) are likely to increase under a changing climate (Capon and Bunn, 2015), as are the significance of some ecological functions, e.g., the provision of riparian corridors for species' migration and the role of riparian and wetland areas as drought and thermal refuges for terrestrial fauna (Capon et al., 2013).

Collectively, the challenges outlined here have significant implications for most aspects of environmental flows and EWM from setting objectives through to delivery, monitoring and adaptive management. Increasing water scarcity and demand, for instance, will likely create a greater requirement for water managers to justify environmental water allocations and demonstrate their benefits as well as to increase the efficiency of their delivery (Horne et al., 2017a). Overall, climate change can be expected to reduce the availability and quality of environmental water allocations in most places as well as shifting these both spatially and temporally. At the same time, the possibilities of what might be feasibly, and desirably, achieved with environmental water can also be anticipated to shift. Herein lies the opportunity of transformational EWM, whereby targets may be more forward-looking in order to deliver the types of goods and services we will need in a climate-changed world.

## ADAPTING EWM

A wide variety of methodologies and frameworks have been developed to guide environmental flows and EWM, ranging from those which focus on calculating local flow regime requirements associated with specific targets (e.g., the Building Block Methodology) to those which consider the broader EWM arena, i.e., including environmental and societal objective setting etc. (e.g., ELOHA; **Table 1**). Additionally, some studies have explored the implications of climate change for many of these existing methodologies (**Table 1**). For the most part, however, such studies have mainly concerned probable hydrologic and, to a far lesser extent, ecological impacts of projected climate change to

**TABLE 1** | Four main methodological approaches used to design environmental flows with examples of relevant climate change assessments (for details of methods and case studies, see Tharme, 2003; Arthington, 2012; Linnansaari et al., 2012).

Methodological approach	Examples	Description	Examples of climate change assessments
<b>HYDROLOGICAL INDICES AND REGIME ANALYSIS</b>			
	Simple index methods (e.g., Montana method, Tennant, 1976)	Estimates % annual, seasonal or monthly flow volume needed to maintain habitat for fish or stream condition.	
	Flow duration curve (FDC) analysis	A FDC shows the proportion of time during which any flow is equalled or exceeded but without regard for the sequence of events. In the UK, an index of natural low flow $Q_{95}$ (the flow equalled or exceeded 95% of time) has been used to define the minimum e-flow (Acreman and Dunbar, 2004).	Wilby (1994) used metrics from FDC analysis to assess effects of climate scenarios on stream flows in the UK. Climate change predictions produced by general circulation models at macro scales were translated into hydrological concerns at the catchment scale. Ecological implications were not assessed.
	Ecologically relevant flow metrics, e.g., the Range of Variability Approach (RVA; Richter et al., 1997)	RVA uses 32 Indicators of Hydrologic Alteration (IHA, Richter et al., 1996) to set limits on flow alterations in terms of magnitude, frequency, timing and duration of low and high flows. The default (where there is no ecological information) is set at $\pm$ one standard deviation, or the 25th and 95th percentiles. The RVA has been applied in numerous e-flow studies. Combinations of ecologically relevant flow metrics are widely used in e-flow studies that aim to conserve near natural flow regimes, or minimize impacts of flow change, or restore flows that have been lost or altered by regulation.	Thompson et al. (2014) used the RVA to predict hydrological change associated with scenarios of climate change in the Mekong Basin. Ecological implications (risks) of hydrologic change were inferred from the literature. Assessment of risk varied across simulated flow scenarios for 7 general circulation models based on 2°C increase in global mean temperature. Highest risks for fish were associated with alterations to low flows and loss of refuge habitats during low water periods. Dhungel et al. (2016) predicted the climate-driven changes in 16 ecologically relevant flow metrics (and 3 main flow classes) in streams across the coterminous United States by 2100.
<b>2. HYDRAULIC HABITAT METHODS</b>			
	Wetted Perimeter method (WP)	Hydraulic variables (e.g., wetted perimeter - WP) are estimated at stream cross-sections as surrogates for flow and habitat requirements of target species or assemblages. The WP method defines a minimum discharge that maintains wetted aquatic habitat for species or assemblages. Hydraulic habitat methods may involve a wide range of stream parameters (e.g., depth, width, velocity, sheer stress, etc.).	Assessment of the impacts of climate change on Atlantic salmon ( <i>Salmo salar</i> ) in the Eden catchment (Cumbria, UK) involved analysis across the catchment to determine hydraulic parameters (flow depths, flow velocities, discharge per meter, width and Froude numbers) for both current and future climates (Walsh, 2004). Hydraulic parameters were compared with those cited in the literature as being suitable for salmonid habitat and survival. Analysis of flow and habitat time series determined the percentage of time such parameters were met under the future climate scenario (based on the UKCIP02 medium-high scenario for 2070–2100) across the study catchment.
<b>3. HABITAT SIMULATION</b>			
	PHABSIM component of the Instream Flow Incremental Methodology, Bovee (1982)	Habitat simulation methods and associated tools predict weighted usable area (WUA) for selected species or assemblages. Applications may produce time-series of habitat availability for a range of biota (invertebrates, fish, aquatic plants, riparian vegetation), and flows to provide for other river values, such as recreation and aesthetics.	PHABSIM has been used to estimate smallmouth bass ( <i>Micropterus dolomieu</i> ) populations under scenarios of changing flow and temperature for historical climate/weather conditions, as well as under climate change scenarios in the Mackinaw River, Illinois, USA (Herricks and Bergner, 2003). The output from PHABSIM was used to model fish populations to flow and a temperature threshold which affects spawning date.

