IMPLEMENTING ENVIRONMENTAL FLOWS: LESSONS FOR POLICY AND PRACTICE

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IMPLEMENTING ENVIRONMENTAL FLOWS: LESSONS FOR POLICY AND PRACTICE

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Editorial: Implementing Environmental Flows: Lessons for Policy and Practice

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Editorial on the Research Topic

Implementing Environmental Flows: Lessons for Policy and Practice

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Water resources and freshwater ecosystems are under pressure from a growing human population, thirstier lifestyles, and climate change (UNESCO and UN water, 2020). Consequently, water-related risks to society are increasing (World Economic Forum, 2020) and freshwater biodiversity is rapidly declining (Grooten, 2018). The UN Sustainable Development Goals (SDGs) include targets for improved water management, including SDG 6.4, which stipulates sustainable water withdrawals, and SDG 6.6, aimed at halting the degradation of water-related ecosystems. The hydrological regimes of rivers and other wetlands can be regarded as a litmus test of whether these targets are met (Tickner and Acreman, 2013). Environmental flow assessment (EFA) is the science-based process of determining appropriate flow regimes for individual water bodies given environmental, socio-economic and cultural objectives. Researchers have developed sophisticated EFA tools (Acreman et al., 2014; Poff et al., 2017) but implementation of environmental flows has been problematic, and research into the challenges of implementation is scarce.

Case studies of environmental flow implementation, successful or otherwise, provide valuable insights into barriers and enabling factors, and illustrate the evolution and propagation of environmental flow practice globally. The Murray-Darling River, Australia, is among the most studied and contested of such cases. Stimulated by severe drought, the Federal Government instigated a basin-wide water allocation planning process in the mid-2000s. Gawne et al. describe the use of conceptual models in the development of the basin plan. They argue that such models inform the setting of ecological objectives, support decision-making where data are scarce, and help integration of basin- and local-scale analyses. As with the Murray-Darling, the ecological condition of the River Ganga, India, has been adversely affected by a high demand for irrigation water. The Ganga is spiritually revered by hundreds of millions of people and the Government of India has placed a high priority on its restoration. Kaushal et al. document approaches to understand and resolve potential trade-offs between environmental flow objectives for the Ganga in Uttar Pradesh and agricultural water demand. They conclude that, contrary to common perceptions, the increase in water needed to restore flows is likely to be small compared to overall water demand. Moreover, agricultural water efficiency measures can ameliorate potential adverse impacts on farmers from changes in water allocation. On a similar theme, Linstead et al. draws on an increasing body of literature that warns of perverse outcomes from increasing irrigation efficiency. He suggests that an effective water allocation regime that explicitly accounts for environmental flows is a pre-requisite if agricultural water savings are to lead to ecological benefits. Even where such an allocation regime exists, he argues that analysis at multiple spatio-temporal scales is necessary to understand the implications for environmental flows of changes to irrigation. Richards and Syallow also analyse the challenges of reconciling farmers' water needs with environmental flows, but at a more local scale. Focusing on village-level Water Resource User Associations (WRUAs) along the Mara River, Kenya, they identify progress in local discourse about sustainable water use, and potential pitfalls of which water managers, NGOs and others pursuing environmental flow implementation should be aware. These include elite capture, donor dependency and a lack of meaningful participation opportunities.

Dams built for hydropower and other uses can substantially impact hydrological regimes, as well as fragmenting aquatic habitats (Grill et al., 2019). Drawing on North American experiences in dam re-operation, Opperman, Kendy and Barrios set out two pathways for embedding environmental flow implementation in the siting, design and operation of water infrastructure. The first emphasizes the potential for basin or jurisdiction-scale policy and management to catalyze implementation efforts widely. The second focuses on measures for specific dams or river reaches of high conservation value. Critically, these two pathways should, wherever possible, be nested such that management efforts are integrated across scales. King and Brown also endorse system-scale assessments of likely infrastructure impacts. They issue a welcome call for integration of EFA as an early stage in Cumulative Impact Assessments (CIAs) of planned dams across river basins, with context-specific selection of EFA methods. Cheng et al. describe the problems for downstream fisheries caused by the Three Gorges Dam on the Yangtze River, China. They document experiments with flow releases from the dam over a 5-year period that have shown the potential for partial mitigation of the decline in fish recruitment without compromising hydropower generation and flood protection. As in the other case studies, future success will depend on continued monitoring, stakeholder engagement, and adaptive management.

Four papers in this Research Topic set out agendas for future research, policy, and practice on environmental flow implementation. Horne et al. report on a horizon-scanning exercise that explored research priorities for improving outcomes from environmental water management. Six themes emerged, including adaptive management, knowledge transfer, and community engagement. Opperman, Kendy, Tharme et al. noted the recent diversification of EFA methods and the need for guidance to practitioners and policy makers as to which method might best suit their context. They suggest a three-level framework—with levels of complexity increasing with each level—for ensuring that approaches to assessment and implementation of environmental flows are linked, and that implementation happens as early as possible. Harwood et al. also consider the policy dimensions of environmental flow implementation. Drawing on eight case studies of "successful" implementation from around the world, they distill critical enabling factors that can provide a foundation for effective policies. These include the existence of appropriate legislation and regulation, collaboration, and leadership, resources and capacity, and monitoring and adaptive management. Capon et al. explore the necessity for environmental flow implementation to be resilient to climate change. They point out that many EFA methods rely on outdated assumptions of hydrological stationarity that might lead to flawed implementation plans. Urging a re-evaluation of conventional approaches, they put forward proposals for adapting objective-setting, planning, and management of water resources to take account of climatic uncertainties.

Cutting across the themes and cases described above, O'Keeffe presents a personal perspective on the need for improved training on assessment, policy, and practice for environmental flow implementation. He describes the evolution of a training approach that was pioneered in partnerships with academic, government, and NGO practitioners. He makes a compelling case for securing three ingredients for successful training and implementation that is adaptable to multiple settings: local champions, with a long-term commitment; understanding and support from stakeholders; and a process that is, initially at least, as simple as possible and that demonstrates quick implementation successes.

The Brisbane Declaration (2007) was a seminal document in global research and policy on environmental flows. Endorsed by hundreds of experts and setting out a common vision for implementation, it guided subsequent efforts worldwide. Arthington et al. describe the extensive consultation process to update the Declaration, a decade on. They present the resulting 2018 Brisbane Declaration with its revised environmental flow definition and urgent call for action to implement environmental flows as a foundation for achieving water-related SDGs. The accompanying Global Action Agenda outlines the pathway for a new era of collaborative endeavor, to more effectively bridge the science-policy interface and accelerate implementation.

The papers in this Research Topic draw on experiences from multiple regions and a wide range of perspectives. As such, they provide a unique blend of insights into the connections (or lack thereof) between research, policy and practice. It is clear that progress is being made; environmental flows are being implemented in rivers and wetlands internationally. Equally, a combination of technical, environmental, socio-economic, cultural, and political complexities will mean that ensuring sustainable water use, and maintaining or restoring freshwater ecosystems, will continue to be challenging. Many of the papers provide explicit recommendations that will help policy makers and practitioners to navigate these challenges. For instance, a clear focus from the outset on supporting the establishment of durable enabling conditions for more sustainable water allocation and infrastructure development processes is crucial. Ensuring robust conceptualization and sufficient knowledge of the natural and social processes that influence water management at multiple scales is also important. Approaches to implementation that explicitly consider future uncertainties are likely to be more resilient than those which are based entirely on past conditions. Choosing the right environmental flow assessment method for the context is always helpful, as is demonstration of early success. There is ample scope for further analysis that delves deeper into lessons from a wider range of cases, especially with respect to social sciences aspects (Anderson et al., 2019) and impacts of implementation on freshwater biodiversity. It will be essential to revisit the insights in this Research Topic in due course to further inform future policy and practice. In the meantime, implementation efforts that are inclusive, pragmatic, adaptive, and multi-disciplinary can bear fruit even where knowledge gaps remain.

DEDICATION

On behalf of the global environmental flow community, we dedicate this Research Topic on environmental flow implementation to our beloved friend and colleague, the late Jay O'Keeffe, Emeritus Professor at Rhodes University, South Africa. Jay was a global pioneer and thought leader in the field of environmental flows. Throughout his career, he contributed his passion, deep insights, on-the-ground experience, and boundless energy to help create the interdisciplinary foundation on which so many other practitioners have been able to build. His true commitment to the mentoring and training of young professionals nurtured a growing capacity for environmental flow implementation in the Global South. We are committed to ensuring his legacy is an enduring one.

AUTHOR CONTRIBUTIONS

DT drafted the manuscript. NK, RS, and RT contributed to revisions of the manuscript. All authors contributed to the article and approved the submitted version.

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REVIEW
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Research Priorities to Improve Future Environmental Water Outcomes

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Significant progress in environmental flow management has occurred in recent years due to several factors. These include governments committing to environmental flow programs, significant progress in scientific understanding, and environmental flow assessment methods that are cognizant of stakeholder participation and co-design. However, there remain key challenges facing environmental water management. In this paper, we report on a horizon scanning exercise that identified the questions, which, if answered, would deliver much needed progress in the field of environmental water management. We distributed an online survey to ask researchers and practitioners in the field of environmental water management to identify the key questions. The authors then consolidated 268 submitted questions and organized them into key themes. The consolidated list was presented to a workshop of environmental water researchers and practitioners, where attendees were asked to review the questions, vote on the most important, and provide feedback on gaps, issues, or overlaps. The breadth of issues facing environmental water management is captured by the six key themes into which questions were classified: (1) Ecological knowledge and environmental flow assessment methods, (2) Adaptive management, (3) Integrated management and river objectives, (4) Knowledge transfer: applying best practice in a global context, (5) Community knowledge and engagement, and (6) Active management. These questions provide a roadmap for research and management innovations that will improve the effectiveness of environmental flows programs.

Keywords: environmental flows, environmental water, horizon scanning, adaptive management, active management

INTRODUCTION

Aquatic ecosystems and freshwater biodiversity are in decline worldwide (Dudgeon et al., 2006). Continued population growth and changing life styles, coupled with climate change, will only increase competition for scarce water resources in many regions in the future, with commensurate increases in the threats to aquatic ecosystems (Meyer et al., 1999; Poff et al., 2002), and in some cases significantly modifying current river ecosystems and generating hybrid and novel systems (Acreman et al., 2014; Laizé et al., 2017). Environmental water management aims to respond to these threats by both protecting and where necessary restoring flow regimes to support aquatic ecosystem function and biodiversity (Meyer et al., 1999; Poff et al., 2002). In 2007, the Brisbane Declaration established an international consensus on the definition of environmental flows, as *"the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and* ***the human livelihoods and well-being*** *that depend on these ecosystems"* (emphasis added). As a result, environmental flows assessments have expanded from site-specific scientific studies to holistic studies that recognize the links between hydrology, ecosystem condition, societal expectations, and socio-economic outcomes. The Brisbane Declaration called for commitment to a number of key actions to restore and maintain environmental flows, many of which were aimed at expanding the number of locations where environmental flows are implemented, broadening stakeholder engagement, and enhancing the capacity required to implement and maintain environmental flows (Brisbane Declaration, 2007).

It is now 10 years since the Brisbane Declaration and there has been clear progress on a number of fronts. First, the concept of environmental flows and "environmental water management" has been widened to reflect the sentiments of the Brisbane Declaration. Environmental flow assessment methods are now cognizant of stakeholder participation and co-design, and recognize the dual role of environmental water in supporting ecological and social values, especially for those who rely on rivers and floodplains to support their livelihood (King and Brown, 2010; Finn and Jackson, 2011). Second, there has been significant progress in our understanding of the scientific concepts and ecological processes that underpin environmental flows (Arthington et al., 2006; Horne et al., 2010; Arthington, 2012; Acreman et al., 2014), and third, environmental water requirements have now been discussed and incorporated into high-level water policy and legislation in many countries across the globe (Hirji and Davis, 2009; Le Quesne et al., 2010; O'Donnell, 2014). This latter development is reflected in the growing number of government agencies and non-government entities funding environmental water projects (Garrick et al., 2011; Pahl-Wostl et al., 2013), and the large sums expended on river flow restoration projects. We have also recently seen the first cases of rivers being granted the same legal status as a person and with the same rights—the Whanganui River in New Zealand, the Ganga and Yamuna Rivers in India (currently stayed pending the outcome of an appeal to the Supreme Court), and Himalayan glaciers, rivers, streams, lakes, and forests (O'Donnell and Talbot-Jones, 2017). Collectively, the establishment of these new legal persons represents the most significant creation of new legal rights for nature since 2010, when Bolivia passed the *Law of Rights of Mother Earth* (Plurinational State of Bolivia, 2010).

Despite this progress in the science, policies and legislation of environmental flows, cases of implementation have been limited, There remain key challenges facing environmental water management, especially in response to the rapid socio-economic and environmental changes currently affecting rivers in many regions of the globe (Poff and Matthews, 2013; Rockström et al., 2014; Zarfl et al., 2015). In this horizon scanning exercise, we identify and discuss the big questions, which, if answered, would deliver significant progress in the field of environmental water management, and would underpin the next wave of efforts to protect and restore these most important aquatic ecosystems.

METHODS

Horizon scanning exercises like the one discussed here provide a useful reference of the current state of the discipline, and help to set the agenda for future research efforts (Sutherland et al., 2006). Past horizon scanning studies in the environmental science field have identified questions using some combination of: (1) a survey to gather as wide a range of opinions in the field as possible, (2) a workshop, and (3) a review process (Sutherland et al., 2006, 2013; Rudd et al., 2011; Parsons et al., 2014; Seddon et al., 2014). We used all three stages of this sequence.

We developed an online survey, the link for which was distributed through the authors' existing professional and research networks. The survey link was also distributed to authors of papers from Environmental Flows sessions at the International Symposium on Ecohydraulics (ISE), the community for the conference at which the later workshop took place. Receivers of the email were also asked to distribute it to their own networks, so the total number of recipients would have been larger. The survey asked researchers and practitioners in the field of environmental water management to identify:

> "What questions, if answered, would allow the biggest progress in the field of environmental water management?"

Respondents were asked to think globally, with no limitation on the scope of the questions, so they could be broad high level questions, or very specific questions.

We then reviewed the survey responses and identified overlaps in content. The questions were consolidated into a smaller list (included in this paper) and organized into key themes. Classification of the questions drew on the diverse and extensive experience of the authors. For example, although many individual questions related to the theme of climate change, the authors considered that climate change is an issue that needs consideration as part of all elements of environmental water management. Thus, climate change has been integrated into all themes rather than being a single theme.

The consolidated list was presented at a workshop conducted during the 11th ISE meeting, held in Melbourne, Australia, in February 2016 (Webb et al., 2016). This international conference drew delegates from over 30 countries, and environmental water management was one the key foci, including several sessions dedicated to this topic. Further, unlike many other conferences that deal with environmental flow science, this conference spans a range of disciplinary perspectives and extends from science to practice. The workshop attracted approximately 40 participants. Questions were arranged into themes, with each theme's questions posted in a different part of the room. Participants were conducted around the room and took place in a discussion facilitated by two of the authors (JAW, ACH) about each theme and question to maximize shared understanding. Participants were asked to review the questions, vote on the most important, and provide feedback on gaps, issues, or overlaps. This paper is based on the questions identified through the survey, refined through the workshop, and complemented by insights and discussions during manuscript preparation.

There are clear limitations in any exercise of this kind. The questions identified will be closely linked to the geographies and disciplines of those involved in the survey. We attempted to mitigate these effects though the multi-step approach, and through the inclusion of a range of backgrounds, specializations, sectors, and locations, but there will no doubt remain some inadvertent bias. However, as seen in the results section, some regions are underrepresented in the survey (e.g., South America, North America and Africa). This is likely due to the distribution lists used for the survey which may have placed greater emphasis on Australia and Oceania. Similarly, there is a greater representation of ecology and hydrology which reflects the dominance of these disciplines more broadly in the science and practice of environmental flows. Importantly, the authors for this journal paper include a broad cross-section, both in terms of geography and discipline to ensure a broad and balanced perspective in the interpretation of the study results. However, a limitation of such horizon scanning exercises is the sample of opinions included in the process. Despite these limitations, this overview provides a valuable snapshot of the big issues for future environmental water management and offers a challenging and timely re-assessment of future research agendas.

RESULTS

Sixty-five individuals responded to the survey, providing a total of 268 questions. A full list of questions obtained through the survey is provided in Supplementary Material. Approximately half of the respondents identified themselves as practitioners, and 61% identified themselves as researchers (i.e., some respondents identified as both). The majority of respondents were ecologists and hydrologists, with a smaller number of engineers, lawyers, economists and social scientists. The majority of respondents were from Europe (27) and Oceania (24), with smaller numbers from North America (8), Africa (3), and Asia (3).

The original questions were consolidated into 57 questions, which were classified into six themes that cover the full range of the environmental water management cycle (Horne A. et al., 2017b). The environmental water management cycle includes establishing a vision and objectives for the river (through broad stakeholder engagement), the science of determining the flow regime needed to achieve the objectives, legal and institutional arrangements to allocate and manage the water, and monitoring, evaluation and adaptive management. During the workshop, 10 questions received much larger numbers of votes than the other 47, demonstrating their importance for workshop participants. Below, these questions have been highlighted and are discussed in detail. The other questions for each theme are presented in boxed text, and are not listed in any particular order.

Ecological Knowledge and Environmental Flow Assessment Methods

At the heart of any environmental flow assessment method lies a need for knowledge of how the ecology of a system has been affected by past human-induced changes in flow regimes, and how it may respond to the partial or full restoration of particular flows. Both the lack and inconsistency of generalizable empirical relationships linking flow changes to ecological response (Poff and Zimmerman, 2010) has seen the predominance of expert-based predictions of ecological response becoming embedded in major environmental flow assessment frameworks (Horne et al., 2010). Recognizing the limitations of such frameworks, river scientists have emphasized the need for empirical flow-response relationships for use in assessments (Arthington et al., 2006; Poff and Zimmerman, 2010; Davies et al., 2014). Even so, most of these recent efforts are still largely based on relatively simple ecohydrological models (Webb et al., 2017). Our respondents and workshop participants concluded that there is still much work required with regard to basic knowledge of river ecology and how to incorporate such knowledge into environmental flow assessments, implementation, and management.

> Q1—Can we demonstrate clear quantitative links between the ecology of aquatic species and alterations in hydrology or hydraulics at different spatial and temporal resolutions, and develop appropriate models of these relationships?

Although our understanding of flow-ecology relationships has significantly improved over the past 20 years (Arthington, 2012), there remain substantial gaps in our knowledge of the ecological effects of flow alterations (Poff and Zimmerman, 2010; Webb et al., 2013). River ecosystems are influenced by a wide range of factors, including species interactions, temperature, and sediment dynamics, that may interact in numerous unspecified ways with flow alteration (Acreman et al., 2014). With much research still reliant on drawing patterns from uncontrolled changes in flow conditions during floods or droughts, a major challenge is to undertake controlled water management experiments at the catchment scale (Konrad et al., 2011; Olden et al., 2014). More collaboration between dam owners/operators, landholders, and scientists is needed to co-develop hypotheses and provide robust tests of these via flow manipulation experiments (Poff et al., 2003). This need to improve our basic understanding of ecological relationships with flow is reflected in Question 1, and the other questions identified below sit under this higher level challenge.

> Q2—Can we determine ecosystem resilience, and thresholds that lead to a major change in ecological condition (or state) (i.e., can failure points be identified)?

Current environmental flow assessment methods hinge on the assumption of a stationary climate (i.e., long term average climate conditions with variation) (Poff and Matthews, 2013). It is now recognized that the climate is changing and future hydrologic regimes are likely to deviate substantially from historical *reference* conditions in many regions (e.g., Reidy Liermann et al., 2012).

BOX 1 | Other key questions for ecological knowledge and environmental flow assessment methods.

- What is the current condition and biodiversity of our rivers worldwide?
- Are organisms adapting to altered hydrological and geomorphological regimes? We assume in our habitat suitability approaches that organisms have preferences that, when not available, permanently diminish their performance and success. How strong is the evidence for this assumption?
- What is the time to, and duration of, ecosystem responses to prescribed environmental flows and what factors affect recovery rate from flow alteration?
- What is an appropriate reference condition in altered systems (altered through for example climate change, significant channel modification or regulating infrastructure)?
- What is an appropriate flow assessment methodology for an ephemeral stream or intermittent river?
- What are the best methods and tools for environmental flow assessments in under-allocated[1]. (rather than over-allocated) systems?
- How should multiple stressors be considered in environmental flow assessment and management?
- How do we better include the role of temperature and water quality in environmental water assessments and desirable outcomes and how will this change under scenarios of climate change?
- Are we adequately considering sediment inputs to streams and their role in hindering and enhancing ecological response?
- How do we identify and create system-scale protected areas that conserve key processes and functions?
- How do we relate broad scale water management issues with protection of habitat and conservation of biodiversity at local scales?
- When is it appropriate to transfer eco-hydrological knowledge between river systems? How do we extrapolate monitoring and evaluation outcomes from one area to another area that has not been monitored?
- What research methods will allow us to use site-scale data to inform large-scale responses to environmental flows, and include these in decision making?

Hybrid and novel ecosystems are likely to be created (Acreman et al., 2014; Moyle, 2014; Laizé et al., 2017). An understanding of ecological thresholds and resilience will become increasingly important as climate change further impacts river flow regimes and ecosystems (Rockström et al., 2014). This will require specific research to understand the resilience and reversibility of particular environmental systems (Groffman et al., 2006; Capon et al., 2015).

Further key questions on *Ecological knowledge and environmental flow assessment methods* are shown in **Box 1**.

Adaptive Management

Adaptive management centers on iterative learning and feedback to change management strategies (Allen and Garmestani, 2015; Webb et al., 2017). Adaptive management is well-suited to problems such as environmental water management, where the outcomes are responsive to management, there is uncertainty about the impacts of management, and yet decisions must still be made (Williams and Brown, 2014). There are multiple sources of uncertainty affecting environmental water management, including climatic uncertainty affecting future water availability and demands for consumptive use, and scientific uncertainty concerning ecological responses to changing patterns of flow variability (Lowe et al., 2017). While many environmental water agencies and policy documents refer to adaptive management, there are few documented examples of its successful implementation (Westgate et al., 2013).

Q3—How do we progress adaptive management processes beyond simply meeting targets toward learning and feedback?

One of the key benefits of adaptive management is its potential to facilitate learning through a structured dialogue between scientists, citizens, and managers (Pahl-Wostl et al., 2007; Ladson, 2009). However, a preoccupation with meeting targets largely limits environmental water management to an audit-based view of success or failure and does not sufficiently value learning. Related to this is the significant challenge for adaptive management of establishing the legitimacy of the environmental water program to operate within institutional settings that allow both success and failure, and therefore maximize the rate of learning. Getting the institutional arrangements correct will be essential to the success of adaptive management (Ladson, 2009). This may require fostering relationships across institutions that bring different skills and incentives (Westgate et al., 2013).

Q4—How to determine (and fund and maintain) an adequate monitoring, evaluation, reporting, and feedback system within an adaptive management cycle to measure hydrology, hydraulics, etc., and the ecological response to environmental flow regimes?

Monitoring and evaluation form an essential, but often time-consuming and expensive, aspect of adaptive management (Williams and Brown, 2014). Without monitoring, there can be no adaptive learning, no way to complete the adaptive management cycle, and no way to update future management in light of new knowledge. One reason identified for the failure of adaptive management is the unfortunately common lack of commitment to monitoring and evaluation by management agencies (Schreiber et al., 2004). Monitoring and evaluation programs need to support both short-term implementation and long-term planning of environmental water programs and must be designed to distinguish flow-related impacts from multiple other pressures affecting ecosystem state and function (see also section Integrated Management and River Objectives). The design, funding, and administration of such monitoring and evaluation programs needs to be identified as early as

[1]In this context, an under-allocated system refers to a system where it may still be possible to increase consumptive water use and retain ecological values of the river. An over-allocated system is one where water abstractions or flow regulation is significantly impacting on the environmental values of the river and a rebalance is required.

BOX 2 | Other key questions for adaptive management.

- How do we operationalize evidence-based environmental water management? How do we translate research evidence into the decision-making processes?
- How can adaptive management approaches best be applied to implementation of environmental flows? Do the text book approaches suit environmental water management?
- How do we capture and disseminate the learnings and lessons from "informal adaptive management"? How can we legitimize this approach?
- How do we maintain support and funding to allow the completion (many times) of the adaptive management loop of plan-implement-measure-respond?

possible, and a commitment made to long-term engagement (Davies et al., 2014). Moreover, a framework needs to be in place to incorporate the lessons from monitoring outcomes and evaluation into updated management practices (Webb et al., 2017). Exploring options to enhance the resourcing, local support and implementation of monitoring and evaluation (e.g., Liu et al., 2014) has the potential to allow adaptive management to occur in places where it may otherwise be neglected. Informal adaptive management (Allan and Watts, 2017) may emerge spontaneously in systems where there is trust and good communication between stakeholders, but no formal process in place.

Further key questions on *Adaptive management* are shown in **Box 2**.

Integrated Management and River Objectives

It must be emphasized that environmental water needs should be considered as a core part of water planning, water infrastructure design and operations, and overall catchment management, rather than independently (Hirji and Davis, 2009). However, while there are approaches that embed environmental flows within broad catchment management (King and Brown, 2010), these decisions are often made somewhat in isolation of one another (Horne A. et al., 2017a), ignoring the well documented effects of other catchment stressors that may act independently or interactively with flows (Jakeman and Letcher, 2003). *Post-hoc* evaluation of environmental water projects has often identified co-occurring stressors as responsible for underachievement from environmental water delivery (Rolls et al., 2012; Mackie et al., 2013). Failure to manage co-occurring stressors in an integrated fashion is partly a function of how catchment and water management agencies have developed over time, but is also partly driven by the different rates at which decision-making processes for different water and catchment uses have evolved over time. Truly integrated catchment management (sensu Smith et al., 2015) would be a major step forward for all stakeholders.

> Q5—How can environmental flows be better integrated into mainstream water resource planning, flood and drought management, river operations and infrastructure planning, balancing the needs of people and ecosystems?

Environmental water is often seen as competing for water with consumptive water users, however, providing environmental flows greatly enhances water security for other users (Tickner and Acreman, 2013; Tickner et al., 2017) and there are significant opportunities to design infrastructure and water delivery to consider environmental water requirements (Poff et al., 2016). Considering environmental water management decisions in isolation from other water management tasks is unlikely to optimize water use across all stakeholders. Where water infrastructure is being planned, opportunities exist to avoid or minimize potential socio-ecological impacts of this infrastructure at a system scale, particularly through appropriate dam placement (Opperman et al., 2015; Winemiller et al., 2016) and the use of dam design features and operational rules that enable environmental water delivery (Poff et al., 2016; Thomas, 2017). These opportunities are rarely available for existing infrastructure that was developed in isolation without consideration of environmental water needs. Environmental flows usually aim to consider all aspects of the flow regime, not just quantity One feature of critical importance to river functions is inundation of floodplain areas and wetland ecosystems (Yarnell et al., 2015). Environmental water management needs to maintain these critical ecosystem processes through the integration of high flow events with flood management for protection of infrastructure and floodplain uses (Acreman et al., 2009; Arthington, 2012). Drought management also presents significant challenges, including protection of refuge habitats for aquatic biota at landscape scale, and options to provide environmental flows in critical river reaches (Bond et al., 2008).

> Q6—How can we improve the management of consumptive water to help meet environmental objectives?

Ideally, the governance structure for managing water resources would encourage development of approaches that maximize shared benefits for both environmental and other water users (for example, by managing water delivery to maximize both consumptive and environmental outcomes, such as enabling river operators to use irrigation or hydro-power water delivery to meet environmental flow requirements). However, environmental water management is often isolated from water management more broadly. This limits the capacity for novel integrated solutions to emerge, and for effective policy debate (Dalal-Clayton and Bass, 2009).

This problem is exacerbated by current institutional boundaries that delineate the environment as separate to productive uses of water, and which can reinforce a competitive mind set between these purposes. For example, although the creation of water rights for the environment in Australia and the western USA has increased the volume of environmental water and improved environmental outcomes (Garrick et al., 2009), it has done so by constructing the environment as just another user of water (O'Donnell, 2017). In Australia, the Commonwealth Environmental Water Holder frequently refers to itself as the largest irrigator in the basin (Docker, 2013). Rather than enabling a collaborative approach that can deliver shared benefits to both the environment and irrigators, this framing places the environment's need for water in direct competition with "other" irrigators' needs. Although these environmental water rights (which are often legally very similar and in some cases identical to irrigator water rights), and the organizations that manage them, have been an important step forward in improving environmental water management, they have also increased the institutional separation between water planning more broadly, and managing water for the environment.

> Q7—What changes will be needed to environmental objectives and water allocation frameworks to support environmental water management under climate change? How are climate change risks distributed amongst water users?

As climate change continues to impact upon water availability, major policy discussions will be required to consider how changes in resource availability are to be distributed amongst water users, and what changes may be required to river basin objectives (Acreman et al., 2014). Integration of environmental water consideration into existing consumptive water management activities requires new tools, skills and governance arrangements for water management institutions. These institutional arrangements and environmental water allocation mechanisms need to reflect conscious decisions concerning how water resources will be managed adaptively over time (Horne A. C. et al., 2017b; O'Donnell and Garrick, 2017b).

Further key questions on *Integrated management and river objectives* are shown in **Box 3**.

Knowledge Transfer: Applying Best Practice in a Global Context

There have been few attempts to systematically assess the global experience on implementation and effectiveness of environmental watering under different levels of development, administrative settings, and political systems (Pahl-Wostl et al., 2013). The challenge and urgency of protecting water regimes is global, but significant advances in environmental water science, policy, and practice have been unevenly distributed among countries and biophysical, social, cultural, and political settings (McClain and Anderson, 2015). A present-day cartogram of published research efforts on environmental flows would be heavily skewed toward North America, Europe, and Australia (Poff and Zimmerman, 2010; Konrad et al., 2011).

> Q8—What are the best methods and tools for environmental flows assessment and implementation in developing countries?

Many developing countries are grappling with the challenges of poverty alleviation, human well-being, and rapid economic development. In such settings there is a need for relatively simple methods that can be used to quantify environmental flow needs in a quick, transparent, and repeatable fashion. Direct and indirect human needs must form an important component of this assessment (Christie et al., 2012). While it is not possible to outline specific approaches in detail here, we highlight the importance of several key elements, including the need to elicit and synthesize local indigenous knowledge together with scientific information where it is available (see Q10), the need to characterize key aspects of the natural flow regime, especially seasonality and inter-annual variability, and the use of conceptual models to identify important components of the flow regime that warrant some degree of protection in order to sustain biophysical processes. Numerous "hydrology only" methods have been developed, which can also be used in a precautionary sense to try and set limits on hydrologic alteration. Arguably the initial goal should be to ensure some degree of flow-regime protection to help prevent irreversible ecological impacts (Richter et al., 2012), until such time that there are policy and funding frameworks in place to support the refinement of sustainable long-term water-sharing arrangements among various competing and compatible users (including the environment).

BOX 3 | Other key questions for integrated management and river objectives.

- How will water resource availability in both surface water and groundwater systems change into the future (climate change, landuse change, interception), and how will changes in water availability impact environmental water management?
- Should environmental flows be managed for restoration of particular elements (species, processes) or for adaptive potential (i.e., management for ecosystem resilience)?
- What is the best approach to determining how much water can be sustainably extracted from a river (e.g., by setting a resource cap)?
- How can environmental outcomes be better represented in trade-off decisions where there are different kinds of information about the benefits in economic terms?
- How can the costs of providing environmental flows and the benefits of ecosystem services be better quantified to support water allocation decisions?
- How can environmental flows be more effectively integrated with other natural resource management activities, such as riparian restoration and the management of invasive alien species?
- How can we build complementary works (e.g., habitat restoration, effects of barriers, invasive species management) into the evaluation framework for environmental flows and future management decisions?
- How can we better understand and address the impacts of increased urban stormwater on urban waterways?
- How do we manage the risk of private property flooding (third party impacts) when providing large events for floodplain inundation?
- How can effective resource caps be implemented where systems are managed across agencies or jurisdictional boundaries?
- What is the best approach to assess how well environmental water is allocated and protected through governance arrangements, policy, and legislation?
- How should we embed environmental flows into the food-energy-water-ecosystem nexus, and the Sustainable Development Goals?

BOX 4 | Other key questions for knowledge transfer: applying best practice in a global context.

- How many countries have included environmental water needs into formal legislation and how is this achieved?
- What models of environmental water governance exist around the world and what can we learn from them?
- What models for embedding environmental flows in water allocation mechanisms are used around the world and how effective are they?
- How can we undertake quick and cost-effective (but still robust) environmental flow assessments in knowledge poor systems?
- Can a better understanding of ecosystem services contribute to implementation of environmental flows in developing countries?
- Are there innovate funding mechanisms that can help secure more water for environmental flows and their management?
- How do we facilitate a rapid response to the decline of aquatic biodiversity?

BOX 5 | Other key questions for community knowledge and engagement.

- How do we build a broader, deeper community engagement in and support for environmental water?
- How do we communicate concepts of uncertainty and variability in the context of environmental water management and outcomes without undermining public support?
- How can centralized 'top down' decision making best be integrated with localized 'bottom up' decision making in environmental water management?
- How should the concept of efficiency (i.e. least cost transactions) be balanced with legitimacy (public support and consultation) for environmental water management organizations?
- How can indigenous and local knowledge be incorporated into environmental flow visions, planning, implementation and adaptive management?

Further key questions on *Knowledge transfer* are shown in **Box 4**.

Community Knowledge and Engagement

A central element of sustainable water management is establishing a shared vision for the river system, acknowledging the diverse uses of the resource, and recognizing the variety of ways that different cultures value the natural environment. The amount of water needed by a river is inherently linked to what type of river and ecological services the stakeholder community wants. The benefits of stakeholder participation in policy and management are well-recognized, leading to a better quality of decision, better acceptance of decisions and development of social capital (Poff et al., 2003; von Korff et al., 2012). This type of legitimacy is crucial to the long-term success of environmental water programs, ranking alongside efficiency and effectiveness as the core elements of good water governance (OECD, 2015).

Q9—How can a more effective partnership between all stakeholders—government, communities, NGOs, and scientists—be developed?

Effective stakeholder engagement requires the involvement of multiple groups, and respect for their different sources of knowledge, values, and visions for aquatic ecosystems. Building a meaningful partnership between stakeholders in which all are committed to achieving successful enviornmental water management takes time, effort, trust, and humility (Horne A. C. et al., 2017a). However, there remain two clear challenges that require novel approaches, these being: (a) the implemention of participatory approaches in practice (Creighton, 2005), and (b) measuring how successful these have been (O'Donnell and Garrick, 2017a).

Q10—How best to build a shared understanding among all stakeholders (including scientists)?

One of the profound shifts in the environmental flows assessment process has been the transition from a purely technical ecological and hydrological assessment, to the inclusion of local communities and their values from the outset (Poff et al., 2003; Rogers, 2006; Finn and Jackson, 2011). Frameworks emerged in South Africa that considered the implications of management scenarios for the people dependent on a river's natural resources (King et al., 2003; Arthington, 2012). However, this process of engagement can become fragmented after the initial environmental flows studies are complete. The management of environmental water is an ongoing process, and the adaptive management and learning processes need to include continued dialogue between local communities, practitioners and researchers. There is a particular challenge to integrate and value local and indigenous knowledge and perspectives with knowledge derived from researchers and technical agencies (Finn and Jackson, 2011; Tan and Jackson, 2013; Tan and Auty, 2017).

Further key questions on *Community knowledge and engagement* are shown in **Box 5**.

Active Management

Increasingly, mechanisms that require active and ongoing decision making by environmental water managers are being used to allocate environmental water, particularly in systems that have high levels of abstractive demands and hydrological alteration. The Murray-Darling Basin, Australia, is perhaps the most notable example of this. By *active management*, we mean systems where environmental water managers hold a right to water and are required to make particular decisions about when and where to release environmental water from storage to achieve the best possible environmental outcomes (Doolan et al., 2017; Horne A. C. et al., 2017c). In other management settings it may

BOX 6 | Key questions for active management.

- How can variability and sequencing of flow events and recovery of species be better integrated into environmental flow assessment methodologies?
- Can we mimic elements of the natural cycle of variability rather than attempting to optimize across all environmental endpoints in all years?
- What is the marginal improvement in biological conditions from incremental change in stream flow or water level (or from one flow component over another) at different stream locations?
- How should ecosystem sensitivity, resilience and recovery rates be incorporated into decision making?
- What tools or prioritization process would support decision-making and trade-offs between environmental water regimes that have different objectives (considering also the water preferences of invasive species)?
- What governance arrangements are suited to the real-time management decisions required for active management?

mean shifting between predefined conditions (wet or dry) that have distinct environmental flow values associated with them (King et al., 2008). These dynamic and reactive decisions require more information from the scientific community concerning the marginal benefits of providing water at a particular time and location, and the sequencing or interaction between flow events and ongoing environmental condition (Horne A. C. et al., 2017c). There is a challenge in linking these short term active decisions to longer term objectives of resilience, with short term and long term management strategies aligned (Poff, 2017). Active management is a new challenge linked to novel allocation mechanisms for environmental water management (Horne A. C. et al., 2017b; O'Donnell and Garrick, 2017b), and although none of the questions relating to active management were given a top-10 ranking, the authors consider this to be a key emerging theme for research in an ever more water-contested and unpredictable future.

Active management is resource intensive. It requires a trade-off between the flexibility and autonomy of these sorts of allocation mechanisms and the expense of ongoing management. It is not yet clear which sorts of river systems are best served by this model.

Key questions on *Community knowledge and engagement* are shown in **Box 6**.

CONCLUSIONS

The future in front of us is well summarized by the following quotation—"*Our future advances will not be concerned with universal laws, but instead with universal approaches to tackling particular problems, and with general theoretical insights about the surprises that may ambush us if we think too narrowly.*" (Kareiva, 2011).

The questions identified in this study cover the full diversity of environmental water policy, science, and practice. The discipline of environmental water management has traditionally been driven from the perspectives of ecology and hydrology, with somewhat separated lines of research around social and institutional aspects of environmental water management (Poff and Matthews, 2013). The results presented in this paper highlight the benefits that would accrue from a more multidisciplinary and inclusive approach in environmental water research and management. This perspective is in keeping with the recognition that sustaining river health and resilience is the foundation for achieving human water security, and with the need to develop infrastructure and institutional arrangements that allow multiple outcomes for society (Tickner et al., 2017).

The questions identified highlight the importance of continuing to develop our fundamental understanding of how natural flow variability influences riverine and other river-dependent ecosystems such as floodplains and wetlands. This has in many ways been the motivation for much of the progress in environmental flows to date (Bunn and Arthington, 2002; Lytle and Poff, 2004). However, our questions also highlight the disconnect between the processes of knowledge generation and the uptake or translation into management processes and adaptive learning.

As environmental water management transitions further into an implementation phase, the institutions and processes that link various stakeholders, and govern the process of allocating and managing environmental water, become vitally important. There is a growing body of work that examines the legal, regulatory and organizational tools for the allocation and management of environmental water (Godden, 2010; Foerster, 2011; Pahl-Wostl et al., 2013), but to date, there has been insufficient work integrating this research into the mainstream environmental flows literature. The OECD recognized in 2015 that water crises were fundamentally crises of governance (OECD, 2015), and environmental water managers need to heed this lesson. Strong institutions underpin accountability, transparency and support efficiency, efficacy and legitimacy of environmental water management (O'Donnell and Garrick, 2017a). As increasing volumes of environmental water are allocated, the importance of institutions and governance and their vital roles will continue to grow.

Many of these challenges will be ongoing and constantly refined (as will the fundamental ecological research). Rather than providing "an answer" this paper has sought to stimulate improvements in the scientific basis and robustness of the entire environmental water management cycle, and new approaches to be able to cope with changing attitudes, environmental conditions, scenarios and priorities. This perspective is highlighted through the themes described above, which are about learning, sharing knowledge and engaging all stakeholders in the complex processes of the water management cycle.

AUTHOR CONTRIBUTIONS

AH, JW, MA, MS, and BR: designed the survey and structure of the paper; AH and JW: analyzed the survey and ran the workshop; All authors contributed to discussions on the key questions and writing of the article.

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SUPPLEMENTARY MATERIAL

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POLICY BRIEF
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Critical Factors for Water Policy to Enable Effective Environmental Flow Implementation

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During the last two decades many countries have recognized the integral part that environmental flows should play in water management and have incorporated environmental flow provisions as they have updated water policy. This brief sets out generic recommendations for governments and other stakeholders on factors that, if reflected in policy frameworks, are likely to enable scaling up of environmental flow implementation. Our recommendations have been informed by a review of political, economic, social and scientific enabling factors that led to environmental flow implementation in eight rivers across the world. Legislation and regulation are pre-requisites for effective environmental flow implementation. Depending on context, we describe a number of other factors that can provide a foundation for effective environmental flows policy.

Keywords: environmental flows, water policy, implementation, enabling factors, water management, dams, water allocation

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INTRODUCTION

UN Sustainable Development Goal target 6.4 recognizes the need to ensure "sustainable withdrawals and supply of freshwater" (https://sustainabledevelopment.un.org/sdg6). In hydrological terms, sustainable withdrawals should allow for the maintenance or restoration of environmental flows (e-flows) for the benefit of downstream water users, maintenance of valuable ecosystem services (e.g., fisheries), and safeguarding of biodiversity and cultural values. Indeed, it has been argued that the environmental litmus test of water security is continued flow through rivers and other freshwater ecosystems of sufficient quantities of water, at critical times of year (Tickner and Acreman, 2013). Many countries have incorporated e-flow provisions as they have updated water policy. Implementation of policies has been challenging primarily because of lack of political will, imperfect understanding of costs and benefits, and limitations in institutional capacity and resources (Le Quesne et al., 2010). Nevertheless, success stories have emerged.

This brief sets out generic recommendations for governments and other stakeholders on factors that, if reflected in policy frameworks, are likely to enable scaling up e-flow implementation to larger spatial scales (basin, jurisdiction), to a greater number of jurisdictions, and to more rivers overall. These recommendations were derived from a review of e-flow implementation in eight rivers across the Americas, Africa, Asia, Europe, and Australia (Harwood et al., 2017, see **Table 1**). The intention is not to produce a prescriptive approach to policy development for e-flow implementation; measures should always be informed by context. Rather, the aim is to stimulate thinking about specific measures that could be encapsulated in, or promoted by, water policies, based on documented experiences.

POLICY OPTIONS AND IMPLICATIONS

Our case study review identified a range of enabling factors; for the purposes of this policy brief we have grouped these into four categories. These factors and examples of their importance in the case studies we reviewed are presented in **Table 2.**

Legislation and Regulation

We found that the fundamental enabling factor that underpins most, if not all, cases of successful e-flow implementation is the existence of conducive legislation and regulation. The type of legislation and regulation behind the implementation of e-flows varies greatly; however, long-term protection or restoration of flows for the environment is dependent on there being a legislated framework within which to act. In broad terms, laws reflect the values of society, thus jurisdictions that have e-flows written into their laws and regulations have demonstrated at least some consideration of the ecosystem services and values that rivers provide. We identify three principal types of legislation that have facilitated e-flow implementation:

1. **Water Management Legislation**
   If the governing entity responsible for water management (national or state/provincial level) has set a standard or regulation that mandates e-flows, it creates momentum for both protection and restoration of e-flows. For example, in Mexico the National Water Law of 1992 recognized the environment as a legitimate user of water.
2. **Endangered Species or Other Environmental Legislation**
   In the US, the Endangered Species Act has been the single most powerful lever for protecting and restoring e-flows. In Australia, commitments to both the Convention on Biological Diversity and the Ramsar Convention were used as the basis for the Commonwealth (federal) government to assume leadership for water decision-making in the Murray-Darling Basin.

TABLE 1 | Details of the case study watersheds.

Country	River	Short description
USA	Savannah	Flows for 500 km from Blue Ridge Mountains into Atlantic Ocean. Droughts in the 1990s, water quality challenges, endangered fish conservation and recreational values presented opportunities to implement e-flows through adaptive reservoir operations
Australia	Murray-Darling	Australia's longest and most important river, flowing through four states and home to 2 million people (including Aboriginal groups), with more than 30,000 wetlands including protected areas. The challenge is to share water so that urban and agricultural supplies are balanced with indigenous and environmental needs. Over-allocation and prolonged drought magnified this challenge and presented the political opportunity to implement e-flows.
China	Yangtze	The third longest river in Asia, home to 177 endemic fish species and provider of 36% of freshwater fish consumed in China. The Three Gorges Dam is by some measures the largest in the world. It has significantly altered the flow regime of the river. Concern about declining freshwater fish catch stimulated collaboration between the dam operator and other stakeholders to trial e-flow releases during critical times for fish reproduction.
UK	Kennet	A small chalk river in southern England and a significant tributary of the River Thames. Over abstraction of groundwater, primarily for urban supply, led to reduced flows over a number of years. Advocacy by environmental NGOs prompted the water utility and environmental regulator to investigate, and eventually implement, e-flows facilitated by the availability of alternative supplies from less stressed catchments.
South Africa	Crocodile	A tributary of the transboundary Inkomati River (shared with Swaziland and Mozambique), the Crocodile River forms the southern boundary of Kruger National Park. The requirements of water-sharing commitments with Mozambique and concerns about water stress led to reconsideration of allocations to irrigated agriculture and urban areas and eventually to implementation of an e-flows regime.
Mexico	San Pedro Mezquital	A largely free-flowing river running for 540 km from the western Sierra Madre Mountains through the Marismas Nacionales Biosphere Reserve and into the Pacific Ocean. Although not currently water-stressed, concerns about future pressures on water resources and impacts on ecological integrity led to implementation of an Environmental Water Reserve which safeguards an annual flow volume for the river.
Pakistan	Poonch	Originates in the western foothills of the Pir Panajal mountain range before running through the Poonch Mahaseer National Park and joining the Jhelum River. An environmental and social impact assessment of the planned Gulpur Hydropower Project highlighted the lack of sufficient consideration of potential impacts on downstream flows. Subsequent e-flow assessment illustrated the potential for redesign of the project to facilitate e-flows and provide environmental and socio-economic benefits.
India	Ganga	Flowing for 2,500 km from the Himalayas to the Bay of Bengal, the Ganga is sacred to hundreds of millions of people but also under pressure from pollution, flow diversions and other threats. The 2013 Kumbh, a hugely significant religious festival during which tens of millions of people bathed in the river, provided a unique opportunity to demonstrate how e-flows could be implemented in the Upper Ganga.

TABLE 2 | Enabling factors that support successful e-flow implementation.