(Continued)

TABLE 1 | Continued

Methodological approach	Examples	Description	Examples of climate change assessments
<b>4. HOLISTIC (ECOSYSTEM) METHODS AND FRAMEWORKS</b>			
	Holistic Approach (Arthington et al., 1992) Building Block Methodology - BBM (King and Louw, 1998) Benchmarking Methodology (Brizga et al., 2002) Downstream Response to Imposed Flow Transformation - DRIFT (King et al., 2003), and its derivative Integrated Basin Flow Management - IBFM (King and Brown, 2010). ELOHA (Ecological Limits of Hydrologic Alteration; Poff et al., 2010).	Underpinned by the NFR paradigm, holistic approaches may consider in-stream and riparian biota, wetlands, groundwater, floodplains, estuaries and coastal waters. Several frameworks also assess social and economic dependencies on riverine species, ecological goods and ecosystem services. ELOHA quantifies flow-ecology relationships and e-flow guidelines or thresholds for rivers classified into contrasting hydrological types at user-defined regional scale (Poff et al., 2010) Limits to change help to guide e-flow recommendations (Kendy et al., 2012; McManamay et al., 2013; Arthington, 2015).	King et al. (2014) applied DRIFT and IBFM to assess the effects of possible future water resource developments on the flow regime and related physico-chemical, ecological and socio-economic attributes of the Okavango river system. This study also assessed the impacts of four climate change scenarios on river ecosystem integrity using DRIFT e-flow assessment procedures (King et al., 2003).

inform vulnerability or risk assessments. Significant assessments of water security risks posed by climate variability, change, and extreme events from a socio-economic have also been conducted (Grey et al., 2013; Hall et al., 2014). Adapting water resources management to climate change, however, requires integrated assessments of vulnerability across socio-ecological systems (Pahl-Wostl, 2007). Here, we provide a broader discussion of the implications of the climate change challenges previously identified with respect to key stages of adaptive management of environmental water. Throughout, we emphasize three guiding principles which we assert are critical to avoiding perverse outcomes of EWM and approaches to climate change adaptation in this sector (*sensu* Capon et al., 2013; Peirson et al., 2015; Finlayson et al., 2017a).

First, climate change highlights the need for EWM to extend its scope beyond conventionally narrow ecological objectives, targets and indicators to encompass functional, social, economic and cultural aspects. Second, the scale of, and uncertainties associated with, climate change effects require that EWM adopt both a broader and more nuanced consideration of its spatial and temporal framing, i.e., both in terms of embracing a wider view and recognizing the spatial heterogeneity and temporal variability involved at finer scales. Finally, effective adaptation of EWM, and ultimately its transformation, will depend on its successful alignment and integration, with respect to both water management more broadly and other sectors such as agriculture and energy production. This final guiding principle conforms to the principles of integrated water resources management, which is itself a target within the freshwater-focused Sustainable Development Goal 6 (United Nations, 2016). Broadening EWM to encompass all aspects of water use and management enables a more integrated and holistic approach to deliver the needs of people and environment (Ludwig et al., 2013; Horne et al., 2017a).