Enabling factor categories	Description of enabling factors	Example
Legislation and regulation	A fundamental factor in most e-flow implementation success stories; Jurisdictions that have e-flows written into their laws and regulations have acknowledged the ecosystem services and values that rivers provide.	Legislation played a particularly important role in the Murray-Darling Basin where the Water Act 2007 led to water reform through the establishment of the Commonwealth Environmental Water Office and the development of the Murray-Darling Basin Plan that limits how much water can be extracted from any sub-basin (i.e., a cap on abstraction).
	Allocation mechanisms can be used as legal or policy tools to impose conditions on water users or establish water reserves for the environment.	Following the implementation of a cap on abstraction in the Murray-Darling Basin, the development of a system that allows the trading of water rights has been immensely important in restoring e-flows.
Collaboration and leadership	A wide range of stakeholder input is critical for e-flow implementation from the outset. It is critical that competitors for water, and agencies that will implement e-flow prescriptions, are part of the decision-making process in setting objectives and determining appropriate flows. Those responsible for implementing e-flows, such as water management agencies, hydropower operators or irrigators, have to buy in to the process otherwise they will continually fight and try to undermine it.	At the start of the process of implementing e-flows in the Savannah River (USA), different interests around the reservoirs (e.g., flood management, hydropower generation, in-reservoir recreation) were concerned that there would be an adverse impact from e-flow implementation on their particular interest, and many individuals and groups resisted these changes. This barrier was overcome by holding workshops and public hearings. Collaborative workshops also enabled the reservoir operators and engineers to participate in the development of e-flows and share their knowledge on how the river responds to reservoir operations.
	A champion is needed to drive the process forward; there are many challenges to e-flow implementation and to overcome these there needs to be a person, several people, or an organization pushing the process along and finding solutions.	One of the most prominent examples of champions in our case studies was Brian Jackson at the IUCMA in the Crocodile River case study who improved e-flow implementation by starting a dialogue with irrigation stakeholders and Kruger National Park to develop appropriate objectives and an e-flow regime the stakeholders accepted.
Resources and capacity	E-flow implementation requires a natural and social scientific understanding of the needs of the species or resource one is trying to protect or restore, and how these needs relate to flow magnitude, timing, duration, frequency and rate of change.	The work done by fish biologists and hydrologists in identifying the spawning locations of Chinese carp in the reaches downstream of the Three Gorges Dam, along with the important hydrologic indicators and their ranges for natural spawning that can be mimicked when designing e-flows, was vital. From a social perspective, the surveys carried out prior to Kumbh 2013 were important in determining appropriate flows for the spiritual rituals.
	Having the institutional capacity to understand the need for e-flows and how these are determined and monitored is an important factor in implementation.	The need for greater capacity was probably most pronounced in the Poonch River case study: here, the need for additional e-flow assessment was determined by an international funding agency (the Asian Development Bank), and the assessment was led by an international consulting firm from South Africa who worked closely with local stakeholders.
	Consistent funding for the technical studies and stakeholder engagement processes required to determine appropriate e-flows is a common barrier to e-flow implementation. Typically these measures cost a small fraction of the wider costs of major water infrastructure schemes, but can save substantial effort later on.	Acting collaboratively, WWF and the Mexican water allocation authority, CONAGUA, were responsible for securing funding for the Environmental Water Reserves program from the Interamerican Development Bank (IDB), WWF, and Alliances of WWF-Gonzalo Río Arronte Foundation and WWF-Carlos Slim Foundation. The involvement of CONAGUA was considered critical in securing the necessary funds.
	Similarly, securing the necessary funding for e-flow implementation, monitoring and management is critical.	WWF and a local NGO successfully campaigned for many years for a legislative change that enabled Thames Water to fund an e-flow implementation scheme on the River Kennet.
	The development of technical standards and guidelines for a region on how to determine, monitor and adapt e-flows for ecological and socio-economic components, and on what methods work best in different situations, are an important tool to streamline assessments and overcome barriers of capacity.	The publication of a national standard on e-flow assessment was a key enabling factor in the San Pedro Mezquital case study as it provided certainty over the approved approach. The importance of environmental standards set by international funding agencies was demonstrated in the Poonch River case study as adherence to these standards led to a more sustainable project design, which enabled the project to proceed.
	Tools are required to help managers make decisions on e-flows based on water availability and balancing the requirements of multiple water-users.	The IUCMA in South Africa uses decision-support and forecasting tools to manage e-flows in real time based on the available water in the Crocodile River. Similarly, the US Army Corps of Engineers uses real-time data collection and reservoir models to aid its releases of e-flow pulses from its dams on the Savannah and other rivers.
Monitoring and adaptive management	Flow data are critical in determining natural flow levels and water availability. Physical, geomorphological, ecological, social and economic data are important in determining how the ecosystem and those who depend on it are responding to e-flow implementation, and to inform adaptive management.	The best example of adaptively managing e-flows based on data collected from a network of monitoring stations in our case studies is the Savannah River, where lessons over an 8 to 10-year period of test releases were used to refine e-flows. From a social perspective, monitoring of e-flow releases on the Ganga River during Kumbh 2013 demonstrated the initial success of that program.

3. **Regulations on Dam Operations**
In the US, licensing (and re-licensing) requirements set by the Federal Energy Regulatory Commission (FERC) have opened the door for e-flow advocates to set dam operating conditions that facilitate e-flows. Regulations in China governing the operations of the Three Gorges Dam have been adjusted to provide e-flows for ecological, social, and economic benefits.

Although fundamental, legislation alone is rarely sufficient. For example, in South Africa the National Water Act enacted in 1998 called for an ecological reserve of water and the formation of catchment management agencies, but it was 2006 before the Inkomati-Usuthu Catchment Management Agency was formed (the country's first) and another 5 years before e-flow implementation. Pahl-Wostl et al. (2012) noted that innovative legal frameworks are necessary to effectively address water related management problems, but are not sufficient without additional policy measures. The precise mechanisms set out in legal frameworks need to be defined according to local context and in light of the nature of e-flow implementation challenges. Horne et al. (2017) described a typology of water allocation mechanisms for environmental purposes, broadly split into two types: mechanisms that impose conditions on water users (e.g., a cap on total water abstraction), and mechanisms that establish a legal right to water for the environment itself (e.g., an environmental water reserve).

Our case studies highlight the role of these mechanisms. For example, a cap on total water abstraction was set for the Murray-Darling Basin overall, followed by Sustainable Diversion Limits for individual sub-basins, which has the effect of protecting all water remaining in the system once limits are reached. Meanwhile, the San Pedro Mezquital River case study is an excellent example of the establishment of an environmental water reserve. The presidential decree in this case includes conditions that provide a clear framework for authorizing future water abstraction.

As a result of the numerous challenges in re-allocating water from existing rights-holders, it is best if e-flows are protected as a reserve or a cap on allocations whenever possible, and if such a cap or reserve is put in place it is done before water becomes over-allocated (Dyson et al., 2008). This will be more politically expedient and cheaper to administer than the re-allocation or reduction of existing rights, or the enforcement of regulations against multiple users. The case studies on the Kennet, Murray-Darling, and Crocodile rivers demonstrate the challenges of attempting to re-allocate or reduce existing water use rights. Nevertheless, the establishment of water trading mechanisms in the Murray-Darling Basin (Murray Darling Basin Authority, 2017) and water banks in the western US (Harwood et al., 2014) indicate that innovative solutions can be found.

Collaboration and Leadership

Human uses of rivers are extremely diverse, as are the ways in which different people, communities and organizations rely on rivers (Horne et al., 2017). E-flow implementation therefore typically faces many politically challenging realities and conflicts between water uses. Given this, Pahl-Wostl et al. (2013) emphasize that the development of e-flows should, from the outset, include input from a wide range of stakeholders on possible trade-offs and synergies between different water uses. A critical early step where stakeholder input is required is agreement on a vision for the river and realistic, achievable, flow-related objectives that most people can support (Dyson et al., 2008). Objectives will be different for different rivers, or even parts of the same river, and will depend on the political, social, economic, and ecological context (O'Keeffe and Le Quesne, 2009).

Our case studies confirmed that collaboration is an essential ingredient for success. Many individuals and organizations have roles to play. Collaboration ensures that stakeholders understand the need for e-flows and how trade-offs between conflicting demands are assessed, and are engaged in the decision-making process. Without this understanding, the implementation process is likely to be undermined by water users unsupportive of e-flows, or not enforced by the agencies responsible for oversight. Structured Decision Making is a valuable process for such collaboration and provides a mechanism for reviewing available information, setting objectives, addressing uncertainty, evaluating trade-offs between competing demands, and making decisions (Gregory et al., 2012).

Given the range of stakeholders involved, the frequent need to resolve conflicts between water users, and the technical and resource challenges often faced (section Resources and Capacity), our case studies highlighted the importance of one or multiple champions to drive the process forward. A champion who holds a senior position within a regulatory authority responsible for water allocation can be a powerful force, often spurring rapid action; however, other organizations such as NGOs can also drive implementation. For Mexico's environmental water reserves (EWR) program, a champion within WWF was successful in persuading the director of CONAGUA, the water allocation authority, of the value of protecting e-flows. The director of CONAGUA, in turn, spurred e-flow assessments in almost double the original target number of watersheds. Together, WWF and CONAGUA were responsible for securing funding for the EWR program, including from the Interamerican Development Bank (IDB).

Political champions for e-flows can also help smooth the road to implementation. This was evident in the River Kennet case study, where a ministerial ally to local and national NGOs helped pass a Water Act through parliament necessary for the e-flow restoration project to secure adequate funding. Champions in international funding agencies can also facilitate action through adherence to standards and the provision of funds, two of the other key enabling factors for successful e-flow implementation (**Table 2**). The role champions and "policy entrepreneurs" (Huitema and Meijerink, 2010) can play has also been highlighted in achieving better water resource management (Lenton and Muller, 2009; Straith et al., 2014).

Resources and Capacity

Scientific understanding has a key role in guiding flow management. However, the particular type of science—or other disciplinary expertise—needed depends upon the outcomes to be protected or attained through e-flow management. Early e-flow science was focused on the conservation of a few targeted species, requiring knowledge and data on the relationship between specific flow conditions and the life cycle requirements of those species. This is still relevant in some situations. In the Three Gorges Dam case study, fish biologists and hydrologists were critical in identifying the spawning locations of Chinese carp in the reaches downstream of the dam, along with the important hydrologic indicators and their ranges for natural spawning that were mimicked when designing e-flows. In other situations, desired e-flow outcomes have expanded to encompass entire aquatic communities, or to include ecological functions such as sediment transport. Consequently, the array of necessary disciplinary expertise has expanded greatly. When social outcomes, such as restoration of fisheries or recreational benefits, are included, the requisite expertise expands again to include economics, human health, and other social sciences.

Effective e-flow implementation requires an understanding of the needs of the species or resource one is trying to protect or restore and how these needs relate to flow magnitude, timing, duration, frequency, and rate of change. However, natural systems, and the communities dependent upon them, are complicated and variable, posing significant analytical challenges. These challenges are compounded when trying to link flows to ecosystem services valued by humans because the causative chain of linkages becomes more complicated (Parker and Oates, 2016). Accordingly, a process for prioritizing trans-disciplinary research, involving natural and social scientific disciplines, should be promoted and supported (Tickner et al., 2017). Nevertheless, e-flow prescriptions should be targeted and only as complex as the context requires. It has proven exceedingly difficult to implement complex e-flow specifications intended to mimic elements of natural flow variability (i.e., by including both intra- and inter-annual variations in flow; Richter et al., 2011).

Lack of resources and/or technical capacity was a barrier to implementation across many of our case studies, as it was in the 20+ case studies examined by Le Quesne et al. (2010). E-flow determination, implementation, and management requires the assembly and analysis of data, individuals trained in a number of different fields, coordination of stakeholders and experts, use of hydrologic models and other decision support tools, and government managers to license and enforce standards. In complex situations with multiple water users, experienced facilitators are also required to balance conflicting needs and facilitate generation of solutions that stakeholders can support. Similar to the implementation of river basin plans (Pegram et al., 2013), these tasks require sustainable funding over many years and the ability to retain expertise. The involvement of various stakeholders often means that capacity-building is a necessary early component of e-flow assessment and determination processes, regardless of jurisdiction. Accordingly, the process may need to start simple to foster understanding and support and demonstrate implementation success within a timeframe that maintains stakeholder support (O'Keeffe, in review).

A common trend across our case studies, both in developed and developing countries, was the learning and understanding gained as the e-flow determination process evolved, and the disappointment that such knowledge often had to be re-taught as a result of turnover. One remedy to the lack of capacity in determining e-flows is to harness the capacity of international organizations experienced in conducting e-flow assessments in a diverse array of scenarios and climates. This approach was taken in the Poonch River case study, as Mira Power hired both a local consultant, Hagler Bailly, and a consulting team from South Africa, Southern Waters, experienced in conducting the Downstream Response to Imposed Flow Transformation (DRIFT; King et al., 2003) e-flow assessment.

Another remedy to an initial lack of capacity is the development of technical standards and guidelines for a region or jurisdiction. This can guide practitioners in appropriate e-flow determination and help overcome inertia when determining which method for e-flow determination is best given the array of techniques available (Tharme, 2003; Acreman et al., 2014). Richter et al. (2011) noted that many good intentions to protect e-flows have stalled due to confusion about which assessment method is "best." The publication of a national standard on e-flow assessment was a key enabling factor in the San Pedro Mezquital case study that provided certainty over the approved approach.

Monitoring and Adaptive Management

Despite marked advances in e-flow science (Acreman et al., 2014), uncertainty remains in the understanding of flow-ecology relationships (e.g., Bradford and Heinonen, 2008; Poff and Zimmerman, 2010; Bradford et al., 2011). Uncertainty means it is important to implement monitoring and adaptive management to ensure that e-flows have the desired outcome. Monitoring outcomes of e-flow implementation is also important to demonstrate the benefits to water managers, the broader public, and politicians (King et al., 2015). Implementing a monitoring program presents its own challenges given the complexity of aquatic ecosystems, natural variability in response variables (e.g., fish abundance and diversity), the multitude of confounding environmental variables (e.g., temperature, land use change), and sustained financial cost. This makes it essential to identify suitable ecological indicators, objectives, methods, and timeframe for the monitoring program (Locke et al., 2008; King et al., 2015), similar to programs aimed specifically at river restoration (Speed et al., 2016).

Monitoring social and economic outcomes generated by an e-flow regime is also critical (Dyson et al., 2008; Pahl-Wostl et al., 2013). Surveys of people's perception of change can also be useful (Speed et al., 2016), and our case studies illustrate growing public awareness of e-flow values, as demonstrated by public acceptance of protective measures implemented for the management of the Poonch River Mahaseer National Park, and in the public support for management of flows within the Ganga River to enable a successful Kumbh 2013. Parker and Oates (2016) note that to ensure equitable distribution of river-related benefits, decisions regarding trade-offs between conflicting needs must be transparent, inclusive, and based on the best available evidence. Only through proper monitoring will the ecological, social, and economic consequences of e-flow decisions be validated and available to help inform adaptive management and future decisions (Richter et al., 2006; Pahl-Wostl et al., 2013; Pegram et al., 2013; King et al., 2015).

ACTIONABLE RECOMMENDATIONS

Our review of case studies demonstrated a number of ways in which policy interventions can facilitate e-flow implementation. The route to success will be dependent on system- and jurisdiction-specific concerns and legal, political, institutional, social, economic, and ecological contexts. This supports the conclusion of Le Quesne et al. (2010) that there is no single correct approach to the implementation of e-flows; instead, the approach must be carefully tailored to the context. It also reinforces insights from broader literature on water resource management about the need to acknowledge complexity (Zeitoun et al., 2016) and the need for trans-disciplinary approaches to policy, planning, and research on water resources and ecosystem management (Tickner et al., 2017). Despite this finding, there are some common truths that emerge from our case study review that lead to the following recommended actions:

1. Enact **clear and effective legislation and regulation**, and maintain the political will to implement and enforce;
2. **Implement some level of protection as early as possible** since it is easier to restrict allocation than to reallocate water;
3. **Engage meaningfully with stakeholders** to garner understanding and support;
4. Secure sufficient **resources and capacity** for e-flow design (including stakeholder engagement), implementation, and monitoring and adaptive management;
5. Consider how e-flow implementation will affect not just **ecological, but also economic and social conditions** for different groups of people;
6. Keep e-flow prescriptions as scientific as possible according to the level of risk and intensity of water use, and within the available financial and human resource constraints–but balance this with the need to **keep science targeted and only as complex as the context allows**, and with the need for clear non-technical communication of the issues with stakeholders; and
7. **Monitor ecological, social and economic outcomes** of e-flow implementation and manage adaptively.

CONCLUSIONS

With the rise of water scarcity across the globe and the pressures on water resources increasing from factors such as population growth, economic transition and climate change, the number of "working rivers" that serve multiple functions is growing. Rivers that provide ecological, social, economic, and cultural value must be healthy; otherwise they will cease to deliver many or all of these benefits. Legislative and policy regimes are being continually updated and e-flows are increasingly playing a central role in water allocation regimes, infrastructure design and operation, and water resource management more broadly. Implementation of e-flows is now a critical part of sustainable water management.

Successful e-flow implementation is invariably underpinned by legislation, but to meet policy objectives for e-flow implementation and achieve the SDG target of ensuring "sustainable withdrawals and supply of freshwater" it will be necessary to develop policies that incorporate measures for, and stimulate investment in, improving technical capacity, engaging stakeholders, setting standards, encouraging champions, establishing monitoring networks, and developing innovative solutions to reallocate water. Our case study analysis showed the range of roles that different stakeholders can play in implementing e-flows and highlights the collective, collaborative effort required. This policy brief builds on this experience and provides recommendations for governments and other stakeholders that will enable the successful scaling up of e-flow implementation if reflected in appropriate legislation and policy.

AUTHOR CONTRIBUTIONS

AH and DT conceived and drafted the outline of the manuscript with input from BR and AL. AH, SJ, and XY acquired and interpreted the information gathered for the work, with DT, BR, and AL providing critical input on implications and recommendations. AH and DT drafted sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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The Contribution of Improvements in Irrigation Efficiency to Environmental Flows

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Increasing irrigation efficiency is often assumed to be a means of saving water and a route to increasing irrigated agricultural production or making water available for other purposes, such as communities, industry or ecosystems. There is a growing body of literature arguing that increasing irrigation efficiency does not reduce consumptive water use in agriculture, implying that no additional water is made available for supporting environmental flows. However, understanding the implications of changes in irrigation efficiency for environmental flows requires assessment at temporal and spatial scales between the daily to seasonal field level analysis of advocates for increasing irrigation efficiency to save water, and the annual basin scale view of some of its critics. When investigated at these intermediate temporal and spatial scales, there may be potential for improvements in irrigation efficiency to mitigate the effects of irrigation on flow timings to an ecologically meaningful extent. In situations where this is possible, in advance of implementing irrigation efficiency programmes, overall water consumption must be limited by an effective water allocation regime that explicitly recognises environmental flow needs in order to prevent expansion or intensification of irrigated agriculture. This paper sets out some of the key issues that practitioners working on environmental flows should consider in order to assess whether or not interventions to increase irrigation efficiency can support environmental flow objectives.

Keywords: irrigation efficiency, environmental flows, water saving, water allocation, sustinable agriculture

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INTRODUCTION

Freshwater ecosystems are in serious decline globally. The Freshwater Living Planet Index, an indicator of the abundance of populations of freshwater dependent species, has declined by 81% since 1970 (WWF, 2016). There are many reasons for this such as infrastructure, pollution, habitat loss or species exploitation (see Collen et al., 2014; Bunn, 2016), but one important reason in many basins is the diversion of water to irrigated agriculture. Globally, irrigated agriculture is the biggest user and consumer of water (Hoekstra and Mekonnen, 2012; Richter et al., 2017). Given the scale of its impact in some basins, therefore, efforts to address freshwater ecosystem decline by protecting or restoring environmental flows often focus on saving water in irrigated agriculture. This is a critical challenge given the importance of irrigated land for food production: 18% of the world's cropland is irrigated but it accounts for 40% of food production (Madramootoo and Fyles, 2010).

The term "environmental flows" is the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems (Brisbane Declaration, 2007). Irrigated agriculture affects each of the quality, quantity and timing components of environmental flows (Causapé et al., 2006; Kendy and Bredehoeft, 2006; Richter and Thomas, 2007; Poff and Zimmerman, 2010; Jägermeyr et al., 2017). The question of whether there are significant water savings to be made by improving irrigation efficiency is a contested one (Perry, 2007) but is of central importance when considering the dominant role of agriculture in total freshwater withdrawals globally, the projected increase in food demand (Tilman et al., 2011), and the deteriorating state of freshwater ecosystems (WWF, 2016). In addition, the influence of irrigation on the timing component of environmental flows, and changes as a result of increased efficiency, are important considerations.

This paper focuses on the interaction between water management in agriculture and environmental flows. Firstly, it looks at whether improvements in irrigation efficiency at a field scale can deliver water savings at basin scales, and therefore potentially contribute to the quantity component of environmental flows. Secondly, it looks specifically at the scope for delivering water savings by reducing non-beneficial evapotranspiration, because this is often a focus of water saving efforts where the limitations for basin-scale water savings of other efficiency improvement approaches are recognised. Thirdly, the key reasons for the differing perspectives on the issues under discussion are examined, as these must be understood by practitioners engaging in irrigated agriculture with an objective to support environmental flows. Finally, the paper examines whether, even in the absence of a contribution to the quantity component of environmental flows, increased irrigation efficiency can contribute to the timing component. The conclusions from the preceding discussion are drawn together to provide key considerations for practitioners engaging with irrigated agriculture to protect or restore environmental flows.

WATER SAVING AT BASIN SCALES FROM INCREASED IRRIGATION EFFICIENCY

Discourses on water saving in agriculture often focus on irrigation efficiency, with the assumption that, if efficiency is increased, more water will be available for expansion of agriculture, or water freed up for industry, communities or freshwater ecosystems. In this paper, "irrigation efficiency" is taken to mean the ratio of the amount of irrigation water consumed by the cropped area (beneficial and non-beneficial ET) to the amount of water supplied to the crop through irrigation (see Perry, 1999). With these broad aims in mind, programmes of irrigation modernisation and efficiency improvement are implemented by a range of actors from the private and public sectors, and non-governmental organisations (Batchelor et al., 2014). There is, however, a growing body of literature that contradicts the idea that water can be saved by increasing irrigation efficiency, rather it can lead to increased consumptive use of water (e.g., Ward and Pulido-Velazques, 2008; Batchelor et al., 2014; Pfeiffer and Lin, 2014; Scott et al., 2014; Kuper et al., 2017; Perry and Steduto, 2017). This is primarily because, in most circumstances, where irrigation water is applied in excess of that consumed as evaporation and transpiration it is returned to rivers (via surface or groundwater) or percolates to aquifers, and is therefore available for use elsewhere, by other users, or at another time. For example, Crosa et al. (2006) and Chen et al. (2003) found that more than 80 and 39.9% of the water in the Amu Darya and the Aksu River, China, respectively is irrigation return flow. Reductions in water applied to the field therefore, while they represent a saving to the farmer, do not equate to real water savings (i.e., reductions in the consumptive use of water) at larger scales. A major exception is where percolation of irrigation water beyond the root zone is going to an irrecoverable sink (e.g., a saline aquifer or water body) where reducing this flow does make additional water available for other uses (Batchelor et al., 2014).

Instead, programmes to increase irrigation efficiency can drive increases in water consumption for a number of reasons (Scott et al., 2014) indirectly related to the efficiency improvement interventions. Where water availability at the farm or irrigation scheme level remains unchanged, and land, labour and other inputs are available, irrigation efficiency improvements can free up water to extend the irrigated area, or grow more profitable crops, perhaps with a higher water requirement (Batchelor et al., 2014). Often, measures to increase irrigation efficiency give greater control of the timing and location of water distribution at a field level and contribute to increased yields. For a given crop variety, climatic conditions, and set of agricultural practices, there is a largely linear relationship between crop production (in kg) and transpiration (Perry and Steduto, 2017). Therefore, any increases in yield per unit area associated with improved irrigation efficiencies imply a proportionate increase in beneficial water consumption.

The outcome, therefore, of programmes to increase irrigation efficiency in a given area is likely to be increased consumptive use of water and reduced availability to other users and aquatic ecosystems downstream. Hu et al. (2017), for example, demonstrated the progressive reduction in the ratio of irrigation return flow to total applied water over the 1990s to 2010s from 0.5 to 0.23 in the Aksu River, as irrigation and cultivation practices developed and irrigation efficiency increased in the context of expanding irrigated agricultural area. Kuper et al. (2017) refer to aquifers and downstream water users as being the "silent victims" of programmes to promote irrigation efficiency. We can reasonably add rivers, wetlands and their freshwater ecosystems to this list.

WATER SAVING BY REDUCING NON-BENEFICIAL CONSUMPTION

In addition to improving irrigation efficiency by reducing percolation below the root zone, irrigation efficiency can be improved by addressing non-beneficial evaporation and transpiration (i.e., evaporation or transpiration from sources other than the crop). In cases where the limitations of increasing irrigation efficiency for saving water at the basin scale are recognised, attention is often turned to addressing non-beneficial consumption as this generally represent a significant fraction of overall field ET. This is done through techniques such as weed control, ground cover with crop residues and mulching, irrigation timing, reducing waterlogging, or the use of advanced irrigation techniques to reduce the wetted area (Batchelor et al., 2014; Richter et al., 2017). For example, mulching is often proposed as an effective means of reducing the fraction of water lost through non-beneficial soil evaporation. However, the evaporation and transpiration components of ET are interdependent (Villalobos and Fereres, 1990; Perry, 2011), interact in complex ways with the crop micro-climate, and cannot be considered in isolation. Under different crop and climate conditions, studies have found increases (Deng et al., 2006), decreases (Yan et al., 2015; cited in Li et al., 2008; Perry and Steduto, 2017), or very little change (van Donk et al., 2010; Balwinder-Singh et al., 2011) in overall ET, and both increases (van Donk et al., 2010; Balwinder-Singh et al., 2011; Yan et al., 2015), and decreases (Li et al., 2008) in crop yield as a result of mulching or use of crop residues to supress soil evaporation. Similarly, proponents of drip irrigation often point to the reduction in wetted area compared with flood irrigation as a proxy for reduced non-beneficial evaporation. However, this fails to account for the increased time the soil surface is wet under drip irrigation, in comparison with other methods (Perry, 2011; van der Kooij et al., 2013), and does not account for the effects of changes to the crop micro-climate on transpiration. The extent to which addressing non-beneficial evaporation and transpiration can provide savings in consumptive water use is, therefore, highly crop and context specific (Clemmens et al., 2008) and cannot be assumed.

ORIGINS OF THE DIFFERENT PERSPECTIVES ON IRRIGATION EFFICIENCY

In the context of drip irrigation, van der Kooij et al. (2013) suggest that incorrect interpretations of actual water savings often stem from a failure to properly quantify and account for the different components of the field water balance. In this review of studies looking at drip irrigation, van der Kooij et al. (2013, p. 106) found that water scarcity is the major justification for research on drip irrigation efficiencies but "none of the studies make explicit how the measured efficiency gains translate into wider water savings, or explain how these will help solving problems of water scarcity." In a comprehensive review of studies looking at the effects of introducing "hi-tech" irrigation Perry and Steduto (2017) found that very few studies document the effects in a way that allows for savings in ET to be estimated. Those that do are inconclusive or demonstrate increased water consumption.

In addition to quantification challenges of measuring transpiration and separating it from soil evaporation in the field (Steduto et al., 2012, p. 82), the lack of precise definitions of terms, and their inconsistent use across and within disciplines, is problematic (Seckler et al., 1996; Jensen, 2007; Perry, 2007; van der Kooij et al., 2013). The ambiguity in the terms used means that the interpretation of results in scientific literature can be dependent on the perspective of the reader, and is potentially incorrect (van der Kooij et al., 2013; Perry and Steduto, 2017). Much of the basis of the apparently contradictory views on water saving in irrigated agriculture derives from the differing perspectives of actors at different scales on who is saving water and for what: e.g., field level (farmer), irrigation scheme level (irrigation manager/engineer), catchment or basin level (water manager, hydrologist or ecologist).

Unambiguous use of terms and careful accounting for different components of water flow would greatly contribute to addressing the apparent dichotomy between proponents of increased irrigation efficiency as a means of saving water for other uses, and those that claim that there is no water saving benefit from improved efficiency.

RELEVANCE OF IRRIGATION EFFICIENCY FOR TIMING OF ENVIRONMENTAL FLOWS

From the perspective of environmental flows, although excess applied water in "inefficient" irrigation is not generally lost to the basin, the process of distribution through an irrigation scheme, percolation, and return to the river, does create a time delay on that flow: meaning that water might be withdrawn at the critical low flow period for ecosystems but returned, depending on the local context, perhaps some weeks or months later, at less ecologically critical times and spread over a longer period. Equally, withdrawing water from part of a catchment or basin and returning in another part might not affect the annual basin water balance but could be significant for particular river reaches or wetlands. Diverting water from such habitats may have significant ecosystem impacts even if no water is lost overall. In addition, the quality of irrigation return flows can be degraded due to agrochemicals or additional salt (e.g., Causapé et al., 2006; Kendy and Bredehoeft, 2006; Perry, 2011).

Kendy and Bredehoeft (2006) demonstrate the effect of irrigation efficiency on flow timings in the context of a Western US surface water irrigated system covering 2949 ha. The authors show that, in a modelling simulation where total crop water consumption remained constant, less efficient irrigation (50% efficient) depleted streamflow immediately downstream to a greater degree than more efficient irrigation (100% efficient) during the irrigation season. As the more efficient scenario is 100% efficient, there are no return flows and streamflow depletion only occurs during the irrigation season. Under the less efficient scenario the total consumptive loss and annual streamflow are the same as the more efficient scenario, but delayed return flows via groundwater augment non-irrigation season flows such that they are higher than the natural flow condition. The consequence of this is that the lowest flow month is shifted from February under natural conditions to August under both efficient and inefficient irrigation scenarios. However, maximum streamflow depletion in the irrigation season is significantly greater under the less efficient scenario. Venn et al.

(2004) report similar observations in terms of the effect of shifting to more efficient types of irrigation (flood to sprinkler) on seasonal flow timings in the Salt River Basin, USA. In a modelling simulation of an irrigation system in the Zarrineh Rud River, Iran, Ahmadzadeh et al. (2016) found no reduction in consumptive water use but changes to seasons flow timings as a result of a shift from surface to pressurised irrigation systems.

Irrespective of the degree of efficiency, therefore, irrigation has an impact on environmental flows through diversion of flows to consumptive agricultural use (Jägermeyr et al., 2017) and the operation of infrastructure such as dams and barrages (Richter and Thomas, 2007). While few studies have addressed explicitly the effects on flow timings of more efficient irrigation resulting from reduced withdrawals during irrigation seasons, Venn et al. (2004); Kendy and Bredehoeft (2006), and Ahmadzadeh et al. (2016) have done so and suggest that irrigation efficiency improvements can benefit environmental flow timings. This can occur both as the absence of an augmentation of non-irrigation season flows from slow (groundwater) return flows (which may be good or bad for environmental flows, depending on the wider catchment context) and reduced depletion of flows during the irrigation season. Clemmens et al. (2008) conclude that irrigation diversions that return to surface water systems change the timing of flows, which can be environmentally beneficial or non-beneficial, depending on the specific context. There is a clear need, however, for further research into this effect to enable generalised conclusions to be drawn as the available evidence is sparse. It should also be noted that realising the potential for ameliorating the impact of irrigation on river flows through increased irrigation efficiency is contingent on effective controls on withdrawals or allocations to prevent associated increases in consumptive use, as described above (Perry and Steduto, 2017).

CONCLUSION

Both those that promote irrigation efficiency at a field level and those that argue that this does not result in water saving at a basin scale over an annual cycle have valid points to make, but neither gives a complete picture for environmental flows. While both localised field or irrigation scheme perspectives, or water accounting approaches (e.g., Karimi et al., 2013) are essential for understanding the wider system context, neither the field scale and irrigation season perspective nor basin scale and annual water accounting perspective are sufficient for understanding the implications of promoting increases in irrigation efficiency for environmental flows. This requires consideration at multiple spatial and temporal scales, including at spatial scales between the field scale and the basin scale, and at temporal scales between irrigation application cycles and annual water budgets. Taking this multi-scale approach creates opportunities to optimise environmental flow gains at a landscape or basin scale using spatial targeting of interventions (e.g., Crossman et al., 2010).

Carried out in isolation, field level interventions to improve irrigation efficiency are unlikely to deliver improvements in environmental flows. There is little evidence of a significant potential for reducing consumptive water use at scale through field-focused programmes designed to improve irrigation efficiency. There is, however, some evidence that in some contexts there is scope for efficiency measures to mitigate the effects of large scale irrigation on flow timings.

Despite the complexities and knowledge gaps, for practitioners wanting to protect or restore environmental flows the preceding discussion points to some elements of a framework for engaging with irrigated agriculture:

A key first step should be to establish quantitatively (e.g., using modelling and field observations) whether, in the specific context being considered, there is potential for increased irrigation efficiency to deliver ecologically relevant improvements to the timing of flows. This assessment should consider the effects at multiple spatial scales (field, farm, irrigation scheme, sub-catchment, catchment, basin) and temporal scales (daily, monthly, seasonal, annual). Significant factors that need to be considered in this regard include, for example, operation of existing irrigation infrastructure, whether excess irrigation water is returned to rivers via surface (fast) or groundwater (slow) flow (Zeng and Cai, 2014), total consumptive water use in agriculture, the distance from the irrigated area to the river, geology, and lifecycles and habitat requirements of species. As discussed above, such assessments should also make use of unambiguous terms and definitions for the components of the water balance.

Where there is potential for improvements in irrigation efficiency to benefit environmental flow timings, interventions at a field level to increase irrigation efficiency must be preceded by the establishment of an effective water allocation system that prevents an associated increase in overall water consumption. Without an allocation regime in place before extensive irrigation efficiency improvements, the potential benefits are unlikely to be realised in the long term as consumptive use will increase through the mechanisms described above (Scott et al., 2014; Perry and Steduto, 2017; Richter et al., 2017).

Allocation schemes should explicitly account for environmental flows, rather than assuming that environmental flows can be delivered as the residual of improvements in irrigation efficiency (Batchelor et al., 2014). Allocations should also account for actual consumptive use and should be adaptable to changes over time in irrigation efficiency i.e., withdrawal or use allocations should decline as the prevailing irrigation efficiency increases to prevent overall increases in consumptive use. Or indeed, allocations can be reduced, with associated farmer support, in order to incentivise increased irrigation efficiency.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and approved it for publication.

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POLICY AND PRACTICE REVIEWS
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The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018)

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A decade ago, scientists and practitioners working in environmental water management crystallized the progress and direction of environmental flows science, practice, and policy in The Brisbane Declaration and Global Action Agenda (2007), during the 10th International River*symposium* and International Environmental Flows Conference held in Brisbane, Australia. The 2007 Declaration highlights the significance of environmental water allocations for humans and freshwater-dependent ecosystems, and sets out a nine-point global action agenda. This was the first consensus document that bought together the diverse experiences across regions and disciplines, and was significant in setting a common vision and direction for environmental flows internationally. After a decade of uptake and innovation in environmental flows, the 2007 declaration and action agenda was revisited at the 20th International River*symposium* and Environmental Flows Conference, held in Brisbane, Australia, in 2017. The objective was to publicize achievements since 2007 and update the declaration and action agenda to reflect collective progress, innovation, and emerging challenges for environmental flows policy, practice and science worldwide. This paper on The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018) describes the inclusive consultation processes that guided the review of the 2007 document. The 2018 Declaration presents an urgent call for action to protect and restore environmental flows and aquatic ecosystems for their biodiversity, intrinsic values, and ecosystem services, as a central element of integrated water resources management, and as a foundation for achievement of water-related Sustainable Development Goals (SDGs). The Global Action Agenda (2018) makes 35 actionable recommendations to guide and support implementation of environmental flows through legislation and regulation, water management programs, and research, linked by partnership arrangements involving diverse stakeholders. An important new element of the Declaration and Action Agenda is the emphasis given to full and equal participation for people of all cultures, and respect for their rights, responsibilities and systems of governance in environmental water decisions. These social and cultural dimensions of e-flow management warrant far more attention. Actionable recommendations present a pathway forward for a new era of scientific research and innovation, shared visions, collaborative implementation programs, and adaptive governance of environmental flows, suited to new social, and environmental contexts driven by planetary pressures, such as human population growth and climate change.

Keywords: environmental water, social-ecological systems, climate change, resilience, Sustainable Development Goals (SDGs), The Brisbane Declaration (2007)

INTRODUCTION

The deteriorating condition of riverine and wetland ecosystems and loss of freshwater biodiversity resulting from water infrastructure impacts, water extraction, and altered flow regimes has led to the field of environmental flows. The science and practice of environmental flows has a long history of achievements as an approach to protect and recover aquatic biodiversity, ecosystem integrity and important ecological services by managing freshwater flow regimes. Reflecting on the past 25 years of this history, Poff and Matthews (2013) nominated The Brisbane Declaration (2007) on environmental flows as a pivotal statement and synthesis. This document brought together the diverse experiences of environmental flows practitioners across regions and disciplines, and set a common vision and direction for environmental flows internationally. The 2007 Declaration was formulated during the 10th International River*symposium* and International Environmental Flows Conference held in Brisbane, Australia, and endorsed by 800 delegates from more than 50 countries. The accompanying nine-point Global Action Agenda called upon "*all governments, development banks, donors, river basin organizations, water and energy associations, multilateral and bilateral institutions, community-based organizations, research institutions, and the private sector across the globe to commit to a suite of actions for restoring and maintaining environmental flows.*"

The Brisbane Declaration (2007) provided evidence of the global dimensions of freshwater ecosystem degradation and its links to human water security. It highlighted the vital importance of environmentally sustainable water resources management, and provided a widely recognized definition of environmental flows (sometimes termed e-flows) as *"the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems."* This definition has since been cited in over 30 scholarly books and hundreds of journal publications and reports, testifying to the value of a consolidated, widely accepted statement of the essence and vital purpose of environmental flows. The Declaration embraced an environmental flows approach based on the natural flow regime (Poff et al., 1997), and stimulated a further decade of research and practice focused on aquatic ecosystem protection, restoration and management. Numerous, diverse water and environment research and development projects, as well implementation initiatives, have tested and strengthened the scientific basis of environmental flows on-the-ground (reviewed in Horne et al., 2017c; Poff et al., 2017). Many have also expanded the scope of assessments from individual sites to whole river basin and regional scales (e.g., King and Brown, 2010; Buchanan et al., 2013; Hart, 2016a,b; O'Brien et al., 2017; Stein et al., 2017). Reflecting these developments, investments in large scale, collaborative e-flow strategies and experiments are increasing across developed and developing regions (e.g., Hirji and Davis, 2009; Konrad et al., 2011; Olden et al., 2014; Hart, 2016a,b; Kendy et al., 2017; Kennen et al., 2018). Parallel efforts have revitalized governance and management arrangements (Foerster, 2011; Pahl-Wostl et al., 2013; Garrick et al., 2017), and promoted multi-stakeholder alliances across researchers, water management agencies, industry, non-government organizations (NGOs), civil society and indigenous groups (Le Quesne et al., 2010; Conallin et al., 2017). Furthermore, environmental water requirements have been incorporated into high-level policies and platforms for river health and catchment management, such as Motion M087 (IUCN, 2012), Resolution XII.12 (Ramsar, 2015) and the European Union Water Framework Directive (European Commission, 2015). Many countries now formally protect and manage environmental water through national laws and regulations, as well as at the basin scale (e.g., King and Pienaar, 2011; Grafton et al., 2012; O'Donnell, 2014).

Fast-forward 10 years to the 20th International River*symposium* and Environmental Flows Conference, held in Brisbane in September 2017. A programme highlight was the celebration of progress with environmental flows since The Brisbane Declaration (2007), and renewal of this influential document to reflect recent developments and emerging challenges. Whilst progress with environmental flows science and water management since 2007 has been immense, major challenges remain in protecting and restoring the integrity of freshwater ecosystems and the ecological services that sustain human cultures, economies, livelihoods, and well-being (e.g., Arthington, 2012; Rockström et al., 2014; Hart and Doolan, 2017; Horne et al., 2017b; Kennen et al., 2018). Environmental flow requirements have still not been adequately assessed for most aquatic ecosystems and have been implemented in even fewer (Moore, 2004; Le Quesne et al., 2010; Gillespie et al., 2015; Harwood et al., 2017). In fact, in spite of admirable global efforts, there is no single global record of environmental flow implementations, nor a good understanding of why some projects have succeeded, while other initiatives have failed even to get off the ground. Major obstacles to environmental flow implementation (elaborated by Moore, 2004; Le Quesne et al., 2010; Harwood et al., 2017) include: lack of political will and public support; constraints on resources, knowledge and capacity; and, institutional barriers and conflicts of interest. For these and other reasons the condition of aquatic ecosystems continues to decline while the pressures continue to grow (Vörösmarty et al., 2013; Bunn, 2016; Reis et al., 2017; Degefu et al., 2018). The world is experiencing a renewed period of dam building driven by new donors and applying different social and environmental safeguards (Zarfl et al., 2015; Greenhill et al., 2016; Kirchherr et al., 2016). Moreover, much of the new construction is concentrated in ecologically sensitive river basins where dams will act as barriers to fish and other migrations, and fragment formerly connected populations (Winemiller et al., 2016; Anderson et al., 2018). Globally, 48% of river volume is moderately to severely impacted by either flow regulation, fragmentation, or both, and this proportion will nearly double if all dams planned and under construction are completed (Grill et al., 2015). Water demands continue to grow in most parts of the world, including semi-arid regions already experiencing medium to high water stress (Luck et al., 2015; Datry et al., 2017). All signs point to increased flow alteration in coming decades and less water for the environment overall. The urgency for implementation of environmental flows is thus greater than ever.

The framing of environmental flows is also transitioning to accommodate increasing uncertainties associated with hydro-climatic and ecological variability (Milly et al., 2008; Poff, 2018; Capon et al., in review), and new societal contexts. Wider appreciation of the social and cultural implications of environmental water and healthy aquatic ecosystems for human riparian communities is an important advance (Johnston, 2012; Lokgariwar et al., 2013; Jackson, 2017). These emerging factors demand new perspectives, renewed research effort, and innovation beyond established approaches to the science and management of water for the environment (Kennen et al., 2018; Poff, 2018; Stoffels et al., 2018; Thompson et al., 2018; Webb et al., 2018). There is also the recognition that there are many flow regime options for a river beyond trying to restore the natural or historical flow regime (e.g., Acreman et al., 2014b; Bond et al., 2014; Poff et al., 2017). Further, choosing between options requires a clear articulation of visions and goals, as well as a capacity to predict the expected outcomes (physical, ecological, societal, economic) from each environmental flow strategy.

With these new perspectives and options on the agenda, this is an opportune moment in the history of environmental flows to build on insights of the 2007 Declaration, a decade on, and re-state the need for more action on water for the environment in all its dimensions. Furthermore, the emphasis of the Sustainable Development Goals (SDGs; UN, 2015) on protecting freshwater and coastal ecosystems could build further momentum for environmental flows to be repositioned as a central element of sustainable water resources management.

The overall objective of this paper is to re-emphasize the pressing need for a more committed effort to protect and restore freshwater ecosystems as resilient social-ecological systems through implementation and adaptation of environmental flows. The paper has four main elements, framed around the development and content of The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018), which is presented in full as Appendix 1.

First, the paper chronicles the inclusive consultation processes employed to gather advice on renewal of The Brisbane Declaration (2007). This section summarizes the thrust of the changes recommended by symposium delegates, and numerous colleagues contacted through professional networks before, during, and after River*symposium* 2017. It also notes some of the suggestions that were not included (e.g., change the term environmental flows to environmental water; provide more detail on linkages and synergies with water-related SDGs), and why it was felt that they could not be incorporated at this time. The main elements of the revised declaration form the second section, which also explains the rationale behind the refined definition of environmental flows and the renewed declaration statements. The third element outlines the Global Action Agenda 2018, setting out over 30 actionable recommendations linked to each declaration statement under three categories of activity (viz. leadership and governance, management, and research). The intent of the actions is to map a pathway forward for a new era of scientific research and innovation, shared visions, collaborative implementation programs and adaptive governance of environmental flows. The 2018 Action Agenda offers ample opportunities for engagement across multiple sectors, disciplines, regions, and cultures. The final section briefly describes future plans for the dissemination and uptake of the renewed document, through global agencies, professional networks, social media, interviews, publications and other follow-up activities. Further, The Brisbane Declaration and Global Action Agenda (2007) is appended as part of the historic record (Appendix 2).

ASSESSMENT OF ENVIRONMENTAL FLOWS POLICY AND GUIDELINES

Consultation on The Brisbane Declaration (2007)

This assessment of environmental flows policy and guidelines is focused on a review of the Brisbane Declaration and Action Agenda (2007) by means of comprehensive consultation processes, and consideration of relevant literature. As a first step, The Brisbane Declaration (2007) was presented for open discussion and critique by a multi-institutional, multi-disciplinary group of social scientists, ecohydrologists and practitioners in an international workshop convened at the National Socio-Environmental Synthesis Center, Annapolis, Maryland, USA, in June 2017. This led to several recommendations on the potential format and content of a revised declaration and action agenda. Secondly, the 2007

Declaration and Action Agenda was placed on a dedicated social media website (https://www.linkedin.com/feed/update/urn:li:activity:6305898179577679872/) with an invitation to all River*symposium* 2017 delegates to offer comment, and suggest changes and additions to enhance the text. Numerous other colleagues were also invited to comment over a 6-month period (2017–2018). A first (2017) draft of the renewed declaration was produced through this consultation phase and posted on social media during the month preceding River*symposium* 2017. Delegates to the symposium were invited to contribute further comments during the 3 days of symposium. A first draft of The Brisbane Declaration on Environmental Flows (2018) was endorsed in principle by delegates at River*symposium* 2017 and numerous colleagues who were unable to attend the event. A second draft of the declaration and first draft of the action agenda were posted for comment, and a further phase of consultations, followed by consolidation of the text by the authors of this paper, produced the final version—The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018)—presented in Appendix 1.

Comments on the 2007 Declaration were diverse and informative, ranging across the definition of environmental flows, the purpose, audience, structure, content and tone of the declaration, the scope and details of the action plan, and the need for supporting documentation (e.g., literature citations). Major points are discussed in turn below, noting, as well, the suggestions that were not included, and how they could be addressed in future (e.g., as elements of projects proposed in the Global Action Agenda).

Definition of Environmental Flows

The definition of environmental flows expressed in the 2007 Declaration attracted many suggestions, the most extreme being to replace the term "environmental flows" with "environmental water" or "water for the environment." Some colleagues suggested that this terminology would convey the intent to include lotic systems (i.e., all freshwater and coastal ecosystems supported by flowing water), lentic systems (i.e., standing water ecosystems such as wetlands and lakes fed by surface or groundwater but not linked to or fed by lotic systems) and groundwater-dependent ecosystems (GDEs). There is merit in the general term "environmental water" (a water volume) instead of environmental flow (a discharge), to embrace the broad ranging treatment of environmental water issues profiled in the recent text *"Water for the Environment: From Policy and Science to Implementation and Management"* (Horne et al., 2017c). Other terminology also has appeal; for example, the European Commission (2015) defines "ecological flows" in terms of "hydrological regimes" to halt the ecological deterioration of aquatic systems and achieve good ecological status. The 2018 Declaration strongly supports the call to embrace all surface and groundwater-dependent aquatic ecosystems, whether flowing or standing, into the science and management of freshwater environmental flows. In the authors' view, ceasing to use the widely accepted term "environmental flows" at this juncture could disconnect the 2018 Declaration from the 2007 Declaration, as well as from the vast body of environmental flows knowledge and implementation experience published before and since 2007.

To maintain continuity of the terminology while broadening the scope to embrace all aquatic ecosystems and their coupled human systems dependent upon flowing, standing or ground water, the 2018 Declaration includes the following definition: "*Environmental flows describe the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems*[a] *which, in turn, support human cultures, economies, sustainable livelihoods, and well-being.*" In this definition, "*Aquatic ecosystems include rivers, streams, springs, riparian, floodplain and other wetlands, lakes, coastal waterbodies, including lagoons and estuaries, and groundwater-dependent ecosystems*" (Appendix 1). By altering the original wording from "*..quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems..*" to "*quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems*[a]", the revised definition meets the call to embrace flowing (lotic), standing (lentic) and GDEs, as well as aquatic ecosystems that may alternate between these states (e.g., ephemeral streams and intermittent rivers). The management of ponds, wetlands, and lakes involves consideration of water volumes, levels and residence time (e.g., Nakamura and Rast, 2011), groundwater connections, and overland flows. The use of the more inclusive concept of environmental flows and the terms "flows and levels" are intended to accommodate such attributes. The expanded scope of the environmental flows definition also includes GDEs of the three main types identified by Richardson et al. (2011) and others (Boulton and Hancock, 2006; Eamus and Froend, 2006). These include aquifer and cave systems; "ecosystems fully or partly dependent on the surface expression of groundwater including wetlands, lakes, seeps, springs, river baseflow, coastal areas, estuaries, and marine ecosystems"; and "ecosystems dependent on subsurface presence of groundwater (via the capillary fringe), including terrestrial vegetation that depends on groundwater fully or on an irregular basis to meet water requirements." Environmental flow management must address the lotic, lentic and groundwater phases of all freshwater-dependent aquatic ecosystems, including their riparian and basin surroundings, to sustain their ecological integrity, ecosystem services and societal values (Bunn, 2016; Datry et al., 2017; Gleeson and Richter, 2017; Horne et al., 2017c; Kennen et al., 2018). To achieve a more integrated approach that considers the water requirements of inter-connected surface and GDEs will be one of the next grand challenges of environmental flows science and management.

A frequent comment on the 2007 definition of environmental flows pertained to the critical recognition of linkages between "*freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems*" (The Brisbane Declaration 2007, Appendix 2). Respondents recommended more explicit reference to the dependence of "*human cultures, economies, sustainable livelihoods, and well-being*" on healthy, resilient freshwater-dependent ecosystems and the role of environmental flows in the lives of people of all cultures. This shift of emphasis is consistent with the recognition that sustaining aquatic ecosystem health and resilience is the foundation for achieving human water security and flourishing livelihoods, for all societies in all regions and across all economic realms (Richter et al., 2010; Vörösmarty et al., 2013; UN, 2015). It encompasses the breadth of relationships from riparian communities dependent on healthy rivers for subsistence livelihoods, including smallholder farmers and fishers, through to societies with complex agricultural water infrastructure controlled under centralized and hierarchical governance arrangements. The statement of peoples' dependencies on and responsibilities toward healthy aquatic ecosystems is in line with the United Nations (UN) Sustainable Development Agenda 2030 and its SDGs and targets (UN, 2015), all of which promote wise use of water, other natural resources and global life support systems (e.g., Bhaduri et al., 2016; Garrick et al., 2017). However, it is also fully recognized that direct use of fresh water is essential for human survival, as specified in the SDGs. Nevertheless, certain conservation values and ecosystem services can still be provided by aquatic ecosystems with modified water regimes. How to decide which values, features and services should be retained or restored is a major dimension of environmental flows.

Links to Sustainable Development Goals

A clear message from consultations was to articulate how environmental flows could contribute to the achievement of the United Nations Sustainable Development Agenda 2030 and the SDGs and targets (UN, 2015). This UN framework presents a "*bold and transformative agenda in support of the twin challenge: protection of Earth's life-support system while reducing hunger and poverty*" (Jägermeyr et al., 2017). Water flows through and underpins all of the SDGs, notably but not only Goal 6 (Ensure access to water and sanitation for all), which includes targets to improve water quality by reducing pollution (6.3), and to protect and restore water-related ecosystems including rivers, wetlands, aquifers, and lakes (6.6, 15.1). Environmental water requirements are explicitly referenced and defined in SDG indicators 6.4.2 (Level of water stress) and 6.6.1 (Change in the extent of water-related ecosystems over time). Environmental flows contribute to improvements in the production of freshwater and estuarine foods such as fisheries (14.2), thereby contributing indirectly to SDGs 1 (no poverty), SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 8 (decent work and economic growth), SDG 12 (sustainable management and efficient use of natural resources), and SDG 16 (peaceful and inclusive societies for sustainable development, and access to justice for all). There are similar links between environmental flows and energy production, cities and other priorities within the SDG portfolio. These direct and indirect linkages and dependencies flow through to the 2018 Global Action Agenda as recommendations for leadership and governance, management, and research activities to integrate environmental flows into programs to achieve SDGs. A fuller articulation of these linkages and dependencies of environmental flows and healthy ecosystems with achievement of the SDGs was recommended during consultations. However, the authors felt that these inclusions were beyond the scope of the 2018 Declaration and Global Action Agenda, and this paper. This type of analysis could form an important future project.

Linkages With Other Resolutions and Declarations

Another suggestion was that the Declaration should build linkages with many other resolutions and declarations (going back to the *Rio Declaration on Environment and Development* 1992, and including, for example, declarations made on water by Indigenous Peoples at the World Water Forums), or at least list them in the document. A long list emerged, however, lacking the space to provide an adequate discussion of linkages and the benefits to be derived from such an exercise, this idea was not developed further. Three particularly relevant water-related policies and platforms for river health and catchment management are mentioned above (Motion M087, IUCN, 2012; Resolution XII.12, Ramsar, 2015; European Union Water Framework Directive, European Commission 2015).

2018 Declaration on Environmental Flows

The main narrative of the 2018 declaration is contained in six statements and the associated amplifying text (Appendix 1). In summary, the core messages are that environmental flows are essential to protect and restore freshwater-dependent aquatic ecosystems, and to deliver important and wide-ranging ecological services that, in turn, support cultures, economies, sustainable livelihoods, and well-being. Environmental flows have been compromised or are at risk in most aquatic systems around the world, and the cumulative global impacts on biodiversity, aquatic ecosystem health, ecological services, and society are severe (Dudgeon et al., 2006; Vörösmarty et al., 2015; Bunn, 2016). However, judicious use of water to better balance human and ecological needs can support biodiversity, resilient ecosystems, and socially-valued ecological services, including those provided by modified and novel aquatic ecosystems (Acreman et al., 2014b; Poff et al., 2016). There is ample evidence that concerted efforts to provide environmental flows can lead to societal and ecological outcomes that are socially acceptable and economically beneficial (e.g., King and Brown, 2010; Hermoso et al., 2012; Chen and Olden, 2017; Harwood et al., 2017). Implementation of environmental flows requires a complementary suite of policy, legislative, regulatory, financial, scientific, and cultural norms and values that ensure effective delivery and beneficial ecological and societal outcomes (Hart, 2016a,b; Harwood et al., 2017; Horne et al., 2017c). The full and equal participation of people of all cultures, and respect for their rights, responsibilities and systems of governance in environmental water decisions can strengthen sustainable outcomes, and these social and cultural dimensions of e-flow management warrant far more attention (Richter et al., 2010; Johnston, 2012; Vörösmarty et al., 2013; Taylor et al., 2016). Challenges to environmental flows science and practice are emerging as societal perspectives shift due to increased uncertainty about water availability under growing human demand and climate change (Milly et al., 2008; Poff and Matthews, 2013; Capon et al., in review). It is anticipated that more variable water regimes and changing patterns of human use will increase the risk of aquatic ecosystem degradation, and intensify the urgency for action to implement optimal water management solutions from human and environmental perspectives (Humphries and Winemiller, 2009; Rockström et al., 2014; Bunn, 2016). To address these issues comprehensively and globally requires more recognition, effort, innovation, commitment, and above all concerted implementation actions, to achieve beneficial outcomes from environmental flows and wise freshwater management for people, biodiversity and ecosystems.

ACTIONABLE RECOMMENDATIONS ON ENVIRONMENTAL FLOWS

The Global Action Agenda on Environmental Flows (2018)

A strong message from the consultations was that actions should be matched to the declaration statements and tailored to particular themes and groups of actors. Drawing upon several sources (e.g., Bunn, 2016; Hart, 2016a,b; Harwood et al., 2017; Horne et al., 2017a,b,c), actions in the 2018 Declaration are organized under three main categories (viz., leadership, management, and research) as summarized in Appendix 1 (**Table A1**).

In this scheme "Leadership and Governance" involves relevant levels of government (international, national, provincial, regional, local) in the development of legislation, policies, regulations and funding mechanisms to institutionalize, promote, and support e-flow science and management within the broader context of jurisdictional natural resource management. Other stakeholders, including civil society and the private sector, can influence governments to lead the development of appropriate instruments.

"Management" involves processes of planning, assessment, implementation, monitoring, and adaptive management of environmental flows by relevant parties including, for example, transboundary, national, and regional water agencies, basin organizations, large water users, NGOs, researchers, cultural groups, indigenous organizations, and other stakeholders (Harwood et al., 2017).

"Research" was added to these two categories to emphasize the ongoing need for deeper investigation of environmental flow issues across the full spectrum of the environmental water management cycle. This cycle ranges from setting a vision for each environmental flow project, to assessing environmental flow requirements and implementing an environmental water plan, to monitoring and evaluating outcomes and adjusting the vision or plan accordingly (Horne et al., 2017a).

Engagement of trans-disciplinary researchers and stakeholders in co-development, partnership or advisory roles is recommended within both the leadership and the management arenas of activity (Conallin et al., 2017). For example, researchers may engage with national, provincial, and local governments to help guide policy development, as seen in several countries (e.g., Australia, South Africa, the European Union). Partnership arrangements with water management agencies can help to guide and monitor environmental flow assessments, and working with NGOs, citizens and indigenous decision-makers is important to integrate scientific and local cultural knowledge of aquatic ecosystems. Models that inform such partnership arrangements abound, each with individual scope, structure and promise of successful outcomes (Jackson et al., 2014; Conallin et al., 2017; Harwood et al., 2017; Stoffels et al., 2018).

The Global Action Agenda (2018) is necessarily brief, reflecting advice from the consultations, and the fact that several recent works have set out detailed statements and summaries of actions needed to advance environmental flows governance, science, implementation and management. As well as Harwood et al. (2017), these include the recent book "*Water for the Environment*" (Horne et al., 2017c), synthesis papers from several special journal issues devoted to environmental flows science and management (Acreman et al., 2014a; Bunn, 2016; Arthington et al., 2018; Kennen et al., 2018; Webb et al., 2018), and a paper setting out the results of a survey of important research priorities to inform future environmental water outcomes (Horne et al., 2017b). The summary of actions in Appendix 1 is less detailed but consistent with the main recommendations of these works.

Actions set out in Appendix 1 also reflect the Global Action Agenda (2007), which emphasized immediate action to: estimate environmental flows (integrated with water quality) and embed environmental flow management in programs and strategies for land-use, water-use, and energy-production; implement and enforce environmental flows; establish institutional frameworks; actively engage all stakeholders; identify and conserve a global network of free-flowing rivers; build capacity; and learn by doing (Appendix 2). Whilst there is ample evidence of progress against each of these actions items (discussed above, and recorded in the cross-section of publications cited herein), this decadal review of progress suggests that a broader scope and explicit action recommendations would add weight to the Global Action Agenda (2018) and should encourage progress in many dimension of environmental flows.

New elements of the Global Action Agenda (2018) include actions to address the direct and indirect relevance and contributions of environmental flows to the achievement of water-related SDGs, the attention directed to recognition, respect for, empowerment and engagement of diverse cultures and communities; and the framing of environmental flows in new global contexts, particularly the implications of climate change. The latter include the implications for water quality, availability, and security, as well as the societal, economic and ecological consequences of shifting climatic and other environmental regimes. Rapid population growth, new geographic patterns of human (and other biological communities), and climate change risks compound the challenges of environmental flow management and ecosystem sustainability (Capon et al., in review). Flow regimes and ecological baselines are changing in many ecosystems and novel ecosystems are emerging, each with implications for riparian cultures, economies and human well-being (Humphries and Winemiller, 2009; Acreman et al., 2014b; Rockström et al., 2014; Poff, 2018). These changes herald a new era of environmental flows science, assessment and management, one that seeks to adapt traditional approaches and methods to the realities of climatic and other environmental changes, ecosystem adjustments, and societal consequences (Poff, 2018; Thompson et al., 2018; Capon et al., in review).

The renewed Action Agenda promotes leadership to implement governance processes for adapting environmental flow management to climate change and human use scenarios, innovation around existing and novel technologies, and further application of trade-off processes to balance ecological resilience and societal benefits, including those provided by ecosystems with modified water regimes (e.g., Hermoso et al., 2012; Poff et al., 2016; Cartwright et al., 2017; Chen and Olden, 2017). Finally, long-term studies of aquatic ecosystem adjustments and societal responses are recommended in climatic and environmental change hotspots using novel experimental designs, meta-data analysis and measurement of ecological variables that capture rates of change in relation to shifting environmental flows, water quality and human water use (Davies et al., 2014; Arthington et al., 2018; Webb et al., 2018). Strengthening scientific understanding and evidence of the different benefits of environmental flows for ecosystems, economies and people under emerging planetary pressures is essential to guide water management toward social- ecological resilience in the future.

Dissemination of the 2018 Declaration and Global Action Agenda

Global dissemination of the final version of the 2018 Declaration presented in Appendix 1 is encouraged through international agencies (e.g., FAO, UNESCO, UNDP, UNEP, Ramsar, WHO), national governments, land and water management agencies, river basin groups, NGOs, professional networks, social media and key fora (e.g., World Water Forum 2018, Brazil, and World Water Week, Stockholm, 2018). Opportunities abound for tracking uptake of renewed Brisbane Declaration (2018), and assessing progress with implementation structured around the Action Agenda. Examples include postgraduate studies, systematic literature reviews, collaborative research and solution laboratories, and projects designed to support achievement of water-related SDGs.

CONCLUSIONS

The Brisbane Declaration and Action Agenda (2007) on environmental flows brought together the diverse experiences of environmental flows practitioners across regions and disciplines, and set a common vision and direction for environmental flow science and management internationally. It provided evidence of the global dimensions of freshwater ecosystem degradation and its links to human water security, and stimulated a decade of research, engagement, and action to protect and restore aquatic ecosystems by means of freshwater flow management. However, in spite of significant progress, environmental flow requirements have still not been adequately assessed for most aquatic ecosystems, and have been implemented in even fewer. All signs point to growing demands for fresh water, increased water stress, more flow regulation, and fragmentation of aquatic habitats, and less water for the environment overall in coming decades. Thus the urgency for implementation of environmental flows, monitoring their social-ecological outcomes and supportive research, is greater than ever. To address these issues comprehensively and globally requires more recognition, effort, innovation, commitment, and above all concerted implementation actions, to achieve beneficial outcomes from environmental flows and wise freshwater management for people, biodiversity and ecosystems. The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018) provides over 30 actionable recommendations to support and advance environmental flow implementation. It heralds a new era of scientific innovation, shared visions, collaborative implementation programs and adaptive governance of environmental flows, with ample opportunities for engagement across multiple sectors, disciplines, regions, and cultures. Working together in a more committed, organized, and inclusive manner to reposition environmental flows as a central element of sustainable water resources management in changing landscapes, climates, and scenarios of water security is now more urgent than ever. Furthermore, the emphasis of the SDGs on protecting freshwater and coastal ecosystems could build further momentum for environmental flows to be repositioned as a central element of sustainable water resources management.

AUTHOR CONTRIBUTIONS

All authors contributed to drafting The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018) and to the preparation of this paper.

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APPENDIX 1

The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018)

The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018) was developed and endorsed by a fast growing international network of environmental flow practitioners comprising civil society, indigenous peoples, the private sector, scientists, water users, businesses, non-government organizations, local, regional and national government agencies, and international institutions. This declaration builds on and supplements the influential Brisbane Declaration and Global Action Agenda (2007) developed a decade earlier during the 10th *International Riversymposium and International Environmental Flows Conference* held in Brisbane, Australia, September 2007. The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018) was endorsed by delegates of the 20th *International Riversymposium and Environmental Flows Conference* (Brisbane, September 2017) and numerous colleagues.

Environmental flows describe the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being. In this definition, *aquatic ecosystems* include rivers, streams, springs, riparian, floodplain and other wetlands, lakes, freshwater dependent coastal water bodies, including lagoons and estuaries, and groundwater-dependent ecosystems (GDEs). The goal of environmental flow management is to protect and restore the socially valued benefits of healthy, resilient, biodiverse aquatic ecosystems and the vital ecological services, economies, sustainable livelihoods, and well-being they provide for people of all cultures.

The Brisbane Declaration on Environmental Flows (2018) presents an urgent call for action to protect and restore environmental flows and resilient aquatic ecosystems for their biodiversity, intrinsic values and ecosystem services as a central element of water resources management, and as a foundation for achievement of the water-related Sustainable Development Goals.

The Brisbane Declaration on Environmental Flows (2018)

Environmental Flows Are Essential to Protect and Restore Biodiversity, Aquatic Ecosystems, and the Ecosystem Services They Provide For All Societies

All aquatic ecosystems need a dynamic environmental flow or standing water regime to sustain their biodiversity and ecological services. Flows vary with climate, landscape factors, human influences, and through time. Flow patterns govern habitat, biodiversity, productivity and aquatic ecosystem resilience. Healthy aquatic, wetland, and riparian habitats often expand during natural wet phases but can become fragmented or diminished in size or function during natural dry phases, and as a result of human water extraction and diversion. Many functionally intact rivers connect to vast floodplains and they contribute beneficial freshwater and sediment inflows to coastal zones. These dynamic processes support important and wide-ranging ecological services that, in turn, support cultures, economies, sustainable livelihoods, and well-being.

Environmental Flows Are Critical to Protect and Safeguard the World's Cultural and Natural Heritage

The intangible spiritual attachments between people, rivers and wetlands are enduring, and the human inclination to revere rivers and celebrate symbols and rituals relating to water is universal. Many human societies ascribe meaning to water and its flow, transmitting shared understandings of the world through cultural objects and practices, including ecosystem protection. Managing environmental water sustainably is necessary to protect and restore these natural and cultural heritage values.

Environmental Flows Have Been Compromised and Today Many Aquatic Systems Around the World Are at Risk

Freshwater species continue to decline more rapidly than terrestrial and marine species, primarily due to pressures from habitat degradation, over-abstraction, pollution, poorly-planned infrastructure, and modified flows. Many new dams under construction, or proposed, will further degrade aquatic ecosystems. As freshwater ecosystems degrade and species are lost, human communities lose important social, cultural, and economic benefits; estuaries lose productivity; invasive plants and animals flourish; and the social-ecological resilience of riverine, wetlands, and estuarine ecosystems weakens. The cumulative global impact is severe. Judicious human use of water to balance human and ecological needs can support biodiversity, sustainable ecosystems, and ecological services.

Implementation of Environmental Flows Requires a Complementary Suite of Policy, Legislative, Regulatory, Financial, Scientific, and Cultural Measures to Ensure Effective Delivery and Beneficial Outcomes

Policy, legislation, and regulation on water, environment, and related sectors (e.g. agriculture, energy) are necessary to explicitly recognize, protect, and support the provision of environmental flows according to context. The determination, delivery, and evaluation of environmental flows should be based on scientific and cultural knowledge collected and analyzed within an adaptive management framework that balances human water requirements and water for ecosystems. Implementation of environmental flows requires adequate financing and sustained support from all relevant sectors.

Local knowledge and Customary Water Management Practices can Strengthen Environmental Flow Planning, Implementation, and Sustainable Outcomes

Ecological, hydrological, and social interactions underpin the economies of riparian communities and their cultural heritage. All societies have developed institutions (laws, norms, values) that draw on such knowledge to govern systems of water access, use, and management. The full and equal participation of all cultures, and respect for their rights, responsibilities, and systems of governance in environmental flow decisions can strengthen sustainable outcomes for cultures, economies, livelihoods, and well-being.

Climate Change Increases the Risk of Aquatic Ecosystem Degradation and Intensifies the Urgency for Action to Implement Environmental Flows

Climate change is introducing increasing uncertainty about water availability and regimes of water flow, temperature, chemistry, and sediment fluxes, and causing biota to shift habitat. Climate change compounds human water security challenges, and will intensify the need for, and pressures on, environmental water. Conventional twentieth century water management approaches, heavily based on supply-side engineering interventions, are no longer sufficient for a world with rapidly shifting hydrology. These factors heighten the need for urgent and co-ordinated action to assess options for environmental flow management, and to implement optimal water management solutions for ecosystems, cultures, economies, sustainable livelihoods, and human well-being.

Global Action Agenda on Environmental Flows (2018)

The Brisbane Declaration on Environmental Flows (2018) calls upon all governments, development banks, donors, water and energy associations, multilateral and bilateral institutions, community-based organizations, research institutions, indigenous groups and the private sector across the globe to commit to the following actionable recommendations (**Table A1**) for protecting and restoring environmental flows as a central element of water resources management, and as a foundation for achievement of the water-related Sustainable Development Goals (SDGs).

TABLE A1 | The Brisbane Declaration on Environmental Flows (2018) and supporting actionable recommendations of the Global Action Agenda on Environmental Flows (2018).

Declaration statements	Leadership and governance	Management	Research
E-flows are essential to protect and restore biodiversity, aquatic ecosystems, and the ecosystem services they provide for all societies	Develop and implement government programs to support provision of e-flows to freshwater-dependent ecosystems, including Groundwater Dependent Ecosystems (GDEs) [1,2] Develop and implement government e-flow programs to support achievement of water-related Sustainable Development Goals (SDGs)[1]	Develop and implement e-flow programs that integrate surface and groundwater processes into e-flow planning, assessment, monitoring, and management[3,4,5] Integrate e-flows into programs and projects designed to support achievement of water-related Sustainable Development Goals (SDGs)[1,6]	Quantify flow-ecology relationships and ecosystem services for all aquatic ecosystems that depend on fresh water, including GDEs[3,4,5] Demonstrate ecological, economic, and societal benefits of e-flows and healthy freshwater-dependent ecosystems in programs and projects that support water-related Sustainable Development Goals (SDGs)[1,66]
E-flows are critical to protect and restore the world's cultural and natural heritage	Develop and implement government programs to generate awareness of cultural heritage values, knowledge, and attachments to freshwater-dependent ecosystems[6,7,8]	Integrate cultural heritage values, knowledge, and attachments to freshwater-dependent ecosystems into e-flow assessment, implementation, monitoring, and adaptive management[6,7,8]	Improve understanding and quantify relationships between e-flows, healthy aquatic ecosystems, and cultural heritage values, and attachments to freshwater-dependent ecosystems [6,7]
E-flows have been compromised and today many aquatic systems around the world are at risk	Develop and implement government programs to protect and restore freshwater ecosystems. Protect healthy freshwater-dependent ecosystems as early as possible[8] Establish programs to implement e-flows during the planning stage of new dams and other water infrastructure[2,8,9]	Apply systematic planning tools to achieve cost-effective protection and restoration of healthy freshwater ecosystem[8,9,11] Base protection and restoration of e-flows on scientific and local knowledge within an adaptive management framework that balances human and ecological water requirements[2,10]	Identify obstacles to implementation of e-flows in different world settings. Improve systematic planning tools and trade-off processes that can guide the location, design, and operation of new dams/other water infrastructure, for social-ecological benefit[9,10,11]
Implementation of e-flows requires a complementary suite of policy, legislative, regulatory, financial, scientific, and cultural norms and values to ensure effective delivery and beneficial outcomes	Develop and implement a legal basis for regulating water use, e-flows, water rights, and licenses, including recognition of cultural heritage values, knowledge, and customary relationships with water[2,7,12] Develop and implement policies and programs to position e-flows as an integral component of water, food, and energy security objectives and water-related SDGs[6,12]	Establish environmental water allocation mechanisms appropriate to basin conditions and governance structures[12] Establish a system to manage consumptive water uses at basin and local scales[12] Utilize basin and system-scale infrastructure planning, design, and operation to protect and enable e-flows even where dams and other types of water infrastructure are needed, as well as in cases of infrastructure retrofitting and decommissioning[11,13]	Investigate existing, and propose new, mechanisms for integrating e-flows implementation in broader water and related resource management system[13,14,17] Research effective design, monitoring, and reporting of e-flow implementation projects and programs, treating them as experiments where feasible[10,14,,15]

(Continued)

TABLE A1 | Continued

Declaration statements	Leadership and governance	Management	Research
	Provide sustained funding to effectively plan, design, implement, monitor, and adaptively manage e-flows[10,14] Provide sustained funding for research and training to enhance understanding of aquatic ecosystem functioning, e-flow planning, assessment, implementation, monitoring, and adaptive management[3,10,12]	Ensure that water management professionals have sufficient technical capacity and knowledge to incorporate environmental flow approaches into water resource management plans, implementation, monitoring, and adaptive management	Establish centers of excellence for research and training to enhance understanding of aquatic ecosystem functioning, e-flow planning, assessment, implementation, monitoring, and adaptive management
Local knowledge and customary water management practices can strengthen e-flow planning, implementation, and sustainable outcomes	Develop and implement arrangements for full and equal participation, and respect for the rights, responsibilities and systems of governance of all cultures and stakeholders in e-flow planning, assessment, implementation, monitoring, and adaptive management[7,15,18]	Empower and ensure the full and equal participation, and respect for the rights, responsibilities and systems of governance, of all cultures and stakeholders in e-flow planning, assessment, implementation, monitoring, and adaptive management[7,15,18]	Co-develop best-practice models to ensure full and equal participation, and respect for the responsibilities, rights and systems of governance of all cultures and stakeholders in e-flow planning, assessment, implementation, monitoring, and adaptive management[7,15,18]
Climate change increases the risk of aquatic ecosystem degradation and intensifies the urgency for action to implement e-flows	Develop and implement flexible governance and management arrangements that enable consideration of climatic and other environmental regime change implications for e-flows and ecosystems. Establish programs to implement adjustments to e-flows in aquatic ecosystems impacted by changing flow and other environmental regimes[2,19,20]	Where climate change may further disrupt e-flows and social-ecological systems, adapt existing approaches to maintain/restore ecological resilience and societal benefits[16,17,20] Monitor ecological and societal outcomes of e-flows in relation to changing flow and other environmental regimes, and adjust implementation plans accordingly[10,20]	Conduct long-term studies of freshwater-dependent ecosystem adjustments and societal responses to changing flow and other environmental regimes in areas experiencing shifts in climate, human demographic patterns, and demands for water[16,18,20] Research new approaches to maintain/restore ecological resilience and societal benefits in such areas[17,19,20]

INFORMATION SOURCES:1, (UN, 2015); 2, (Horne et al., 2017a); 3, (Poff et al., 2010); 4, (Gleeson and Richter, 2017); 5, (Bunn and Arthington, 2002); 6, (Bunn, 2016); 7, (Jackson, 2017); 8, (Finlayson et al., 2017); 9, (Hermoso et al., 2012); 10, (Webb et al., 2017); 11, (Winemiller et al., 2016); 12, (Horne et al., 2017c); 13, (Harwood et al., 2017); 14, (Thomas, 2017); 15, (Poff et al., 2003); 16, (Davies et al., 2014); 17, (Pahl-Wostl et al., 2013); 18, (Conallin et al., 2017); 19, (Rockström et al., 2014); 20, (Poff, 2018).

APPENDIX 2

The Brisbane Declaration (2007)

Environmental Flows[1] are Essential for Freshwater Ecosystem Health and Human Well-Being

This declaration presents summary findings and a global action agenda that address the urgent need to protect rivers globally, as proclaimed at the 10th International River*symposium* and International Environmental Flows Conference, held in Brisbane, Australia, on 3–6 September 2007. The conference was attended by more than 750 scientists, economists, engineers, resource managers, and policy makers from more than 50 countries.

Key Findings Include

Freshwater Ecosystems Are the Foundation of our Social, Cultural, and Economic Well-Being

Healthy freshwater ecosystems—rivers, lakes, floodplains, wetlands, and estuaries—provide clean water, food, fiber, energy, and many other benefits that support economies and livelihoods around the world. They are essential to human health and well-being.

Freshwater Ecosystems Are Seriously Impaired and Continue to Degrade at Alarming Rates

Aquatic species are declining more rapidly than terrestrial and marine species. As freshwater ecosystems degrade, human communities lose important social, cultural, and economic benefits; estuaries lose productivity; invasive plants and animals flourish; and the natural resilience of rivers, lakes, wetlands, and estuaries weakens. The severe cumulative impact is global in scope.

Water Flowing to the Sea is *Not* Wasted

Fresh water that flows into the ocean nourishes estuaries, which provide abundant food supplies, buffer infrastructure against storms and tidal surges, and dilute and evacuate pollutants.

Flow alteration Imperils Freshwater and Estuarine Ecosystems

These ecosystems have evolved with, and depend upon, naturally variable flows of high-quality fresh water. Greater attention to environmental flow needs must be exercised when attempting to manage floods; supply water to cities, farms, and industries; generate power; and facilitate navigation, recreation, and drainage.

Environmental Flow Management

Environmental flow management provides the water flows needed to sustain freshwater and estuarine ecosystems in coexistence with agriculture, industry, and cities. The goal of environmental flow management is to restore and maintain the socially valued benefits of healthy, resilient freshwater ecosystems through participatory decision making informed by sound science. Ground-water and floodplain management are integral to environmental flow management.

Climate Change Intensifies the Urgency

Sound environmental flow management hedges against potentially serious and irreversible damage to freshwater ecosystems from climate change impacts by maintaining and enhancing ecosystem resiliency.

Progress has Been Made, but Much More Attention is Needed

Several governments have instituted innovative water policies that explicitly recognize environmental flow needs. Environmental flow needs are increasingly being considered in water infrastructure development and are being maintained or restored through releases of water from dams, limitations on ground-water and surface-water diversions, and management of land-use practices. Even so, the progress made to date falls far short of the global effort needed to sustain healthy freshwater ecosystems and the economies, livelihoods, and human well-being that depend upon them.

Global Action Agenda

The delegates to the 10th International River*symposium* and Environmental Flows Conference call upon all governments, development banks, donors, river basin organizations, water and energy associations, multilateral, and bilateral institutions, community-based organizations, research institutions, and the private sector across the globe to commit to the following actions for restoring and maintaining environmental flows:

Estimate Environmental Flow Needs Everywhere Immediately

Environmental flow needs are currently unknown for the vast majority of freshwater and estuarine ecosystems. Scientifically credible methodologies quantify the variable—not just minimum—flows needed for each water body by *explicitly* linking environmental flows to specific ecological functions and social values. Recent advances enable rapid, region-wide, scientifically credible environmental flow assessments.

Integrate Environmental Flow Management Into Every Aspect of Land and Water Management

Environmental flow assessment and management should be a basic requirement of Integrated Water Resource Management (IWRM); environmental impact assessment (EIA); strategic environmental assessment (SEA); infrastructure and industrial development and certification; and land-use, water-use, and energy-production strategies.

Establish Institutional Frameworks

Consistent integration of environmental flows into land and water management requires laws, regulations, policies and programs that: (1) recognize environmental flows as integral to sustainable water management, (2) establish precautionary limits on allowable depletions and alterations of natural flow, (3) treat ground water and surface water as a single hydrologic

[1] *Environmental flows* describe the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems.

resource, and (4) maintain environmental flows across political boundaries.

Integrate Water *Quality* Management

Minimizing and treating wastewater reduces the need to maintain un-naturally high streamflow for dilution purposes. Properly-treated wastewater discharges can be an important source of water for meeting environmental flow needs.

Actively Engage all Stakeholders

Effective environmental flow management involves all potentially affected parties and relevant stakeholders and considers the full range of human needs and values tied to freshwater ecosystems. Stakeholders suffering losses of ecosystem service benefits should be identified and properly compensated in development schemes.

Implement and Enforce Environmental Flow Standards

Expressly limit the depletion and alteration of natural water flows according to physical and legal availability, and accounting for environmental flow needs. Where these needs are uncertain, apply the precautionary principle and base flow standards on best available knowledge. Where flows are already highly altered, utilize management strategies, including water trading, conservation, floodplain restoration, and dam re-operation, to restore environmental flows to appropriate levels.

Identify and Conserve a Global Network of Free-Flowing Rivers

Dams and dry reaches of rivers prevent fish migration and sediment transport, physically limiting the benefits of environmental flows. Protecting high-value river systems from development ensures that environmental flows and hydrological connectivity are maintained from river headwaters to mouths. It is far less costly and more effective to protect ecosystems from degradation than to restore them.

Build Capacity

Train experts to scientifically assess environmental flow needs. Empower local communities to participate effectively in water management and policy-making. Improve engineering expertise to incorporate environmental flow management in sustainable water supply, flood management, and hydropower generation.

Learn by Doing

Routinely monitor relationships between flow alteration and ecological response before and during environmental flow management, and refine flow provisions accordingly. Present results to all stakeholders and to the global community of environmental flow practitioners.

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Managing the Three Gorges Dam to Implement Environmental Flows in the Yangtze River

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The construction of the Three Gorges Dam, along with other development in the Yangtze River basin, has had profound consequences for the river's flow and sediment regime. This has had major impacts on the geomorphology and ecology of the river downstream of the dam, with related impacts on biodiversity, including fish populations, livelihoods, and water security in the middle and lower Yangtze. Changes to fish populations have included a fall of around 90% in the total number of fish fry for the four economically-important Chinese carp species, caused at least in part by alterations in the flow regime. In response, there has been increased research into the significance of flow regimes for Chinese carp, as well as other aspects of river health. A partnership between the Chinese Government, the dam operator, scientists, and conservationists has led to pilot environmental flow releases over a 5-year period in an attempt to mitigate some of these impacts. Subsequent monitoring has shown that numbers of fish fry are increasing from the low they had fallen to in 2008. Drawing on lessons from the pilot environmental flow releases, in October 2015 the official regulations that govern operations of the Three Gorges Dam were amended to incorporate additional objectives, including incorporating environmental flow releases as part of the routine operation of the dam. This paper describes the processes that led to the environmental flow program from Three Gorges, a review of monitoring data collected during the pilot environmental flow releases, the subsequent amendment of the dam operating rules, and prospects for expanding environmental flow implementation in the Yangtze River in coming years.

Keywords: dam re-operation, Three Gorges dam, environmental flows, river fisheries, Yangtze river

INTRODUCTION

Environmental flows have become an important strategy for maintaining and restoring rivers and their social and environmental resources and values. Recent decades have seen major progress in the science that underpins environmental flow assessments. Although widespread implementation of environmental flows has been constrained by a number of challenges (Le Quesne et al., 2010), implementation of environmental flows has been seen in an increasing range of contexts (Harwood et al., 2017). In China, the concept of environmental flows has gained currency in the river basin management discourse in the last decade (Chen et al., 2016), but examples of implementation remain rare (Sun et al., 2008; Li et al., 2009; Chen and Zhao, 2011). Nevertheless, recent shifts in policy priorities that emphasize the need for more environmentally sustainable approaches to socio-economic development have led to an increased focus on river restoration, including environmental flow implementation (Speed et al., 2016).

In this paper, we describe a program to implement environmental flow releases from the Three Gorges Dam on the Yangtze River (China)—by some measures, the largest dam in the world. We focus on the management, policy and institutional factors that contributed to environmental flow implementation because documenting these examples of application can provide insights for practitioners and managers in other parts of the world (Harwood et al., 2017).

Since 2003, the Three Gorges Dam has regulated flow on the Yangtze River, the third longest river in the world. Dam operations have modified the Yangtze's flow regime and affected flow-dependent processes such as the maintenance of wetlands and fish migration and spawning. The impact of the dam on Yangtze fisheries has been one of the most widely recognized consequences of the dam. For example, the annual harvest of four commercially important carp species dropped by 50–70% compared to the pre-dam baseline with even more dramatic declines in larvae and eggs below the dam (Xie et al., 2007).

Concern within government and the public led to discussions about how to mitigate the negative impact of the Three Gorges Dam on the downstream ecosystem. Researchers and conservationists, including international organizations such as Worldwide Fund for Nature (WWF) and The Nature Conservancy (TNC) recommended that the dam should be re-operated to help restore some of the Yangtze's crucial natural hydrological processes. In 2011, a program to release environmental flows from the dam was initiated and the dam operator [the China Three Gorges Corporation (CTG)][1] has released a flood pulse from the dam in May or June every year since. The primary purpose of these environmental flow releases has been to promote carp spawning. Drawing on lessons from the pilot flow releases, in October 2015 the regulations that govern operation of Three Gorges Dam were amended to incorporate additional objectives and operational requirements that now provide for environmental flow releases as part of the routine operation of the dam.

In this paper we will summarize: (1) the biophysical processes and relevant aspects of the biodiversity of the Yangtze River and how they were affected by the Three Gorges Dam, with a focus on changes to flow regime and populations of four Chinese carp; (2) the regulatory context for dam operations in China, including requirements to maintain fish populations; (3) the processes through which CTG, agencies and stakeholders planned environmental flow releases; (4) the annual flow releases and impacts on carp recruitment; and (5) recommendations for future research and adaptive management.

[1] China Three Gorges Corporation official website, http://www.ctg.com.cn/english/

BACKGROUND ON THE YANGTZE RIVER AND THREE GORGES DAM

The Yangtze River is Asia's longest river, flowing more than 6,000 kilometers from west to east. It sustains 416 fish species, including more than 178 endemic and ancient species, such as the Chinese Paddlefish (*Psephurus gladius*) and Chinese Sturgeon (*Acipenser sinensis*) (Ye et al., 2011). The Yangtze also supports high numbers of birds, especially in the productive wetlands at the river's middle section and mouth that serve as an important stopover and wintering ground for birds traveling Asia's north-south migratory route.

Two independent climate patterns drive the hydrology of the Yangtze River: the upper basin experiences the Indian summer monsoon and the middle parts of the basin experience the East Asian summer monsoon (Ding and Chan, 2005; Chen et al., 2014). Annual precipitation in the basin varies from nearly 900 mm in the upper basin to 1,500 mm in the lower basin (Zhang et al., 2010; Chen et al., 2014). Due to these patterns, flows in the middle reaches of the Yangtze River, including the region immediately upstream of the Three Gorges Dam, are greatest in July with average flow reaching ~30,000 m^3/s. Flows then decline gradually to an average of ~4,000 m^3/s in February before rising again in the spring to reach the July peak.

Spanning more than 3 million square kilometers, the Yangtze Basin is home to one-third of China's human population. Throughout history, the river has also supported the rise of early agricultural civilisations, the growth of some of China's largest cities and facilitated shipment of agricultural and industrial goods from the country's interior to the port of Shanghai and beyond (Normile, 1997; Yasuda et al., 2004). While the Yangtze has played a key role in the rapid development of China, the river's ecological functions have undergone dramatic declines resulting from pollution and other anthropogenic impacts.

In recent years, the Yangtze's flows have been harnessed to generate hydroelectric power for one of the world's fastest-growing economies. Hydropower expansion has been driven in part by goals to reduce emissions from coal-fired power plants. Twenty-nine major dams have been built or are planned on the mainstream of the Yangtze. Most of the hydropower sites in the Upper and Middle Yangtze have already been developed and almost all of the hydropower potential in the Jinsha River (the name of the upper mainstream of the Yangtze) is now under development.

The Three Gorges Dam is located at Sandouping, about 40 km upstream of the city of Yichang on the mainstem Yangtze River (**Figure 1**). First contemplated by Sun Yat-sen in the early twentieth-century and with design work undertaken as long ago as 1930s, construction of the dam began in December of 1994 and, by November of 1997, the river had been successfully cut off. In June 2003, the second phase of the dam was finished, and the water level in the reservoir rose to 135 m. Construction of the dam was completed in 2009 and water levels in the reservoir

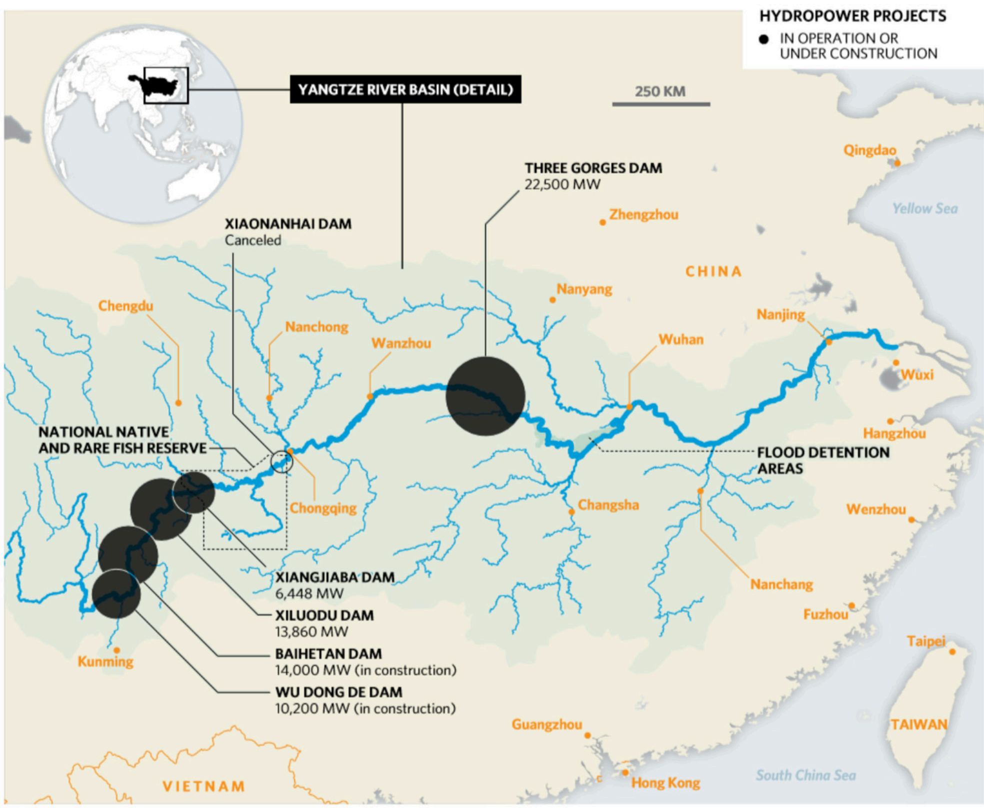

FIGURE 1 | The Yangtze River and the hydropower development in the main stem. Reproduced from (Opperman et al., 2017) with permission from The Nature Conservancy.

rose to the design level of 175 m in November of that year. The dam has a length of 2,309 m at crest elevation 185 m, and a total storage capacity of 39.3 billion m^3 including flood control storage of 22.2 billion m^3. This flood storage can effectively control most floods originating from upstream and significantly reduce flood risk for cities and agriculture in the Yangtze's valley downstream. The hydropower plant of the Three Gorges Dam includes 32 turbines of 700 MW each, with a total installed capacity of over 22,000 MW and an average annual energy output of 84.7 TWh, which would be sufficient to meet the average electricity demand of Pakistan (CIA, n.d. and CTG official website http://www.ctg.com.cn/english/)[2]

CARP IN THE YANGTZE RIVER AND ENVIRONMENTAL CHANGES FROM THREE GORGES DAM

The Yangtze River supports four species of carp, which are among the most important freshwater commercial fish species in China: the Silver Carp (*Hypophthalmichthys molitrix)*; the Bighead Carp (*Aristichthys nobilis*); the Grass Carp (*Ctenopharyngodon idella*), and the Black Cgarp (*Mylopharyngodon piceus*). In the Yangtze, adult fish of all these species migrate upstream to the middle and upper reaches to spawn during the rising flow levels of the spring (Anonymous, Fish Research Laboratory, Institute of Hydrobiology of Hubei Province, 1976; Yi et al., 1988).

Carps have specific hydrological requirements for spawning. Water temperatures must exceed 18°C, with spawning most effective between 21 and 24°C. Spawning is triggered by the rising water temperatures and increases in flow that occur during the late spring. Adults spawn in the open water and eggs and larvae drift downstream. Larval fish float until they have developed in size and are capable of moving into nursery habitats along the river's edge. These nursery habitats include floodplain lakes and seasonal wetlands that are hydrologically connected to the Yangtze, including Dongting Lake and Poyang Lake (Zhang et al., 2000; Chen et al., 2009). This period of development generally requires at least 100 km of river distance with flowing water because the eggs can sink if flow velocity is below 0.2 m/s.

Fish numbers in the Yangtze River and associated fishery harvests have been declining due to overfishing, illegal fishing, and water pollution from industrial waste discharge, agricultural chemical runoff, aquaculture, and community sewage (Cao et al., 2008; Ye et al., 2014). The changes of fish early resources since 1997 have shown in **Figure 2**. Fish have also been negatively impacted by habitat loss and degradation from dredging and

[2]CIA n.d. CIA World FactBook, Pakistan, Available online at https://www.cia.gov/library/publications/the-world-factbook/geos/pk.html (viewed 1/3/18).

from the disconnection of floodplain lakes and wetlands from the main river (Fang et al., 2006; Cheng et al., 2014). The disconnection the lakes to the river prevents fish from accessing both spawning and nursery habitats. Further, the extensive construction of dams and reservoirs in the Yangtze Basin—more than 5,000 total with a storage capacity >100,000 m^3—has resulted in extensive barriers to migration and changes in the natural flow regime (Li et al., 2016).

Specific impacts of the Three Gorges Dam include its effects on habitat, connectivity, and the flow regime. The consequences of these changes for carp have been closely studied. According to a hydrological analysis at Yichang Station, downstream of the dam site, the construction and operation of the dam has resulted in changes in flow patterns, including more erratic flows and increased flow variability during April and May. These changes are likely the result of releases to create storage space in the reservoir in anticipation of the upcoming flood season. This modified flow regime is significantly less effective in stimulating spawning behavior of the carps. Thus, since the completion of the Three Gorges Dam, the change of the flow pattern and the decline of the average flooding period are the key factors affecting the natural spawning of the four carp species (Yangtze River Fisheries Research Institute, 2011). It is possible that these pressures have acted synergistically to impact fish populations.

Since the Three Gorges Dam started impounding water in 2003, populations of the four carp species in the Jianli section of the Yangtze (∼350 km below the Three Gorges Dam) have declined rapidly. The number of egg and larvae in surveys had already dropped from 7 to 8 billion in the 1960 to 1–2 billion by the 1980s and 1990s (Survey Team of Spawning Grounds of Domestic Fishes in Chanjiang River, 1982; Yi et al., 1988), but the completion of Three Gorges Dam led to an even more dramatic decline. The number of egg and larval fell from 1.9 billion in 2002 to 400 million in 2003 following closure of the dam and to 42 million in 2009 (Yangtze River Fisheries Research Institute, 2011; **Figure 2**).

DRIVERS THAT LED TO ENVIRONMENTAL FLOW IMPLEMENTATION FROM THREE GORGES DAM

Beginning in the 1970s, fishery managers within the Chinese government were aware that the Yangtze's fishery resources would be seriously affected by proposed dams on the main stem of the Yangtze—first Gezhouba (a smaller dam ∼40 km downstream of Three Gorges, completed in 1988) and then Three Gorges Dams (**Figure 1**). The social and environmental impacts of the Three Gorges Dam received considerable attention—both within China and globally—since the dam's planning stages in the 1990s. Subsequently, the dramatic decline of the four carp species, described above, received widespread media attention within China, prompting the public and conservation organizations to apply pressure to regulators and CTG to find solutions to address the issue.

Evolving regulatory requirements for environmental protection provided the strongest driver for dam operators to seeks solutions to mitigate impacts on the carp. Following decades of rapid economic growth, the Chinese government has begun to strengthen environmental protections to address the negative impacts of that growth. In 2005, China's State Environmental Protection Administration (the precursor to the Ministry of Environmental Protection) required that hydropower projects release environmental flows to support a range of other downstream resources and values, including social and environmental benefits. This has included releases to support fisheries and to maintain water quality. This requirement was repeated and detailed in a series of subsequent policies by government agencies including the Ministry of Water Resources (MWR), Ministry of Environmental Protection (MEP), Ministry of Agriculture (MOA), and National Energy Administration (NEA) (Chen et al., 2016). These requirements on flows were built into the Optimized Operation Scheme of the Three Gorges Dam (guidelines for the dam's operations), issued by The State

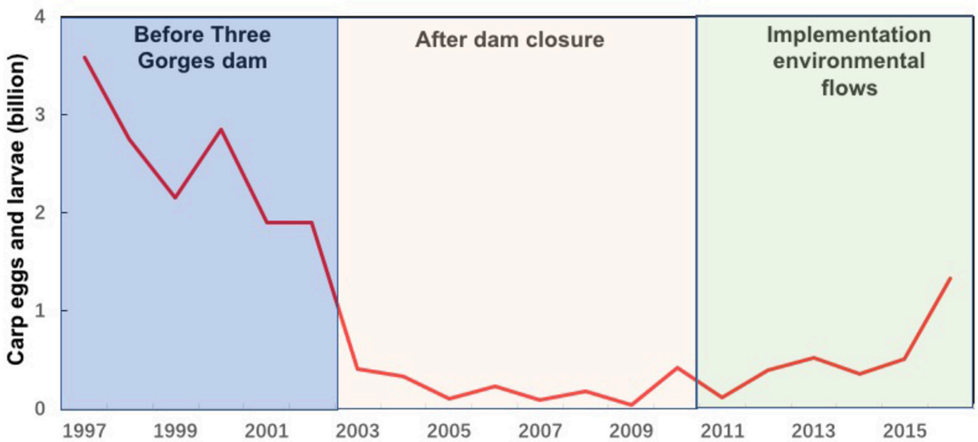

FIGURE 2 | Annual results of monitoring of carp egg and larvae in the Yangtze downstream of Three Gorges Dam during three periods: before the dam, after dam closure, and during the period of environmental flow operation.