## Objectives and Targets

Throughout the world, environmental flow studies and EWM has typically been triggered by highly visible signs of environmental

degradation (e.g., biodiversity declines, species invasions, toxic algal blooms) and have thus often sought to reactively address specific concerns involving particular taxa (e.g., riparian trees, fish or waterbirds), ecosystems (e.g., iconic wetlands) and/or, to a much lesser extent, human well-being (Arthington and Pusey, 2003; Poff, 2009). Conventional objectives of EWM in many cases have been to deliver flows which support the habitat and life-history requirements of selected taxa with more holistic approaches generally seeking to reinstate historical “natural” flow regimes to restore freshwater ecosystems and their biota to some semblance of “pre-development” conditions (Table 1; Poff et al., 2007; Poff, 2018). In Australia’s Murray-Darling Basin, for example, objectives for environmental watering often include the maintenance or restoration of historical extents of key vegetation communities in particular wetland ecosystems (Capon and Capon, 2017). Similarly backwards-looking objectives are also promoted through the management aims of the Ramsar Convention which requires signatory parties to maintain the ecological character of listed wetlands in the condition described at the time of listing (Finlayson et al., 2017a). Such approaches to EWM assume that: (1) past flow regimes are desirable for both present and future conditions (Capon and Capon, 2017); (2) ecological integrity will improve within a system once historic flow attributes are re-instated (*sensu* the “Field of Dreams hypothesis”; Palmer et al., 1997; Hilderbrand et al., 2005); (3) ecosystems have an optimal state and restoration has a static endpoint (Capon and Capon, 2017); and (4) flow is a master variable, distinct from other ecologically important drivers that may impact water quantity and quality, e.g., land use and sediment dynamics (Karr, 1991; Poff et al., 1997; Poff and Matthews, 2013). These assumptions are difficult to justify, however, in the face of a rapidly changing and increasingly extreme and unpredictable climate (Milly et al., 2008; Poff and Matthews, 2013; Poff et al., 2017) on a human-dominated planet in which many rivers and wetlands exist within catchments drastically modified in terms of their geomorphology, sediment delivery and vegetation (Acreman et al., 2014a; Davies et al., 2014). Furthermore, there is growing recognition that ecosystems



are not static but rather dynamic systems that exhibit a wide range of trajectories of socio-ecological change in both space and time (Suding et al., 2004; Capon and Capon, 2017; Poff, 2018).

Under climate change, developing environmental flow and EWM objectives based either on historic flow regimes or structural ecological targets associated with particular taxa or local ecosystem attributes is increasingly both unrealistic and undesirable (Poff et al., 2017). Solely with respect to ecological outcomes, for instance, robust objectives must consider the probability of shifts in species' distributions and the appearance of novel ecosystems as well as emerging triggers for EWM beyond restoration or rehabilitation, e.g., protection of refuge habitats or provision of corridors for species migration (Davies, 2010; Acreman et al., 2014a; Moyle, 2014). Growing water scarcity also calls for better integration, and therefore efficiency, of water management objectives for human and environmental purposes. Climate change thus prompts a need to systematically develop multiple integrated objectives for EWM that incorporate socio-economic, cultural and ecological aspects (Dunlop et al., 2013). In particular, adaptive EWM goals might have a greater emphasis on ecosystem functions and services valued by society, e.g., water filtration, bank stability, shading, cultural values etc. (Capon and Capon, 2017). Specific objectives relating to the resilience or adaptive capacity of particular ecological functions or values may also be appropriate, especially in catchments which are characterized by high levels of climate variability and extreme events (Jones et al., 2012). Transformative EWM objectives might even include over-restoration of wetland ecosystems (e.g., Davies, 2010), such that certain ecological functions are enhanced beyond their historical limits, e.g., creation of new aquatic refuges where climate change has negatively impacted historical ones. Such designer EWM objectives may become the norm as natural environments are replaced by novel and/or managed systems that are valued for their particular benefits to ecosystems and people (Acreman et al., 2014a). To be equitable, however, EWM goals may also need to consider the values and maintenance of wild rivers and naturalness (e.g., Ridder, 2007; Arthington, 2012). Indeed, appropriate goals for EWM will vary between highly regulated and developed catchments and those which are less modified and set aside as protected areas (Finlayson et al., 2017b; Finlayson and Pittock, 2018). In less modified catchments, for example, more open-ended ecological goals for unregulated water management might be appropriate (Capon et al., 2013) with a focus on promoting more climate-resilience rather than maintaining past reference states (Finlayson and Pittock, 2018).