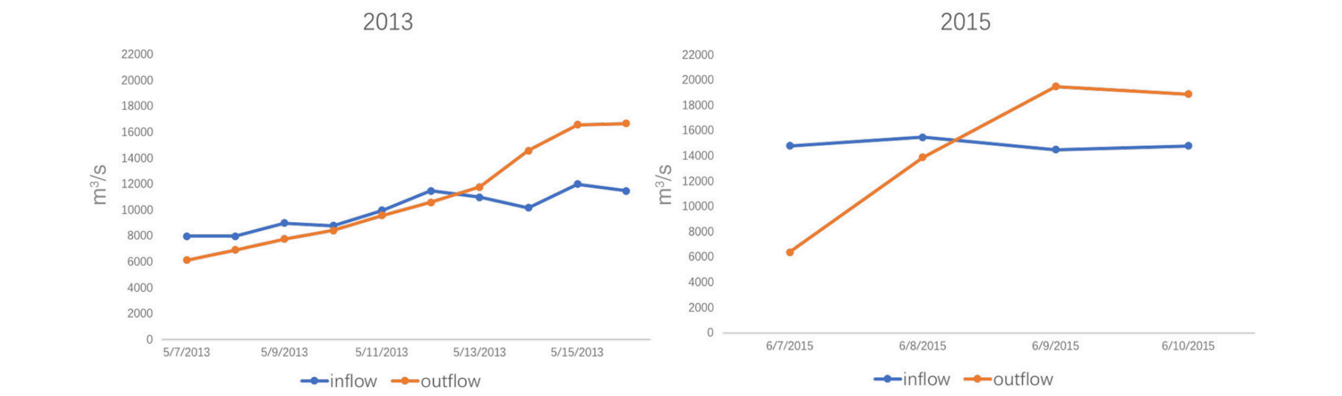

FIGURE 3 | Examples of environmental flow releases (m^3/s) from Three Gorges Dam (2013 and 2015).

Council. The Operation Guideline of the Three Gorges Dam and Gezhouba, approved by the MWR, requires that the dam operation should "maintain river health" by controlling certain flows and water levels in the reservoir and below the dam.

Scientists understanding of the carps' spawning requirements suggested that an environmental flow should mimic the Yangtze's natural flood pulse to promote spawning. However, the Three Gorges Dam is a multi-purpose project that has major functions of flood control, electricity production, navigation, and drought alleviation. The implementation of environmental flows needed to be integrated into the operational requirements that encompass these multiple purposes and thus required engagement with diverse stakeholders.

A range of stakeholders and agencies came together to determine how to provide improved flow conditions for carp, including CTG, the Changjiang (Yangtze) Water Resources Commission (CWRC) under MWR, the Yangtze Fishery Resources Management Committee (YFRC) under the MOA, and the power grid. This consultation process addressed barriers to reoperation, complemented by a research program. For example, the MOA (which is responsible for fishery resources management in China) and CTG funded a research program, including field surveys, analyses of hydrologic and fish biology data, and modeling of operations. The research focused on the relationship between flows and spawning, including identifying hydrologic indicators and thresholds, and how changes to flows would affect other major purposes, such as flood control. This research program is ongoing to monitor the effects of environmental flow operation and analyze further potential improvements to operations.

The information gained from the research program was then integrated into the decision processes for the operation of the Three Gorges Dam. Operations of the dam during flood and drought seasons is determined by the Yangtze River Flood Control and Drought Relief Headquarters (YFDH). The operational plan is drafted based on a structured decision-making (SDM) process involving relevant agencies (Gregory et al., 2012), which is then submitted to the YFDH for approval. A number of government agencies are consulted during this process, including CWRC and YFRC, and those concerned with environmental protection, land and resources, the electricity grid, and navigation. Following the direction set by the YFDH, the operational department of the CTG oversees operations of the Three Gorges Dam. The operational guidelines for the dam clearly stipulate that flood control takes priority over water resources operation (water released for downstream economic production, human needs, and environmental needs), which has priority over electricity production and navigation. For example, in order to cope with salt water intrusion in the Yangtze River estuary in 2014, the reservoir released more water (1.73 billion m^3) and lost electrical generation of 160 MWh.

The evolving regulatory requirements for dam operators to maintain river health along with a period of stakeholder consultation and research resulted in changes to the operations of the Three Gorges Dam in 2011. Operational changes included both those aimed at water management to benefit social and economic values downstream (flow releases to mitigate droughts and saltwater intrusion) and flows to promote carp spawning. Drawing on the lessons from the pilot environmental flow releases, in October 2015 these requirements were subsequently incorporated into the official joint regulation of the Three Gorges Dam/Gezhouba cascade released by the MWR.

IMPLEMENTING ENVIRONMENTAL FLOWS AT THREE GORGES DAM

Dam operation was first modified in 2011, for two purposes: drought mitigation during the early part of the year; followed by a flow release in May to mimic the Yangtze's natural flood pulse and promote carp spawning. Under this operating mode, flows can be released during periods of drought, between January and April, with discharges up to 6,000 m^3/s, which is 1,500 m^3/s (25%) higher than the typical inflow discharges during that time of year. Flow releases to promote carp spawning have been made in the early flood period (late May to June), and have lasted for 3–10 days, continuously increasingly the flow during the spawning period of the carps. During these releases, the usual base flow (6,160–14,700 m^3/s) is increased by an additional 1,000–6,000 m^3/s. These environmental flow releases have now been implemented for seven consecutive years. Examples of environmental flow releases from Three Gorges Dam in 2013 and 2015 were shown in **Figure 3**.

A monitoring program samples carp eggs and larval fish in the water column below the dam before, during and after the period of environmental flow release. Monitoring results available to date indicate that carp reproduction has increased with these new flow releases. The average number of carp eggs and larvae sampled at Jianli station was 230 million per year between 2003 and 2010 (before implementation of environmental flows) and 540 million between 2011 and 2016, during the period that environmental flows have been implemented (data from Yangtze River Fisheries Research Institute, 2016) (**Figure 2**). In June 2014, the average density of eggs and larvae in the reach from Yichang to Yidu was three times higher after the environmental flow release than before, and the density on the third day of operation was seven times higher than before the release began (Chen and Li, 2015).

While these results show that carp reproduction appears to be increasing after a period of significant decline (between 2003 and 2010), it is not yet possible to fully attribute that increase to the environmental flow program. The relevant authorities would need to publish more rigorous statistical analyses that control for other factors (water quality, habitat, fishing pressure, background hydrology) before firm conclusions can be drawn on the extent to which the environmental flows can explain the increases.

CONCLUSIONS

Although the full analysis of impacts has yet to be published, the re-operation of Three Gorges Dam to promote carp spawning provides an important example of how regulations, stakeholder engagement, and science can be combined to inform re-operation of a major dam and to broaden the range of objectives for dam management in China and, potentially, beyond. A combination of environmental, socio-economic, and political pressures and opportunities stimulated policies, processes and institutional interactions that led to the re-operation program. An understanding of how this situation unfolded can provide insights that might be useful in other contexts.

This case study is particularly valuable as it involved one of the largest dams in the world and occurred within a country with extremely limited examples of environmental flow implementation. The environmental flows program of the Three Gorges Dam can serve as a precedent for the re-operation of other dams in China—the country with the most dams in the world. Further, Chinese companies and investors have achieved substantial market shares in the construction of hydropower dams around the world. A high-profile example of dam management for environmental objectives could influence how dams are planned, designed and operated in other countries.

Keys factors for achieving environmental flow implementation included:

- *Public and agency support for mitigating negative impacts.* The public, conservation organizations, and various agencies recognized that Three Gorges Dam had caused considerable adverse environmental impacts and they advocated for solutions to mitigate these impacts.
- *Regulatory requirements to maintain river health.* China's evolving environmental regulations reflected and amplified the concerns described above. The State Environmental Protection Agency published policies requiring hydropower projects to release environmental flows to support downstream resources and these requirements were supported by further guidance from the MWR and the MOA. These agency actions provided a regulatory driver for CTG to pursue reoperation of Three Gorges Dam to support an expanded range of management objectives.
- *Science to inform environmental flow implementation.* The spawning requirements of carp are relatively well known and the environmental flow program has included considerable investment in further research. Fish biologists and hydrologists collaborated to identify the locations of spawning grounds of four Chinese carp. They also identified the critical hydrologic indicators (water temperature, discharge before the flow rise, daily rate of flow rise, and duration of flow rise) that trigger spawning behavior. The research institutions have also conducted ongoing monitoring that can provide the foundation for understanding the environmental outcomes from environmental flows and to inform adaptive management.
- *Collaboration among a range of agencies and stakeholders.* First, government institutions led environmental flow implementation at the Three Gorges Dam. The YFDH and the CWRC coordinated and managed the comprehensive operation of the dam including the environmental flow operation, and the MOA's Office of Fisheries Law Enforcement for the Yangtze River Basin actively promoted the environmental flow implementation for Chinese carp. Second, a multi-institutional interdisciplinary team funded by the CTG contributed to the development of environmental flow plans and objectives, including the science program described above. Third, international conservation organizations, such as WWF and TNC, supported the dam's environmental flow program. For instance, in 2008, WWF collaborated with relevant institutions to establish the Expert Working Group of Environmental Flows in China to promote environmental flow research and improvements to practice. This Working Group collaborated closely with CTG and other stakeholders in the environmental flows program of the Three Gorges Dam and other initiatives, including reconnection of river and lakes, measures to aid carp breeding, and ecological operational guidelines.

Below we provide several recommendations (drawn in part from Harwood et al., 2017) about how environmental flows program at the Three Gorges Dam could be improved and how this case study can be used to inform and promote implementation of environmental flows in China and globally.

- *Continue adaptive management and expand research.* The various agencies and stakeholders should continue collaborating to pursue adaptive management for the environmental flow program. Additionally, data collection and analysis should be expanded to better understand the relationship between changes in the flow regime and the response of carp reproduction. This can improve understanding of the effectiveness of the flow releases, in terms of biological outcomes, and inform adaptive management.
- *Coordinate flows throughout the Yangtze basin and embed environmental flows within broader management to conserve Yangtze fisheries*. Environmental flows can only address part of the management objectives for fish in the Yangtze and so the flow program should be embedded within a larger program focused on water quality, habitat, and fisheries management. Additionally, the current flow program is focused on carp but other taxa, especially those which are protected or threatened (such as Chinese sturgeon), merit further attention, as does the relationship between river flows and linked freshwater habitats, such as lakes and wetlands. Beyond the Three Gorges Dam, the Yangtze basin contains thousands of dams, including hundreds of large dams. Management of these dams could be coordinated at the basin scale to promote broader environmental flow regimes, consistent with the Chinese government's recent support to focus on environmental restoration for the Yangtze basin. This basin-scale management of flows could be coordinated with management of the major floodplain lakes, including managing lake levels and connectivity with the Yangtze River.
- *Use the precedent of re-operating the world's largest dam to influence environmental flow implementation throughout China and globally*. Chinese agencies can continue to learn from the environmental flow program at Three Gorges Dam and apply these lessons to broader application of environmental flows in China. The insights and publicity from re-operating such a high-profile dam can be used by advocates, within and outside of government, to influence Chinese policies on dam operations within China and also the policies and practices that govern how Chinese companies and others plan, design, and operate dams elsewhere around the world.

AUTHOR CONTRIBUTIONS

LC organized the overall paper, collected data, information, and related documents, and was a primary contributor to writing the paper. JO conducted the main data analysis, contributed to the framework of the paper and made the largest contribution to writing text. DT suggested the framework of the paper and contributed to writing and revisions. RS drafted the abstract and contributed to revisions. QG provided background information and joined the discussion of the paper's framework. DC provided the essential data for paper writing and contributed to revisions.

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A Three-Level Framework for Assessing and Implementing Environmental Flows

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In the decade since the Brisbane Declaration (2007) called upon governments and other decision makers to integrate environmental flows into water management, practitioners have continued to seek ways to expand implementation of flow restoration or protection. The science and practice of environmental flow assessment have evolved accordingly, generating diverse methods of differing complexity from which water managers or regulators need to select an approach best fitting their context. Uncertainty over method choice remains one of several of the more readily overcome barriers that have contributed to slowing the implementation of environmental flows. In this paper, we introduce a three-level framework intended to help overcome such barriers by intertwining holistic environmental flow assessment with implementation. The three levels differ based on the availability of resources and level of resolution required in the flow recommendations, with the framework designed to guide the user toward implementation at any level as soon as possible, based on at least some of the recommendations. Level 1 is a desktop analysis based on existing data, typically conducted by one or a few scientists. Level 2 is similarly mostly reliant on existing information, but brings together a multidisciplinary set of experts within a facilitated workshop setting to use both this knowledge and professional judgment to develop flow recommendations and fill data gaps. The most comprehensive assessment level, Level 3, guides the collection of new data and/or construction of models to test hypotheses developed by the expert team. Key characteristics of this framework include: (1) methods are matched to the levels of resources available and certainty required; funds for research are invested strategically to address critical knowledge gaps and thereby reduce uncertainty; (2) the framework is iterative and information generated at one level provides the foundation for, and identifies the need for, higher levels and; and (3) processes for flow assessment and implementation are intertwined, meaning they move forward in coordinated fashion, with each process informing the other. Using practical cases from North America, we illustrate how environmental flow assessment at each level has led to implementation, with changes in policy or management.

Keywords: hydrology, river restoration, water management, freshwater ecosystems, environmental flows

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INTRODUCTION

Hydrological alteration—defined as changes in the magnitude and temporal pattern of a water flow regime caused by the storage, regulation, diversion and/or extraction of water by dams and other infrastructure—is one of the primary contributors to the decline of freshwater habitats and species (Postel and Richter, 2003). Recognizing these threats, biologists and managers in the 1970s began to advocate for maintaining river flows, with an initial emphasis on identifying and protecting a "minimum flow" to remain in rivers and streams. However, as scientific understanding of river function has matured, so too have the expectations for water resource management. The terms used to describe flow protection have evolved to keep pace: from minimum flows to "instream flows" and, today, "environmental flows." The term "environmental flows" reflects current understanding that river ecosystems and processes are maintained by a diverse range of flow levels and events—commonly referred to as a "flow regime"—including high flows that extend beyond the river channel (Poff et al., 1997).

The science and practice of environmental flows have also evolved; a review by Tharme (2003) described more than 200 environmental flow assessment methods in use, with the types and application contexts ever advancing (Arthington, 2012; Poff et al., 2017) and Konrad et al. (2011) evaluated more than 100 monitored environmental flow experiments. Following this maturation of the science and technical sophistication of environmental flow assessment, water managers and regulators are now confronted with a multitude of assessment options. Hirji and Davis (2009) report that uncertainty over methods has contributed to slow implementation of environmental flows. Further, it has become recognized that the specific method selected to define environmental flows is an important factor determining whether or not environmental flows are subsequently implemented (Warner et al., 2014).

In this paper, we introduce a framework for environmental flow assessment and implementation intended to reduce uncertainty over methods and help address several other constraints to implementation. Rather than prescriptively answer which flow assessment methods are "best," we describe a flexible and iterative framework through which methods are selected based on the specific context, resource and data availability, and the level of certainty required. Throughout the framework, processes for flow assessment and implementation are explicitly linked. The framework is intended to match methods to resources and to develop flow recommendations that are appropriate for the management context, increasing the likelihood of implementation.

In recent years, environmental flow practitioners have advocated system-scale holistic assessments to dramatically increase the number of rivers which have flow recommendations in place (Poff et al., 2010; Kendy et al., 2012) and to catalyze greater implementation (Poff et al., 2017; Opperman et al., in review). The framework described here can be applied at both site-specific and regional scales.

Environmental Flows: Evolution of Assessment and Challenges to Implementation

Environmental flow management requires the application of methods to define environmental flow requirements and for these requirements to be integrated within water resources management (LeQuesne et al., 2010). The four main categories of methods that were evident early on, namely hydrologic (predominantly desktop), hydraulic, habitat simulation, and holistic methods (Tharme, 2003; Annear et al., 2004) remain in use today (Poff et al., 2017). A common limitation associated with many of the most widely used hydrologic, hydraulic and habitat simulation methods, typically inherent in their design or the nature of their implementation, is that they tend to produce a single flow level or a narrow set of flow levels (Hatfield and Paul, 2015; Poff et al., 2017).

In part because of the narrow representation of flow variability in many common environmental flow methods, "holistic" approaches emerged in the 1990s (Tharme, 2003). Examples include Downstream Response to Imposed Flow Transformations (DRIFT; Arthington et al., 2003) and Building Block Methodology (BBM; King and Louw, 1998; King et al., 2008). Holistic approaches seek to protect or restore a diverse set of socially and ecologically important river resources and processes across the full spectrum of low flows to flood events characterizing a river's flow regime within and between years. Holistic methods were originally developed to be deployed in river basins for which data were limited and were intended to produce more scientifically credible results than simple hydrologic desktop approaches.

In 2007, the Brisbane Declaration called on governments and other decision makers to support widespread assessment of flow needs and to integrate environmental flows into water management (Brisbane Declaration, 2007). Ten years later, practitioners are still seeking to apply flow assessment and flow restoration or protection more broadly (Acreman et al., 2014; Harwood et al., 2017). Reviews of environmental flow implementation (Hirji and Davis, 2009; Horne et al., 2017) have found several consistent obstacles that constrain implementation, including: (1) maintaining political and stakeholder support for implementation; (2) institutional inertia within agencies that manage water; (3) matching flow assessment methods to the regulatory and social context; (4) cost; and (5) marshaling capacity and expertise.

The three-level framework, described in the following section, is specifically intended to address some of the obstacles that have slowed application of both assessment and implementation. It was developed based on experience with a set of processes (featured in this paper as case studies) in which flow assessment has led to implementation of flow recommendations through changes in management and/or policy.

THREE-LEVEL FRAMEWORK FOR ENVIRONMENTAL FLOW ASSESSMENT AND IMPLEMENTATION

To be effective, an environmental flow assessment must address three primary challenges. First, rivers are extremely complex ecosystems and a broad range of climate-driven flow levels and events is necessary to maintain the river ecosystem's diverse components, including fish, birds, invertebrates, channel morphology, riparian vegetation, and river-floodplain connectivity. Human dependencies on the river ecosystem—ranging from fishing and flood-dependent agriculture to spiritual activities—are coupled with these ecosystem components. The second challenge is that, to effect any change, environmental flow recommendations must actually be implemented within complex and often contentious river management contexts (Horne et al., 2017). Finally, the level of complexity of the environmental flow assessment must be tailored to the financial resources available.

The first challenge suggests that environmental flow methods must be sufficiently comprehensive and holistic (Poff et al., 1997; Richter et al., 1997)—that is, the methods must address a range of flow levels and events and consider diverse resources and processes that are characteristic of, and important to, that river system. Methods focused on single species or minimum flow levels fail to capture the complexity of relationships between flow and the processes through which rivers produce a range of ecosystem services. The other two challenges suggest that environmental flow assessment methods must be tailored to the specific management context and must produce recommendations that can be understood, appreciated, and implemented by water managers, and supported by the public. Taken together, all three challenges emphasize that there is no single method that will work best in all situations and that methods must be selected and implemented based on a range of factors, including the specific geographic context (e.g., spatial scope, type of resources at stake), the availability of data and funding, and the level of certainty required.

Here we describe a three-level framework for developing and implementing environmental flows in the pursuit of ecologically sustainable water management (*sensu* Richter et al., 2003). Tharme (1996), Arthington et al. (2003), and Poff et al. (2017), among others, recommend that practitioners apply a hierarchical approach to environmental flow assessment. This framework builds on that recommendation, with steps to promote implementation embedded throughout the hierarchy.

While the three levels vary in their intensity and complexity (**Table 1** and **Figure 1**), each can be considered holistic because each level explicitly addresses a range of flow levels and events and encompasses diverse value sets, riverine resources/assets, and processes. The framework can be used for environmental flow assessment and implementation in diverse settings, from rivers or regions with relatively few data to those with extensive data. The specific assessment methods used within this framework systematically progress in complexity, from relatively simple desktop methods to resource-intensive approaches that require significant modeling capacity and the collection of new data.

The key characteristics of this framework include:

- The framework is iterative such that higher levels are deployed only to the extent they are necessary, and information generated at one level identifies the need, and provides the foundation and priorities, for higher levels. Funds for data collection and/or research and modeling are invested strategically to address the most important issues and reduce the most important uncertainties first.
- Processes for flow assessment and flow implementation are coupled. Many of the key characteristics of the assessment process are used to design and initiate flow implementation—through mechanisms such as caps on withdrawals or experimental flow releases from a dam (Horne et al., 2017)—as soon as possible. This early implementation is critical for generating both learning opportunities and support for further investment, if needed. To facilitate this linkage between assessment and implementation, scientists should work with water managers to the greatest extent possible throughout the process, in settings that encourage collaboration, knowledge sharing, and problem solving (e.g., see Acreman, 2005).

The three levels can be viewed as sequential steps but, in some cases, a lower level may address a management need and lead toward implementation without requiring a higher level (**Figure 1**). In many cases, opportunities exist to implement one or more flow recommendations immediately, while various constraints and/or uncertainties prevent other recommendations from being implemented without further analysis and refinement. Thus, flow assessments at each level of the hierarchy can potentially generate one or more recommendations that can be implemented (and monitored) quickly while also focusing subsequent, higher-level assessment on resolving the constraints and/or uncertainties that impede implementation of the remaining flow recommendations.

In the following sections, we describe each of the three levels and, to illustrate that the framework can be applied at a range of scales, provide examples of both river-specific and regional-scale applications. For regional applications, such as water resource planning, water withdrawal permitting, and basin-wide dam operations, we draw on the Ecological Limits of Hydrologic Alteration (ELOHA) framework (Poff et al., 2010; Arthington, 2012; Kendy et al., 2012) which can be used within widely differing governance and management systems (Pahl-Wostl et al., 2013). The ELOHA is a flexible framework for determining and implementing environmental flows for all the rivers within a region using existing hydrologic, geomorphological, biological, and social information (Jackson et al., 2014; Poff et al., 2017). Its premise is that although every river is unique, many exhibit similar morphological and ecological (or social) responses to flow alteration. By assessing existing information for groups of similar rivers with varying degrees of hydrologic alteration, scientists can quantify relationships between flow and resources for different river *types*, which inform the environmental flows needed to meet objectives for river conditions.

TABLE 1 | Characteristics of the three levels of flow assessment and implementation.

Level of environmental flow assessment and implementation	Degree of confidence required	Cost	Appropriate application
Level 1—holistic (eco)hydrologic desktop	Low	Low (e.g., <USD 10,000)	Precautionary, first-cut flow recommendations for planning
Level 2—holistic expert panel	Moderate	Moderate (<USD100,000)	Opportunities exist to protect or experiment with flow regime (i.e., some degree of operational or management flexibility)
Level 3—holistic research-driven	High	High (e.g., >USD 100,000)	High degree of certainty is required before changes in flow management or policy can be considered
Implementation and adaptive management		Budget is variable; sustainable budget needed for monitoring	All situations should result in implementation, monitoring, and adaptive management.

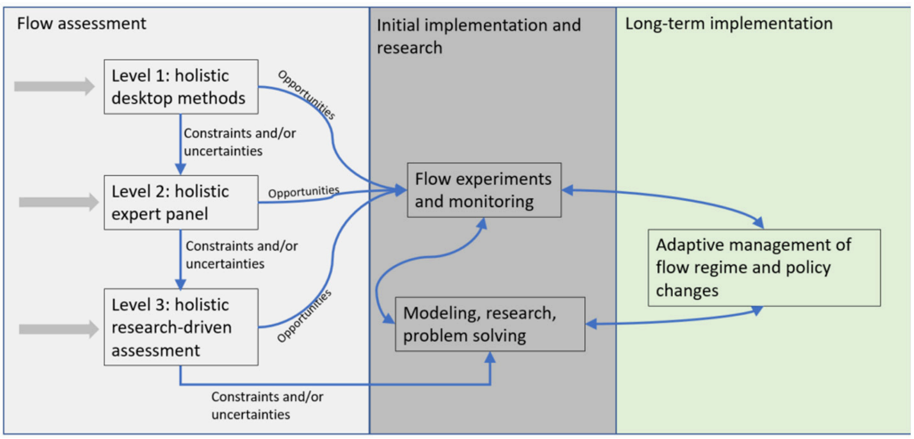

FIGURE 1 | Three-level framework for environmental flow assessment and implementation. Levels are selected based on the specific geograhpic context (e.g., spatial scope, type of resources at stake), the availability of data and funding, and the level of confidence required of the flow recommendations. The levels can stand alone (thick gray arrows indicate alternative entry points) or levels can be sequential (vertical sequence from Level 1 to 3). All levels have the potential to produce flow recommendations that can be implemented through collaboration with water managers (arrow marked "opportunities" leading to "flow experiments").

Level 1: Holistic Hydrologic Desktop Methods

A Level 1 approach is appropriate for developing initial flow recommendations for a river or for regional planning and preliminary standard setting. This level also serves to provide the information foundation for higher level approaches. In this framework, a Level 1 application can be considered a "desktop" method, in that new data are not collected and it can be conducted by a small team. However, it strives to be far more holistic than common hydrologic desktop methods, many of which feature "look-up tables" to define a flow level (e.g., a percent of mean annual flow). While these "look-up" desktop methods are quick and inexpensive, they generally provide overly simplistic flow levels that do not fully account for river functions and processes. Below we describe how a Level 1 (desktop) approach can incorporate elements of holistic methods.

A holistic hydrologic desktop approach synthesizes two primary sources of information: (1) hydrologic data—typically measured or modeled daily or monthly streamflow; and (2) basic principles of biophysical processes of rivers, augmented with the known linkages between the flow regime and key riverine resources. In the absence of specific information on a focal river, practitioners can draw on broader literature with an emphasis on information relevant to similar river types (e.g., in terms of geomorphology, drainage area, valley characteristics) and ecosystems. What advances a holistic desktop approach beyond simple "rules of thumb" is the application of this review to the hydrological analyses to develop recommendations quantified across the full flow regime, often using ecologically relevant low flow and high flow indices, in contrast to a single, or seasonally variable, minimum flow. In at least one case, a holistic desktop method directly incorporates geomorphic and ecological sub-models (Hughes et al., 2014).

An example of a hydrological analysis tool that can support a comprehensive hydrologic desktop approach is the Indicators of Hydrologic Alteration (IHA; Richter et al., 1996; The Nature Conservancy, 2009). The IHA calculates 67 ecologically relevant flow statistics from a hydrologic record of daily flow values

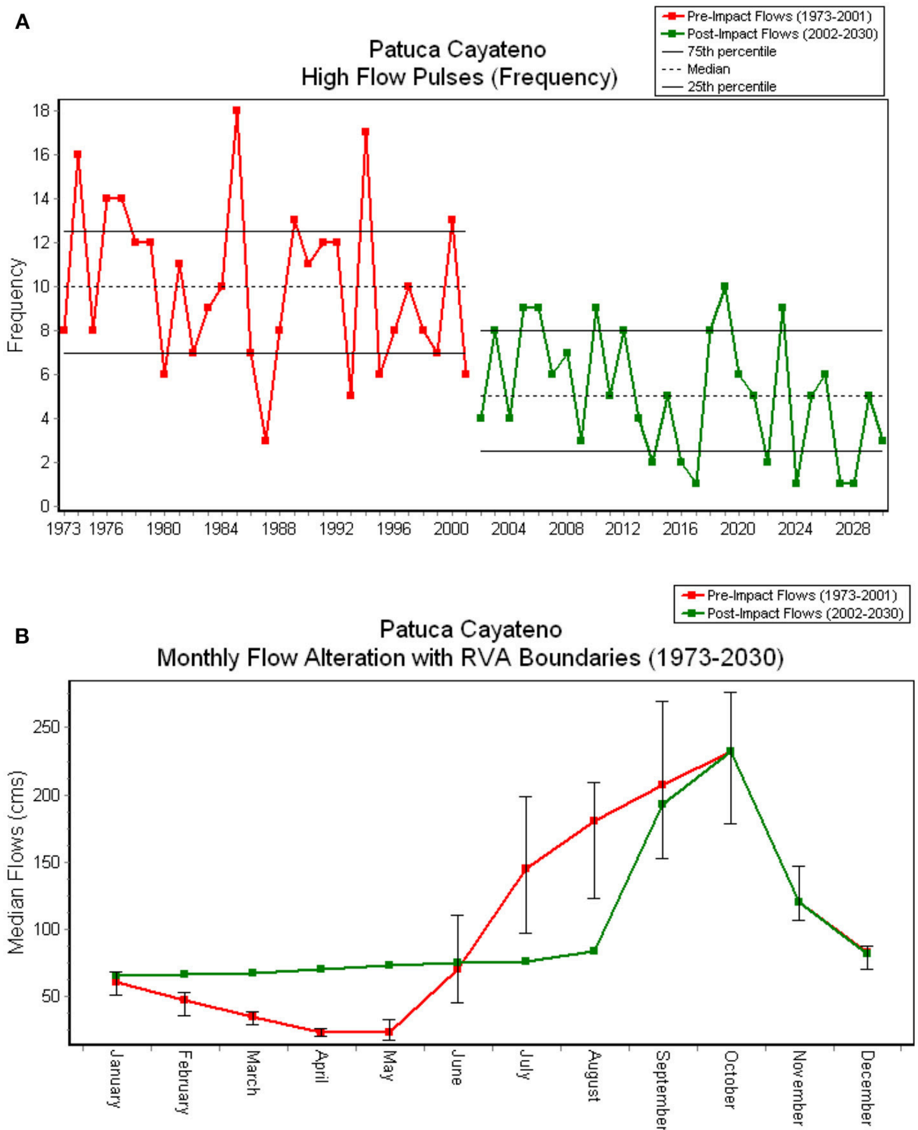

FIGURE 2 | Output from the software Indicators of Hydrologic Alteration (IHA) for the Patuca River, Honduras. The red lines show natural ("pre-impact") flows from 1973 to 2001 while the green lines show the "post-impact" flows. Note that in this case the dam on the Patuca River has not been built yet and the "post-impact" flows are actually the same flow data set (1973–2001) run through a model simulating flows with dam operations. Thus, the years 2002–2030 do not actually represent future years but are given those dates because of how IHA processes data. Panel **(A)** shows that the dam will reduce the frequency of high-flow pulses from ~10 per year to 5 per year because the reservoir will be refilling during the initial onset of the rainy season (June through August), as shown in **(B)**, when high-flow pulses tend to occur. Flow recommendations were developed based on these hydrological analyses combined with a literature review on tropical lowland rivers and an expert panel workshop (Esselman and Opperman, 2010).

(**Figure 2**) (Richter et al., 1996, 1997). IHA can categorize flow levels into "environmental flow components" (EFCs), which include large floods, small floods, high-flow pulses or freshets, low flows, and extreme low flows (Mathews and Richter, 2007). The U.S. Geological Survey (USGS) has developed similar hydrologic analysis software called Hydrological Assessment Tool (HAT; Cade, 2006). Although HAT and IHA do not directly generate environmental flow recommendations, their calculation of flow metrics, informed by a literature review of the linkages between the flow regime and river processes, can form the basis of a Level 1 environmental flow assessment (Richter et al., 1997).

In Texas, the EFC algorithm of IHA was used to develop the Hydrology-based Environmental Flow Regime (HEFR) method for establishing first-approximation environmental flow recommendations. The recommendations are expressed in terms of the magnitude, frequency, duration, timing, and rate of change of subsistence flows, high flow pulses, base flows, and overbank flows (Texas SB3 Science Advisory Committee, 2011). In South Africa, the Revised Desktop Reserve model is a desktop approach that moves beyond hydrology to also include linked sub-models for hydraulics and ecology to produce low flow recommendations (with a simpler approach for high flow recommendations) (Hughes et al., 2014). An ELOHA study (described below) can provide relevant information on linkages between flow and resources for rivers in the focal region. Thus, the ELOHA results can inform a Level 1 process for a river within that region and could potentially provide precautionary flow recommendations.

Hydrologic desktop methods are equally amenable to site-specific and regional applications, because the same simple, robust algorithms can be used for both. For example, a major advantage of HFER for regulatory use is its consistent application across all rivers in Texas (Texas SB3 Science Advisory Committee, 2011). Richter et al. (2011) suggested a precautionery and regime-based desktop calculation of initial flow recommendations, expressed as the allowable degree of alteration in daily flow magnitude. With minimal computational effort, this "presumptive standard" approach maintains natural flow variability within a "sustainability boundary." Richter et al. (2011) note that, in the absence of a more rigorous flow assessment, this boundary can serve as a precautionary preliminary flow recommendation and, because of its simplicity, can be applied at regional scales.

In situations with low risk or controversy and/or immediate need for guidance, a Level 1 assessment could produce flow recommendations that lead to preliminary withdrawal limits or to experimental flow releases from reservoirs (see Green River case study below). An important role of a Level 1 assessment could be to spur dialogue between river scientists and water managers, providing a foundation for generating further interest and funding for higher level assessments, if needed.

A Level 1 Flow Assessment and Subsequent Implementation at the Green River

The Green River, a tributary to the Ohio River in Kentucky (USA), supports high levels of freshwater species richness including 151 fish species (12 endemic) and 71 mussel species. The Nature Conservancy and the US Army Corps of Engineers ("the Corps") began collaborating in 1998 to determine strategies for restoring the flow regime below Green River Dam, a multipurpose dam operated primarily for flood control (this collaboration led to the Sustainable Rivers Program, described below). Work on the Green River began as a Level 1 effort, with initial flow recommendations developed through a hydrological analysis using IHA combined with insights on the relationships between flows and river processes gleaned through discussions with a small group of biologists familiar with the river. The biologists were specifically asked to articulate important life stages and the associated seasons—with as much temporal specificity as possible—and habitat requirements for a diversity of species native to the Green River system. Through this process, the team generated a set of flow recommendations to present to reservoir operators.

Water managers within the Corps analyzed their operational flexibility and found that, by adjusting the timing and rate of filling and drawdown, they could meet important components of the environmental flow recommendation. Note that although the flow recommendations were developed through a Level 1 process, the evaluation of how to integrate those recommendations into water management required modeling of reservoir operations. The Corps began to implement new operations that achieved environmental flow objectives in 2002 and this new operation scheme was formalized with a revision to the dam's Water Control Manual in 2006 (**Figure 3**; Konrad et al., 2012; Warner et al., 2014).

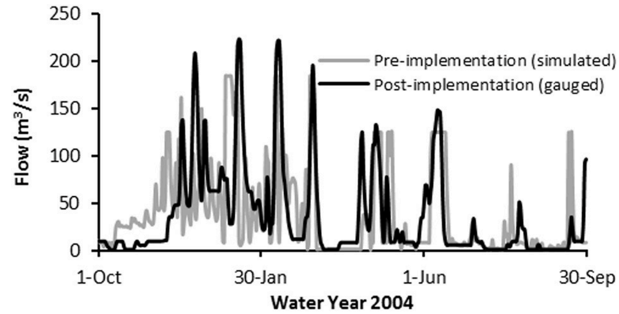

FIGURE 3 | Flow regime on the Green River below the Green River Dam following implementation of environmental flows ("Post-implementation") compared to the flow regime produced by previous operations ("Pre-implementation"). The post-implementation hydrograph comes from gauged data whereas the pre-implementation hydrograph was modeled by applying the previous operation scheme to the same gauged flow data. From Warner et al. (2014).

Level 2: Holistic Expert Panel Environmental Flow Assessment

A Level 2 process is centered around an expert panel assessment. This level still does not require new data collection to generate flow recommendations, but can draw on considerably more information than does a Level 1 process. Using expert panels, flow recommendations are developed through professional judgment supported by literature review and quantitative analysis of existing data, including the types of analyses conducted during a Level 1 process.

Numerous flow methods feature expert panels, including the Building Block Methodology (King and Louw, 1998; King et al., 2008), Downstream Response to Imposed Flow Transformations (DRIFT) (Arthington et al., 2003; King et al., 2003), and the Savannah Process, so called because it was first used on the Savannah River (Georgia and South Carolina, USA) (Richter et al., 2006). A Level 2 process can be conducted in places with very limited existing data (e.g., see Esselman and Opperman, 2010) to places with extensive existing data (e.g., on flows, water quality and fisheries).

While results from a process relying on expert judgment are not as replicable as those from a quantitative model, such as PHABSIM, Kondolf et al. (2000) suggest that such models "only give the illusion of objectivity because [they] always involve simplifying assumptions" and that model output should be combined with professional judgment. Similarly, Castleberry et al. (1996) suggest that quantitative models should not "substitute for common sense, critical thinking about stream ecology, or careful evaluation of the consequences of flow modification." Most importantly, expert panels expediently fill knowledge gaps for ecosystem components for which sufficient data to rigorously quantify flow relationships are lacking. For example, whereas comprehensive data on fish populations exist in many places, flow-related data for aquatic vegetation are rare. The credibility and replicability of expert panels can be increased through structured processes with diverse participants representing the range of stakeholders, as opposed to *ad hoc* contributions (Dyson et al., 2003; Acreman, 2005), and through structured pre-workshop literature review using a weight-of-evidence approach to assess the strength of hypothesized flow-resource relationships (Taylor et al., 2013). Cottingham et al. (2002) recommend a set of "best practices" for ensuring the defensibility of expert panel approaches.

The primary steps of a Level 2 process are summarized in **Table 2**. While these steps correspond most closely to processes focused on implementing flow changes in one to a few rivers, the process for a regional-scale Level 2 process can be quite similar. After discussing the steps of a river-focused process, we then describe some of the distinct steps for a regional Level 2 process intended to inform policy, such as setting standards for a state's water withdrawal permitting process.

Participants for the expert panel flow workshop should be drawn from a broad range of disciplines, encompassing biophysical sciences as well as those who understand the linkages between flows and the cultural, economic and recreational values of the system. Within a workshop (step 3), participants are tasked with developing a set of flow recommendations. Importantly, each recommendation is framed as a hypothesis or set of hypotheses that describe the resources or processes supported by each flow component, including the relationship between flow and cultural or recreational resources (**Tables 3**, **4**). Throughout the workshop, participants identify uncertainties and, during the final discussion, develop a set of research priorities. The uncertainties, research priorities and flow-ecosystem hypotheses inform subsequent research, modeling and analysis. For example, a recommendation for a small flood may be hypothesized to provide fish access to and use of floodplain habitats for spawning. The flow recommendation should include various hydrological parameters (e.g., 300 – 400 cms for a duration of >3 weeks during April–May) that are hypothesized to provide the appropriate conditions for this process to occur, and participants should identify their confidence in these parameters. If a better understanding of this linkage is identified as a research priority, subsequent research and modeling can then focus on these processes and refine the estimates of the flow parameters that support them. Of critical importance is how data gaps and uncertainty are managed during the workshop. Specifically, gaps in knowledge are recognized and captured, but do not prevent a quantified flow recommendation from being developed (Warner et al., 2014).

The steps provided in **Table 2** are primarily based on environmental flow assessment and implementation projects conducted under a partnership, the Sustainable Rivers Program (SRP), between TNC and the U.S. Army Corps of Engineers following the "Savannah Process" (Postel and Richter, 2003; Richter et al., 2006). The Corps is the largest dam owner and

TABLE 2 | Steps in a level 2 process.

Step	Description
1. Orientation workshop	A workshop for stakeholders and potential contributors; the organizers describe the forthcoming process and primary objectives, and ask stakeholders to suggest additional participants and sources of data and information. This meeting also initiates the dialogue on specific objectives.
2. Build the information base	This second step encompasses the key components of a Level 1 process—the hydrological analysis and literature review, generating a summary report with information on hydrological patterns, including hydrological alteration, and a review of research and data available for the river basin with an emphasis on the linkages between the flow regime and important biophysical processes. Distributed in advance of the expert panel flow workshop.
3. Expert panel flow workshop	The flow workshop includes participants from a broad range of disciplines (e.g., river and riparian ecologists, hydrologists, geomorphologists, fisheries and wildlife biologists, and social scientists who understand cultural, economic and recreational values of the system) drawn from a spectrum of organizations—academia, private sector, non-governmental organizations, and resource agencies representing Federal, Tribal, state and local governments. The objective of the workshop is to recommend a comprehensive environmental flow regime.
4. Dialogue with managers	Scientists and practitioners begin a dialogue with water managers and users about the feasibility of implementing the various initial flow recommendations. Through this dialogue, scientists and water managers identify opportunities for initial changes to operations that can serve as experimental releases and flow recommendations that cannot be implemented without further study or due to various constraints (**Figure 1**).
5. Initial operational changes and flow experiments	Relatively rapid implementation of at least a sub-set of recommended flow components that are clearly feasible within current operational requirements.
6. Targeted research and modeling	To resolve uncertainties or to find solutions to implementation constraints, participants can develop a research and modeling program. Developing this program will generally require additional funding and moves the process toward Level 3.
7. Long-term implementation, monitoring and adaptive management	To be durable, an environmental flow program must move beyond initial recommendations and experimental implementation and toward long-term implementation. This will generally require that the new flow regime be articulated within the policies that govern water management for that river. Sustainable funding will likely be required to ensure ongoing monitoring and adaptive management.

TABLE 3 | A sample of the initial flow recommendations from a Level 2 process for the Middle Fork of the Willamette River (Warner et al., 2014).

Environmental Flow Component (EFC)	Hydrological characteristics	Related ecosystem functions
Low flow levels for Chinook spawning	*Magnitude*: 1800–2500 cfs *Frequency:* every year *Duration:* Following spawning, flows must remain at level that occurred during spawning, or somewhat higher, until eggs have hatched and juvenile fish have left the spawning gravels *Season:* September and October	• Provide sufficient flows to support incubation of eggs • Avoid stranding of redds (locations of deposited eggs within gravel)
Spring flow pulses	*Magnitude:* 4,000–15,000 cfs *Frequency:* 1–5 per year, based on precipitation events *Duration:* Mimic duration of unregulated events *Season:* March 1–July 1	• Provide flows for downstream migration of juvenile salmon and smolts • Create lateral habitats on floodplain margin • Disperse seeds and establish cottonwood seedlings • Smooth transitions after winter high flows are required for aquatic species to move between lateral refuges
Floods	*Magnitude:* 25,000–40,000 cfs *Frequency:* Once every two years *Duration:* Approximately two weeks *Season:* November 15–March 15	• Transport sediment and create new pools and riffles • Create new floodplain surfaces through overbank erosion and deposition • Create new floodplain surfaces through bar development • Create surfaces for regeneration of cottonwood and other riparian trees

Note that each recommended environmental flow component (EFC) is expressed in terms of magnitude, frequency, duration and season. Also, each EFC is associated with a set of 'related ecosystem functions' that the particular EFC is hypothesized to support.

operator in the USA, and more than 60 of the agency's 700 dams are now included in the SRP. The implementation occurring at several SRP sites demonstrates the value of involving water managers—those who manage the dams whose operations would need to change to implement environmental flows—in key points in the assessment process to facilitate subsequent implementation (Warner et al., 2014; Harwood et al., 2017).

Water managers, such as dam operators, are generally involved in the first three steps, but the integration of flow science and assessment with water management is most pronounced in the subsequent steps. Following the expert panel workshop, the flow recommendations are discussed by a group of scientists and water managers (step 4). Water managers can generally place the flow recommendations into three categories: (1) those that can be implemented feasibly within current authorities and obligations ("opportunities"); (2) those that may require additional research and modeling prior to implementation (e.g., flood routing analysis to determine what levels of high flows can be released without causing flood damages); and (3) those that would require major changes—in physical conditions or authorities, policies, water rights or contracts—to overcome constraints (Bach et al., 2007). For example, a dam may not be able to release a recommended high-flow pulse without engineering changes or an agency may not be able to restrict water withdrawals during non-drought periods without regulatory changes.

Flow recommendations identified as "opportunities" can potentially be implemented relatively quickly (step 5). The rapid implementation of a portion of the recommended flow regime provides dam operators with experience making operational changes to implement flows and can generate important publicity and awareness for the environmental flow process. Further, if coupled with a monitoring program, these actions provide scientists with an opportunity to study how processes and ecosystems respond to management changes. Most of the SRP sites have initiated early implementation of some components of the recommended flows, as illustrated for the Bill Williams River case below.

Additional research and/or modeling are generally required to resolve uncertainties or find solutions to overcome the constraints that prevent implementation of other components of the flow recommendation (step 6), another step where scientists and water managers should collaborate effectively. While this step likely requires securing additional budget, note that it does not necessarily require establishment of a distinct research program, as in a new entity within a single institution. Rather, the research program can instead be advanced through improved coordination of efforts and resource allocation across institutions involved in the environmental flow project (Warner et al., 2014). For example, a number of sites with the SRP—such as the Bill Williams (Arizona) and Big Cypress/Caddo Lake system (Texas/Louisiana)—have established technical working groups that meet 2–4 times per year to coordinate upcoming environmental flow implementation, monitoring and research priorities, and associated resource commitments.

To be durable, an environmental flow program must move beyond initial recommendations and experimental implementation, and the new flow regime must be articulated within the policies that govern water management for that river. For example, the operations of each Corps dam are guided by a Water Control Manual. Until the Water Control Manual has been revised to incorporate environmental flows and associated adaptive management activities, the new flow regime is essentially experimental and temporary. The Green River case

TABLE 4 | A sample of the flow recommendations from a Level 2 process for all small rivers (drainage areas of 130 – 500 square kilometers) in the Great Lakes catchments of New York and Pennsylvania, USA.

Environmental Flow Component (EFC)	Hydrological characteristics				Related ecosystem functions
	Summer	**Fall**	**Winter**	**Spring**	
High flows *Annual/Interannual (≥bankfull)* *High flow pulses (<bankfull)*	**All seasons** • Maintain magnitude and frequency of 5-year (small) flood • Maintain magnitude, duration of channel forming (1 to 2-year) events **All seasons** • <10% change to the magnitude of high flow pulses (monthly Q_{10}) • No change to the frequency and duration of high flow pulses (monthly Q_{10})				• Recruit woody debris • Maintain ice scour for dynamic floodplain vegetation • Cue reproduction for riffle-associate fishes • Maintain channel morphology
Seasonal flows	**All seasons** • <10% change to upper seasonal flow range (between the monthly Q_{10} and Q_{50}) • <10% change to monthly Q_{50} **Summer and Fall (July–Oct)** • <10% change to lower seasonal flow range (between monthly Q_{50} and Q_{70})		**Winter and Spring (Nov–Jun)** • <10% change to seasonal flow range between monthly Q_{50} and monthly Q_{80}		• Sustain fluvial fish abundance in the summer • Prevent fish assemblage summer • Prevent fish assemblage shift from fluvial specialists to habitat • Sustain benthic insectivore populations in the summer • Stimulate movement and maintain access to upstream spawning habitats for migratory salmonids in the fall the fall • Maintain extent of available spawning habitat for riffle associates in the spring
Low flows	**Summer and Fall (July–Oct)** No change to low flow range (between monthly Q_{70} and Q_{99})		**Winter and Spring (Nov–Jun)** • No change to low flow range (between monthly Q_{80} and Q_{99})		• Avoid dewatering channel margins and exposing mussel habitat • Maintain extent of riffle habitat

Note that each recommended environmental flow component (EFC) is expressed in terms of magnitude, frequency, duration and season. Also, each EFC is associated with a set of 'related ecosystem functions' that the particular EFC is hypothesized to support. Hydrologic characteristics are expressed as relative, rather than absolute, values so they can be applied to any river. Adapted from Taylor et al. (2013).

study, above, provides an example of how a new flow regime was formalized through changes to a dam's Water Control Manual.

Richter et al. (2006) offers an extended case study of a Level 2 process for the Savannah River (Georgia, USA), including the structure of the expert panel workshop and the process of initial implementation. Esselman and Opperman (2010) provide an example of how this process was adapted to a river—the Patuca, in Honduras—with extremely limited existing data or information, combining a study of Traditional Ecological Knowledge with an expert panel workshop to develop flow recommendations. Warner et al. (2014) provide an overview of the SRP and a series of Level 2 processes that linked flow assessment with implementation.

Level 2 for Regional Standards to Inform Policy

A Level 2 process at the regional scale, intended to inform policies such as water withdrawal permitting, can follow much of the sequence for river-specific processes described above and in **Table 2**. Importantly, an expert panel process, augmented by literature review and analyses of existing data, can provide a mechanism to synthesize diverse information to guide a set of recommendations, corresponding to steps 1–3 above. Instead of developing flow recommendations for a single river, the panel recommends environmental flow criteria for different *types* of rivers within a basin or region. Discussions then could be held with operators of dams across the region, to explore opportunities for implementation, although more likely the dialogue with managers (step 4) will be conducted with those who will implement or regulate the policy at a regional scale. Similar to a river-specific process, it may be possible to implement some recommendations—such as protection of high flows—immediately (corresponding to step 5), while further research or problem solving (step 6) may be required before other recommendations can be integrated into policy or management, thus elevating the assessment to Level 3. For example, studies on how low-flow protections might impact water users (e.g., Buchanan et al., 2016) may be required before low-flow protections are integrated into policy. The case study below for the Susquehanna River basin (USA) illustrates how a Level 2 process can lead to the adoption in policy of some flow protection standards.

A Level 2 Process to Set Basin-Scale Flow Policy for the Susquehanna River Basin

A Level 2 approach was used to develop environmental flow recommendations simultaneously for all rivers and streams within the 72,000-square-kilometer interstate Susquehanna River catchment, USA. Through consultations with experts, a technical team assembled a broad list of ecological indicators, including flow-sensitive taxa groups, vegetation community types, and physical processes. A basic habitat classification based on watershed size, temperature, and flow stability was developed for organizing and synthesizing information. Based on hydrologic desktop analysis, the technical team defined monthly high, seasonal, and low flow components for each major habitat type. The technical team then surveyed scientific literature to find dependencies between these indicators and specific flow components and, where possible, to extract relationships between flow alteration and ecological response. Using species distribution data and expert consultations, they associated species groups with major habitat types and described common traits and microhabitat preferences for each species group.

The vast array of ecosystem flow needs convinced the project team that it needed to develop environmental flow recommendations for many different taxa for each major habitat type—even those that lack large databases. Rather than assume that a single species or group of species can represent all ecosystem needs, the team based its flow recommendations on (a) existing literature and studies that described and/or quantified relationships between flow alteration and ecological response, (b) expert input, (c) the analysis of long-term flow variability at minimally-altered gages, and (d) results of water withdrawal scenarios that tested the sensitivity of various flow statistics (DePhilip and Moberg, 2010).

The resulting low flow policy, adopted by the Susquehanna River Basin Commission (http://www.srbc.net/policies/lowflowpolicy.htm), avoids the use of a single annual minimum flow value for low flow protection and, instead, uses a series of seasonal or monthly values that more accurately reflect the seasonal variability of streamflow and associated ecosystem needs. However, additional rulemaking is needed to meet the high-flow recommendations that resulted from this Level 2 process.

Level 3: Holistic Research-Driven Flow Assessment

The descriptions of Levels 1 and 2, and corresponding case studies, indicate that a Level 3 research program will often be necessary to resolve uncertainties and overcome constraints to implementation. Thus, Level 3 will often be required for processes initiated at lower levels. As Level 3 will often require a significant budget, this framework suggests that lower levels can be carried out first because they may lead to some changes to operations or policies relatively quickly and these changes can initiate ecosystem restoration, provide an opportunity for learning and potentially increase the profile and support for the assessment and implementation process—thus helping to secure resources for Level 3.

In some situations, however, it will be most effective to begin the process at Level 3 (**Figure 1**), such as those that require a high degree of certainty before any operational changes can made. Such situations may include those where water is over-allocated and heavily contested, the presence of endangered species limits operational flexibility, defined policies dictate management, or binding (or nearly binding) long-term decisions are being made. In these situations, decision makers will require a higher degree of analytical rigor before initiating an environmental flow program. Thus, a Level 3 process is characterized by greater up-front investment in more sophisticated methods for examining tradeoffs and predicting results from operational changes or flow allocation rules.

We recommend that a Level 3 process retain many of the features of Level 2 that are intended to develop collaborative relationships—facilitating subsequent implementation—and target research funds to the most important issues. Thus, a Level 3 process can share many steps with a Level 2 process. For example, a Level 3 process can include workshops to identify key questions, priorities, and sources of existing information and expertise, so that the subsequent research program does not duplicate previous efforts. Similar to a Level 2 process, these steps focus on identifying which environmental flow, research and modeling methods are most appropriate for the specific situation.

A Level 3 research program focuses on resolving uncertainties and undertaking the research priorities identified in expert workshops (whether that was a workshop initiated under the Level 3 process or under a lower-level process). Further, a Level 3 process should also provide opportunities for dialogue between researchers and managers to understand potential constraints so that the research program can also pursue alternative solutions. The technical methods employed during a Level 3 research program may include methods specifically designed to determine environmental flow needs (e.g., those reviewed by Tharme, 2003) but usually encompass a much broader range of analytical methods that are not typically considered "environmental flow" methods. These may include, for example, hydraulic models to study thresholds for floodplain inundation; models for water temperature, sediment transport, meander migration, or riparian recruitment; or monitoring of fish population movements. An environmental flow process on the Roanoke River (Virginia and North Carolina, USA) used a range of research tools and methods over a period of 20 years, including hydrologic and hydraulic models of floodplain inundation and an adaptive management program studying floodplain tree regeneration in response to changed flow regimes (Pearsall et al., 2005). The research program provided the basis for two agreements in 2016 that will formalize environmental flows on the Roanoke: a settlement agreement that will govern flows from a privately managed hydropower dam and a revision to a Water Control Manual for a dam managed by the Corps (Opperman et al., 2017).

Level 3 Research Program on the Bill Williams River (AZ)

The Bill Williams River, in western Arizona, is a tributary to the Colorado River. Alamo Dam was constructed on the river in 1968, primarily for flood control, and flow regulation from the dam dramatically decreased the frequency and magnitude of floods. The river's riparian corridor supports some of the last and largest remaining stands of willow-cottonwood forest in the lower Colorado basin, providing habitat for 350 bird species. To restore river and riparian habitats, TNC and the

Corps began to explore alternative flow regimes as part of the Sustainable Rivers Program and, in March 2005, the Bill Williams River Corridor Steering Committee sponsored an expert-panel workshop to develop environmental flow recommendations. Participants included 50 scientists and resource managers and were divided into three groups: (1) aquatics, with a focus on fishes and aquatic macroinvertebrates; (2) riparian system - birds; and (3) riparian system—terrestrial fauna (other than birds). Each group developed flow recommendations for floods and base flows, defined in terms of magnitude, timing, duration, frequency and rate of change, necessary to maintain the processes and biota in its respective system (e.g., aquatics). The three groups then reconvened and reached agreement on a unified set of flow recommendations (Shafroth and Beauchamp, 2006).

Following the workshop, the Corps released experimental floods in 2005, 2006, and 2007 (Hautzinger, 2007; Shafroth et al., 2010; Konrad et al., 2011, 2012). on the Bill Williams under the SRP began as a Level 2 effort, with environmental flows defined and select components (controlled floods) implemented within a matter of months. Building upon the initial few years of experimental releases and monitoring, work expanded into a Level 3 effort with agency and academic scientists organizing a multi-institutional research program coordinated through the Bill Williams River Technical Steering Committee and designed to model flow recommendations and study the experimental floods, using a variety of models and field research techniques. Modeling capabilities of the system now encompass a reservoir operations model, one- and two-dimensional river hydraulics models to estimate stage–discharge relationships, a groundwater model to estimate surface- and groundwater interactions in a large, alluvial valley where surface flow is frequently absent and a coupled hydrology-ecology model (the Ecosystems Function Model), used to link a one-dimensional hydraulic model with riparian tree seedling establishment requirements in order to produce spatially explicit predictions of seedling recruitment locations (Shafroth et al., 2010).

As hypothesized during the environmental flow workshop, preliminary results have found that experimental floods were able to breach beaver dams, shifting the ratio of lotic to lentic habitat on the river closer to pre-dam conditions (Andersen et al., 2011). The floods also have resulted in proportionately much higher mortality among invasive *Tamarix* seedlings than native *Salix* saplings (Shafroth et al., 2010). Documenting these and other responses to controlled floods helps scientists and water managers refine the environmental recommendations for the Bill Williams River and inform its adaptive management, illustrating the value of a monitoring program.

DISCUSSION

Here we have proposed a flexible and iterative three-level framework for selecting appropriate holistic methods for assessing environmental flow needs within a process designed to simultaneously advance environmental flow implementation. This framework builds on earlier hierarchical methods and frameworks for participatory and collaborative environmental flow assessment.

The framework is intended to match the specific technical methods (and thus the cost and complexity of the assessment) with the highest priority research needs, the level of certainty required, and the level of resources available—and to move toward implementation as soon as possible. For example, if a dam that controls a river flow has considerable operational flexibility, then a Level 2 approach can relatively quickly produce flow recommendations that initiate experimental releases. These changes in the dam operations provide excellent opportunities for learning from real-world flow experiments as well as giving the dam operators experience with adjusting flows to support river ecosystem health, and giving scientists experience with monitoring to learn from flow implementation (Olden et al., 2014). In some cases, such as when releasing a prescribed flood, publicity generated around the flood release can raise awareness about the environmental flow program (e.g., Kendy et al., 2017).

The integration of environmental flow protection into water management in Mexico illustrates how a hierarchical approach to setting environmental flows can promote early implementation. The Mexican environmental flow standard was published in 2012 (Secretaría de Economía., 2012) and ratified in 2017. The standard includes a three-level hierarchical approach for environmental flow assessments: hydrological methods for the planning level, holistic methods for river basins where potential social or ecological conflicts are present, and methods that incorporate new data collection and hydrological and ecological modeling to inform decision making in basins where new infrastructure is proposed and thus greater certainty is required. Based on desktop analyses, Environmental Water Reserves (EWR) were proposed for 189 basins, covering 40% of national territory, with high conservation value and low potential for conflict over water (Barrios et al., 2015; Opperman et al., in review). In contrast, detailed studies of hydrology, sediment transport, and economics were conducted to explore potential conflicts between an EWR and a proposed hydropower dam on the San Pedro River. These studies demonstrated that operation of the dam would not be consistent with the EWR and the dam was canceled (Harwood et al., 2017).

In addition to being scientific processes, Levels 2 and 3 have important social dynamics that are intertwined with the scientific components. The workshops for these levels are intended to encompass a broad range of expertise and stakeholders. By doing so, the assessment process captures previous knowledge and experience for the focal river or region, reducing the likelihood of redundant efforts. Assembling diverse experiences and judgments also can sharpen the critiques of flow recommendations and research plans, improving their clarity and credibility. The shared sense of ownership for the flow recommendations among multiple stakeholders can increase their credibility, likelihood of implementation, and durability.

The interactions between scientists, practitioners, and water managers occur throughout the process. This allows water managers to understand the objectives and rationale for an environmental flow program to a much greater extent than if they are simply presented with a set of flow recommendations at the completion of a scientific assessment process. These exchanges among scientists and water managers also promote an appropriate balance between modeling/research and applied learning through operational changes and empirical results. If the managers are able to suggest operational changes that can be accomplished relatively quickly, then scientists can move beyond modeling and begin learning from real-world flow experiments. Conversely, if the managers anticipate specific issues or concerns that may arise, then scientists can focus their analyses on resolving those uncertainties.

Most of the locations where this framework has been developed and applied are currently in various stages of environmental flow implementation or protection—ranging from experimental flow releases to long-term formalization of specific flow levels within policy (Konrad et al., 2011, 2012; Kendy et al., 2012). Warner et al. (2014) provided a summary of several of these locations and offered the following observations about characteristics of the processes that have followed this framework and implemented changes to flow management:

- The process to define environmental flows is fully and explicitly embedded within the broader process of water management decision making
- Water managers/engineers are integrated from the beginning into the process to define environmental flows
- Environmental flow recommendations are articulated in terms that are readily usable by water managers
- The process for defining environmental flows manages uncertainty and knowledge gaps, turning them from potential roadblocks into catalysts for implementation;
- The process of defining environmental flows is used to strengthen both the professional relationships and subsequent coordination between scientists and water managers/engineers, which contributes to improved scientific knowledge and is foundational to long-term implementation and adaptive management.

Implementation of environmental flows has yet to reach the levels that environmental advocates and water practitioners have strived to achieve (LeQuesne et al., 2010; Harwood et al., 2017; Horne et al., 2017). The framework introduced here is intended to address several of the challenges to implementation, including uncertainty about which methods are most appropriate, the cost of flow assessment, and a disconnect between flow recommendations and management realities. The flexible, hierarchical approach and the social features of this framework are intended to help overcome those challenges.

AUTHOR CONTRIBUTIONS

JO, EK, RT, AW, EB, and BR worked on projects that contributed to the development of the framework described in this paper. JO and EK wrote the first draft. RT, AW, EB, and BR provided edits and writing contributions.

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Transforming Environmental Water Management to Adapt to a Changing Climate

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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
HYDROLOGICAL INDICES AND REGIME ANALYSIS			
	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 ± 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.
2. HYDRAULIC HABITAT METHODS			
	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 (*Salmo salar*) 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.
3. HABITAT SIMULATION			
	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 (*Micropterus dolomieui)* 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
4. HOLISTIC (ECOSYSTEM) METHODS AND FRAMEWORKS			
	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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Different Conceptualizations of River Basins to Inform Management of Environmental Flows

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Environmental flows are a critical tool for addressing ecological degradation of river systems brought about by increasing demand for limited water resources. The importance of basin scale management of environmental flows has long been recognized as necessary if managers are to achieve social, economic, and environmental objectives. The challenges in managing environmental flows are now emerging and include the time taken for changes to become manifest, uncertainty around large-scale responses to environmental flows and that most interventions take place at smaller scales. The purpose of this paper is to describe how conceptual models can be used to inform the development, and subsequent evaluation of ecological objectives for environmental flows at the basin scale. Objective setting is the key initial step in environmental flow planning and subsequently provides a foundation for effective adaptive management. We use the implementation of the Basin Plan in Australia's Murray-Darling Basin (MDB) as an example of the role of conceptual models in the development of environmental flow objectives and subsequent development of intervention monitoring and evaluation, key steps in the adaptive management of environmental flows. The implementation of the Basin Plan was based on the best science available at the time, however, this was focused on ecosystem responses to environmental flows. The monitoring has started to reveal that limitations in our conceptualization of the basin may reduce the likelihood of achieving of basin scale objectives. One of the strengths of the Basin Plan approach was that it included multiple conceptual models informing environmental flow management. The experience in the MDB suggests that the development of multiple conceptual models at the basin scale will help increase the likelihood that basin-scale objectives will be achieved.

Keywords: environmental flow, river, restoration, degradation, adaptive management

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INTRODUCTION

The increasing demand for water resources globally means that social, economic and environmental objectives are not being met, particularly when freshwater ecosystems are already severely degraded in many areas (Vorosmarty and Sahagian, 2000). Given strong hydrological connectivity of water resources throughout a river basin, and particularly the dependence of downstream communities on management of the upstream catchment, demands a basin-scale approach to planning sustainable water resource systems. A number of strategies have been proposed and implemented to address and seek long term sustainable water resource use over catchment and basin scales including Integrated Water Resource Management (Vorosmarty et al., 2013), Strategic Adaptive Management (Freitag et al., 2014; Laub et al., 2015), Socio-ecohydrological management (Falkenmark and Folke, 2002) among others (Stewardson et al., 2017). The successful implementation of all these approaches relies on there being adequate and accessible information to inform water planning decisions at the basin-scale (Huntjens et al., 2010; OECD, 2011; Neto et al., 2018).

Lack of, or incomplete information concerning the flow regimes required to sustain environmental values at both local and basin scales represents a significant threat to sustainable water management. The science of river restoration and environmental flows is, however, relatively young (Poff and Matthews, 2013) and while the importance of understanding large scale, long-term processes is recognized (McCluney et al., 2014; Thorp, 2014; Vorosmarty et al., 2015), it remains an emerging challenge (Poff and Matthews, 2013). Historically, environmental flows science and practice has focused more on the conservation of single species, progressing to consider ecosystems and then regions (Poff and Matthews, 2013). More recently there has been some theoretical consideration of river macro-systems; networks of connected and interacting habitat patches (McCluney et al., 2014). Given the large-scale implications of climate change, incorporating such basin-scale thinking into river management is more critical than ever for sustaining ecosystems and human communities into the future.

The broad range of scales, from meters to 1000 km at which freshwater systems operate demands that managers need to understand the role of environmental flows in sustaining environmental values at each scale (Soranno et al., 2010; Palmer et al., 2014; van den Belt and Blake, 2015). This represents a further challenge for managers for several reasons. First, ecological theory for larger scales is limited (Heffernan et al., 2014). Second, the larger the spatial scale, the longer the time scale over which the effects of flow regime changes will generally take place (Poff et al., 2017). For example, changes in channel morphology may take decades to stabilize (Vietz and Finlayson, 2017), while other changes may occur rapidly in response to severe events such as extreme floods (Friedman and Lee, 2002; Nelson and Dub, 2016) or anoxic blackwater events (Whitworth and Baldwin, 2016; Watts et al., 2018). Third, there have been limited opportunities to examine large-scale responses to changes in flow regimes and in particular introduction of environmental flows. Most published experimental environmental flow studies deal with individual rivers, with many restricted to a single reach downstream of a large dam (Olden et al., 2014). The monitoring of these environmental flows is also constrained, with many projects focusing on monitoring short-term outcomes of flow events rather than long-term responses to flow regimes (Olden et al., 2014; Flotemersch et al., 2016). As a consequence, uncertainty in system responses increases with scale, with greatest uncertainty associated with catchment or basin scale environmental flow responses.

One of the consequences of uncertainty at basin scales is that it affects managers' capacity to undertake smaller scale interventions that contribute to basin scale objectives. The risks associated with undertaking numerous small-scale restoration activities to achieve large scale outcomes have been recognized for some time (Bernhardt et al., 2007; Kondolf et al., 2008). One of the ways of managing this risk is to identify the contribution that the small-scale restoration activity is expected to make to achieve the larger scale objective; a task that is aided by the development of conceptual models (Kondolf et al., 2008).

The purpose of this paper is to describe how conceptual models can be used to inform the development, and subsequent evaluation of ecological objectives for environmental flows at the Basin scale. Objective-setting is the key initial step in environmental flow planning (Horne et al., 2017) and subsequently provides an input into adaptation of the basin scale water management framework and a foundation for effective adaptive management of environmental flows including monitoring and evaluation. We use the example of ongoing environmental flow management in Australia's Murray Darling Basin (MDBA, 2011a; Hart, 2016) to illustrate the main points because it is one of the first examples of a flow restoration project seeking to plan, deliver and evaluate environmental flows across an entire river basin (Poff and Matthews, 2013; Olden et al., 2014; Stewardson et al., 2017). We begin by examining the approach taken to setting objectives for environmental flows and identifying the emerging limitations with a particular emphasis on basin scale matters. We then further develop the conceptualization proposed by McCluney et al. (2014) to consider the variety of conceptual models available to be adapted to inform adaptive environmental flow management at the basin scale. Finally, we discuss ways in which inclusion of a basin-scale conceptualization in environmental objectives may influence both management and evaluation of environmental flows drawing in the example of the Murray-Darling Basin.

CONTEXT

The MDB, in Australia's south-east, covers just over 1 million km^2, 14% of the total area of the continent (Crabb, 1997) and supports 50% of Australian irrigated agriculture and 2 million people (Roshier and Reid, 2002; Kingsford et al., 2013; Hart and Davidson, 2017). The Basin spans four states and the Australian Capital Territory, and as with dryland rivers around the world, flow is highly variable. The condition of the Basin's water dependent ecosystems has declined in response to multiple stressors (Walker et al., 1994; Davies et al., 2008). In response, Australian governments implemented the National Water Initiative and the Federal government passed the Water Act that required development of the Murray-Darling Basin Plan (Capon, 2014). The Basin Plan seeks to optimize social, economic, and environmental outcomes through the integrated management of water resources within a long-term adaptive management framework. A key element of the Plan was acquisition of water entitlements to contribute to a healthy and working Murray-Darling Basin.

The Basin Plan requires development of a long-term adaptive management framework that includes monitoring of the outcomes and evaluation of their contribution to achievement of Basin Plan objectives (MDBA, 2011a; Gawne et al., 2013). Effective monitoring programs are based on management objectives, a conceptual model, availability or feasibility of collecting data and stakeholder interest (McCluney et al., 2014). The monitoring needs to include hydrological, hydraulic and environmental response indicators (McCoy et al., 2018), however, here we focus on environmental response indicators.

Planning, allocating, and delivering environmental flows have been informed by the environmental objectives identified in the Basin Plan, specifically the protection and restoration of water dependent ecosystems and species of conservation significance (MDBA, 2011a). This objective is operationalized for environmental flow planning and management based on three considerations. The first is, an evaluation of the way flow regimes have been modified. Second, a focus on important environmental assets (e.g., Ramsar listed wetlands) and their water requirements. Third, and nested within the ecosystem approach, is the use of established species' flow requirements as surrogates for ecosystem water requirements. Species included are long-lived vegetation (River red gum, Black box) and colonial nesting waterbird breeding (Swirepik et al., 2016). This approach is complemented by the incorporation of the specific water requirements of species of conservation significance (e.g., southern golden bell frogs, *Litoria raniformis* Bino et al., 2018 Murray hardyhead fish, *Craterocephalus fluviatilis* Wedderburn et al., 2013).

The ecosystem approach focuses attention on the ecosystem as a discrete ecological entity rather than a component of a larger system (Capon and Capon, 2017). The approach taken to environmental flows in the MDB is similar to that used in other major river restoration initiatives around the world. This is where environmental flows have been allocated to meet the requirements of riparian (Porse et al., 2015) and wetland (Sklar et al., 2001; Lane et al., 2015) vegetation, fish, (Dodrill et al., 2015; McCoy et al., 2018), and waterbirds (Gaff et al., 2000; Wingard and Lorenz, 2014).

The approach taken in the MDB reflected common practice around the globe (Olden et al., 2014), however, the focus on ecosystems and species diverts attention away from the connections between ecosystems which although known, were not incorporated into the conceptual models that informed environmental flow management. The following are three examples of large scale or tele-connections known to act across the Basin. Many rivers in the southern basin experience anoxic blackwater events when floodwaters return to the main channel and have the potential to adversely affect fish communities hundreds of kilometers downstream (Whitworth et al., 2012; Watts et al., 2018). The second example is native fish, which are known to be capable of long distance movements for some time (Reynolds, 1983). As technology has enabled improved tracking of fish it has become clear that for at least some species, long distance movements are important in breeding (Koster et al., 2017) and re-colonization of disturbed habitats (Thiem et al., 2017). The third example is waterbirds who have long been known to disperse long distances in search of suitable habitat (Frith, 1957, 1963; Roshier et al., 2001). Flow is an important influence on these movements at a variety of scales whether it be providing a network of habitats that act as dispersal corridors (Dorfman and Kingsford, 2001; Roshier et al., 2001) or foraging (Roshier and Reid, 2002; Kingsford et al., 2013) and/or refuge habitats in adjacent river basins (Wen et al., 2016).

As the outcomes of environmental flows in the MBD have been evaluated (Gawne et al., 2016, 2017), it has become apparent that these types of relationships may well be important in linking short-term outcomes to achievement of Basin Plan objectives. This raises the question of why these connections were not included in the initial conceptualization. There are likely several reasons including that the approach was a common approach used in other systems, including the Murray River where environmental flows had already achieved significant short-term outcomes (MDBA, 2011b). Second, that compared to what was known about ecosystem and species water requirements, relatively little was known about tele-connections or their water requirements. With the information emerging from the monitoring and the adaptive management framework, there is increasing attention being directed toward thinking about the long-term context for the short-term environmental flows and implications for environmental flow management and evaluation.

McCluney et al. (2014) proposed a macrosystem conceptualization based on functional process zones (hydrogeomorphic patches). This model appears to align with the blackwater example above, but it is not clear to what extent it applies to waterbirds (and their passengers Figuerola and Green, 2002) or native fish. Given this and the possibility that each river basin may require its own conceptualization, the next section of the paper provides an overview of current understanding and conceptualization of river basins and their characteristics.

River Basin Models

River basins have been conceptualized in a wide variety of models (e.g., River Continuum Concept; Vannote et al., 1980) which vary in their descriptions of basin-scale properties and processes and how these might interact to produce basin-scale responses to anthropogenic pressures and management interventions. These contrasting perspectives are positioned along a continuum from a null hypothesis (i.e., that a river basin is not a system at all but rather an aggregation of smaller-scale systems) through to more holistic views in which everything is interdependent and any small change has the capacity to exert an influence at a basin-scale. Along this continuum, different river basin models also vary with respect to the level of importance ascribed to different parts of the system and the connections among them (**Panel 1**).

The most obvious and straightforward way to characterize a river basin is with a linear accumulation of its constituent

PANEL 1 | Models of Basin-scale ecological structure and function

River basins can be conceptualized differently with implications for prioritization, monitoring and evaluation of environmental flows. Model selection may differ depending on management objectives or decision-maker preferences. Four major conceptual models are:

1. *"Black boxes"*

The simplest conceptualization of a river basin is as a "black box," i.e., a single unit with inputs and outputs and particular attributes, e.g., the size, type, number, and diversity of components etc. This model assumes the basin is a system but ascribes no significance to the distribution of, or relationships among components and processes.

Application of this model to environmental flow management leads to the development of targets associated with input (e.g., flow volumes) and outputs (e.g., fish production or end of valley salt loads). Variable responses to equivalent management interventions are likely to be difficult to explain under this model.

2. *River basins as "plum puddings"*

Socio-politically, river basins are often conceived as being comprised of assets. This can range from a small number of large assets (plum pudding model); i.e., a relatively non-significant matrix in which iconic or significant sites are embedded. This model is reflected by many broad-scale conservation approaches, e.g., National Reserve systems, Ramsar sites, etc.

This model sits at the more holistic end of the conceptualization spectrum and suggests two options for monitoring:

1) If plums are high value assets whose function is to sustain values then the condition of basin-scale values could be evaluated by aggregating the condition of plums. Effect of flows on plums would be monitored and that would be sufficient.

2) If plums are sources of biota supplying a sink matrix, then both plum response and their connections with the rest of system may be monitored.

3. *River basins as linear networks*

River networks are linear, heterogeneous, continuous, and hierarchical (Fausch et al., 2002) and longitudinal patterns are important. Linear networks are a useful framework for considering in-stream processes: fish migration, nutrient cycling, stream metabolism etc. This view of river basins is epitomized by river continuum model and nutrient spiraling concept (e.g., Newbold et al., 1981), but river network characteristics have now been found to explain fish (Jaeger et al., 2014), macroinvertebrate (Clarke et al., 2008) and algal (Liu et al., 2013) community characteristics.

Within the network model, the critical components are the different river reaches while the critical connection is the longitudinal connection. Within reach outcomes would translate to the basin scale through either unique characteristics of particular reaches or the influences that propagate to other components through the longitudinal connection.

If this model is used, assessment at basin scale focuses on the critical components of the system (upland and lowland sections) and the exchanges between them.

4. *River basins as dynamic patch mosaics*

Basins are comprised of a patch mosaic (McCluney et al., 2014) in which patch composition, size, distribution and interactions drive basin structure and function. The patch mosaic conceptualization has three significant benefits. It improves integration of terrestrial and aquatic systems and supports examination of how relationships between patches vary through time. Consideration of patch dynamics also provides additional perspectives on heterogeneity within a basin. Third, the patch mosaic provides a basis for consideration of the role of disturbance in river basins through effects on mosaic composition, distribution and interactions.

Within the patch mosaic, the critical patches may include plums or river reaches described in the plum pudding and river network models but will include other components believed to interact with the river system at the basin scale. The critical connection will vary depending on the type of patch. Within patch outcomes would translate to the basin scale through either unique characteristics of particular patches (e.g., supporting an endangered species) or an outcome that propagates to other patches in the mosaic (e.g., patch acts as a source of recruits).

Adoption of a patch dynamic mosaic requires that the critical components are identified and assessed which may require a significant increase in information although this will be influenced by the scale, and the definition of patches.

5. *Process models*

Process models describe key ecological processes (e.g., primary productivity, dispersal, recruitment) that sustain the basin's character (composition, structure and function). While some process models can be derived from broad scale data (e.g., remotely sensed), many require small-scale information that then needs to be scaled up to the basin scale. The advantage of process models is that they are likely to be more sensitive to environmental change and changes in process are likely to precede basin scale compositional or structural changes.

Components within a process model will include the patch types that support the process and associated connections among them. Process changes will become significant at the basin scale if a process is unique to a patch (patch is a breeding site for a rare fish), if the process changes in a large number of patches across the basin (e.g., primary production) or the process outputs propagate across the basin (e.g., dispersal).

Development and application of a process model requires that process information and, where necessary, the information required to scale it up to the basin also be generated. Once again, this is likely to require a significant increase in the amount of information needed.

components: an inventory of their type and measures of their abundance and rates of change over different time intervals. We regularly do this at large-scales for climatic variables (e.g., mean annual temperature, total annual rainfall, etc.) and socio-economic variables (e.g., total human population, number of settlements, % area irrigated) but may be less comfortable with, or less equipped to calculate, similarly scaled-up metrics for many ecological attributes beyond simple counts (e.g., number of Ramsar wetlands). Recent decades, however, have seen progress in determining basin-scale measures of some physical and biogeochemical processes, such as annual water balance, total sediment yields (e.g., De Rose et al., 2003) and total nutrient loads (e.g., de Vente and Poesen, 2005). Improved mapping technologies (i.e., remote sensing and GIS) have also facilitated better determination of topologic features at basin-scales including number of wetlands, inundated area, total stream length, distribution of stream morphological types (Brierley and Fryirs, 2016), persistence of permanent water (Bunn et al., 2006), and density of stream confluences (Benda et al., 2004). Biodiversity characteristics can similarly be described for a basin as a whole, i.e., numbers of species, composition, functional diversity etc. Describing river basins as a single unit and its associated inventory of characteristics provides a basis for the development of a black box conceptualization (**Panel 1**) to support management. The black box conceptualization makes no assumptions about whether the basin is a system or an aggregation. In terms of setting objectives for and evaluating environmental flows, a black box model makes no assumptions about the system and would be appropriate in situations where either very little is known, or where environmental flow management is undertaken at the scale of catchments within the Basin, and the focus was evaluating effectiveness across the Basin.

More elaborate descriptors use knowledge of both the presence of ecological components and some, albeit limited, knowledge of species' distributions. For example, in the process to get a wetland Ramsar listed, the nomination needs to provide information against 9 criteria concerning the role of the wetland in representing or supporting biodiversity in the region and the conservation status of dependent biota (Ramsar, 2016, page 45). If managers have undertaken a review of the basin's environmental assets then the basin description can include descriptions of these assets. In contrast to the "black box" model that describes the basin as a single entity, this information enables the basin to be conceptualized as a unit containing a limited number of high value assets; the plum pudding model (**Panel 1**). The plum pudding conceptualization still makes no assumptions about whether the basin is a system or an aggregation, but does provide a focus for delivery of environmental flows within the basin and their evaluation.

Beyond whole of basin characteristics, there are conceptualization of river basins that account for their internal structure and function. The Riverine Ecosystem Synthesis (RES) described rivers as being comprised of a series of Functional Process Zones (FPZ) (Thorp et al., 2006; McCluney et al., 2014) and a number of classification systems for rivers (Kasprak et al., 2016) and wetlands (Pressey and Adam, 1995; Brooks, 2017) are now available. At a finer scale we also have information on the structure of specific wetlands (Swirepik et al., 2016) or habitats that support particular taxa (e.g.,Young et al., 2011) that may be key ecological assets at a basin-scale. The spatial organization of such ecological constituents (e.g., species' distributions) can differ considerably between basins that possess otherwise comparable compositional attributes (e.g., the same species pool). The degree of spatial heterogeneity of ecological attributes at a basin scale may be particularly important, not least because riverine macrosystems often display high cross-scale resistance to disturbances as a result of temporal asynchrony between their constituent patches (McCluney et al., 2014). Basins with greater spatial heterogeneity might therefore be expected to exhibit greater resilience to certain disturbances than more ecologically homogenous basins (Stendera et al., 2012). The temporal asynchrony introduces an important temporal dimension to the delivery of environmental flows given that the specific sites important for sustaining populations are likely to vary through time. The Commonwealth Environmental Water Office (CEWO) have already recognized this in the MDB and classify years according to water availability with refuges prioritized during very dry years and lateral connectivity prioritized during very wet years (CEWO, 2013, p16). It is, however, possible that this temporal variation may operate at both longer and shorter time scales.

From a functional perspective, patterns of internal connectivity (longitudinal, lateral, and vertical) are significant, including floodplains and their catchments, and where known should be included in descriptions of river basin character (Nislow et al., 2010; Crook et al., 2015). Connectivity governs the movement of materials, energy and biota within and between basins and is recognized as fundamental to basin-scale ecological function and resilience (Pringle, 2003). Different organisms, life history stages and processes, however, operate across different scales such that critical patterns of connectivity vary depending on the species or process being considered (Fuller et al., 2015). Some species, for example, are broad-ranging across basins creating opportunities for the existence of strong links between distant regions whilst others are more restricted (Poiani, 2006). The spatial arrangement of different ecosystems and their associated habitats within basins will affect connectivity and (e.g., proximity of feeding and breeding habitats) is therefore of basin-scale ecological importance. Information on patterns of internal connectivity enable development of a network conceptualization. The network describes the interactions between parts of the basin mediated by the patterns of connectivity. The precise nature of the network model will depend on the biota being considered with linear networks being appropriate for macroinvertebrates (Clarke et al., 2008) and fish (Lois and Cowley, 2017; Radinger et al., 2017), while a dispersed network may be more appropriate for waterbirds (Kingsford et al., 2010; Pedler et al., 2014) and their passengers (Reynolds et al., 2015).

Access to information on the distribution and abundance of ecosystem types within a basin enables development of a patch dynamics conceptualization and associated description (van Coller et al., 2000; Landis, 2003; Talley, 2007). While a patch dynamics model does not make any assumptions about whether or how the patches interact, it does provide an important source of information on changes in the relative abundance of patches and the landscape mosaic in which they are located. This information can then inform development of hypotheses around issues of connectivity and interdependence. A patch dynamic model may be of value when considering the management of environmental flows under climate change in which the system will need to adapt but continue to sustain nominated values (Girard et al., 2015).

Our limited knowledge of many species distributions and interactions in freshwater ecosystems often precludes the estimation of more process-based biological measures, e.g., patterns of dispersal, recruitment etc. Remote sensing techniques, however, increasingly enable a degree of quantification of certain biological processes (e.g., primary production) and ecosystem condition (e.g., vegetation greenness) at basin scales (Dornhofer and Oppelt, 2016). More elaborate descriptors depend on knowledge of both the presence of ecological components and the interactions among them and may include measures such as biomass production or carrying capacity e.g., of fish; (Ziv et al., 2012). River basins can also be characterized with respect to their overall ecological interactions with other systems at continental or global scales. Examples include a basin's role in sustaining migratory species or whether it is a sink or source of organisms (Heffernan et al., 2014). Development of a process-based conceptualization remains a significant challenge due to measurement difficulties, high degree of spatial and temporal heterogeneity and the range of scales over which they operate. With some being very localized but important at a Basin scale (e.g., sustaining habitat for a migratory bird), localized but propagating out to influence a significant area (e.g., waterbird recruitment) or being widespread across the basin (e.g., tree recruitment).

Ultimately, what is required are models that include the basin characteristics (structural, functional) that are relevant to the question being asked while achieving a balance between the simplistic and fatuous at one extreme and the complex but incomprehensible at the other. A "plum pudding" model, for example, may be appropriate for federal or regional authorities responsible for the management of national parks or Ramsar wetlands while decision-makers concerned with national or continental-scale comparisons of river basins may be best served by "black box" models. Model selection may also be informed by current ecological understanding of the basin-scale component or process being targeted by management. Managers concerned with basin-scale vegetation conservation, for example, might therefore opt for a patch dynamics model, as it most closely describes vegetation habitat (van Coller et al., 2000) while network models, describing habitat and connectivity, may better suit those managing fisheries (Crook et al., 2015; Eros, 2017).

Basin-scale Effects of Environmental Watering

The models described above will help formulate environmental flow objectives, but additional information is required to monitor and evaluate the anticipated contribution of smaller-scale environmental flows to achievement of basin-scale objectives (Kondolf et al., 2008). There are three conceptual pathways by which smaller-scale environmental flows can contribute to basin-scale objectives. First, some localized outcomes of small-scale environmental flows may be of basin-scale significance simply due to the uniqueness of the values which they support, e.g., survival of an isolated population of an endangered species (Bino et al., 2018). Second, the cumulative effects of multiple watering interventions dispersed either spatially or through time (or both) can influence ecological character and condition at the basin-scale including measures of presence/absence and totals/rates of constituent elements as well as their spatial arrangement and heterogeneity e.g., riparian vegetation (Shafroth et al., 2017; Cunningham et al., 2018). Finally, small-scale watering interventions can exert an influence on large-scale processes or basin-scale properties. For example, local watering may influence basin-scale patterns of connectivity, e.g., by bridging a gap in wetland "stepping stones" along a flyway for migrating bird species (Amezaga et al., 2002; Kingsford et al., 2010) or facilitating recolonization by species persisting in local refuges (Thiem et al., 2017). Similarly, the cumulative effects of multiple watering events will influence the spatial heterogeneity and juxtaposition of ecological patches within a basin therefore influencing portfolio effects and basin-scale resilience (McCluney et al., 2014).

Identification of a basin scale concept and flow-contribution concepts are an important input to the design of a monitoring program (Bernhardt et al., 2007; Wingard and Lorenz, 2014). Monitoring responses to environmental flows remains a challenge due to both knowledge gaps (McCoy et al., 2018) and the complex relationship between flow and ecological response (Summers et al., 2015) which can lead to variable responses (Souchon et al., 2008; Poff and Zimmerman, 2010). These challenges increase at larger scales due to the increased number of confounding variables that may influence or obscure environmental responses (Summers et al., 2015). Given the levels of uncertainty about the influence of flow regimes at the basin scale, applying our conceptual understanding to the design of effective monitoring and evaluation is necessary to support basin-scale adaptive management (Convertino et al., 2013).

Measurement and Monitoring

There are numerous criteria for selecting indicators (Cairns et al., 1993; Dale and Beyler, 2001; Doren et al., 2009) and innumerable potential indicators that could be monitored (Jorgensen et al., 2013; Pander and Geist, 2013; McCoy et al., 2018). In the MDB example, selection of environmental indicators of environmental flow outcomes was influenced by this extensive literature on indicators (Donnelly et al., 2007; King et al., 2015), the management (Basin Plan) objectives and the objectives of the monitoring program (Gawne et al., 2013). Monitoring design was, therefore, based on a train of logic that started with the flow objective conceptualizations, which informed environmental flow planning which then informed the design of the monitoring program. As a consequence, any changes in the basin scale conceptualization would cascade down to influence the monitoring program.

The water requirement conceptualizations led to a monitoring program based on seven sites across the MDB that examine short (<12 months) and long-term (1–5years) outcomes for hydrology vegetation (Stewardson and Guarino, 2018), in-channel metabolism and fish populations (Gawne et al., 2014). While some of the sites were extensive (e.g., Murrumbidgee site covers 750 river km), the focus on sites without consideration of tele-connections increased two risks. The first, discussed earlier, is that both short-term responses and long-term legacies would be more, or less, likely to occur due to the influence of tele-connections. Including consideration of tele-connections may have allowed inclusion of additional data that would have helped explain some of the expected variation in response to flows through time and among sites (Poff and Zimmerman, 2010). Second, the design increases the risk that long-term legacies of environmental flows are not detected because they become manifest outside the monitored areas. For example, fish may move laterally or longitudinally to complete their life cycle (Eros, 2017) or vegetation may produce seeds that influence either downstream systems (Nilsson et al., 2010; Greet et al., 2011;

Parolin et al., 2013) or systems subsequently visited by waterbirds (Figuerola and Green, 2002).

The general indicators used to monitor and evaluate Basin Plan environmental flows (vegetation, metabolism, fish) may not have been influenced by the conceptualization. It is likely, however, that the specific metrics (e.g., population characteristics), process indicators linking flow to general indicators and the sampling design would have been different. This suggests that the basin conceptualization will influence the selection of indicators. As an illustration we have taken the framework developed by Noss (1990) that classifies biodiversity indicators as compositional, structural, or functional and provided examples of basin-scale indicators relevant to each of the conceptual models (**Table 1**). As described in **Table 1**, a "black box" conceptualization suggests the selection of indicators concerning totals of compositional elements (e.g., species numbers) or rates of functional processes (e.g., biomass turnover). In contrast, a basin network model is more likely to monitor structural or functional measures concerning the arrangement and operation of network nodes and segments. This does not preclude the application of other criteria for the selection of indicators (e.g., diagnostic ability, feasibility or sensitivity Doren et al., 2009) but consideration of the conceptual model ensures that monitoring outputs enable evaluation of our understanding of the system which is an important part of adaptive management (Parrott and Quinn, 2016; Roberts et al., 2016).

The pathway by which indicator responses contribute to Basin scale objectives (**Figure 1**) was an important input to the design. Where small-scale effects have basin-scale significance due to their uniqueness, sampling is often constrained to areas directly influenced by management interventions. In contrast, if basin-scale outcomes are to be achieved through aggregated effects of multiple small-scale interventions, sampling will also need to quantify the proportion of the basin influenced by management interventions. Similarly, if basin-scale outcomes are expected to occur via large-scale propagation of changes from a small area of intervention, then sampling will need to assess the entire basin or, using the appropriate conceptualization, monitor those areas in which outcomes are expected.

Evaluating Ecological Significance at a Basin-scale

In addition to selecting appropriate indicators to evaluate basin-scale outcomes of environmental watering, frameworks to assess measured indicators and their variation in time and space in relation to management objectives are also required. In many cases, decision-makers will want to know

TABLE 1 | Examples of the different types of compositional, structural, and functional indicators that would be relevant to each of the different conceptual models (adapted from Noss, 1990).

	BASIN-SCALE INDICATORS		
Conceptual models	**Compositional**	**Structural**	**Functional**
	Indicators of the constituent parts of the system	Indicators of the ways that the constituent parts are arranged within the system	Indicators of processes that influence the system's structure, composition, or condition
Black box	Means, totals—e.g., species, habitats		Inputs/outputs—e.g., nutrients
			Rates of processes—e.g., decomposition
			Retention of materials/biota—e.g., sediment
Plum pudding	Number of iconic sites—e.g., Ramsar wetlands	Spatial arrangement of iconic sites	Disturbance processes
	Number of rare species Population size of rare species		Demographic processes of key species
Reticulated network	Numbers of nodes	Identity, distribution, length of reaches	Movement of organisms
	Number and types of reach (functional process zone)	Connectivity among reaches	Retention of material e.g., detritus
		Fragmentation e.g., Barriers	Transformation of organisms e.g., herbivory, predation
			Transformation of material e.g., decomposition
Patch mosaic	Identity, distribution, richness of patches	Heterogeneity	Patch persistence and turnover
	Species minimal viable population size(s)	Fragmentation	Presence and distribution of refugia
	Minimum extent of ecosystem type(s)	Juxtaposition of patches	Metapopulation dynamics
Process	Species or patches that influence processes	Distribution of energy flow processes in space and time	Energy flow rates
	Species or patches that influence system response to disturbance	Locations of sediment sources and sinks	Patch persistence and turn-over
			Sediment and geomorphic processes
			Nutrient fluxes
			Contaminant fluxes

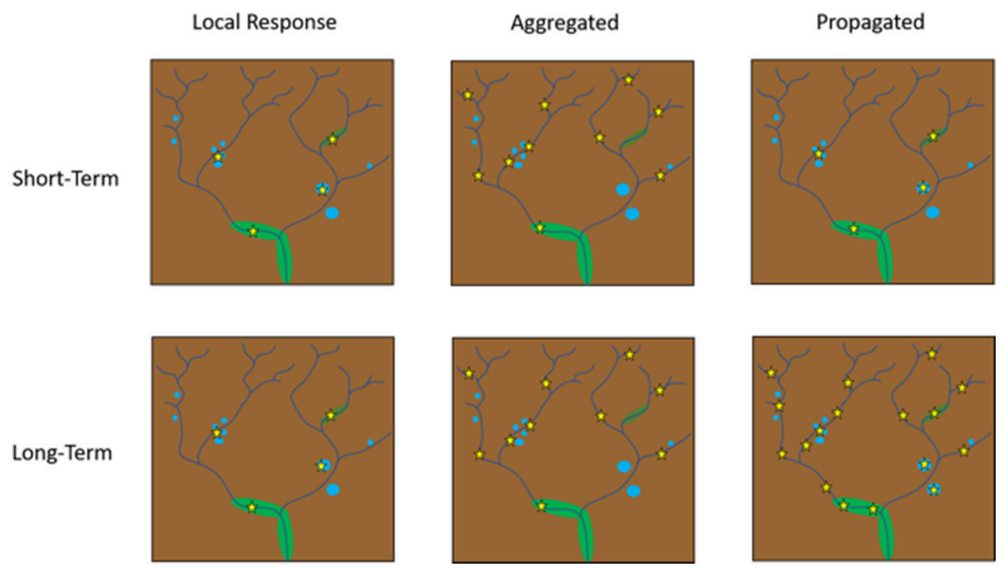

FIGURE 1 | An illustration of how the pathway by which management interventions are expected to influence basin-scale outcomes may influence monitoring of basin-scale indicators. If interventions are expected to produce local outcomes of basin significance, then both short and long-term monitoring will focus on the areas targeted by management actions. If interventions are expected to have significant basin-scale outcomes through the aggregation of outcomes across the basin then monitoring (both long and short term) would seek to generate a basin scale estimate through a selection of random or fixed sites. If, however, interventions are expected to have significant basin-scale outcomes through the propagation of outcomes across the basin then monitoring in the short term should focus on the intervention sites to quantify the area-scale short-term response. Long-term intervention monitoring (both long and short term) would then seek to quantify the extent to which long-term outcomes had propagated from the sites where short-term outcomes had been observed. Key to diagrams (—) river channel, (●) wetland, (⬬) floodplain, and (☆) sample site.

what changes are ecologically significant at a basin-scale. Most commonly, significant changes reported by ecological monitoring involve evaluation of indicators against targets which are usually defined in relation to socio-political values or the quantification of biological components or processes or some combination of both (Carwardine et al., 2009). Basin-scale objectives for environmental watering may include such socio-politically determined targets as the maintenance of the ecological character of all Ramsar wetlands or the conservation of endangered species within that basin. More ecologically informed targets, however, could be developed in relation to structural and functional indicators associated with network or patch mosaic models, e.g., the maintenance of particular levels of heterogeneity or connectivity between habitat types. Indicators arising from "black box" basin models may also be used to develop targets such as keeping catchment sediment loads below certain threshold values. In all cases, however, the particular significance level assigned to indicators to specify targets will necessarily be subjective and based on what is deemed to be an acceptable (or unacceptable) level of change (e.g., nil loss, no more than 30% change etc.).