To avoid perverse outcomes and maladaptation, adapted EWM objectives and targets also need to be developed with respect to multiple nested spatial and temporal scales and take into account connectivity and spatial heterogeneity (McCluney et al., 2014). Local objectives for particular wetlands, for example, might be designed in relation to those developed for wetlands with which they are hydrologically or otherwise connected as well as those set for larger levels of spatial organization, such as river basins and broader landscape scales (e.g., waterbird flyways). Similarly, different goals will be required for the short-, medium- and long-term, especially in relation to climate change adaptation of EWM, and these also need to be appropriately

aligned so that long-term transformation is not prohibited by actions in the short-term (Finlayson et al., 2017a). Finally, because EWM is itself critical to the adaptation of human society to climate change, transformative EWM objectives and targets should additionally be developed in conjunction with broader adaptation strategies and goals of water management more generally, like those associated with the Sustainable Development Goals (SDG) and SDG6 in particular, as well as those of other sectors (Hadwen et al., 2015; United Nations, 2016).

## Planning and Prioritization

Systematic spatial and temporal planning and prioritization of environmental watering actions are increasingly critical under climate change (Adams et al., 2017), especially given the need outlined above for more nuanced and aligned environmental flow and EWM objectives and targets over multiple scales. Furthermore, planning under climate change must take into account the many uncertainties involved including multiple plausible trajectories of change over the long term (e.g., Representative Concentration Pathways) as well as the possibility of extreme climatic events (e.g., heat waves, mega-droughts etc.) and other surprises in the short-term (Leigh et al., 2015), all of which generate high levels of uncertainty regarding both the supply of and demand for environmental water. Uncertainties relating to human responses to climate change and planning in other sectors (e.g., agriculture) will also influence environmental water availability and needs in space and time.

Rather than the traditional focus of environmental flows and EWM on reinstating historic flow regimes (**Table 1**), climate change calls for actively designing flows which address set objectives and are adaptive, resilient and robust across a range of scenarios, especially in regulated and highly modified catchments (Acreman et al., 2014a,b; Rockström et al., 2014). Such designer flow regimes could incorporate a provision to deliver "emergency flows" in response to extreme events or other surprises, e.g., dilution flows in response to pollution events, or flows to support unexpected waterbird breeding events. As per setting climate-ready EWM objectives and targets, planning and prioritizing environmental watering actions and designing flow regimes under climate change should be conducted across multiple spatial and temporal scales. Rivers, for example, require planning at catchment and basin scales while wetlands typically need finer scale priorities (Palmer et al., 2008). Conventional approaches to EMW have often focused on iconic wetlands (Swirepik et al., 2016) rather than whole catchments, with limited regard for the shifting habitat mosaics which comprise freshwater ecosystems and their associated landscapes and which drive dynamic ecosystem processes and biodiversity patterns (Datry et al., 2016). Instead, environmental water delivery needs to be prioritized at basin and broader regional scales (*sensu* the ELOHA framework: **Table 1**) to account for landscape connectivity and network structure (McCluney et al., 2014) and to better enable consideration of tradeoffs and synergies between ecological, social, economic and cultural values (Capon and Capon, 2017). Limited information and predictive certainty at local scales also requires ecologists, natural resource managers

and policy makers to broaden their spatial scale of actionable influence (Matthews et al., 2011; Poff and Matthews, 2013).

The uncertainties associated with climate change further compel greater flexibility and adaptability in EWM planning. Multiple planning pathways, for instance, might be developed in which objectives, targets, priorities and designer flow regimes vary in relation to antecedent or projected conditions (e.g., prolonged drought). Such plans would require the inclusion of trigger points to dictate when shifts between different management regimes should occur. While conventional EWM plans have typically had limited consideration of temporal context (Rolls et al., 2012), some recent exemplary environmental water plans, e.g., the Murray-Darling Basin Plan, have begun to incorporate multiple time frames (e.g., annual and long-term plans) with decision points shaped by temporal context and conditions (e.g., drought vs. flood years; MDBA, 2014); this approach has been adopted in other jurisdictions (e.g., the state of Victoria).