Non-target based, but quantitative approaches to evaluating the significance of conservation actions have also been proposed. Linear and curved utility functions, for example, enable managers to assess the benefits of incremental increases in the application of conservation measures (Davis et al., 2006; Wilson et al., 2007). Although such approaches can be criticized for failing to provide managers with clearly assessable goals (e.g., Carwardine et al., 2009), non-target based approaches can also promote a more nuanced approach to decision-making involving trade-offs rather than absolutes (Capon and Capon, 2017). With regards to evaluating the basin-scale significance of environmental flows, for instance, utility functions could enable managers to consider trade-offs between predicted benefits and the amount of water delivered.

Multiple Conceptual Models

An interesting point to emerge from the development of long-term intervention monitoring in the MDB was that the integrated concepts that underpinned environmental water planning (flow changes, ecosystem water requirements, and species water requirements) were subsequently disaggregated to support objective setting and evaluation processes. This pragmatic application of conceptual knowledge arose from the need for strong supporting science and the development of an ecosystem scale conceptualization. This raises the question of whether development of a basin scale conceptualization, as per Poff and Matthews (2013) would have improved outcomes. A basin scale model may have focused attention on the basin scale rather than on the water requirements of individual ecosystems with unknown consequences for those ecosystems. A unified basin-scale model may also not have supported the application of model components to environmental flow objective setting, monitoring or evaluation. This is not to say that monitoring and evaluation is not revealing new basin-scale insights, rather that if a basin scale model were to be developed, that the approach adopted in the MDB, has a number of benefits. Specifically, that examining the system from several different perspectives provides a strong foundation for an environmental flows program and carries with it the opportunity to pick, choose, integrate and adapt the relevant perspectives for the various activities required to plan, deliver and evaluate those flows (Hart, 2016).

The development and application of multiple models provided a means of dealing with complexity and through comparison of different models identifies cross-scale interactions and trade-offs. Here we have emphasized the spatial component, but it is likely that the variety of environmental flow types and their legacies will also require individual conceptualizations which underscores the need for multiple models.

Many large-scale restoration programs utilize multiple models. In some instances, the different models focus on different threats (Nõges et al., 2016; Davis et al., 2017). In other systems multiple models are developed to forecast responses by different biotic groups (Sklar et al., 2001; Lovich and Melis, 2007). In many ways these approaches are similar to the approach taken in the MDB in that their focus is ecosystems and species and while there may be a basin-scale conceptualization (Perry, 2004) the development of multiple basin scale conceptualizations appears unusual. The experience in the MDB suggests that the development of multiple conceptual models at the basin scale provides an improved foundation for the adaptive management of basin-scale management of environmental flows.

Challenges and Future Directions

Current Limitations

There are two broad limitations. The first, as noted earlier are knowledge gaps in macro-system ecology (McCain, 2013; McCluney et al., 2014). There have been significant improvements in our understanding of river basins that mean we can now describe the key ecological constituents, and some of the critical connections and processes that sustain values such as diversity and the provision of ecosystem services (Trabucchi et al., 2012; Boulton et al., 2016; Flotemersch et al., 2016). While managers can be confident in the identification of key constituents, there has been little examination of the number, area or distribution of these constituents required to sustain values, due at least in part to ongoing questions about the effectiveness of protected areas for freshwater systems (Chessman, 2013; Hermoso et al., 2016). Similarly, the importance of longitudinal and lateral patterns of connectivity is now recognized, but there is more uncertainty about biotic connections including the movements of some species of fish (Baumgartner et al., 2014; Stoffels et al., 2014, 2016) or hydrochory in sustaining plant communities (Nilsson et al., 2010; Parolin et al., 2013). It is likely that this knowledge will accumulate slowly as many macro-scale changes are likely to occur over extended periods of time from decades (e.g., population declines) to centuries, e.g., shifts in channel morphology (Jiang et al., 2018). In many instances macro-scale responses to anthropogenic disturbances take time to become manifest (Petts and Gurnell, 2005; Mac Nally et al., 2011) and we have limited capacity to predict outcomes (Stendera et al., 2012; Savenije et al., 2014). We have a much better understanding of smaller-scale, faster acting responses to change, however, there are challenges associated with scaling these up to a basin scale due to the complex nature of these systems (de Vente and Poesen, 2005; Thorp, 2014).

The second limitation is the integration of macro-scale considerations into basin-scale integrated water management. At the scale of an individual ecosystem, it is feasible in some instances to isolate or insulate the system from some major pressures. This can be achieved by creating protected areas or by focusing limited resources on a small number of systems. For example, the Living Murray program in south-eastern Australia allocates environmental flows to five iconic wetland sites along its 2,500 km length in order to ensure outcomes are achieved (MDBA, 2016). The limitation of this approach is that it is not dealing with the stress at the scale at which it occurs, so that interconnectedness among ecosystems within a basin can constrain rehabilitation (Dudgeon et al., 2006).

There are also numerous technical and logistical challenges associated with the adaptive management of environmental water at the basin scale. Limited information on basin characteristics and their response to change affects development of an appropriate reference or benchmark for setting objectives and evaluating management interventions. Managing at the basin scale also requires engagement of a greater diversity of people and institutions, which brings a new suite of challenges (Margerum and Whitall, 2004).

Opportunities

Despite the major challenges identified above, CEWO is already exploring opportunities to incorporate macro-scale ecology into the management of environmental flows. For example, coordinated delivery of flows to multiple wetlands (CEWO, 2017) and coordinate releases from several rivers to support native fish populations (CEWO, 2018). These changes in the delivery of environmental water represent the completion of the adaptive management cycle at the operational level. The intervention monitoring is also in the process of being reviewed and there will be opportunities to adapt the monitoring design to include consideration of these types of water actions and their associated large scale, long-term responses. The Basin Plan is reviewed every five years with a major review to be undertaken in 2024 (Australian Government, 2012). This will be an opportunity to apply the knowledge generated from the allocation of water across the Basin to the conceptualization that underpins the management, monitoring and evaluation of environmental flows. In preparation for the review there will be opportunities to utilize the data gathered by the intervention and condition monitoring to start to identify some of the cross-scale interactions and connections that influence macrosystem responses to environmental flows (Thorp, 2014). This process could apply some of the lessons learnt from other large-scale, long-term monitoring programs, such as the U.S. wadeable streams assessment (Paulsen et al., 2008) or European water directive monitoring (Kaika, 2003; Hering et al., 2010) to undertake comparisons among river basins. The outputs of this analysis would help reduce uncertainty around the water required to sustain environmental values across the Basin and support the successful implementation of adaptive management at the basin scale in accordance with the Basin Plan (Australian Government, 2007, 2012).

The identification of macro-scale influences of flow regimes is likely to create further technical challenges in terms of the monitoring and evaluation of environmental flows at multiple scales. There are, however, advances in our capacity to monitor responses to environmental flows, including remote sensing and GIS modeling that increase managers' capacity to generate basin-scale data. For example, remote sensing can now support river morphology (Belletti et al., 2017), organic matter input (Hoffmann et al., 2016) and individual tree condition (Shendryk et al., 2016) assessments. Improvements in monitoring technology are also likely to improve opportunities for extensive on ground monitoring through increased community participation, telemetry and techniques such as environmental DNA. There are similar advances in our capacity to manage the large data sets created by these new monitoring approaches (Koo et al., 2015; Etzion and Aragon-Correa, 2016). The existence of large complex data sets also provides opportunities for novel analytical techniques to extract more value from the data collected (Phan et al., 2016).

CONCLUSIONS

Environmental flow management at the basin scale currently represents a significant challenge, due to river basin's the complexity associated with achieving social, economic, and environmental objectives, knowledge gaps, and technical challenges in generating information at the basin scale. Basin-scale management is, however, important if environmental values are to be sustained at both the basin scale but also within high value rivers, wetlands and rivers. Inclusion of basin scale considerations is also likely to create opportunities to better understand the relationship between basin condition and the delivery of ecosystem services (Capon and Bunn, 2015). Given its importance and the limited resources available, it is important that the principles of adaptive management are applied, and that available knowledge is effectively applied to support the planning, monitoring and evaluation of environmental flows. Within this context the development of a series of conceptual models focused on individual objectives that can be integrated or adapted to suit the different decisions required at different steps in the adaptive management process will facilitate application of knowledge, provide a means of dealing with complexity and a platform for identifying synergies, trade-offs and risks associated with proposed management actions.

AUTHOR CONTRIBUTIONS

BG, Project leader of the LTIM project. Undertook major revision of first draft and responses to subsequent feedback from collaborating authors. SC, Member of the leadership team that developed LTIM Authored first draft. JH, Member of the leadership team that developed LTIM. Worked with BG on finalization of paper. SB, Member of the leadership team that developed LTIM. Worked with BG on finalization of paper. CC, Member of the leadership team that developed LTIM. Provided feedback on successive drafts until she went on maternity leave. MS, Member of the leadership team that developed LTIM. Provided feedback on draft manuscript. MG, Member of the leadership team that developed LTIM. Provided feedback on draft manuscript. RS, Member of the leadership team that developed LTIM. Provided feedback on draft manuscript. FG, Member of the leadership team that developed LTIM. Provided feedback on successive drafts of the manuscript. PE, Member of the leadership team that developed LTIM. Provided feedback on successive drafts of the manuscript.

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PERSPECTIVE
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A Perspective on Training Methods Aimed at Building Local Capacity for the Assessment and Implementation of Environmental Flows in Rivers

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This paper describes the development and delivery of a global training programme for environmental flows in rivers. The programme was developed in South Africa, and formalized with WWF. It has been delivered at various levels of detail, to specialist teams of scientists and managers (as learning-by-doing), and to large numbers of post-graduate students, in more than 20 countries worldwide. The intention has been to build local capacity and initiate E flows implementation. The general format of the training is described, and a number of examples and case studies are used to demonstrate the successes and pitfalls of the process. The examples concentrate on the need for long-term commitment and persistence in the face of multiple impediments, chief among them the need to change mind-sets of water policy makers, managers, scientists, and all levels of stakeholders, who traditionally view rivers as resources to be used to the maximum extent, rather than as valuable assets to be protected. They also illustrate examples of misunderstanding and resistance to implementing E flows. Although there are many prerequisites for success in implementing E flows, three essential ingredients for successful training and implementation have emerged over the past 25 years: the need for local champions, with a long-term commitment; the need for understanding and support from all levels of stakeholders; and the need (at least initially) to simplify the process as much as possible, so as to foster understanding and support, and to demonstrate successes within a time frame that maintains that support.

Keywords: river, environmental flows, training, capacity-building, implementation, lessons learned

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INTRODUCTION

Environmental flows (E flows) "describe the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems, which in turn support human cultures, economies, sustainable livelihoods and well-being." (The Brisbane Declaration, 2007, in Arthington et al., 2018). This is one of the most important developments in water policy and management in the past 25 years, and even 8 years ago Le Quesne et al. (2010) stated that they knew of no major countries that do not now include, or are developing, legislation and policy that requires E flows. Arthington et al. (2018) confirm that many countries continue to introduce E flows into their water legislation.

This paper is a personal, and often anecdotal, recollection of the development and implementation of training courses, projects and programmes, mostly designed to kick-start environmental flows (E flows) implementation programmes in the host countries. Training programmes have been facilitated by the author in more than 20 countries around the world over the past 25 years. The training template (see below) gradually evolved as training-by-doing in more than 20 detailed environmental flow assessments (EFA) in South African rivers during the 1990's, and was formalized after a meeting of the WWF Global Water Programme in Hyderabad, India, in 2004. Subsequently, many of the trainings have been carried out as part of WWF river basin programmes, coordinated by local WWF country offices, and using local scientists and managers. This has the major advantages that the training is provided in response to a local demand, rather than following persuasion by a consultant, and the trainer is coming into the process as part of a local team, rather than as a foreign intruder. The training is designed to start a process, and to build local capacity, so that coherent decisions can be made, with sufficient experience and expertise, by national specialists and policy-makers, as to whether and how to implement E flows. As an outsider coming in, I have not felt it my place to proselytize or evangelize for E flows, and a viable exit strategy is required so that local interests take responsibility.

Since 2004, the trainings have varied from multiple-year programmes involving detailed EFAs on pilot rivers [the Rio Conchos in Mexico (WWF-Mexico, 2006), the Rio Sao Francisco in Brazil (Medeiros, 2008), the Mara River in Kenya/Tanzania (Lake Victoria Basin Committee and WWF-ESARPO, 2010)], the Great Ruaha River in Tanzania (WWF-Tanzania Country Office, 2010), the Kilombera sub-basin of the Rufiji River in Tanzania (McClain et al., 2016), the Upper Ganga River (O'Keeffe et al., 2012), and then the Ramganga River (Kaushal et al., 2018) in India), to shorter (one week to 1 year) projects in Wisconsin (USA), Ecuador, Peru, the UK, the Netherlands, Switzerland, Turkey, Mocambique, Zambia, South Africa, Pakistan, India, China, Mongolia, and Australia.

The ultimate objective of the training is to develop a team (or teams) of local scientists and managers, and informed stakeholders at all levels, who have experience with, and are eventually able to run their own E flows programme, so that the country can take ownership and responsibility for their own implementation. As will become clear, the results have been mixed, with the development of sustainable E flows programmes run by local teams in some countries (e.g., India), while in other countries (e.g., Mongolia) the initial training workshop has been followed by no observable follow-up or contact. This paper provides a description of the training model or template used, examines case studies of success and failure, and draws lessons which may help future training and capacity-building.

THE TRAINING TEMPLATE

The process developed with WWF was generally in response to the requirements of river basin initiatives run by WWF country offices. If such offices requested training in E flows, they would be asked to identify and contract a team of local scientists and managers, from local universities, research institutes, government ministries, and/or basin offices. The team should include: Hydrologist; Hydraulics surveyor/modeler; aquatic ecologists including at least fish and invertebrate specialists, and riparian/floodplain Botanist; Geomorphologist, preferably fluvial; Water Quality specialist; Sociologist and/or Socio/economist. A local coordinator (often from the WWF country office) should also be appointed, to oversee the organization and logistics of the training, and possibly to learn to facilitate the overall EFA process, with a view to becoming the local champion. The government/management agencies should be encouraged to appoint staff to attend and contribute to the entire training, with a view to taking ownership of the national process.

The process starts with the choice of a river or river section for a pilot EFA and training-by-doing. Ideally, this should be a relatively small river, not yet over-allocated. The size makes the field-work more manageable (and cheaper), and the limited allocation makes it easier to achieve an early implementation of E flows, demonstrating the success of the process. Unfortunately, these criteria are rarely met, because the lure of a large important river, already in crisis management, is too inviting. Such rivers offer high-profile opportunities, but are usually too complex and over-developed to offer quick success. Perhaps the best compromise is to choose a river of each sort, and embark on simultaneous pilot projects, providing both high profile and the prospect of a quick successful demonstration.

The facilitator would run an initial week-long training workshop, at which the preferred EFA methodology is decided upon, the tasks and responsibilities are defined for each specialist group, and a planning schedule is drawn up. This will usually be followed by a field trip with all the specialists, to choose sites suitable for hydraulic rating and detailed sampling; and to demonstrate and try-out sampling methods and data collection. Because the specialists are already expert in their own fields, the emphasis is simply on how to integrate their expertise within a clearly defined EFA process. Following the initial training, the local coordinator and team should be able to spend seasonal periods of the next year collecting and analyzing the required information. At different times in this process, meetings should be held with riparian and institutional stakeholders, to explain the purpose and process of the EFA, and to involve them in choosing environmental objectives for the pilot river. This is an extremely important part of the EFA process, since it can build understanding and ownership of the project, and an involvement in objective-setting lends legitimacy to the outcomes. An effective model for this stakeholder involvement is described in O'Keeffe et al. (2017) for the Rufiji River in Tanzania.

Once the field-work and analysis is complete, each specialist group should prepare a starter document, summarizing the available information and data collected, and providing a detailed set of flow-related objectives for their component. The document should also include classification tables for each site, indicating present state, current trajectory of change, the importance of improving or maintaining the component, and the proposed Ecological Management Class (EMC, the overall desired condition for each site). At the flow assessment workshop (usually a week long) the specialist groups discuss a range of seasonal flows for each site, and reach a consensus on which flows will provide for as many of the component objectives as possible. Each flow is then provided with detailed motivations, and a set of consequences if it is not provided. The hydrologist provides a check that the recommended flows are within the potential of the river to be provided (i.e., within the natural bounds of the flow regime). Normally, three different flow scenarios will be assessed—the target scenario which most closely achieves the environmental objectives, an improved scenario to reach a class higher than the target, and an increased use scenario which would reduce the environmental state by one class. These alternative scenarios provide managers with an idea of the consequences for water use of maintaining the river in different conditions. The flow assessment workshop will be run by the facilitator, while mentoring the proposed local champion.

Following the initial pilot project training, a second pilot EFA should be set up on another river. This pilot should be largely run by the local champion, as facilitator, with the outside facilitator as a background mentor and advisor. Ideally, the original specialist teams should carry out the second pilot, with changes dictated by their success in the initial EFA (see section on set-backs below). The original teams should include further apprentices to be trained in the process. After the second pilot EFA is completed, there should be at least one experienced specialist team in place, a local champion capable of facilitating the process, staff members of relevant government organizations who understand and can implement the recommended flows, and large numbers of stakeholders who have some understanding of the process.

EXAMPLES

Implementation in Progress

The training programmes are intended to provide an initial impetus for E flows implementation, by creating local capacity, understanding and momentum. Experience has shown that it will usually take a number of years, often more than a decade, before this impetus results in the provision of E flows in one or more rivers. An early example of this was the training in Mexico, where WWF-Mexico Country Office appointed a local team to assess E flows for the Rio Conchos in 2004. The Conchos is a large river, flowing northwards into the Rio Bravo/Grande, over-allocated for irrigation and with trans-boundary flow obligations to the USA. Typically for such a complex system, the implementation process has become bogged down, mainly by the intransigence of irrigation farmers, and latterly by the increasing lawlessness in the state of Chihuahua (Barrios, pers. comm., 23rd October, 2017). However, Eugenio Barrios (Director of Water Programmes, WWF-Mexico Country Office) goes on to write: "the Conchos E flow proposal was key to develop the Mexican E flow Standard, and later to change our approach to low water conflict basins. We created the water reserves concept to implement E flows. It has been very successful and currently we are on track to set E flows in 350 river basins out of 700" (Barrios, pers. comm., 23rd October, 2017). Barrios et al. (2015) lists 6 pilot basins in which flow implementation has already started.

A similar situation has developed in Brazil, where an initial E flows training was coordinated on the Lower Rio Sao Francisco, by Professor Yvonilde Medeiros of Bahia Federal University in 2006. Prof Medeiros is also a member and technical consultant on the Sao Francisco Water Basin Committee. The Sao Francisco is a large river and has a series of 5 hydro-power dams which feed into the national electricity grid. The EFA concentrated on the 50 km of river downstream of the lowest dam to the river mouth. The training EFA was completed in 2008, but implementation of the recommended E flows is still under discussion: "The National Water Authority (Agencia Nacional de Agua-ANA) are coordinating the member states of the Sao Francisco River Basin in a discussion about rules for reservoir operation during wet periods and periods of water scarcity" (Prof Medeiros, pers. comm., 23rd October, 2017).

India provides the most complete example of the training process. In 2009, an EFA was initiated by WWF-India on the Upper Ganga River, from Gangotri to Kanpur, combined with a training programme for a team of Indian scientists appointed by WWF-India. Although other E flows initiatives were also under way, the Ganga project was the first comprehensive assessment and training in India. The project was completed in 2012, and was followed by a second EFA on the Ramganga tributary of the Ganga. This second EFA was coordinated and facilitated by Nitin Kaushal, Associate Director—Sustainable Water Management & Wild Rivers WWF-India, who was mentored by the author during the Ganga and Ramganga EFA's. Nitin was ably supported and encouraged by senior staff at WWF-India, including Suresh Babu (Director, River Basins and Water Policy) and Sejal Worah (Programme Director). Together, this team and some of the senior scientists on the E flows team approached the Government of the state of Uttar Pradesh, to release the recommended flows in the Ganga during the 6 weeks of the Kumbh Mela religious festival held at Allahabad from January to March, 2013. (Kumbh Mela is held once every 12 years, and attracts the largest gathering of people in the history of the world). The state government agreed to provide the flows, and the river was wide, deep, and relatively clean for the 89 million pilgrims who visited the river during the 6 weeks of the festival (WWF-India, 2013). Flow monitoring and interviews with pilgrims during the festival indicated that the recommended flows were met or exceeded throughout the 6 weeks, and that more than 95% of interviewees were satisfied with the state of the river during their visit (Kaushal, 2015; WWF-India, 2013). A further short-term "Demonstration E flow" is planned for the Ramganga (Kaushal, pers.comm., 23rd October, 2017), and these will hopefully demonstrate and promote the advantages of E flows to the Indian government and to local stakeholders. There is already a national policy advocating E flows, but, as Nitin points out: "National Water Policy 2012, and Ganga Notification of 2016 are key policy items, that talk about E Flows and are useful instruments. The Ganga River Basin Management Plan is a useful and powerful document to push for E Flows, but the state has to come on board which is a long-drawn game." (Kaushal, pers.comm., 23rd October, 2017).

Tanzania has been engaged in E flows research, assessment and training in a number of river basins since an early training course by the author in Dar es Salaam in 2005. The Water Resources Management Act of 2009 included the requirement for a Reserve, part 2 of which is for the protection of aquatic ecosystems, and is equivalent to an environmental flow. Training began with a joint Kenyan/Tanzanian project to assess E flows for the transboundary Mara River. This has been followed by EFA's on the Wami, Ruvu, Pangani, Great Ruaha and Kilombera Rivers (both the latter being sub-basins of the Rufiji River Basin). These projects have been facilitated by a number of different international consultants (including the author on the Mara, Ruvu, Great Ruaha, and Kilombera), using a variety of assessment methodologies, and all including elements of further training. A number of the same Tanzanian specialists have been used on many of the EFAs, so there is presently a local team of highly experienced specialists, familiar with a number of the commonly used EFA methodologies, on a range of different rivers (e.g., O'Keeffe, 2013). Despite the many assessments, implementation has been slow, at least partly due to the absence of a committed champion, either from the ranks of the specialists, or from government. According to Willie Mwaruvanda (a former Basin Officer for the Rufiji Basin, who was involved in the EFA for the Great Ruaha), E flows have been considered in the preparation of Integrated Water Resources Management and Development Plans in six Tanzanian river basins, but there has been so far "little implementation of E flows here in Tanzania. In the Ndembera [a tributary of the Great Ruaha] the design of a dam is complete. I think the Government is looking for funds for its construction. Its purpose will be to provide E flows for the Great Ruaha in the National Park" (Mwaruvanda, pers. comm., 31st October, 2017). The initial EFA for the Mara River was accepted by the Lake Victoria Basin South Commission (LVBSC), with plans to protect the E flows, which are almost entirely presently flowing down the river, as it has no large impoundments or major abstractions. Low flows during droughts are at risk of abstraction for irrigation, upstream of the Maasai Mara and Serengeti protected areas, so the LVBSC has put in place a requirement for on-farm, off-stream storage before any further irrigation licenses are approved. Similarly, the flows in the Kilombera Rivers are at present virtually natural and unabstracted, so that the E flows simply need to be kept in the rivers in the future, and there is plenty of potential for consumptive water uses above the E flow requirements.

The above case studies indicate at least some progress toward E flow implementation, and there are other cases where one can be hopeful that progress is being made. The shorter training courses in Wisconsin, the UK, the Netherlands, and Switzerland have all been attended by a majority of delegates from developing countries, usually as part of longer courses and post-graduate degrees in aspects of water management and science. Between 2005 and 2017, these courses have been presented to more than 430 present and future water professionals around the world (including at least one person who has since been appointed as his country's Minister of Water). It would be impossible to ascribe any E flows implementation solely to these courses, but one can surmise that delegates returning to their countries with an understanding of E flows will, at least in some cases, have helped to promote the process.

In other cases there has been significant implementation of E flows, but not as a result or even necessarily connected to the training that the author has facilitated. In China, for example, courses were provided to government staff, water managers and scientists on the Yellow River and the Yangtze, but the E flows in the Lower Yellow River pre-date the course (Gippel et al., 2012), and in the Yangtze were planned well before the course. Again, one can hope that the courses fed into a national groundswell of understanding and acceptance of E flows.

Set-Backs, Impediments, and Lack of Noticeable Progress

Important as the examples of progress are, it is just as useful to know that many projects to initiate E flows may founder and stall early on, and to understand why. My involvement in a number of countries (e.g., Peru and Mongolia) was over after an initial training workshop. This doesn't necessarily mean that no progress has been made through other channels. There are many possible reasons for the failure of E flow initiatives in different countries, despite the fact that most countries now include, or are developing, legislation and policy that requires E flows (Le Quesne et al., 2010). These may include a lack of capacity in one or more of the enabling factors listed here in the discussion (from Harwood et al., 2017), but, in my experience, the most common, and the most intractable factor is to change the mind-set of people. O'Keeffe et al. (2017) suggest that "Introducing the idea of environmental flows to stakeholders (who may have little or no experience of the issue) is often challenging. Globally, there is a basic view that rivers are a very valuable resource for human use and that the main product they provide is freshwater, the basis of life, livelihoods, food production, industry, and sanitation. A consequence of this view is that water flowing out of the end of a river, if not a waste, may at least be perceived as a lost opportunity for improving human welfare. Accepting the premise of environmental flows, that water should be left in the river, and that a fairly high proportion of mean annual runoff may have to be left in the river if relatively good environmental conditions are to be maintained, requires a 180° change of this mind-set. To convince people that this change is useful and desirable needs compelling reasons." Even when a country has the necessary legislation, which argues a national desire to implement E flows, the acceptance of the need to set aside significant amounts of (often scarce) water, rather than to use it to grow food etc., does not come easily, especially in countries where water ministries and management have traditionally been run by irrigation engineers and dam builders. It may take a generation before environmentally-minded managers come to the fore. In this paper, rather than list and analyse the many reasons that may get in the way of E flows implementation, I want to present examples which demonstrate some of the difficulties which people have in understanding and accepting E flows.

The following are examples where, for different reasons, elements of the E flows process has not worked, or been understood. The examples are not intended to ridicule the people involved, and names, rivers and (mostly) countries are left out to minimize personal offense. They rather illustrate the difficulties that many people, even experienced professionals and scientists, have in managing the concepts of E flows. The following are all cases which I personally experienced:

Early on in the development of E flows, a very senior hydrologist commented, after an EFA presentation: "If you want to apply 20% of the mean annual runoff as an E flow, it is impossible to do that for a seasonal river, where there is zero flow in the dry season." In deference to his seniority and gray hairs, (I was young and timid then), I waited until afterwards to point out to him that 20% of zero is still zero, and that we were in no way advocating flows when the natural condition would be dry.

In the early days of the South African Water Act of 1998, a classification system of A to F was used, in which A class was pristine and natural, and F was critically/extremely modified. Classes E and F were designated environmentally unsustainable, and therefore unacceptable as management objectives. Any rivers currently in E or F class would, by default, need to be improved to at least D class (largely modified). It took very little time for a group of water professionals, resolutely anti-environmental flows, to propose that the management objectives for all rivers in A, B, or C classes should be to exploit them to a D class, since they would remain sustainable in this state. The purpose of E flows is certainly not to motivate for increased degradation of rivers.

In the course of discussions to set E flow requirements for a particular river, the fish specialist recommended seasonal flows extending into the riparian vegetation, at depths that would allow fish to forage for the invertebrates living among the reeds and rushes. The invertebrate specialist countered this with considerably shallower recommended flows, to prevent the fish from feeding on the invertebrates.

During one initial training course, we split the delegates into 5 groups to do separate assessments of E flows on the same floodplain section of a large river, which happened to form the state boundary between a northern and a southern state of the host country. Four of the groups came up with very similar quantities of environmental water, primarily to inundate the valuable floodplain forests. The fifth group recommended about half the water volume of the other groups. On enquiry, it became clear that all the members of the fifth group were from the southern state, and were certainly not going to allocate scarce water to the floodplains on the northern side, so had confined their recommendations to the southern banks of the river.

A very senior scientist, appointed to lead the biodiversity group at an initial training, was originally an algologist, and produced long species lists of his favorite family of algae for each EFA site, as his contribution to the E flows analysis, after two years of courses and field-work. I congratulated him on his endeavor, and asked him how he intended to use these lists to assess E flow requirements. "Flow?" he said, "I don't know anything about flow!"

A botanist appointed as riparian/floodplain vegetation specialist insisted that the vegetation needed to be permanently inundated, at least to its base. Since the river was deeply incised this would have required flows of around 50 times the natural flows during the dry season. He was adamant that this was nevertheless necessary.

A very senior scientist, appointed to lead his country's E flows programme, had a unique view of the EFA process, insisting that the only measurements relevant to setting E flows were water depths, and anything else was wasted effort. He was also adamant that flows have no effect on water quality.

A hydraulics engineer, appointed to provide rated cross-sections of a large floodplain river, was obviously more used to working on in-stream structures such as weirs, and resolutely refused to extend his surveys beyond the immediate channel-banks of the river. As a result, the EFA was carried out without any quantifiable way of estimating floodplain water requirements.

These are only a few of the difficulties encountered in E flows work. Other examples include the many EFA methodologies designed to provide the minimum quantity of environmental water, among them the notorious Q_{95} methodology (e.g., Lozano Sandoval et al., 2015), which sets E flows at constant extreme drought levels—a guarantee of eventual serious degradation to the ecosystem. In general, these impediments are of the following kinds:

- Those who are resolutely anti-environmental flows, considering them "a waste of water for fish and bugs" (e.g., 1, above). Thankfully, such environmental dinosaurs are increasingly rare.
- Those who reluctantly accept the requirement for some sort of E flows (usually where legislation requires it), but who exert every effort to ensure that only token water volumes are ever allocated (e.g., 2. above).
- Those specialists who become "component loyal" within the E flows process, insisting on flows purely for their species or processes, irrespective of hydrological possibilities or whole ecosystem effects (e.g., 3 and 6. above).
- Those who may be expert in their own field, but fail to make the transition to the multi-disciplinary requirements of E flows (e.g., 4, 5, and 7. above).

Coping with such set-backs often requires strategies which could be described as low cunning, from the facilitation and coordination team. Many specialists are resistant to change, and seniority is often highly correlated with increasing resistance. Since holistic E flow processes rely on multi-disciplinary analysis and assessment, it is usually possible to leave out the more improbable flow recommendations, or hide them in unread appendices. For example, the algologist's biodiversity team included highly competent fish, mammal, reptile and invertebrate specialists whose combined analysis obviated the need to include input from the team leader. To be fair, the algologist provided baseline data which may well eventually prove valuable in understanding the biodiversity of the river, and the scientist in 6. Above is well-connected as an advisor to the national minister of water, and has been politically effective in promoting the concept of E flows, despite his eccentric grasp of the details.

DISCUSSION

This has been an unapologetically personal and largely subjective reflection of the E flows process. I accept that scientific credibility is a requirement for the implementation of E flows, but it is not in itself nearly sufficient, and this paper tries to trim the imbalance in much of the E flows literature, which concentrates on scientific understanding of the ecological effects of flow, and has developed increasingly complex processes for assessing and implementing E flows. Without the understanding and recognition of the purpose and importance of E flows, among policy makers, managers, scientists, and all other stakeholders, the most detailed scientific analysis will be impotent and unused. Scientific research underpins the prediction of the effects of flows on riverine ecosystems, but setting environmental objectives, deciding on management initiatives, promoting the implementation of E flows, and supporting the process, are all dependent on societal values, rather than science. I hope that I have shown that many people (even senior water professionals and scientists) struggle with the concepts and details of E flows, and are guided more by their biases and convictions than by any in-depth objective grasp of the technicalities. If even the specialists struggle with this, then how diverse and eccentric will the understanding of non-specialist stakeholders be? O'Keeffe et al. (2017) have argued for a simple stakeholder-enhanced approach to E flows, at least in the initial stages of implementation (and especially in developing[1] countries), and other authors have shown the resistance and misunderstandings that can result from over-elaboration (e.g., Dickens, 2011). A cogent argument is presented by Stirzaker et al. (2010) of the need to identify and stick to required levels of simplicity in dealing with complex problems, in which their hypothesis is that: "Decision makers responsible for natural resource management often complain that science delivers fragmented information that is not useful at the scale of implementation." I would argue for a graduated development of E flows capacity in countries new to the process, in which robust transparent methodologies, avoiding the use of opaque models, are initially used to familiarize local teams with the basics of E flows. Having gained a few years of experience and confidence, these teams can then choose to graduate to the more complex methodologies.

Lessons Learned

Harwood et al. (2017) list a series of "enabling factors" for the implementation of E flows, which they have culled from a review of a series of global case studies in the report. These are summarized as:

1. Legislation and regulation
2. Collaboration and stakeholder engagement and understanding
3. Driving force—a champion
4. Technical knowledge, understanding, and tools
5. Resources and capacity
6. Standards and guidelines
7. Monitoring networks and adaptive management
8. Reallocation and trading mechanisms

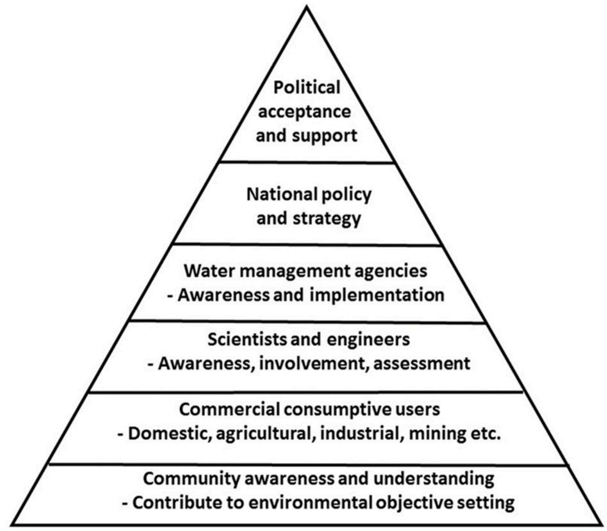

FIGURE 1 | Different levels of stakeholder involvement in the E flows process. Modified from WWF-Zambia (2016).

I would agree that at least some application of all of these factors is required for successful E flow implementation, but, in my experience, the over-arching requirement is number 3—the need for champions, with a long-term commitment to enabling and implementing the E flows process. Committed and effective champions can be the catalyst for initiating all the other enabling factors, but, without one (or more), the process at best becomes disoriented and dis-integrated. Eugenio Barrios (Mexico), Yvonilde Medeiros (Brazil) and Nitin Kaushal and his colleagues (India), are all examples of champions who have been engaged for more than a decade, and continue to build support and capacity for E flows in their countries. Ideally, two champions, or even a group, should be the aim. One should be from the government agency tasked with E flow implementation, and the other(s) may be from a university, research institute, an NGO such as WWF, and/or from a major stakeholder group. It has also become clear that factor 2—stakeholder engagement and understanding, is a pre-requisite for success, as I have argued above. **Figure 1** provides a "stakeholder pyramid," indicating the different levels of involvement in the E flows process.

I would add two more lessons that can facilitate the E flows process and help to ensure fairly rapid implementation. They are both simplifications of the process that are not always possible, but should be sought out, because they can fast-track success and provide demonstrations of the advantages of the process:

1. Find a river (such as the Kilombero or Mara, discussed above) which is currently relatively unstressed and not over-allocated, so that the E flows are still in the river, and don't have to be clawed back from unenthusiastic users.
2. Start the process on a small river which is accessible, easy to work on, and in which E flows are more likely to be implemented.

[1] I know that some people dislike the term developing countries, and consider it to be pejorative. I am profoundly proud to belong to a developing country, and would not want to be part of a so-called developed country, implying that nothing further needs to be understood or advanced. We all know of one or two powerful national leaders that embody this arrogant *credo*.

Initial successful demonstrations, achieved relatively quickly (in a matter of years rather than decades), are infinitely more persuasive than any number of theoretical discussions, meetings and workshops. The resistance to these simplifications, as I have pointed out in the case studies, is that such rivers may not have the high profile, priority and importance of large complex rivers such as the Ganga, Sao Francisco or Conchos. The case of the Mara is fortunate because it is not only relatively unallocated at present, but it drives the iconic mass migrations of millions of wild animals in the Maasai Mara and Serengeti, which earn large amounts of foreign exchange in tourism for Kenya and Tanzania, so that it has the high profile and importance as well.

This paper is about the people involved in E flows assessment and implementation—how they can help the process and how they can hinder it. There is ample literature about the scientific aspects of E flows, but this paper takes the science as an accepted requirement, and makes the point that the people involved, their knowledge, beliefs, and biases, their commitment and persistence, are probably more important in determining the success or failure of E flows than any other factor.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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Environmental Flow Assessments Are Not Realizing Their Potential as an Aid to Basin Planning

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Multiple planned dams in developing countries, mostly for hydropower, are threatening some of the world's great river systems. Concern over their social and environmental impacts has led to hydropower being excluded from the sustainability term 'green energy.' Better planning, design and operation of hydropower dams could guide where to build and not to build, and how to mitigate some of their negative impacts. Impact assessments presently done for dams include Cumulative Impact Assessments (CIAs) or similar at the basin level, and Environmental Impact Assessments at the project level. These typically do not detail how the river ecosystem could change and the implications for its dependent social structures. A comprehensive Environmental Flows (EFlows) Assessment does provide this information but is almost always not linked to the other impact assessments. When done at all, it is often rudimentary; rarely basin-wide; and almost always done after major development decisions have already been made. A more effective approach for any basin targeted for hydropower or other large dam development would be to formally and automatically embed the requirement for a basin-wide, detailed EFlows Assessment into a CIA. This should be done at the earliest stage of planning, before dam sites are selected and allocated to developers. The EFlows method adopted matters, as it dictates the scope and flexibility of a study. Rapid one-size-fits-all methods do not provide the detail that governments and other stakeholders need to understand the possible future of their river basins, negotiate and make informed decisions.

Keywords: river degradation, EFlows, basin-wide, hydropower, Cumulative Impact Assessments

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BACKGROUND

The global demand for energy is driving an unprecedented surge in dam building to generate hydropower (Zarfl et al., 2015). Much of this construction is in areas relatively untouched by development until the last decade or so, targeting natural areas and river systems that supply water, food and lifestyle support to hundreds of millions of people. The scale of new or planned large dams is immense: more than 300 in the Mekong Basin of which 176 are for hydropower (http://www.cgiar.org); 60 in the Brazilian Amazon and 200 in the Northeast Indian Himalayas (https://www.internationalrivers.org). Southern Africa's largest river, the Zambezi, already has four hydropower projects (HPPs) producing 5 GW of installed hydropower, with a further 130 GW of potential identified (Beilfuss, 2012). China plans 120 GW of new hydropower from the Salween, Mekong, Yangtze and Brahmaputra Basins.

It is widely recognized that dams offer numerous benefits to humanity, but the scale of hydropower construction now planned or underway will adversely affect the diversity and resilience of whole river systems, crossing national boundaries with substantial knock-on effects into politics and human conflict (Zarfl et al., 2015; King and Brown, 2018). Concerns over the social and environmental impacts of HPPs (US EPA, 1989; Abell, 1994; Vörösmarty et al., 2010; Pierce-Smith, 2012) are such that hydropower has been excluded from the sustainability term 'green energy' (Maurer et al., 2011; Gibson et al., 2017). The growing negative image of hydropower seems to stem from a common, intractable business-as-usual view that fails to engage meaningfully with the importance of the full range of values and uses of river ecosystems. There is an apparent widespread–not necessarily universal–inertia to embracing new thinking in large-scale water planning. As governments, international funders and River Basin Organizations commit themselves to more caring and equitable development, their adherence to these principles is far from assured. Sustainable development of water resources is at greater risk than ever before. A new wave of river degradation is underway and hydropower is becoming firmly linked to this.

We believe that hydropower has a potentially valuable role to play in some national economies, and that better planning, design and operation of HPPs could help mitigate some of their negative impacts. This would have to include, from the earliest stage of planning, formal inclusion of detailed information on the ecological functioning, ecosystem services and social values of targeted river ecosystems, for the full range of stakeholders to consider. In three decades of such work, we have found that comprehensive Environmental Flows (EFlows) Assessments generate a vital portion of the necessary data and understanding for this to happen, providing information that was not available to decision makers until the last decade or so.

EFLOWS ASSESSMENTS

EFlows Assessments provide information on the links between river flows and river health. In their most comprehensive form, they describe the predicted basin-wide ecological and social outcomes linked to scenarios of different water management options. Where new hydropower is involved, the scenarios can also encompass different permutations of dam numbers, locations, designs, operations and power generation. This provides important insights on dam viability, consequences for ecosystems services and biodiversity, and the trade-offs needed to ensure sustainability. Such information is invaluable in helping guide decisions on whether or not to build, the design of meaningful mitigation measures, the fine-tuning of dam operation and, in some cases, identification and design of biodiversity offsets.

Conventional wisdom is that the level of detail for an EFlows Assessment should increase as the scale of the assessment decreases, so that basin-wide assessments can be done as rapid, low-resolution, low-confidence inputs and project-specific assessments as high-resolution detailed inputs (Richter et al., 1997; Arthington et al., 2003; Acreman and Dunbar, 2004). We have come to believe that this is not necessarily so and, under the scale of HPP and other dam development now underway, the EFlows approach that would most often make sense is one that is basin-wide and highly detailed.

WHY?

HPPs' impacts on rivers are specific to their design, location and operation, and to the nature of the targeted river. Many HPPs in one basin each contribute an impact, plus an additional layer of group impacts that no single HPP might produce. In multi-HPP planning, now all too common for the world's large river basins, we can no longer afford to consider proposed projects in isolation but need in-depth EFlows investigations at an early stage of planning that consider the potential incremental and cumulative impacts over a whole basin from a suite of projects (e.g., NCEA, 2015).

At present, HPP investigations are largely confined to economic and engineering considerations, with perhaps some preliminary low-resolution, broad-scale biodiversity inputs. Governments might provide a list of planned HPP sites with pre-granted environmental licenses (Maurer et al., 2011), but typically the criteria for their selection relate to power generation and the cost of energy. These sites may then be allocated to developers (IFC, 2012). Major decisions on location, design and price of electricity are thus frequently made with at best rudimentary consideration of the social, biodiversity and river-health implications for the whole basin. In some cases, a Strategic Environmental Assessment (SEA; NCEA, 2015), Cumulative Impact Assessment (CIA[1]; IFC, 2013) or similar is done to guide decision-making in these basins, but almost always these post-date the major decisions on number and location of HPPs, and are relegated to tinkering with an already-laid plan (Meynell et al., 2014). Further, unless they include a detailed, systematic EFlows Assessment they too run the risk of failing to identify or address key environmental and design challenges related to the river ecosystem and its dependent people.

Developers may thus later be faced with, and could understandably be reluctant to address, issues that had not been spelled out when the project was awarded. These could include a requirement to release EFlows beyond those factored into their bid, to forego peak-power generation, or to meet international funders' safeguards or performance standards, such as "no nett biodiversity loss" (IFC, 2012). At a fairly advanced stage of planning, potential impacts that did not form part of the original decision to invest might surface and need to be addressed through adherence to the mitigation hierarchy of Avoidance, Minimization, Restoration and Offsets (Mitchell, 1997; IFC, 2012), with new implications for the viability of the project. Faced with such potentially deal-breaking uncertainties some

[1]The International Finance Corporation (IFC) defines a CIA as "*the process of analyzing potential cumulative impacts and risks of proposed developments in the context of the potential effects of other human activities and natural environmental and social external drivers on chosen valued ecosystem components over time, and proposing concrete measures to avoid, reduce or mitigate such … impacts and risk to the extent possible*" (IFC, 2013).

companies are becoming reluctant to participate in auctions (Maurer et al., 2011).

HOW DO DETAILED BASIN-WIDE EFLOWS ASSESSMENTS ADD VALUE?

An holistic detailed EFlows Assessment uses permutations of potential water-resource developments in scenarios to predict changes in river health, river resources (such as fish and other food items), biodiversity, river-dependent rural lifestyles and other strategic considerations. The predictions are made at a level of detail that stakeholders can relate to. Done at the basin scale, an EFlows Assessment can identify: the incremental and cumulative effects of all proposed projects on the above; thresholds in the degree of environmental and social impacts; the least- and most-sensitive river reaches in a basin; barriers to flow, sediment and biota that would be least or most destructive; which tributaries could best be developed and which conserved with natural flows and fish migrations (sacrificial v sacrosanct); the configuration, design and operation of dams that would best promote biodiversity and support fish populations; which rivers are most important to rural communities and why; and how much water in what pattern of flows would be required to maintain different parts of the river system at various levels of health. Opportunities and risks not apparent in single-dam studies are revealed and mitigation impossible at the project scale may become possible in the wider context.

From the perspectives of the developers, funders, governments and society it makes sense to have all of this information available, in detail and at a basin level, before the development pathway for the basin is agreed and project sites are chosen and awarded. Because of this, EFlows Assessments are becoming a prominent vehicle through which IWRM manifests, allowing informed stakeholder and biodiversity negotiations before decisions are made. The challenge is ensuring the appropriate investigations are done at the appropriate time.

HOW MUCH DEVELOPMENT IS TOO MUCH?

From such work, the concept of Development Space (i.e., development potential) has evolved to address concerns over the widespread development-driven degradation of river systems (**Figure 1**). The concept provides a limit, identified by the stakeholders via EFlows scenarios, beyond which further development should not proceed because of the resulting social and ecological degradation (King and Brown, 2010). Demonstrating a real road to sustainable development, the country/ies involved accept the limits of development that they identify from the scenarios, and can then apportion the Development Space among themselves in an agreed way that could allow slower-developing countries/sectors to still have their share to use as and when they wish. This becomes, in essence, the foundation of the basin development pathway. Multiple such basin studies form the foundation of country, region or global-based optimization of development and biodiversity protection (Zarfl et al., 2015). Although the end point of the Development Space could theoretically be shifted to the right over time, its value in terms of sustainability lies in not readily doing that but by rather strategizing to live within its limit.

ADVANTAGES OF THE BASIN-WIDE APPROACH

The basin-wide EFlows approach reflects the principles of the World Commission on Dams (WCD, 2000) and has the potential to identify win-win situations. Although governments and developers may view such large-scale planning as onerous and individual project developers feel it is outside their scope of operations, it has the potential to produce multiple benefits for them (Opperman and Harrison, 2008).

- Less uncertainty and controversy: the overall basin plan is negotiated and agreed, and thus there is lower risk for individual developers and funders.
- More streamlined project-level review: there is greater certainty during the review process for individual projects because many of the issues will have been identified and addressed at higher levels of planning.
- Less expenditure on assessing impacts: the EFlows Assessment and biodiversity offset studies are river/basin specific rather than project specific, with costs of these studies shared by developers in a basin. Later more limited EFlows Assessments for individual projects would cost less than if they were stand-alone.
- Fewer operational constraints: a potentially significant portion of the mitigation obligation of an individual project will be accomplished through contribution to basin-/regional-scale mitigation.
- Positive public recognition: the approach should lead to better energy and conservation outcomes, meeting a standard that the public increasingly demands of development.
- Preferential access to funding: the approach advances hydropower as a source of renewable and sustainable energy in the global market, providing access to carbon-offset markets and mechanisms.

WHAT NEEDS TO CHANGE?

The sequence of phases of new dam projects is Scoping, Pre-feasibility, Feasibility, Construction and Monitoring. The available impact assessment processes are SEAs, which have a broad spatial and sectoral scope and include strategic political, economic and institutional considerations (NCEA, 2015; Bidstrup et al., 2016); CIAs, which are sectoral and, in the case of hydropower, operate at the spatial scale of river basin or sub-basin; and EIAs, which are project focussed (Baxter et al., 2001). EIAs and CIAs are tasked with proposing concrete measures to avoid, reduce or mitigate identified impacts (Mitchell, 1997), while SEAs generally are not. Conservation Assessments (CA) of whole river basins also occur, but tend to not be linked to, or necessarily inform, water-resource development plans.

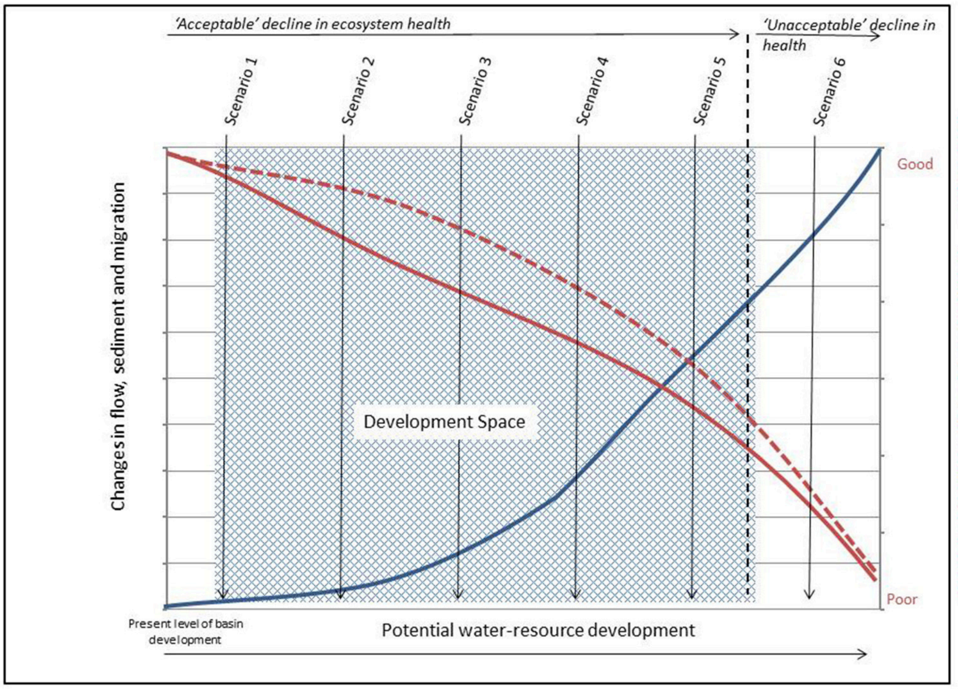

FIGURE 1 | The concept of Development Space, defined by stakeholders after consideration of EFlows scenarios.

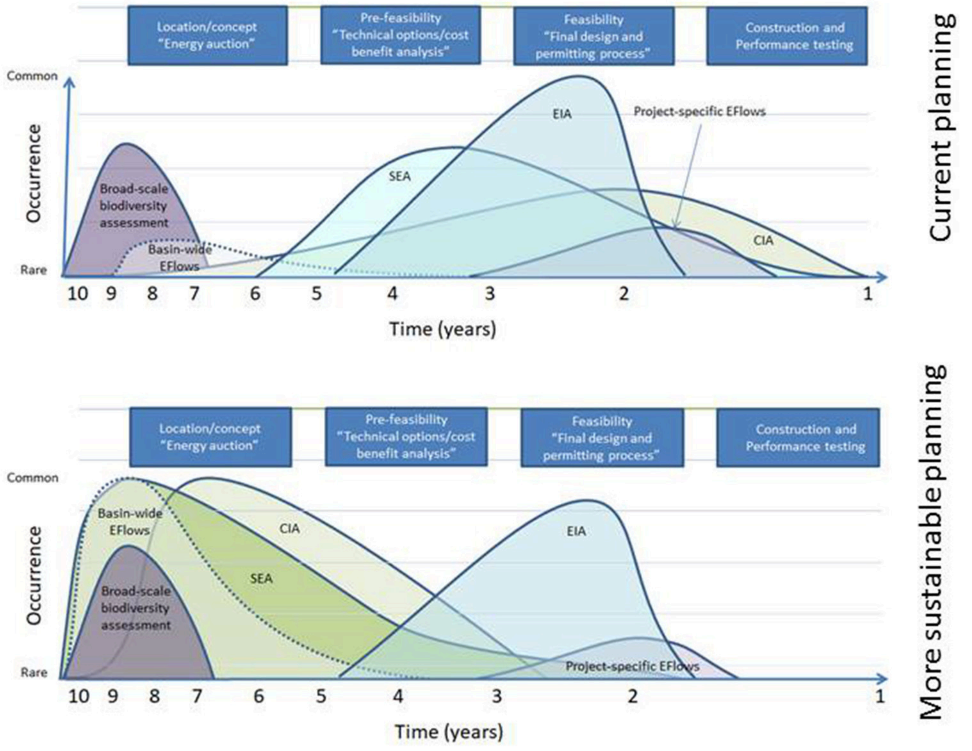

FIGURE 2 | Present and suggested future timing of the various conservation and impact assessments for new dams.

TABLE 1 | Summary features of some basin studies showing status of Cumulative Impact Assessments and Environmental Flows Assessments. (Documents are listed under individual basin headings in References).

Basin	Location	For whom were the studies done?	Date	Initiated by	# HPPs/dams at time of study		Stage of basin development	Purpose of study	Funder	What was assessed?	EFlows status	EFlows Influence on decisions	References
					Planned	Existing							
Nam Ou	Lao PDR	Govt. Lao PDR	2011	Not known	7	4	Advanced	Develop a Watershed Management Strategy	Sinohydro	Desktop CIA of impact of seven HPPs	No	None	http://eng.sinohydro.com ESL, 2011
Enguri	Georgia	JSC Henskra Hydro	2017	International funder—to address their E&S safeguards	22	5	Medium	Demonstrate adherence to lender's E&S safeguards	Asian Development Bank	Desktop CIA of impact of one HPP added to existing dams	No	None	SLR Consulting, 2017
Trishuli	Nepal	Upper Trishuli 1 Hydropower Company	2014	International funder—to address E&S safeguards	33	14	Advanced	Demonstrate adherence to lender's E&S safeguards	International Finance Corporation	Semi-quantitative CIA including EFlows Assessment	Coarse holistic	Possible	ESSA Technologies, 2014
Kwanza	Angola	Ministry of Energy and Water, Angola/Odebrecht	2015	Reviewer identified lack of CIA	19	3	Early	Meet requirements of EIA peer auditors	Hong Kong and Shanghai Banking Corporation	Semi-quantitative CIA including EFlows Assessment	Coarse holistic	Possible	Fluvius Southern Waters, 2015 Mthethwa, 2016
Poonch (Indus headwater)	Pakistan	AJK and Pakistan Governments; Mira Power	2014	International Funders as part of the E&S work for Gulpur HPP	5	0	Early	Demonstrate adherence to lender's E&S safeguards	International Finance Corporation	Semi-quantitative CIA including EFlows Assessment	Detailed holistic	Yes, for additional HPPs	Annandale and Hagler Bailly Pakistan (Pvt) Ltd, 2014 HBP/Southern Waters, 2014
Lower Mekong	Lao PDR, Thailand, Cambodia, Viet Nam	Mekong River Commission	2014–2017	Mekong River Commission	120	63	Advanced	Development planning	International funders of Mekong River Commission	Semi-quantitative CIA including EFlows Assessment	Detailed holistic	Unknown, but now to be used in sustainable HPP studies	DHI, 2015 ICEM, 2010 MRC, 2006 MRC, 2011 Pierce-Smith, 2012 MRC, 2017a MRC, 2017b
Okavango	Angola, Namibia, Botswana	OKACOM	2010 and ongoing	OKACOM	5	0	Essentially undeveloped	Basin planning	Initially GEF, then World Bank Group, DFID, UNDP, EU, USAid and more in subsequent planning studies	Semi-quantitative CIA including EFlows Assessment	Detailed holistic	Yes, fundamental input to basin planning	OKACOM, 2011a,b; King et al., 2014; King and Chonguiça, 2016; CRIDF, 2017; World Bank et al., in press

#*HPP, hydropower project; E&S, environmental and social. Documents are listed under individual basin headings in References.*

For two decades or more it has been obvious that detailed EFlows Assessments, with their in-depth insights into river functioning, should be automatically embedded into each of the above kind of impact assessments where dams are involved, but almost always they are not. As a result, the substantial changes that can occur to the river ecosystem and its dependent social structures with development are not elucidated. Although some progress has been made in including EFlows work in single-dam projects, basin-wide EFlows Assessments, within or outside the other impact assessments, remain rare. This is at a time when such over-arching perspectives of potential change are more urgently needed than ever before.

A better approach for a basin where multiple HPPs are planned is to synchronize an in-depth, basin-wide EFlows Assessment with a CA, SEA, or CIA as appropriate, at the earliest stages in the planning process (**Figure 2**). Together they support discussion and negotiation on the desired basin development pathway, the basin Development Space, and what to build and not build. With this completed and decisions made, potential developers would better understand their environmental and social commitments, with the benefits as listed above. Fine-tuning via an EIA could be done for individual projects as they came online.

EXAMPLES OF BASIN-WIDE APPROACHES

Basin development is proceeding at such a pace that countries may be planning strategically from a technical perspective, but are not necessarily planning for sustainability. Globally, there is a sequence–mildly chronological but also influenced by who is developing where, funded by whom–from basins where attention to the maintenance of healthy river systems is rudimentary or comes too late, to ones where careful planning precedes any decisions on large-scale development (**Table 1**).

The CIAs and EFlows Assessments that are done today are most often at the insistence of international lenders. Earlier ones tended to have no or poor guidance on the scope of the CIA and how to include river impacts in a structured way. Many of the assessments have no hope of influencing decisions, and in several cases most if not all dams were already existing or decided upon when they started. Of the examples in **Table 1**, only the Okavango assessments represent a genuine inclusion of EFlows in the earliest stage of basin planning (King et al., 2014).

The recent partial rectification of this through guidelines on CIAs (e.g., IFC, 2013) and EFlows (e.g., World Bank Group, 2018); the Early Stage Protocol of the International Hydropower Association's Hydropower Sustainability Assessment Protocol (IHA, 2018); and other initiatives (e.g., NCEA, 2015), may lead to increased integration of the discipline of EFlows in planning and impact assessment exercises.

CONCLUSION

In basins where widespread water-resource development is taking place, comprehensive basin-wide EFlows Assessments should be a fundamental part of SEAs, CIAs or equivalent (Anantha and Dandekar, 2012; Meynell, 2013; ASTAE, 2014). Together, they should be done at the earliest stage of basin planning, before sites are selected and allocated to developers, in order to provide information on the expected cumulative impacts on the river ecosystem and linked social structures. SEAs and CIAs usually do not provide these insights as the associated EFlows studies are often poor in detail and quality, and produce simple minimum flow recommendations. This situation cannot be well-analyzed because websites may indicate what minimum flow was allocated to the river without providing the documents that led to that decision or stating what the flow was meant to achieve. Minimum flows so recommended do not capture the complex impacts of dams on river ecosystems, and so do not support meaningful engagement with stakeholders on the likely future state of their river. Where a basin-wide EFlows Assessment is done, the method used matters as it dictates the scope and flexibility of a study. Rapid one-size-fits-all methods do not provide the detail that governments and other stakeholders need to negotiate and make informed decisions (ASTAE, 2014; World Bank Group, 2018).

A common impediment to changing the situation of ineffective EFlows studies done at the wrong time (if at all) is the developer's requirement to have been awarded a dam site before investing in relevant basin studies. Developing countries may not have the funds to complete pre-emptive basin-wide environmental and social studies themselves before offering dam sites to bidders, and tend to restrict their analyses mainly to power generation options and the cost of energy. There is growing realization that basin-wide studies in early planning have cascading economic, social and sustainability benefits, as listed above, but the means of doing them independently of the developers and timeously is in its infancy. There is an urgent need for a concerted effort from international funders, governments, EFlows professionals and the international bodies of impact assessors to turn the planning sequence around, and strengthen sustainability planning for countries that may lose more than they gain through careless development.

AUTHOR CONTRIBUTIONS

The authors listed made an equal direct and intellectual contribution to the work, and approved it for publication.

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Water Resources Users Associations in the Mara Basin, Kenya: Pitfalls and Opportunities for Community Based Natural Resources Management

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Water Resources Users Associations (WRUAs) in the Mara Basin, Kenya, are community-based natural resources management institutions set-up following the Integrated Water Resources Management framework. They are the most local participatory governance structure currently in place managing the tributaries of the Mara river. WRUAs are the link between environmental services from the river and livelihoods of local communities. Opportunities and pitfalls for the undertaking of their roles are assessed through the analysis of four WRUAs. Recognition of local knowledge, procedural considerations in the setting-up and carrying out of activities, as well as distributional aspects of the WRUA undertakings are evaluated in the paper. The authors argue that typical issues identified in critical community management literature appear in this case study: elite capture, dependency on donor support, lack of meaningful participation, and difficulties for scaling up initiatives. However, WRUAs have positively impacted environmental services in a localized and indirect manner, opening opportunities in terms of awareness, scaling water conservation initiatives, and conflict resolution. Future development of WRUAs can improve environmental flows particularly if a targeted follow-up is maintained by encouraging leadership and monitoring the relationship between donors, elites, and marginalized community members.

Keywords: water resources users associations, community based natural resources management, ecosystem services, Mara Basin Kenya, integrated water resources management, water institutions

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INTRODUCTION

The wide embrace and support for participatory, decentralized, and devolved approaches to natural resource management (Community Based Natural Resources Management) is due to the alternative it provides to traditional top-down centralized approaches; it aims to ensure equitable distribution of benefits emanating from natural resources, and the sustainable development of local communities (see Hulme and Murphree, 1999; Kapoor, 2001; Treisman, 2007; Kumasi et al., 2010). Furthermore, sustainable development objectives (stemming for example from the Agenda 21, and the Bruntland Report) underscore the importance of including stakeholder participation—in particular local people—in all stages of decision making and resource utilization from their local environment (Hutton et al., 2005; Mbaiwa, 2005). Governance under decentralized arrangements has been considered conducive to increasing the accountability of organizations at all levels (Crook and Manor, 1998), as well as providing more effective management of natural resources at local levels (Ribot, 2003). Decentralization and participation have often been promoted as means to optimize water efficiency and work toward full cost recovery, although it is still debated how full cost recovery and equitable distribution can both be met (Watson et al., 1999; Smet, 2003; Rap and Wester, 2013; Suhardiman and Giordano, 2014; Rusca et al., 2015). Indeed, a number of challenges such as incomplete transfer of authority to local organizations, lack of transparency and accountability, and usurpation of power by local elite have been reported as negatively affecting the equitable distribution of resources (Ribot, 2002; Shackleton et al., 2002; Hobley, 2005; Zulu, 2009). Local elites are defined as "a small group of well-connected and resourceful individuals who 'exert disproportionate influence over collective action' " (Beard and Phakphian, 2012, p. 150 in Wong, 2013, p. 380). Continued conflict over access and utilization further points to gaps or weaknesses in the set-up of community-based organizations. These discussions prompt an in-depth investigation to identify and comprehend operations of existing community-based organizations, as well as their impact on environmental flows and water users' livelihoods. Environmental flows are also called reserve flows in Kenya, Tanzania, and South Africa, where basic human needs are included, in addition to the needs of aquatic ecosystems. The concept of reserve flows offers a holistic view of aquatic ecosystem services and their allocation for various uses; this is done by recognizing their social aspects, such as providing food, water, medicines, building material, support for grazing, as well as resources for cultural and religious activities (King et al., 2000). This vision goes beyond the instrumental view of water as an economic good. In this paper the term "environmental flows" only is used.

CBNRM is born from neo-liberal agendas and decentralization: responsibility for the sustainability and cost-efficient use of the resource is transferred to users through the crafting of local institutions. New Institutional Economists such as Ostrom (1990) developed a large part of the current thinking on CBNRM, focusing on collective management of ecosystems, to improve human wellbeing whilst empowering locals to manage resources without damaging, depleting or degrading them (Fabricius et al., 2007). It is believed communities will invest in environmental conservation if they can utilize the resources on a sustainable basis for their own benefit, and if it can demonstrate that sustainable natural resource management brings positive economic returns. CBNRM is based on crafting appropriate institutions under which resources can be legitimately managed and exploited by resident communities, for their economic advancement—for instance poverty alleviation and food security—through rational choice. Based on the 8 design principles of Ostrom (1990), World Bank funded studies have established lessons based on projects' best practices to identify the ideal set-up within which CBNRM can take place. These are for example: benefits accruing from the management of a resource should exceed costs; the resource must have a measurable value to the community; those living with the resource should receive higher benefits, and be more involved in the decision making regarding the resource than the larger groups; good practices by communities should always be rewarded, and if the communities do not invest in good management then benefits should fall (Wanje et al., 2017). Participation of local communities in planning, management and decision making is considered an important element in the conservation of natural resources (Stoll-Kleemann and Welp, 2008), although it may take different forms depending on the level of community involvement in resource management, ranging from low to high (Agrawal, 2001). According to Rodríguez-Martínez (2007) and Schultz et al. (2011), involvement could either be through consultation, taking joint decisions, or self-managing natural resources; CBNRM ideally also aims for an integration of indigenous property rights, values, and ecological knowledge in the management of the resource (Kellert et al., 2000). An example for this type of integration is allowing some space to maneuver around the very structured format of management plans: pre-designed formats currently do not allow to ask open ended questions to gather information about new emerging issues, such as planning for the effects of climate change.

In line with the cost-recovery view of managing natural resources, the ecosystem services approach acknowledges that the exploitation of natural resources is a potential driver for economic growth. Overdependence and unregulated exploitation of resources have been a major threat to the continued existence of these resources, and their ability to continue providing environmental resources and services upon which rural communities depend (Reardon and Vosti, 1995; De Groot et al., 2002). Harnessing the benefits local communities obtain from natural resources (ecosystem services) has been proposed as a way to achieve sustainable development and address the cycles of chronic poverty so pervasive in Africa. Ecosystems services (ES) are essential parts of human livelihood and productivity supplies, in that human/environment interactions affect supply and demand of ES (Vrebos et al., 2015). Overuse, misuse, or mismanagement of ES thus occur whenever service demands exceed supply (Wangai et al., 2016). To counter this, CBNRM has been suggested as a panacea to environmental problems, although critical views have shed light on some of the reasons why participative natural resources management has not always been successful in providing ecosystem services in an equitable and cost-efficient way to local communities. The social justice literature discusses these issues by proposing a framework—developed in the following section—for improving equity in the context of developing local institutions for conservation.

Community Based Natural Resources Management for Water Resources in Kenya

Kenya has shifted to decentralized control over water resources, despite growing skepticism around the application of Integrated Water Resources Management (IWRM). It has done so by applying the IWRM framework and associated Dublin principles, including a participatory approach to water management (Molle, 2008; Allouche, 2016; Manzungu and Derman, 2016). The enactment of the Water Act of 2002, as well as the constitution in 2010 and the recent 2016 Water Act all acknowledge the importance for community participation in the management of resources, resulting in the formation of Water Resources Users Associations (WRUAs) within the six drainage areas of Kenya (Lake Victoria North Basin, Lake Victoria South Basin, Rift Valley Basin, Athi River Basin, Tana River Basin, Ewaso N'giro River Basin). The 2002 act recognizes the roles played by stakeholders in effective water resource management and gives provision for their inclusion in resource management through WRUAs defined as community groups "focused on the management and conservation of water resources of a particular area, river or aquifer" [(The Water Act, 2002): section 15 (3)(e)]. WRUAs key objectives are to promote controlled and legal water use activities; good management practices that make efficient and sustainable use of water resources; the safeguarding of environmental flows for downstream ecological demands and basic human needs; the reduction of water use conflicts; and catchment conservation measures to improve water quantity and quality. In the past 15 years, international donors—under the principles of IWRM—have focused on including community participation in the effort to conserve the Mara River Basin endowed with rich forest, wildlife and water resources. Kenya seeks to preserve environmental flows, meaning domestic use and environmental flows—understood as social goods—take priority over economic water use (e.g., for large scale irrigation).

This paper discusses the roles, pitfalls, and opportunities for WRUAs, as community-based natural resources management (CBNRM) institutions responsible for the safeguarding of environmental flows in the Mara River Basin. The roles and impacts WRUAs have, as community organizations managing water resources for environmental services, are analyzed by using the equity framework developed by Schreckenberg et al. (2016) (see also Franks et al., 2016) and introduced in the paper's framework. Following this, the Mara Basin's context and deriving ecosystem services on which the basin's population depends are discussed. The case study analysis section evaluates opportunities and pitfalls of four Mara basin WRUAs through the framework's lens. Shedding light on the opportunities and pitfalls emerging from the crafting of institutions will hopefully offer insights to water resources managers implementing CBNRM projects. Finally, the discussion brings together the different WRUA assessments, before concluding on the impacts WRUAs have had in regulating ecosystem services from the Mara basin rivers. The paper then suggests actionable recommendations for water resource managers pursing to overcome barriers to CBNRM.

KEY CONSIDERATIONS FOR UNDERSTANDING CBNRM: FRAMEWORK FOR ANALYSIS

Key characteristics of CBNRM organizations are now discussed using the equity framework suggested by Schreckenberg et al. (2016) (see also Franks et al., 2016) and drawing from theoretical perspectives and practical examples emerging from critical research. The equity framework discusses enabling processes which empower and allow equitable sharing of benefits, as growing evidence shows that these factors allow for more effective conservation (Oldekop et al., 2015). The framework identifies three interlinked dimensions which necessitate a set of enabling conditions: (a) recognition, (b) procedure, and (c) distribution.

Recognition

In theory, CBNRM aims to transfer power through participation and recognition of traditional knowledge and customary property rights of marginalized peoples (Gilmour and Fisher, 1991; Little, 1994; Lynch and Alcorn, 1994; Strum, 1994; Sarin, 1995). This means that the disproportionate influence of powerful actors on decision making processes must be counteracted (Schreckenberg et al., 2016). Indeed, in practice, some actors manage to increase their authority through CBNRM mechanisms for their own interests (as found by Kellert et al., 2000 in their study on CBNRM in Nepal, Kenya and the United States, and Jere et al., 2000 in a study of eight CBNRM projects in Malawi): participation was found to be unevenly spread across communities, partly due to corruption and weak leadership. Communities stepping out of pre-designed and approved management plans would undergo intervention by government officials, showing how local ecological knowledge outside modern scientific understanding may be dismissed by powerful actors. In this case, the incorporation of local and modern knowledge appears difficult, as modern scientific understandings are not made more accessible to local people (Kellert et al., 2000). Furthermore, the outcomes of CBNRM are evaluated based on external—as opposed to local—scientifically constructed criteria, revealing a paradox of CBNRM: its aim is to integrate knowledge embedded in specific environmental and social spaces, but evaluated through seemingly objective formalized scientific criteria (Blaikie, 2006). Negotiating a hybrid understanding of knowledge is subject to relationships of power between the outsiders and insiders to the CBNRM projects (Batterbury et al., 1997).

Procedure

Procedural equity consists in insuring that participation is inclusive of all actors, and effective. The values of communities should be respected, and traditional decision making institutions must be strengthened (Schreckenberg et al., 2016). Under CBNRM, conflict resolution takes place through mechanisms starting from local to national authorities (Kellert et al., 2000).

Due to centralized government's minimal human and financial capacity for monitoring open access resources, CBNRM is believed to offer an alternative, by handing over the policing role to local residents—who are additionally aware of *de jure* and *de facto* tenurial arrangements for the access of shared resources (Blaikie, 2006). However, Kellert et al. (2000) found that although CBNRM allowed for new platforms to discuss and resolve conflicts, conflicts increased overall because of the higher expectations new management mechanisms created. In addition, the creation of new pre-designed organizations also created institutional overlap, as well as opportunities for rent-seeking from local elites (Blaikie, 2006).

Distribution

In order to encourage conservation practices, CBNRM also aims to improve social and economic standards of local and rural peoples (Wells and Brandon, 1992), particularly through a more equal distribution and allocation of resources (Kellert et al., 2000). However, it also often comprises costs associated with conservation, for example the exclusion of livelihood activities from certain areas (which sometimes entails the distribution of compensation). Debates persist on whether compensation should be divided equally or whether those most affected should receive targeted compensation (Schreckenberg et al., 2016). In their study on CBNRM in Nepal, Kenya, and the United States, Kellert et al. (2000) found that the distribution of material and political benefits from resources, as well as the devolution of decision making powers, benefited more certain groups of people (e.g., those living closer to the center of CBNRM headquarters, or board members). Shackleton et al. (2002) conclude from 13 case studies across Africa that although the overall benefits of CBNRM vary widely, the negative trade-offs generally fall onto the poor. In another study of eight African countries, Shackleton and Campbell (2001) argue that when the state limits its involvement in the shaping of CBNRM, communities are better able to shape the social-environmental relationship to their advantage.

Since CBNRM aims to conciliate conservation goals through economic and social incentives (Kellert et al., 2000), it tackles both rural poverty and biological diversity (Parker, 1997; Butler, 1998; Mehta and Kellert, 1998; Wainwright and Wehrmeyer, 1998). In the context of water resources, this entails providing better ecosystem services for the poor, including improved water in terms of quantity and quality, with minimal trade-offs. CBNRM suggests the setting-up of local institutions, acting as regulators and platforms to negotiate the practicalities of harnessing conservation, and economic and social welfare.

Studies have however shown how some of the newly established institutions for CBNRM in developing countries switched their focus toward community development activities to pursue social and economic advancement, rather than focusing on the protection of biodiversity (Kellert et al., 2000). In other cases however, expatriate workers involved in the implementation of CBNRM have admitted that the programme aims are conservation and that the community developmental aspect is worked on in order to achieve the aim of conservation (Taylor, 2001). In this case, the pro-poor component of CBNRM is arguably retro-fitted in order to legitimize certain funding streams (Blaikie, 2006). It is thus questionable whether conservation goals can truly be coupled with economic and social development, or whether the CBNRM form through which these two goals are advocated is ill designed. In the particular case of Kenya, the lack of environmental and socio-economic data meant that the idea of a sustainable equilibrium point between conservation and usage was impossible to determine, and therefore implement (Kellert et al., 2000).

Enabling Conditions

The equity framework—based on recognition, procedure and distribution—rests on the idea that there are enabling conditions which are beyond the control of stakeholders, which may allow for greater equity within CBNRM initiatives. These are the presence of adaptive learning approaches, aligned statutory, and customary laws and norms, and finally awareness and capacity from the actors to achieve recognition and participate effectively (Schreckenberg et al., 2016, p. 15). The participatory aspect of CBNRM heavily rests upon the concept of community, the term itself holding a certain number of assumptions: it can be understood as a spatial unit, a social structure or a set of norms which are shared with a group of people (Agrawal and Gibson, 2001). The overlap of these criteria with the nature and scale of the resource being managed does not always correspond (Blaikie, 2006). Moreover, participatory approaches to natural resources management assume that the community is somehow a homogeneous unit, forgetting the complex web of social arrangements and decision making. Equally, there is a certain optimism about the benefits of participation, forgetting that it also has a cost (Cleaver, 1999). Overall, participatory approaches to development encounter great success because they are believed to bring monetary efficiency and effectiveness, at the same time as bringing empowerment and democratization (Cleaver, 1999). However, empowerment as an outcome is difficult to measure, although it entails the influence of participants over project frameworks (Eyburn and Ladbury, 1995; Cleaver and Kaare, 1998; Cleaver, 1999), including the recognition of other forms of science. Lastly, critical views question who is to be empowered: if communities are the most appropriate unit for governing natural resources, then how is external intervention justified? (Cleaver, 1999; Blaikie, 2006).

METHODOLOGICAL CONCERNS: LINKING INSTITUTIONAL AND ECOSYSTEM SERVICES OUTCOMES

The Mara basin case study provides grounds to discuss recognition, procedure, distribution, and enabling conditions for the Water Resources Users Association to govern the environmental flows of the tributaries of the Mara basin. Environmental flows are a direct and measurable outcome of the effectiveness of the setting-up of new governance systems, such as the inclusion of CBNRM initiatives. The Mara river is a case in point as it provides for numerous livelihood activities which depend upon its ecosystem services (themselves dependent on sustained environmental flows), as well as renowned national parks. The IWRM framework from which WRUAs stem, as well as the environmental justice literature concerned with social equity recognizes the need to combine ecosystem health with equitable sharing of water resources (Savenije and Van der Zaag, 2008). The Brisbane Declaration (2007) defines environmental flows as "the quantity, timing, and quality of water required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems." In this sense, there is a strong link between access to healthy resources, and a healthy life through sustainable livelihoods supported by water resources. Ecosystem services are thus the connection between the socio-economic system and the ecological system (Boerema et al., 2016). The idea of durably securing environmental flows has emerged as a key concept, with the role of maintaining healthy river basins amidst competing water demands (Tharme, 2003). Environmental flows and the ecosystem services derived from them are thus key indicators of the effectiveness of WRUAs. To date, the government of Kenya is looking into making a final determination to establish what the value of environmental flows should be (in this case valuing a minimum flow to cover basic human needs and environmental needs). At the moment, the environmental flows must be a value not <Q95 (Q95 represents a magnitude of flow that is exceeded 95% of the time in the river, meaning that depending on the flow variability of the river, the percentage of the flow for Q95 can cover a range of values).

This paper presents research conducted over 8 years—between 2009 and 2017—with local WRUAs in the Mara basin, responsible for preserving ecosystem services stemming from environmental flows. The study covers qualitative data from the set-up to the follow-up of WRUAs' daily activities within the basin. Qualitative research has been conducted through participative observation, interviews, surveys and monitoring tools to investigate the impact of WRUAs over environmental flows and livelihoods of local people engaged and disengaged from WRUAs activities. Four WRUAs have been selected based on time of existence and location (upper and lower tributaries of the Mara have been chosen). Amala and Isei WRUAs have been in existence for over 5 years (stemming from Mara WRUA which started in 2003), whereas Naikarra and Leshuta WRUAs were constituted <5 years ago. Amala and Isei WRUAs are located on the upper tributaries of the Mara River Basin, as opposed to Naikarra and Leshuta WRUAs, which cover downstream tributaries of the Mara. These WRUAs furthermore make interesting case studies for the application of current policy, as Amala and Isei WRUAs, and Leshuta and Naikarra WRUAs used to be united prior to the regulation stipulating a maximum coverage of 150–200km^2 per WRUA. All qualitative data was transcribed and coded inductively and deductively, sorting key information through the equity framework developed in the previous section. The data was classified according to the three identified interlinked dimensions of recognition, procedure and distribution, alongside a set of enabling conditions. Key indicators and factors for opportunities and challenges stemming from these dimensions are discussed in the following sections, in link with the role of WRUAs for ecosystem services preservation.

POLICY AND IMPLEMENTATION ASSESSMENT: CASE STUDY OF WRUAS IN THE MARA RIVER BASIN

The Mara basin (see **Figure 1**) covers an area of 13,750 km^2, taking its source in Kenya in the Mau Escarpment, traveling through the Maasai Mara and Serengeti national parks and finding its outlet in Lake Victoria, Tanzania (Mango et al., 2010). Six sub catchments form part of the Mara basin on the Kenyan side: these are Nyangores, Amala, upper Mara, Engare Ngobit, Talek, and Sand. The Amala and Nyangores rivers are perennial, whilst the Talek, Sand and Engare Ngobit only contribute seasonally (Mati et al., 2008). Rainfall occurs between 1,000 and 1,750 mm per year in the source area at an altitude of around 2,932 m. The amount of rainfall decreases to 300–1,000 mm per year at the middle and outlet areas situated at an altitude of around 1,134 m (Dessu and Melesse, 2012). Small scale crop farming is the dominant land use within this zone, whereas lower parts of the basin with an annual rainfall of 500–700 mm supports activities such as irrigated agriculture, livestock rearing and wildlife conservation.

In recent years, the Mara basin has experienced land use changes, with increases in population (the 2009 census estimated the Kenyan population within the Mara at around 590,000; Kenya National Bureau of Statistics, 2010), increased forest and savannah grassland clearance for grazing, expansion of large scale irrigation, tourism, and mining (Hoffman et al., 2011). These changes have given rise to peak flows, and reduced low flows (Mati et al., 2008). Kenya's water law (Republic of Kenya, 2007) recognizes the need to secure environmental flows, prioritizing environmental flows, and access to domestic water over any other abstraction for economic purposes. Environmental flows are sustained as long as the reduction in quantity of quality of the flow is not jeopardizing freshwater ecosystems dependent on them. The organisms governing water quantity and quality influencers therefore deserve close scrutiny. Under Kenyan Law (Republic of Kenya, 2007) management and use of water resources are regulated by the Water Resources Authority (WRA), and WRUAs are involved as grassroot managers. The following responsibilities are the main roles of WRA:

- Planning, management, protection, and conservation of water resources
- Allocation, apportionment, assessment, and monitoring of water resources
- Issuance of water permits
- Water rights and enforcement of permit conditions
- Regulation of conservation and abstraction structures
- Catchment and water quality management
- Regulation and control of water use
- Coordination of the IWRM Plan;

whereas WRUAs hold the following roles:

- Involvement in decision making process to identify and register water user
- Collaboration in water allocation and catchment management
- Assisting in water monitoring and information gathering
- Conflict resolution and co-operative management of water resources

IWRM plans are developed at the sub catchment level through sub catchment management plans. The operations and activities of WRUAs are in line with the IWRM and sub catchment management plans. The catchment management plans have been developed to date, and constituted WRUAs have their individual sub catchment management plans; these are prepared during the

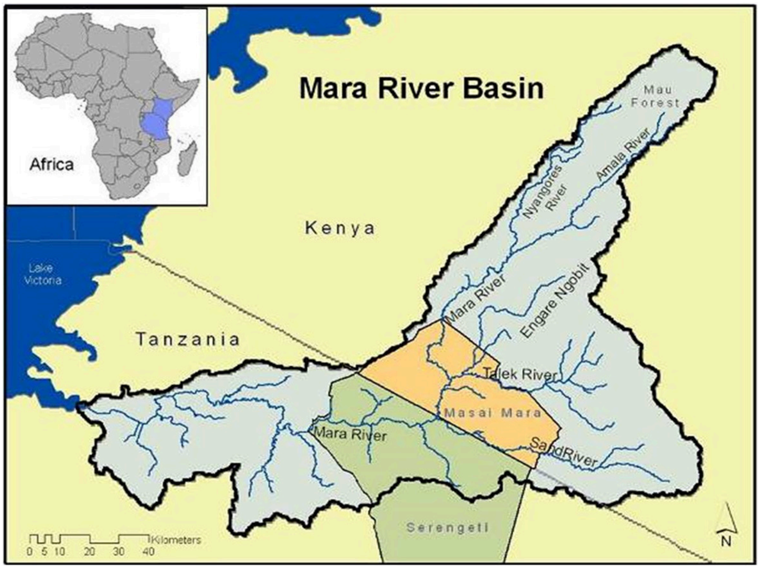

FIGURE 1 | Map of the Mara River Basin (Reza, 2013).

formation phase of the WRUAs. The Water Act (2002) (section 15) and Water Act 2016 anchor these plans at various levels. Concerning the monitoring of environmental flows, it is key to note that this task is not yet in the hands of WRUAs.

There is a significant difference in river usage between the upper stream tributaries (Amala, Nyangores, and upper Mara) and the downstream tributaries (Ngare Ngobit, Sand, and Talek), meaning that a wide range of ecosystem services are being used along the entirety of the river. This also means that WRUAs focus on different aspects of ecosystem management and provision. Services which cover all areas are the following: water abstracted for basic human needs (drinking, cooking, and sanitation); ecosystem services deriving directly and indirectly from environmental flows: fish, wild fruit, medicinal plants, as well as organic and inorganic material (for firewood, building); water for productive livelihoods, such as livestock watering and irrigated cultivation (this categorization follows the reserve quality standards in reference to the environmental flows assessment as stipulated by Kenyan Water laws; Republic of Kenya, 2007) (Wambugu, 2017). Overall, the main economic activity is small scale agriculture, followed by livestock keeping, as well as tourism in the national parks (Hoffman, 2007). The lower reach catchments are mostly populated by Maasai who are nomadic pastoralists, whereas the upper catchments are mostly populated by Kalenjin who practice small-scale agriculture. Water-related activities can be divided between those which are included in the water permitting system and those which constitute the environmental flows (water usage for basic needs without infrastructure such as cattle troughs or improved irrigation intakes, and water for ecological use). Wambugu (2017) shows that a large majority of households depend on the Mara tributaries for fulfilling basic human needs. The lower sub catchments—in particular Talek—are highly dependent on the river for their livestock subsistence (with little other livelihood activity as the rainfall is too low for agriculture), whereas the upper catchments depend on the river for cultivation during planting and dry seasons, as well as fishing activities. Given the high dependence of all dwellers of the Mara basin on the rivers, managing and distributing resources between upstream and downstream communities is of high importance.

The IWRM framework advocates the management of water resources from the lowest to the highest levels of governance, with the lowest organizational level being WRUAs. For a WRUA to be formally recognized it must be registered as an Association with the Attorney General under the Societies Act as well as enter into a Memorandum of Association with the WRA. Between 2003 and 2008 there was only one WRUA (Mara WRUA) covering the entire basin. The size of the WRUA was however unable to cope with the following challenges: firstly, the vastness of the basin presented logistical challenges to bring together members; secondly, diverse ecological characterization of the basin created problems, as the upper and mid catchment experienced totally different issues from pastoralists in the lower catchments. Hence the platform under Mara WRUA did not address these challenges effectively. In 2009, with the support of different development partners [including World Wildlife Fund (WWF)] and in collaboration with the WRA, the WRUAs were reorganized along the major tributaries of Nyangores, Amala, Lower Mara, Talek, and Sand river (see the six sub catchments illustrated in **Figure 1** on the Kenyan side of the basin). In 2010, an amendment of the Water Act of 2007 provided a clear direction on the coverage area of a sub catchment, resulting into the disintegration of the 6 existing WRUAs into 25 smaller units to conform to the water regulation (see **Figure 2** representing the 25 planned WRUAs, excluding the Mara WRUA which currently only serves as a platform). There are 25 planned WRUAs in total,

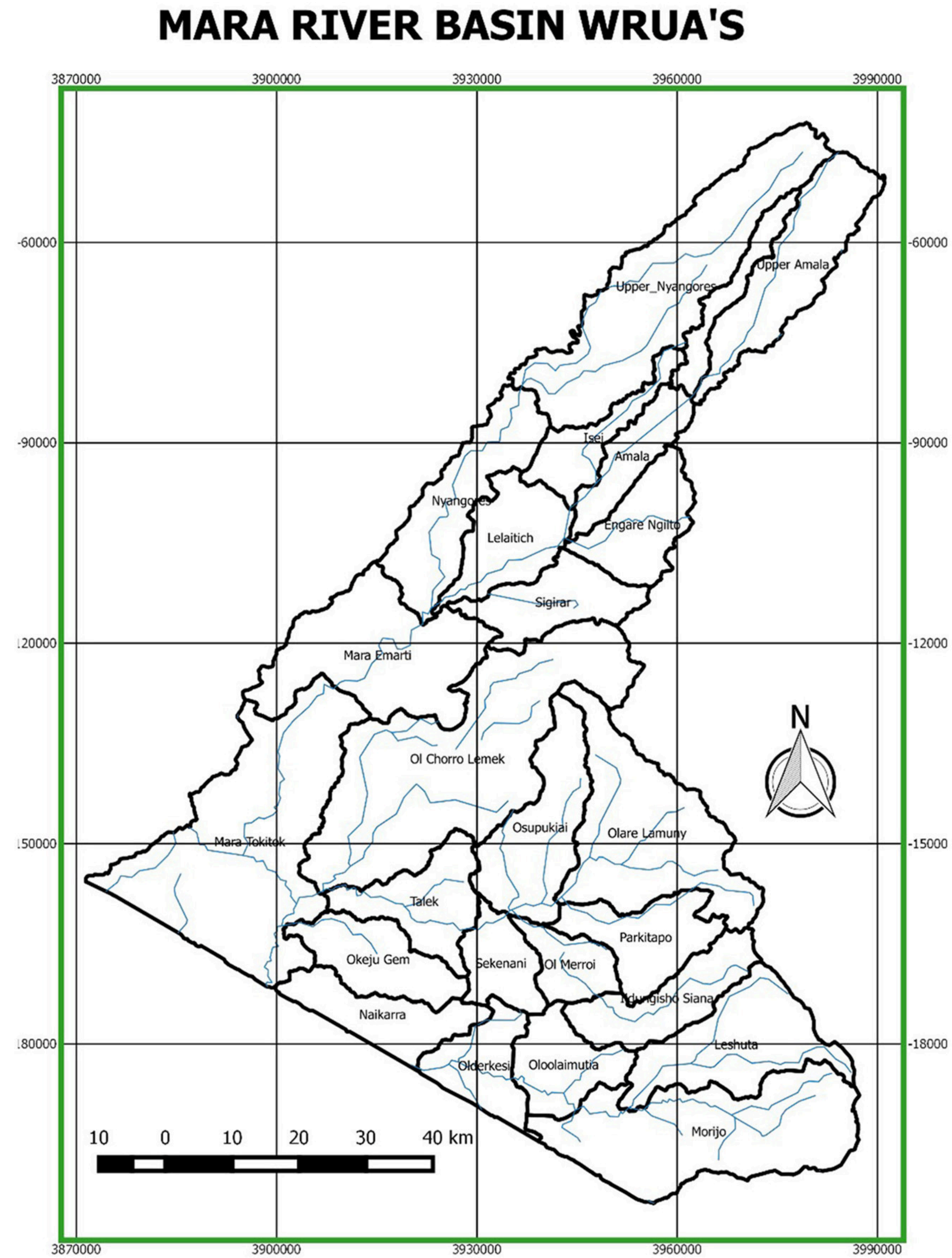

FIGURE 2 | Mara River Basin WRUAs (GIZ, 2018).

with only 19 fully constituted; the WRUAs are spread across the basin, each one of them covering between 200 and 250 km^2 as per the 2007 Water Act (see **Figure 2**).

The WRUAs sub catchment management plans (SCMPs) outline the conservation and catchment restoration duties of the WRUAs as such:

i. Controlling abstractions by monitoring and identifying legal and illegal abstractors
ii. Pollution control through monitoring the dumping of waste into rivers and streams
iii. Improving farming and land management practices to reduce soil erosion and to improve agricultural productivity
iv. Protecting riparian zones to reduce sedimentation in the river
v. Improving access to clean water by protecting springs.

The making and final production of SCMPs vary slightly from WRUA to WRUA, however professionals from the WRA and funding NGOs follow a standardized procedure and template, resulting in similar SCMPs across all of the basin.

Four categories of WRUA membership exist:

1. Riparian land owners (either individual or community group)
2. Abstractors who directly draw water from water points such as rivers or springs (e.g., schools, hospitals, and churches)
3. Commercial and industrial businesses
4. Ex-officio members such as relevant government departments and non-governmental organizations operating within the sub catchments.

One becomes a *bonafide* member upon payment of a membership fee and an annual subscription, which varies across the different categories (from KSH 100 to KSH 2,000).

This paper chooses to present the assessment of four WRUAs, representing up, mid and downstream cases, covering a variety of ecological and livelihood contexts within the Mara basin. The aim is to discuss the WRUAs within the equity framework to evaluate the impact the creation and rolling out of WRUA activities may have had on ecosystem services provided by the river, as well as livelihoods. WRUAs are first introduced, and **Table 1** assesses them in light of the equity framework.

Amala WRUA

The Mara River basin initially only had one WRUA (Mara WRUA—now unofficially an overarching organization for WRUAs), which was subsequently officially divided into smaller units to cope with the scale of the basin and the efficiency of the tasks undertaken by the WRUA. Amala was therefore born out of the Mara WRUA in 2009, with the prerogative of operating within the Amala sub catchment. Members within a self-help group started the WRUA and in 2012 it evolved to attain status of an association through registration under the Societies Act, with the support of WWF. Today, Amala WRUA also counts village chiefs within its WRUA members. Amala WRUA holds its office with the overarching Mara WRUA, and together they sustain a tree nursery and keep records of basic river measurements. Amala WRUA's activity is mostly to protect riparian zones by replacing farming with productive trees such as mango, avocado and banana trees. Donor-led activities have also been implemented in line with its SCMP, for example through bee keeping training, and the donation of dairy cows and sheep to provide for alternative livelihoods in order to move away from unsustainable agricultural practices affecting environmental flows.

Leshuta WRUA

Leshuta WRUA covers the lower parts of the Mara River Basin, having evolved from the larger Naikaraa WRUA (which covers the Sand River) after the enactment of water regulations slicing coverage areas of WRUAs. Leshuta WRUA was registered in 2012 after experiencing water scarcity due to its location in a semi-arid region. A community meeting was convened with the help of members who had already subscribed to the larger Sand River WRUA and came from the Leshuta zone. The purpose was sensitizing the community about water resource problems and different ways of managing and conserving under the stewardship of a WRUA. Both outside and local knowledge were considered to shape the WRUA's objectives and priority areas of action. As with other WRUAs, members first register as a self-help group [or community-based organization (CBO)], where a minimum of 30 members is required. Initiatives have shaped in theory but not effectively in practice for the following: protection of water spring to reduce chances of pollution and improve accessibility by locals; identification of suitable sites for locating water tanks for harvesting and storage of water; identification of water pans that have been constructed and rehabilitated; rehabilitation of degraded sites through tree planting and establishment of tree nurseries; monitoring and reporting incidences of illegal tree felling (cedar) to relevant authorities; supporting local member learning centers through equipping them.

Isei WRUA

Isei WRUA is unique within the Mara River Basin, as it broke off from the main Amala WRUA before introduction of water rules specifying WRUA coverage area. Isei displays particularly good initiative as it has strong leadership from a retired hotelier who is aware and passionate about environmental conservation. The establishment of Isei WRUA started as a table banking system between 15 members who had agreed upon some principles such as land planning in farms, terracing, tree planting, and conservation of spring areas as they are the main source of water. In addition to these practices, the WRUA agreed that every member should grow 500 self-funded tea tree seedlings to add a livelihood component to the WRUA. There is a strong livelihood component to this WRUA: it has managed to link environmental protection with income generation.

Naikarra Sand River WRUA

The donor (WWF) was behind the constitution of Naikarra WRUA, situated on the Sand river, in the lower reaches of the Mara river in Kenya. Local communities were sensitized about the roles of a WRUA with regard to water resources conservation. Interim officials were elected at the awareness meeting, and they themselves further steered the recruitment of members from different parts of the catchment. Initiatives for environmental

TABLE 1 | Equity analysis of 4 Mara WRUAs.