To minimize the risk of maladaptation, adaptive EWM planning should also occur in conjunction with planning concerning water resources infrastructure, e.g., extension or construction of new water storage or abandonment of infrastructure at high risk of stranding (e.g., Winemiller et al., 2016). Transformative EWM planning would also ideally be aligned with planning in other sectors, e.g., conservation, agriculture, urban planning etc. (Adams et al., 2017) so as to consider, for instance, potential threats to the effective delivery or outcomes of environmental water actions posed by activities in other sectors as well as risks posed by in turn by environmental water to other sectors (e.g., drowning of crops).

## Flow Delivery

Delivery of environmental water under climate change is likely to face considerable challenges in relation to water supply, especially in drying catchments where environmental water may be sacrificed to meet human demands. Adaptation approaches will be highly idiosyncratic depending on context, especially levels of river regulation and catchment modification. In regulated rivers, for example, adaptive environmental water delivery may entail dam reoperation (e.g., revised release rules or floodplain management) which takes into account risks and uncertainty associated with climate change (Watts et al., 2011; Poff et al., 2016). Expansion and construction of environmental water delivery works (e.g., pipes and levees to deliver and retain water on floodplains) might also be employed to enable watering of high value assets (e.g., floodplain forests). Such approaches, however, are associated with a high risk of perverse outcomes (Bond et al., 2014; Capon S. J. et al., 2017) and might be considered as either a last resort or a “band-aid” approach until other options become available. Hard engineering adaptation approaches to water delivery further risk stranding and/or mass failure and should be constructed with safety margins and regular reviews (Capon et al., 2013; Capon and Bunn, 2015). In unregulated catchments, environmental water delivery is typically achieved via rules governing water extraction, diversions and storage which might similarly be revised in light of climate change risks (Bond et al., 2008). The effectiveness of such

delivery mechanisms, however, will depend on adherence to these rules which, in turn, may depend on both institutional (e.g., monitoring and regulation) and social and cultural factors. Such adaptation approaches might therefore be supported by “soft” strategies aimed at fostering community involvement in the development and enforcement of environmental water rules.

Effective delivery of environmental water under climate change will be particularly promoted through improved integration of EMW with actions in water resources management more broadly as well as those in other sectors. Greater alignment of surface and ground water management, for example, may enhance capacity to deliver appropriate flows to many groundwater influenced freshwater ecosystems (e.g., Arthington, 2012; Gleeson and Richter, 2017). Similarly, flows delivered primarily for human demands (e.g., irrigation) can be designed so that ecological benefits are maximized, e.g., by “piggybacking” irrigation releases with environmental water (Watts et al., 2011). In turn, environmental water could be delivered so that socio-economic and cultural benefits (e.g., religious celebrations, recreational use) are also maximized (e.g., Jackson, 2017). Finally, the quantity and quality of water available for environmental watering actions, as well as ecological responses to these, are very likely to be influenced by pressures in the broader catchment (e.g., vegetation clearing; Davis et al., 2015). Consequently, improved catchment and riparian management is likely to play an important role in adapting environmental water delivery and sustaining ecosystems and livelihoods that depend on EWM (e.g., Stewart-Koster et al., 2010; Sheldon et al., 2012).

## Monitoring and Evaluation

Monitoring and evaluation (M&E) of environmental water actions have often been sparse under conventional environmental flow and EWM programs which have therefore generated limited understanding of whether or not interventions have achieved their objectives or, indeed, if objectives are even appropriate (Souchon et al., 2008; King et al., 2015). Climate change compels that considerable effort be directed toward M&E, however, so that ecological and human benefits of EWM can be demonstrated and adaptive management and learning appropriately supported. King et al. (2015) identify three major types of monitoring programs in EWM, all of which will be needed to adequately evaluate and adapt EWM in the face of climate change: (1) condition or program-level monitoring to assess ecological changes over large spatial and temporal scales; (2) compliance or operational monitoring focusing on water delivery targets; and (3) intervention monitoring to assesses responses to specific management interventions that may occur over both short and longer time periods.

To inform adaptive management, M&E must be clearly aligned with management objectives and targets which therefore need to be as specific as possible so that they can be both measured and evaluated while accounting for multiple possible outcomes (McDonald-Madden et al., 2010; King et al., 2015). Consequently, the selection of indicators used to monitor EWM will probably need to be adapted in light of climate change given likely revisions of objectives and targets. In particular, functional ecological indicators (e.g., species traits)

which reflect the resilience or adaptive capacity of ecological components and processes as well as socio-economic and cultural indicators describing the human benefits of EWM might be incorporated in addition to traditional structural ecological traits (e.g., species composition; Leigh and Datry, 2017). Holistic environmental flow frameworks (**Table 1**) facilitate input from diverse stakeholders and increasingly evaluate the social and cultural implications of environmental flows and water management alternatives (e.g., King and Brown, 2010; Finn and Jackson, 2011; Lokgariwar et al., 2014; Conallin et al., 2017). Poff (2018) also calls for a more robust and dynamic predictive science involving time-varying flow characterizations, and more use of process (e.g., demographic) rates and species traits rather than the present reliance on measurement of ecosystem state variables.

M&E related to the conservation of particular species or communities (e.g., threatened taxa, migratory waterbirds) must take into account shifting distributions of species in response to climate change (James et al., 2017). Because such changes are likely to occur both within and beyond the spatial confines of individual catchment planning regions or other jurisdictional boundaries, this emphasizes the need for collaborative M&E and adaptive management of EWM over multiple scales and institutional levels. Transformative M&E especially will require coordinated collection, evaluation and dissemination of monitoring data if responses of target species, ecosystems and landscapes to EWM are to be detected under climate change (Olden and Naiman, 2010; Wilby et al., 2010).

The benefits of monitoring and evaluating environmental flows using an adaptive management approach have long been recognized but unfortunately limited in application, perhaps because adopting such an approach or redesigning existing, non-adaptive programs accordingly can be somewhat daunting for managers and scientists alike (Richter et al., 2006; Pahl-Wostl, 2007; Webb et al., 2018). The challenges that climate change poses for EWM, however, make integrating M&E into broader planning and management frameworks essential to achieving effective outcomes and avoiding maladaptation. Nevertheless, adaptive management processes can take time with some indicators taking months or years to respond to particular flow interventions, delaying decisions on how or even whether to adapt plans for future interventions. A more variable climate means that environmental changes, including changes to river flows, may occur more rapidly and conventional (potentially slow) adaptive approaches may therefore need rethinking. To be transformative, EWM must be proactive and anticipatory rather than reactive (Pahl-Wostl, 2007; Bond et al., 2008; Wiens, 2016). Models that can predict likely outcomes of management interventions under different climate scenarios are therefore likely to become

increasingly valuable as an M&E tool (Webb et al., 2018). Anticipating future climate scenarios (e.g., a drier or wetter future) using “signpost” indicators of change within a regular monitoring schedule to trigger pre-emptive action will also allow environmental water management to respond more adaptively to climate change. Additionally, real-time data may also be required to capture rapid changes in environmental conditions so that interventions and management practices can be adapted accordingly in a timely manner (Wilby et al., 2010; Costigan et al., 2017). Technological advances in the collection and analysis of “big data” make such proposals increasingly realistic.

## KNOWLEDGE NEEDS

While there remains a paucity of knowledge concerning hydrological processes and flow-ecology linkages in most places (Arthington, 2012; Davies et al., 2014; Olden et al., 2014), effective adaptation and transformation of environmental flows and EWM under climate change is likely to be further hindered by several additional major areas of knowledge deficiency. In particular, relationships between ecosystem structure, function and the provision of ecosystem services, as well as how these respond to changes in flow, tend to be poorly understood in freshwater ecosystems (Dudgeon, 2014). Indeed, human values and benefits derived from freshwater ecosystems in general are not well understood or quantified, particularly with respect to how these are underpinned by flows and ecological responses to these (Arthington, 2015). Greater knowledge regarding likely effects of changes in climatic stimuli and extreme climatic events on all of these relationships, as well as their interactions with other drivers and pressures, is also needed to inform adaptation and transformation of EWM (Capon, S. et al., 2017). Linking human and environmental uses of water, through the lens of integrated water resources management, will require the adoption of connected systems-thinking approaches for EWM. Climate change offers an opportunity to link these oft segregated components of the system and deliver the needs of all in a transformative and proactive way.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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