	Amala WRUA	Leshuta WRUA	Isei WRUA	Naikarra WRUA
Recognition	Initiatives from Amala WRUA have not been bottom-up as they stem from SCMP templates. In Amala's case, activities rolled out are those chosen by donors rather than prioritized by the WRUA. For example, donor offering 50 high value trees when demand from members is higher.	Leshuta WRUA has used the knowledge of local communities to identify water points to be rehabilitated. Leshuta WRUA was involved in identifying schools short of learning equipment, as per the priorities identified by local communities during the Participatory Rural Appraisal of the SCMP, although donations of equipment have no direct impact on water conservation.	Isei WRUA came to exist under its current chairman who had been aware of environmental issues through close involvement with WWF during its setting up phase in the Mara River Basin. The 15 initial WRUA members agreed to each engage 15 more community members into agroforestry practices (such as tree planting, terracing, and farm planning). Although initiatives picked up very well, these activities all follow the SCMP which can be described as an adjustable template. The WRUA was weak in driving this process and focused on pleasing the donors.	The constitution of Naikarra WRUA was donor driven and spread through sensitization on water and environmental sustainability. Interim officials were elected at the awareness meeting, and they themselves further steered the recruitment of members from different parts of the catchment. The WRUA drove its own activities through its own labor and resources for the building of gabions and fencing off areas to protect springs.
Procedure	Amala WRUA is a bridge between the wider community and water related agencies. In this case chiefs are WRUA members, so conflict resolution is effective as communities accept their mediating role. The WRUA leadership has had to involve higher instances (such as the county government or WRA) to solve issues around polluted water discharge in the river, illegal water abstraction, and riparian protection.	Conflict resolution is mainly handled by the WRUA members as it is presumed that members are knowledgeable on these matters. Previously, matters related to water resources were handled by local administration constituted of chiefs and village elders.	Isei WRUA established by-laws to enable the cessation and control of certain activities such as bathing in the river and farming along riverbanks. Members of the WRUA are selected to monitor these regulations, including within the areas overseen by chiefs. The WRUA is responsible for the implementation of water related issues, however chiefs come in as local administrators and in most cases are also members of the WRUA and offer reinforcement.	Area chiefs are members of the WRUA and play a significant role in resolving conflicts. There have been meetings to sensitize the community against engaging in malpractices such as bathing and washing in the rivers as well as spraying livestock next to water points. The appointed land demarcation committee (who are all WRUA members), have played a critical role in guiding locals on riparian zones and spring protection, working closely with government officials.
Distribution	There have been indirect benefits from dairy cows and sheep, as well as high value fruit trees donated to sub groups within the WRUA, starting from the chairman and most active members. Bee keeping training was also provided. The aim is generating income for the WRUA as well as encouraging environmentally friendly livelihood practices.	Leshuta has to date not impacted the livelihoods of WRUA and non WRUA members. Implementation of identified activities is highly dependent on other stakeholders such as government entities, NGOs, and corporate entities. Most agencies operate in areas where they have some interest and pick the WRUA as an entry point. The only direct livelihood initiative within Leshuta WRUA is a table banking system of motor cycle owners to generate regular revenues. Collectively, the motor cycle owners group own 40 herds of goat, from which the proceeds are distributed amongst members when they are sold. Leshuta WRUA seeks to improve the interactions the community has with water resources to reduce cases of degradation.	There are arguments within the WRUA about unequal benefit sharing (e.g., from livelihood component improving the marketing of farm produce). However, Isei WRUA has overall been able to achieve conservation objectives through improvements in land management practices by terracing farms, protecting springs, planting trees in schools and on farms to increase catchment tree cover. Dairy cows and goats were donated to farmers to contribute to income generation and sustainable livelihoods. Beekeeping has increased among members to maintain trees. The secretary of Isei WRUA himself affirmed that his involvement in the WRUA has moved him out of poverty by the increase in milk production, avocado and honey sales. He no longer experiences water shortages from the neighboring spring which was degrading from deforestation.	Benefits from Naikarra WRUA are environmental rather than livelihood oriented: gabions have been built across gullies to control soil erosion, and springs have been protected at the cost of the WRUA. A donor contributed to piping and distributing water to different water points in order to separate livestock from human water use. The WRUA helped organize water abstraction within the community to reduce conflicts. It does not appear that some people have benefited more than others, rather redistribution has reduced the intense pressure and conflicts there had been in accessing water.

(Continued)

TABLE 1 | Continued

	Amala WRUA	Leshuta WRUA	Isei WRUA	Naikarra WRUA
E-flows	Water quality (in terms of erosion reduction) has been addressed over time, in sections of the sub catchment where soil and water conservation interventions have been established. This is linked to livestock husbandry, where more fodder is planted by farmers along contours and river banks, and therefore acting as a soil control measure. This is however confined to the number of farmers who have taken the initiative seriously, thus the results are localized to the area. There is a very close linkage between improved milk production, soil erosion control by established grassed contours, and associated fodder crops.	Notable impacts in terms of water quality and quantity have been observed to date, although most interventions have not been directly measured. Instead, many water users are getting on board and getting sensitized about e-flows. This WRUA has also created a strong platform for water related conflict resolution, directly linked to water quantity. The environmental impacts resulting from interventions are usually long term, though the short-term effect is the realization of existing problems within the catchment, resulting from the scramble for scarce water resources. Attention is called upon causal factors and feasible solutions.	Increased water yields from protected springs and the cutting down of eucalyptus trees (which had chocked the catchment). These initiatives contributed to increased flows both for human use and e-flows. Additionally, reduced erosion and subsequently low silt load in one of the streams in Isei sub catchment has been observed following contour farming and the protection of riparian zones in that particular section of the catchment. However, there is a need to for ground data collection and analysis for quantification. Impacts are on localized scales.	Increase access of clean water by locals resulting from improvement and protection of a degraded spring. Construction of gabions across the gullies, and erosion checks have reduced the amount of silt in the receiving stream.

protection have been undertaken with the WRUA members' own resources, although livelihood components to sustain the work efforts are lacking.

The following **Table 1** provides the equity analysis of the four Mara WRUAs presented above. Recognitional, procedural, and distributional criteria are evaluated for each WRUA in detail. The discussion then consolidates learnings from the case studies to evaluate these CBRNM organizations and assess the pitfalls and opportunities for their impact on environmental flows.

DISCUSSION: OVERALL IMPACT OF WRUAS ON REGULATING ECOSYSTEM SERVICES

Regarding recognition, conservation objectives are set by the national government and partnering donor agencies. However, local ecological knowledge is also used, for instance to identify which trees to plant along riparian zones for water preservation, according to localized environmental specificities. Unless the leadership of the WRUA is very active in terms of networking and implementation of activities, the WRUA is often dependent on donors for undertaking activities: this implies that donor objectives come before community objectives. This may occur even when the donor is selecting which activity to fund from the SCMP. In some cases, members of the WRUAs have been part of previous independent CBOs with links to water; nonetheless, WRUAs can barely be qualified as developed from grassroots. Roles in terms of improving water quality of the river for domestic distribution through small towns remain similar between original CBOs and WRUAs, however the structure in which WRUAs are set-up and the constitutions which they hold, as well as the SCMPs they develop, all follow procedures set at the national level by the ministry of water, and implemented through regional WRAs. Templates guide the general role as well as specific activities and tasks. Furthermore, it is questionable how WRUAs may be CBOS whilst being accountable upwards to the WRA at the same time as downwards to the community. WRUAs respect local riverbank ownership rights, whilst sensitizing farmers to better land management practices, to avoid negatively affecting water resources. This sensitization does not go against ancestral local practices: in fact, restoration practices advocated by WRUAs were practiced by past generations and have been abandoned by current generations, trying to reduce costs of production through unsustainable management practices. Sustainability and motivation to undertake activities will only be possible if communities can decide on priorities, rather than follow pre-designed templates. Awareness on linkages between livelihoods and impacts on water resources is however needed.

Procedurally, WRUAs play a significant role in solving conflicts. In the case of river pollution, the WRUAs have reduced bathing and washing in rivers, as well as spraying livestock next to water bodies. They are also increasing the accountability of water users by enforcing rules which have been ignored by newer generations, such as farming along riparian zones (which are protected), and abstracting water illegally. Better management practices are not reported to impact livelihoods negatively, as there are alternative measures farmers are able to explore, since riparian farming is forbidden. If illegal abstractors assess abstraction of water for irrigation purposes as their source of livelihood, they can apply for permits for abstracting water for irrigation, and these permits give directions to ensure sustainability measures. WRUAs have improved access to solving water related conflicts, as they are a visible channel for communities where the WRA is less visible. WRUAs are present on the ground on a daily basis, and are therefore available at all times for water related issues. In the case of raw sewage dumping by tourist facilities, the National Environmental Management Agency and the WRA were unaware and unable to act quickly on the issue due to their physical distance; whereas the local WRUA witnessed and started a procedure in due time. WRUAs are the WRA's eyes on the ground: they are able to whistle blow illegal water abstraction and cattle dipping (application of acaride). Transparency in the conflict resolution process depends on the WRUA and cases, however it is very clear that they are perceived as a bridge between local communities and higher authorities: their presence at grassroot level is known, especially for those with active leaders. The inclusion of traditional authorities such as chiefs is key for buy-in, although it may signify elite capture. To avoid this, awareness and inclusiveness must be well spread across the community.

In terms of distribution of benefits, elite capture is very much discernible in most WRUAs, whereby a few specific members have been benefitting from the training and materials donated (often the most active members of the WRUA). This is emphasized when the leadership of the WRUA is nominated, and decides who can benefit from training and resources from donors (for example in the case of Naikarra and Amala WRUAs). The upstream WRUA of Amala has undertaken activities which could produce a real increase in revenue for those who have been part of activities (such as high value tree planting for soil conservation). It is therefore key to understand who has or has not been able to benefit from this initiative. Downstream WRUAs dependant on lower tributaries (Talek and Sand rivers) such as Leshuta and Naikarra are less engaged in crop farming but their livelihoods are highly dependent on water access for livestock. To date it is however difficult to assess the impacts of the downstream WRUAs on livelihoods. Elite capture may be a necessary process to have community buy-in and support from authoritative figures, however special attention and close follow-up must be ensured to avoid further marginalization of less powerful members. Water related activities could potentially provide a new opportunity to marginalized people to gain authoritative leverage within the community.

In order to enable equitable distribution of the benefits of community-based water resources management, awareness of environmental issues linked to water processes must be widely spread. Without this realization, community mobilization, and motivation are extremely difficult. Low awareness generates disbelief in the potential benefits to gain from conserving water resources, and environmentally harming livelihoods activities are continued, albeit being illegal. Despite the low registration and annual subscription fees (starting from KSH 100), community members fail to participate due to the lack of visible results from being part of the WRUA. In Amala WRUA for example, only 100 out of 600 members decided to renew their subscription to the WRUA: slow returns coming from initiatives implemented under the WRUA are the main cause. Overall, linkages between up and down stream WRUAs are weak, thereby diminishing opportunities for WRUAs to have a real impact on improving environmental flows and ecosystem services. Up and down stream WRUAs over the entire basin are covered by the unofficial Mara umbrella WRUA (which acts as a platform for WRUA communication with the Mara basin as a whole, and will soon be transferred to the status of Mara forum for official recognition); however, planned quarterly meetings and annual general meetings rarely occur due to lack of funds. A major pitfall for Mara basin WRUAs are the lack of up/down stream relations at a tributary scale, within sub-catchments.

Since the methodology and results for valuating environmental flows has not yet been determined in the basin, a measured evaluation of the impact of WRUAs on environmental flows is extremely difficult to undertake. This requires more in-depth studies and is an area for further research.

CONCLUSIONS AND RECOMMENDATIONS

The impact WRUAs have over environmental flows and livelihoods of local communities within the Mara basin must be thought about in indirect and localized terms, as opposed to generalized to the catchment. The hydrological and land use data available is too coarse to establish a link between localized WRUA conservation interventions, and direct impact on environmental flows, downstream livelihoods and national parks. This is why the term environmental flows is used here to evaluate the effects of WRUAs on ecosystem services that stem from the provision of environmental flows. The WRUA SCMPs clearly show the links between environmental flows and livelihoods, as conservation activities impact both. WRUAs therefore have a role in balancing initiatives which may positively impact the ecosystem, but negatively impact livelihoods in the short term, and vice versa. They can also identify and potentially balance benefiters and losers of environmental initiatives.

WRUAs have had the effect of improving the conservation of water resources at localized scales by encouraging environmentally sustainable livelihood practices. Springs have been protected, assuring continuous flow of water and prevention of incidences such as the drying up of both springs and streams. However, silt load reduction in rivers adjacent to farms which have on farm soil conservation structures encouraged by WRUAs arguably does not significantly change the scenario on a catchment scale, with only few farmers taking up these practices. Although some large-scale irrigators are involved in improving the sustainability of the river basin (one in particular who initiated the Mara WRUA very early on), many other large-scale water users are not involved in WRUAs. The process of requesting and building water resources management plans is generally not bottom-up, but donor led. Thus, the types of impacts WRUAs have depend on whether the donor is environmentally or socially embedded, as WRUAs have become entry points for donors to channel their programmes. WRUAs therefore tend to be cross-sectorial: more so when they were set-up starting from pre-existing CBOs already undergoing a range of activities. The intensity of involvement in the WRUAs is rewarded by access to resources; however, this may mean that poorer households unable to offer labor or time do not have access to rewards, leading to weak implementation of the SCMPs. The inclusion of traditional conflict resolution mechanisms generates effective outcomes, as communities refer to their known leaders—higher authorities are only referred to when this process fails. Although it allows for elite capture, the legitimacy required by leaders to convince action from community members may only be available from pre-existing structures. Assessing the impacts of WRUAs in the Mara basin reflects the difficulties in measuring environmental impacts of CBNRM institutions. The web of linkages between environmental services and livelihoods is complex, when set in different scales, landscapes, and stages of institutional development. The question of distribution is key to evaluating desired outcomes: it is crucial to justify who the difficultly measurable outcomes are for, and through which processes they will be implemented.

The following recommendations result from these conclusions:

- *Integration of local knowledge and priorities.* SCMPs are not shaped entirely bottom-up; participatory methods to engage with environmental flows need to allow sufficient space for finding localized and overlapping solutions for livelihood and environmental objectives, both in the short and long term.
- *Procedural transparency.* There is a need for procedural transparency in the setting-up and daily rolling-out of CBNRM activities, to enable stronger accountability. The policy and implementation furthermore need to clarify whether WRUAs are accountable downwards to local communities or upwards to the WRA.
- *Compensation mechanisms.* In the short term, some conservation activities carried out by the WRUAs negatively impact precarious livelihoods; WRUAs should share benefits from environmental initiatives and attached livelihood components with those most affected. An equilibrium must be negotiated where there are trade-offs between conservation and use of water resources.
- *Targeting enabling conditions.* CBNRM does not take place in a vacuum. Projects must consider and target enabling conditions in order to achieve sustainable and equitable outcomes.

ETHICS STATEMENT

Minimal Risk Ethics approval granted on 8th of July 2015 Number: MR/14/15-392 by Research Ethics Office King's College London. Oral consent from interviewees was sought.

AUTHOR CONTRIBUTIONS

NR has contributed to the paper by choosing the topic, the framework, constructing the argument, and writing, contributing to data collected in the field and by putting the paper together. DS has contributed to the paper with her field data and experience, as well as literature review.

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Towards a Healthy Ganga—Improving River Flows Through Understanding Trade Offs

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Scores of Indians living worldwide, since the times immemorial have revered river Ganga. The very presence of Ganga is not only critical from a socio-cultural perspective; but it contributes to various economic and livelihood activities for the people residing in the basin. It is one of the most complex river basins in the world, in terms of the number of people residing in its basin space and the pressure on its water resources. Thus, the river is facing multiple challenges. There is a growing debate in India for improving the health of the Ganga River, mainly at two fronts, i.e., its water quality and quantity. WWF-India along with its partners is working towards the conservation of Ganga since last decade. Whilst the work has been multi-dimensional, ranging from the issues of flows in the river to water pollution, climate change adaptation and habitat and biodiversity conservation; however, in this paper the aspect of adequate flows in the river Ganga is discussed. During 2015–16, along with partners, WWF-India conducted an action research study in over 2 million hectares of culturable command area of two irrigation systems taking off from River Ganga, to understand the barriers to implement Environmental Flows (E-Flows) in the critical stretch of river Ganga (between Haridwar and Triveni Sangam Allahabad). Under this initiative, the team tried to bridge the knowledge gap about potential trade-offs for implementation of E-Flows in a critical stretch of Ganga. The team made an attempt to understand the surface water allocation and water use scenario in western and central part of the state of Uttar Pradesh, where the Ganga water is used for agricultural purposes through major irrigation infrastructure. The E-Flows recommendations for critical locations downstream of two barrages, i.e., headworks of two major irrigation schemes, were developed. This paper discusses approaches for management of trade-offs to restore E-Flows in this stretch of Ganga and includes various management options—like (i) promotion of irrigation water use efficiency and (ii) institutional aspects. The paper argues that, whilst there is a widespread apprehension that, from the Ganga river water resources use, any curtailment in the allocation quota for irrigation would lead to an adverse impact on the farming community. However, actually after assessing the trade-offs, it can be inferred that although the E-Flows implementation in this stretch of Ganga would require enhancement of water in the river, but that requirement may not be substantial. Toward the end of the paper, challenges and opportunities for E-Flows implementation in the Upper Ganga are discussed.

Keywords: Environmental Flows, water allocation, tradeoffs, Ganga, irrigation, water use efficiency, barrage

INTRODUCTION

The river Ganga, with over 2,525 km[1] long main-stem, is one resource that sustains multiple functions—pertaining to ecological, socio-cultural and livelihoods. The mythological stories and anecdotes about the river and its association with the people and the nature dates back to times immemorial. There have been instances when the river, its health, its aquatic life, its flows and its water levels are related to various socio-cultural and spiritual aspirations. For instance—the Gharial is considered to be the carrier of goddess Ganga. The dolphin (Platanista *gangetica gangetica*) in the Ganga is considered to be companion of goddess Ganga. The good quality water and desired water levels in the Ganga are essential for cultural activities, including *aachman* (an auspicious activity, under which a pilgrim takes some water from the river on his/her palm and drinks it) and *snan* (another auspicious activity, under which a pilgrim takes holy dip in the river, for which waist deep water close to the river bank is generally desirable for such activity).

Globally, today's annual human water withdrawals are to the tune of 3,480 km^3, i.e., 2,409 km^3 for irrigation and 1,071 km^3 for Household-Industries-Livelihoods (1980–2009 average), which harms many river stretches around the world (Jägermeyr et al., 2017). The Ganga is facing large-scale human interventions since 1850s, when major irrigation systems called the Upper Ganga Canal (UGC), whereas the Lower Ganga Canal (LGC) were constructed in 1870s; this led to diversion of Ganga water resources for irrigation and other purposes. One needs to appreciate that every change in flow regime of a river is associated with some form of compromise of the integrity of the ecosystem structure and functions (Richter and Thomas, 2007). The interventions cause changes in ecosystem functions, and consequent ecosystem services for human community. This makes the target Environmental Flows not necessarily natural flows, but rather negotiated flows, set by either objectives (deciding what you want to achieve and setting flows to achieve it) or by scenarios (negotiating between different users) (Acreman and Dunbar, 2004).

As per Brisbane Declaration (2007), "The Environmental Flows (E-Flows) describe the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems."

The Consortia of seven IITs (Indian Institute of Technology) and other partner organizations developed the Ganga River Basin Management Plan (GRBMP) for the Government of India and submitted the main GRBMP document (Ganga River Basin Management Plan, 2015). As per a report on "Environmental Flows: State-of-the-Art With Special Reference to Rivers in the Ganga River Basin" [which has been prepared in 2011 as part of Ganga River Basin Management Plan (2011) exercise] the E-Flows are defined as:

"The temporal and spatial variations in quantity and quality of water required for freshwater and estuarine systems to perform their natural ecological functions (including material transport) and support the spiritual, cultural and livelihood activities that depend on them."

The team follows the E-Flows definition of GRBMP and this one is recognized (in Indian context) by the National Mission for Clean Ganga (Ministry of Water Resources, River Development and Ganga Rejuvenation) Government of India.

In the year 2010, the WWF (World Wide Fund for Nature) along with TNC (The Nature Conservancy) came out with a global publication on E-Flows Implementation Challenges, which analyzed the "as-is" scenario in restoring E-Flows in many countries across the globe. Based on a study across 64 countries and with 272 respondents, Moore (2004)[2] examined the trends in six major regions; based on that study, Moore concluded that, (i) the understanding of socio-economic costs and benefits and (ii) political will, are the two most important critical challenges for implementation of E-Flows. In many ways, these two aspects are interrelated, as an informed political leadership, in terms of socio-economic costs and benefits would be more willing to take decisions in favor of E-Flows.

It is recognized that the large scale irrigation systems on Ganga has contributed immensely to the betterment of agricultural economy of the region, which has certainly enhanced the socio-economic status of people in the western and central Uttar Pradesh (second state, on the main-stem of Ganga). Besides this, the entire Indo-gangetic plains have become a fertile land with the help of Ganga water and the sediments that flow with this water. On the other hand, during the last half a century, many new challenges have compounded the pressures and stresses onto the Ganga, its water resources and its aquatic life. These challenges mainly include—(i) ever-growing towns into cities and cities into mega-cities on the banks of Ganga, (ii) industrialization along the settlements on the banks of Ganga, (iii) excessive groundwater exploitation and chemical inputs in agriculture, and (iv) changes in copping pattern, including water

[1] Source: https://nmcg.nic.in/courseofganga.aspx

[2] Source: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.540.8546&rep=rep1&type=pdf (Page No. 6).

intensive crops, which are leading to enhanced surface and ground water withdrawals.

The successive Governments, on its part, have been trying to improve the health of river Ganga since 1980s and despite creation of pollution control infrastructure, the health of the river Ganga has not visibly improved. The renewed impetus toward Ganga conservation since 2010 has raised hopes, and since then, the Government has taken several policy decisions, which are being implemented. However, such a task is full of challenges, especially, in a complex river basin, whose population density is 520 person/km² as compared to national average of 312 person/km²[3] as per "Demography of Ganga Basin" (National Mission for Clean Ganga, 2012). Another layer of complexity includes multiple departments—handling water related affairs. On the other hand, this time, the Government of India entrusted the task of development of Ganga River Basin Management Plan (GRBMP) to a consortia of 07 IITs[4]. As per the main document of GRBMP (released in January 2015), the vision for management of Ganga river includes two key aspects, i.e., *Arival dhara* (continuous flows)—*Nirmal dhara*[5] (unpolluted flows) in Ganga. As part of this work, the consortia of IITs, also did E-Flows assessment for the mountainous stretch of river Ganga, which has several hydropower projects. This work was built on the earlier work of WWF India, under which E-Flows assessment for Upper Ganga was done by improvising and using one of the holistic methodologies during 2008–2010. As per the GRBMP, the measures for sustainable management of Ganga river basin are given in three categories, i.e., short-term, medium-term and long-term. At present, various governmental agencies, multilateral and bilateral funding agencies are putting in resources to pick some of the measures from the GRBMP document to pilot them or implement them (as the case may be) on the ground. On the other hand, with the support from the Government of India, the Centre for Ganga River Basin Management Studies (cGanga) has been created at IIT Kanpur to guide and oversee the works around Ganga rejuvenation in light of the GRBMP.

There have been attempts to answer the E-Flows requirement in the Ganga, and therefore, besides the pollution discussions, the debate for Ganga conservation within the formal circles is around allocation of water for E-Flows. In this regard, two important and critical, but old irrigation systems (Upper Ganga Canal and Lower Ganga Canal, however both these systems have undergone modernizations drives from time to time) in upstream states on the Ganga main-stem (Uttarakhand and Uttar Pradesh) are generally discussed. It has been debated whether there are prospects and opportunities to enhance the flows in the river Ganga downstream of these interventions.

The National Commission on Integrated Water Resources Development Plan (NCIWRDP—Government of India), in the year 1999, has called for enhancement of water use efficiency across all sectors by at least 20%. In other words, irrigation efficiency should be improved from the present average of about 35–40% to the maximum achievable i.e., around 55–60% (Central Water Commission-Ministry of Water Resources, River Development and Ganga Rejuvenation, 2008). The National Water Mission of Government of India in the year 2009 called for enhancing 20% water use efficiency in its National Action Plan on Climate Change (National Action Plan on Climate Change, 2009)[6].

In the case of Uttar Pradesh (which is a critical state when it comes to large-scale withdrawal of Ganga water resources for irrigation),(Kaushal and Kansal, 2011) concluded that current proportion of water allocation for agriculture is bound to get reduced in near future. As per SWaRA (State Water Resources Agency—Uttar Pradesh), the agri-water allocation of about 96% in the year 2001 will get reduced to about 79% by the year 2050, which would mainly be due to increasing domestic and industrial demand.

The ongoing work around Environmental Flows (E-Flows) in the Ganga, which is more than a decade old now, leads to the "next-generation" questions, i.e.,

✓ if the E-Flows are to be maintained, from where the water will come?
✓ what would be the trade-offs for E-Flows implementation?
✓ what would be the implications onto the committed sectoral water uses?

This paper attempts to answer some of above policy questions, through summarizing a research study (2015–16) that WWF-India along with its partners (Indian Institute of Technology-Kanpur, *Aarthik Vikas Evam Jan Kalyan Sansthan*—Lucknow and Institute of Rural Management, Anand) have conducted, under a CGIAR (Consultative Group on Integrated Agricultural Research) Research Programme on Water Land and Ecosystems, funded by IWMI (International Water Management Institute—Sri Lanka) on "Healthy Ganga—Cleaner Water and More Productive Ecosystems[7]" The role of these institutions and organizations in the project is listed in **Table 1**.

The paper, in a way, attempts to package a complete picture—ranging from an understanding about the current water resources use pattern from the river Ganga at critical location, including ground realities in this regard and the E-Flows requirements at such a location; to, ascertaining how the recommended E-Flows can be secured in such an over-committed river system. It ties well with the general debate within the country and more specifically in the Ganga basin that, *"for the E-Flows realization, from where the water will come from and what is going to be the implication on other sectoral uses?"*

Efforts are made in this paper to provide insights and suggestions, that may find place in overall policy discourse on securing water for maintaining E-Flows in Ganga, in specific and in other river systems, in general (where heavy diversions for irrigation are existent). It is argued that there are opportunities which can support long term E-Flows realization in the Ganga.

[3]Source: National Mission for Clean Ganga. Information is referred from: https://nmcg.nic.in/demography.aspx

[4]Consortia of 07 IITs: Indian Institute of Technology – country's premier technical institutions. Seven IITs include: IIT Kanpur, IIT Roorkee, IIT Delhi, IIT Kharagpur, IIT Guwahati, IIT Bombay, IIT Madras.

[5]Source: information extracted from: https://nmcg.nic.in/grbmp.aspx

[6]Source: http://www.nicra-icar.in/nicrarevised/images/Mission%20Documents/WATER%20MISSION.pdf

[7]For project details, please refer to https://wle.cgiar.org/healthyganga

TABLE 1 | Name of institutions, organizations and their role in the project.

S. No.	Name of Institution/Organization	Role under the project
1	WWF-India	Assessment of Ganga water resources, its allocation and use Understanding the baseline scenario from the perspective of the irrigation-department, with respect to irrigation that is dependent on Ganga's surface water resources Valuation of Ecosystem Services of Ganga river Implementation framework for E-Flows at 2 critical locations Cost-benefit analysis for E-Flows implementation
2	IIT Kanpur	E-Flows assessment for 2 critical locations on Ganga
3	Aarthik Vikas Evam Jan Kalyan Sansthan, Lucknow along with WWF-India	Baseline surveys—farmers in Upper Ganga Canal (UGC) and Lower Ganga Canal (LGC)
4	IRMA Anand	Understanding the gender aspects

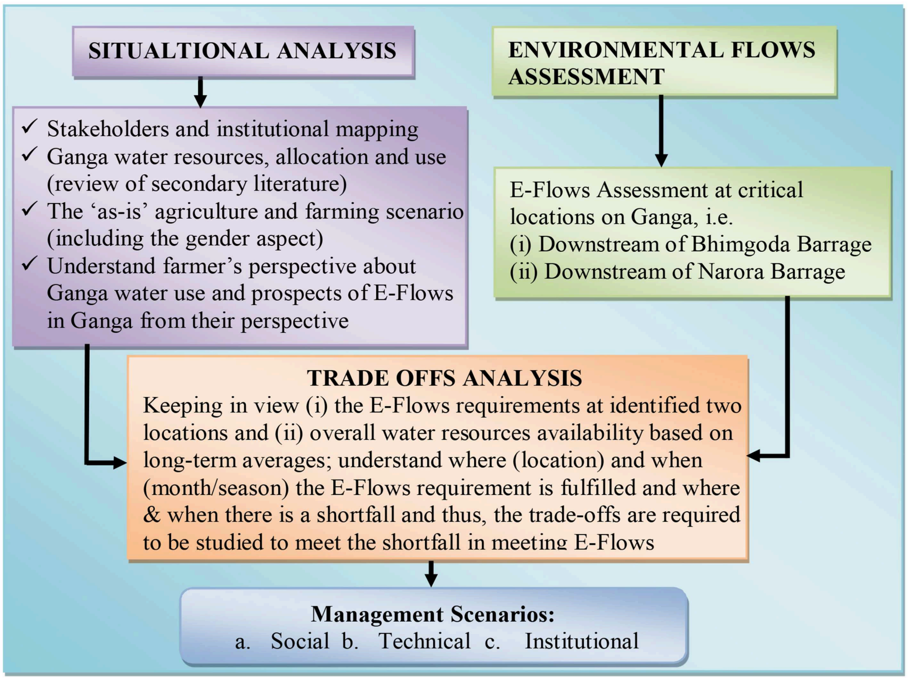


FIGURE 1 | Process chart exhibiting the methodology for the work.

Figure 1 illustrates the step-by-step approach for this work, in which each task-head is based on (i) field-oriented primary information and (ii) secondary literature, including formal documentation.

One of the preliminary aspects of the approach is to understand the "as-is" scenario. Therefore, the first and foremost task was to understand the key stakeholders, their significance and their current roles in allocation-management-use of Ganga water resources.

For this task, key stakeholders were identified and various modes of engagements were adopted to generate the required information, these modes included—one-to-one discussions, interactive sessions, Focused Group Discussions, individual interviews, workshops etc. The listing of stakeholders, type of engagements and objectives of the engagements is given in **Table 2**.

The wide spectrum of stakeholders with whom the team interacted can be seen in **Figure 2**. The review of secondary literature and field surveys were conducted almost simultaneously and the collected data was deliberated upon, initially within the team and later on with the stakeholders, i.e., officials from respective government departments, through Stakeholders Consultations.

The trade-offs are primarily assessed for the biggest user of Ganga water resources, i.e., irrigation. An attempt is made to ascertain how much irrigation water savings can be achieved at varying percentages of efficiency in irrigation water use; the idea is that the saved water can be used for enhancing the flows in the river.

PROJECT AREA AND SITUATIONAL ANALYSIS THROUGH ACTION RESEARCH

The implications of current policies on surface water allocation (withdrawals from the river) and use (at state level) are discussed

TABLE 2 | Key stakeholders and objective of interactions with them.

S. No.	Stakeholder	Type of engagement	Objective of engagement
1	Farming community who is dependent on the Ganga water resources through UGC, LGC, and groundwater which is often recharged by the river and the canal systems (as the canal system is largely earthen)	Surveys and Focused Group Discussions	To understand the overall agriculture scenario, dependence on surface water resources, problems and prospects of E-Flows implementation and willingness of farmers to contribute to this noble cause, as they also visit banks of Ganga during auspicious days for socio-cultural rituals, so a "healthy Ganga" is of their interest as well
2	State Irrigation Department, who is currently the "water-manager" when it comes to management of Ganga water resources for all the uses; primarily irrigation, but also domestic and industrial, wherever applicable	Individual interviews and Focused Group Discussions	To understand the overall surface water use scenario across the sectors, departmental challenges in dealing with this aspect. Their perception about enhancing flows in the river Ganga and potential approaches for implementation
3	National Mission for Clean Ganga and other State Departments	Focused Group Discussions	To ascertain their perspectives about the E-Flows maintenance in Ganga vis-à-vis committed uses

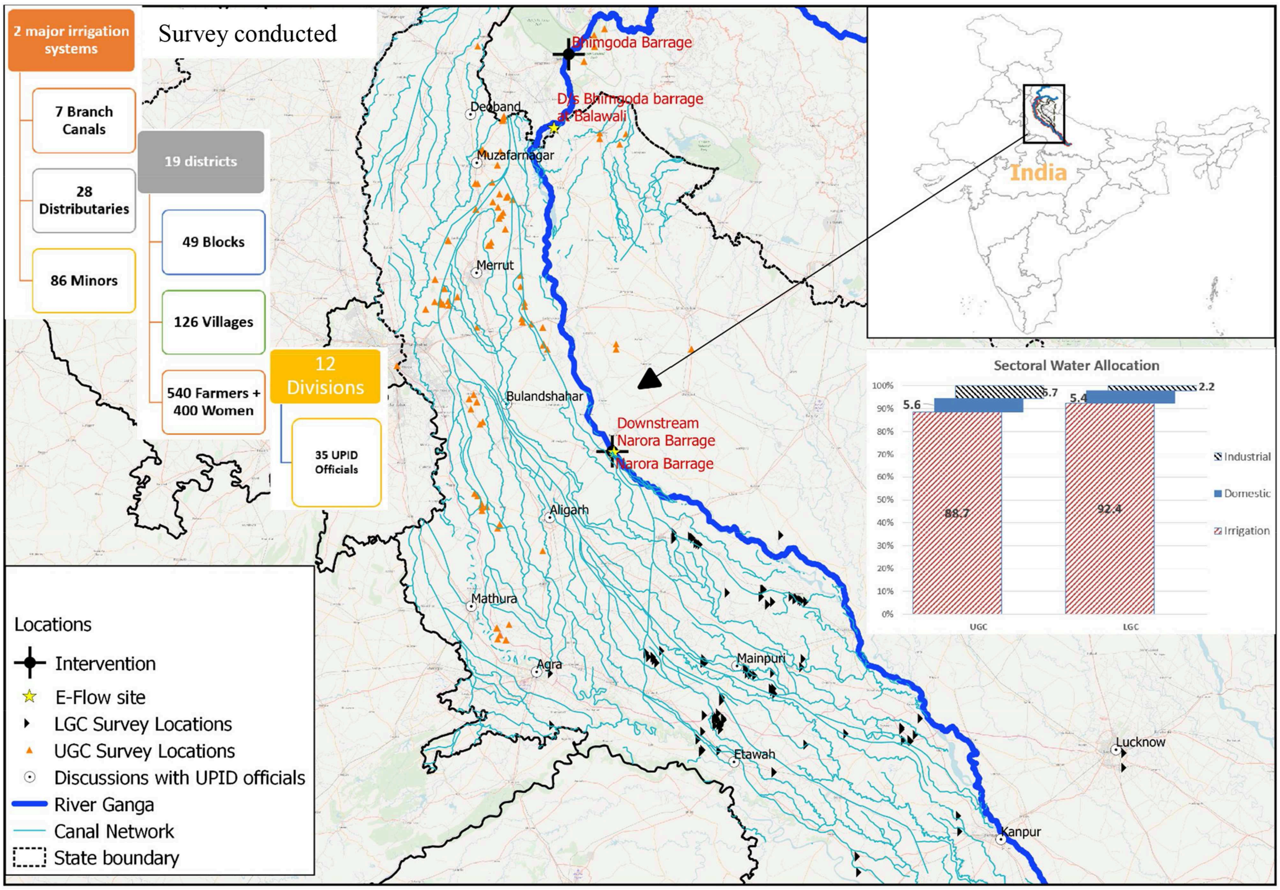


FIGURE 2 | Map of project area with intervention (irrigation projects), survey locations, and sectoral Ganga water allocation (Source: WWF India).

through an action research study that was conducted in the upper Ganga. The surface water allocation at state level is generally governed by populist considerations around ensuring water for irrigation; however, the aspects of National Water Policy are also considered, nevertheless the key motivation remains the earlier one. The management of water resources and its efficient use is something that is very much there in policy realm, but in practice, this is not close to anticipated targets and objectives of both, Governments of India and of the state of Uttar Pradesh.

This research was conducted in catchment of critical stretch of River Ganga, where the river faces heavy abstractions, which are perennial in nature, i.e., the relevant districts of state of Uttar Pradesh (UP) and a district in state of Uttarakhand, which borders with UP, i.e., Haridwar. The project area map along with information about intervention and survey locations is given in **Figure 2**.

There are two major perennial irrigation systems taking off from river Ganga, one at Bhimgoda Barrage located in the holy city of Haridwar, which is the headwork of Upper Ganga Canal (UGC) and supports irrigation in about 11 administrative districts in Uttar Pradesh and one district in Uttarakhand[8] (Uttar Pradesh Irrigation & Water Resources Department - formerly called Uttar Pradesh irrigation Department).

On the other hand, another key intervention is at Narora Barrage, which is the headwork of Lower Ganga Canal (LGC) system that supports irrigation in about 10 districts of UP. Together these two irrigation systems have a Cultivable Command Area of over 2 million hectares (Uttar Pradesh Irrigation and Water Resources Department, 2017a). **Figure 1** exhibits the project area, i.e., all the districts falling in UGC and LGC. Additionally, the figure indicates precise sites, where interactions, interviews and FGDs (Focused Group Discussions) were conducted. The figure also illustrates the sector-wise percentage of water use through these two interventions and the sample size of respondents.

This information in **Figure 2** indicates heavy water resources usage for irrigation and other purposes (as these canal systems also provide water for domestic supplies to some of the cities within the basin—including National Capital Region (NCR) and in Uttar Pradesh, plus some industrial supplies) from Ganga's water resources. Therefore, any effort for implementation of E-Flows in Ganga will have to closely look into these "committed" uses.

Field Survey Findings

The findings were used as inputs for developing the overall understanding about trade-offs, associated cost and benefits of maintaining E-Flows in the critical stretch of River Ganga. In this section, the findings are organized in a thematic manner.

Farming Practices and Their Perception for Healthy Ganga

There is a plethora of inferences that one can draw from the field investigations in the LGC command with different stakeholders, and the same is summarized below in bullet points. These points can be considered while devising policy and strategy for long term E-Flows implementation in Ganga through sustained irrigation water use efficiency measures.

- Over 95% farmers adopt "flooding" as the medium for irrigating their fields, which indicates huge scope for promotion of irrigation water use efficiency. The main crop (in around 80% of command area) is wheat in *Rabi* (November-April) and paddy (in about 57% of command area) in *Kharif* (June–October). There has been a steep rise in sugarcane cultivation since last few decades and that has tremendously put pressure on available water resources.
- The water distributions method amongst farmers is mainly on a rotational (*Warabandi*) basis, the figure about water distribution through "*Warabandi*" (on rotational basis) and "mutual-understanding" (for rotational distribution) approach are about 72%. The majority of farmers use earthen channels for conveyance of water from the canal to field.
- The knowledge and awareness about Participatory Irrigation Management (PIM) and Water Users Associations (WUAs) is a mere 3%. However, now the Uttar Pradesh Irrigation Department is forming Water Users Associations (WUAs) in the entire LGC command area; to be followed by formation of WUAs across all irrigation schemes in the State.
- About 90% of farmers felt the need for training and capacity building toward modern agriculture and irrigation techniques. Less than 12% of farmers go for "soil-health" testing at the farms.
- The data collected over literacy status among the farmers suggests that, over 37% farmers are high school (tenth standard) passed, and about 10% are graduate or above. This indicates great scope for andragogy based extension services for disseminating water efficient agriculture practices.
- Close to 90% farmers visit Ganga for various festivities and 51% of them are satisfied with current water levels and its cleanliness.
- About 73% farmers realize that, the aquatic life in river Ganga is on negative trajectory. About 81% farmers felt that, additional water supplies should be ensured in Ganga to sustain Ganga's aquatic biodiversity.

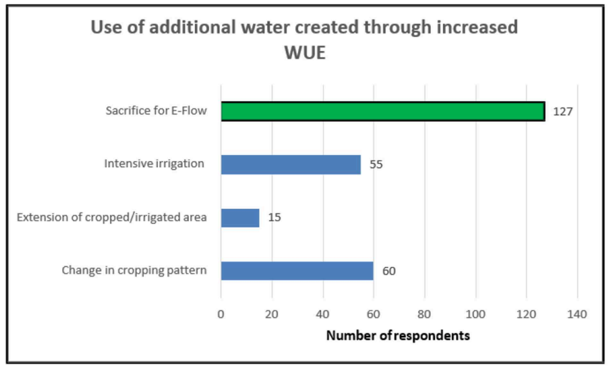


FIGURE 3 | Preference of farmers to use saved water through WUE initiatives in LGC.

The finding around willingness of farmers to transfer saved water from irrigation to the river Ganga threw some interesting perspectives, and the same is illustrated in **Figure 3**; however about 50% of farmers are willing to transfer their saved water to river Ganga.

Perspective of Departmental Officers

The mandate of state Irrigation Department is to provide water for irrigation to the command farmers, which has been the priority of the officials; however, they understand the implications of reduced flows in River Ganga upon its health. The key messages from them include:

[8]Source: Uttar Pradesh Irrigation Department website: http://idup.gov.in/pages/en/topmenu/dept.-activities/civil/en-irrigation-by-canalsirrigation-by-canals

- In view of growing demand for water for irrigation, due to some of the changes in cropping patterns, the canal systems are over-stretched to deliver water up to the tail end and this often leads to reduced water supplies at the tail-end. The canal systems are developed and designed to provide "protective" irrigation, whereas the current demand is to the tune of "intensive" irrigation.
- Gauges at the head of minors are often in dilapidated state; hence precise water discharge monitoring is a challenge.

Most of the officials were positive about enhancing flows in Ganga to improve the health of the river; however, they feel that rationalizing the allocations of Ganga water resources from existing commitments would be a key challenge. Their suggestions include following:

✓ Farm level water use efficiency is required to be promoted and practiced; if feasible, such efforts should be incentivized.
✓ Awareness campaign and demonstration drives should be carried out toward irrigation water use efficiency.
✓ Organic farming, usage of less water consuming crops should be promoted.

Environmental Flows at Critical Locations on River Ganga

As part of the study, the team from IIT Kanpur (Indian Institute of Technology Kanpur) conducted E-Flows assessment at two main intervention locations on Ganga river (i) Downstream Bhimgoda Barrage and (ii) Downstream Narora Barrage. The process of arriving at E-Flows values is illustrated in **Figure 4**.

For the purpose of this paper, the actual-flows gap vis-à-vis E-Flows requirements are presented only for one intervention, i.e., downstream of Narora Barrage (as the key E-Flows gaps during the lean season are observed at this location); on the other hand, in case of downstream of Bhimgoda Barrage, the lean season flows were not that far off from E-Flows requirements (as per this study). Therefore, the trade-offs are not as challenging as in the case of downstream of Narora Barrage. The percentage[9] of shortfall from present water availability downstream of Narora Barrage vis-à-vis E-Flows recommendations are presented in **Figure 5**.

It is to be noted that the crisis time, in terms of shortfall in present day flows vis-à-vis recommended E-Flows, is during the months of December, January, February and April. The December-January month coincides with the timing of maximum water requirement for irrigation as well.

Whilst the E-Flows recommendations are largely based on the requirements (during different life-phases) of Indian Major Carps (*Labeo calbasu, Catla catla, Labeo rohita, Cirrhinus mrigala*), it was also correlated whether the water levels, thus achieved through this aquatic biodiversity-centric E-Flows recommendations, are able to provide desired water levels for the socio-cultural aspirations/activities, which were discussed in the beginning of the paper. It is the lean season when most of the socio-cultural festivities are organized, and therefore, the desired water-levels are critical for having satisfactory socio-cultural rituals. It was observed that the water levels required by these fish species are able to meet socio-cultural requirements. On the other hand, the current flows are unable to meet various biological requirements of above-mentioned fish species during "lean-season." O'Keeffe et al. (2012) discussed the presence of dolphins around Narora in the Ganga main-stem, as this stretch is a conducive dolphin habitat in the upstream of Narora Barrage.

It is worth mentioning that the hydrological information that has been used in this E-Flows assessment is of pre-Tehri dam timeframe (as long-term hydrological information is required to be used as a standard practice in E-Flows assessment). However, since the commissioning of the Tehri dam (in 2006), the flows scenario in the Ganga might have changed, and thus, the E-Flows requirements may vary. This is a matter of further research.

With a developed understanding so far, in terms of present Ganga water resources allocation-management-use vis-à-vis desired E-Flows; the next task was to ascertain the trade-offs and generate scenarios for potential consideration, which is discussed in the upcoming section on recommendations.

RECOMMENDATIONS

Looking at the field findings, there is a clear case for improvement in the current irrigation and agricultural practices; which would not only benefit the river but also the farmers. On the other hand, an assessment of shortfall in E-Flows at downstream of Narora Barrage was done by comparing the present-day flows and the E-Flows requirements. After ascertaining the E-Flows shortfalls at downstream of Narora Barrage, various options (that will allow realization of E-Flows) were explored and the same are categorized as different "Management Scenarios." These "Management-Scenarios" may be considered by the policy makers and the water managers.

Social and Technical—At Farm Level

In order to achieve the objective of E-Flows maintenance, both "on farm efficiency" and "conveyance efficiency" need to be enhanced. It is worth understanding at this juncture what we mean by irrigation water use efficiency; keeping in view the current irrigation scenario, we look forward to following asks through which water use efficiency can be enhanced in irrigation in the command area of LGC:

a. Flood irrigation is the key means of irrigation at the moment and that needs to change to furrow irrigation initially and later on micro-irrigation should be considered. However, furrow irrigation alone has the potential to save over 20% irrigation water.
b. Introduction of different varieties (less water intensive or the ones requiring lesser time-period) of the same crop and gradually explore the possibility of marginally changing the cropping pattern to less water intensive crops.

As part of another project (Rivers for Life Programme 2012–2017: supported by HSBC Water Programme), the team (comprise of some authors and other colleagues at WWF

[9]NOTE: Due to 'classified' nature of Ganga river flows information, the authors have reported the E-Flows shortfall in terms of percentages rather than in absolute values.

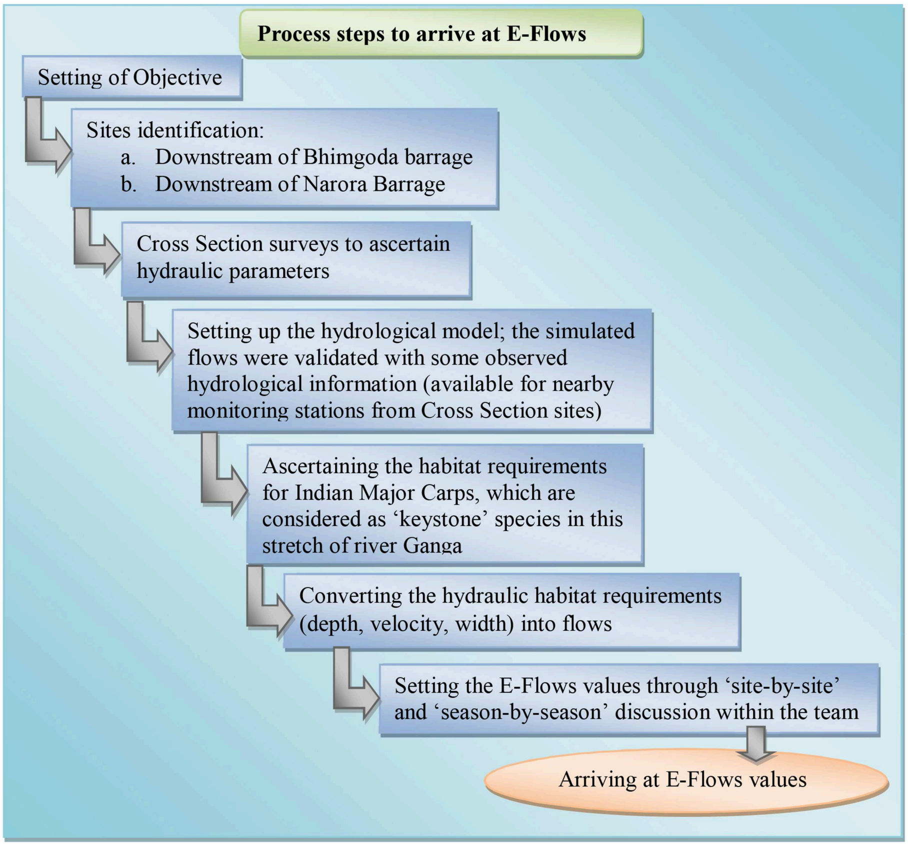


FIGURE 4 | Flow chart to illustrate the process to arrive at E-Flows recommendations (Source: WWF India and IIT Kanpur).

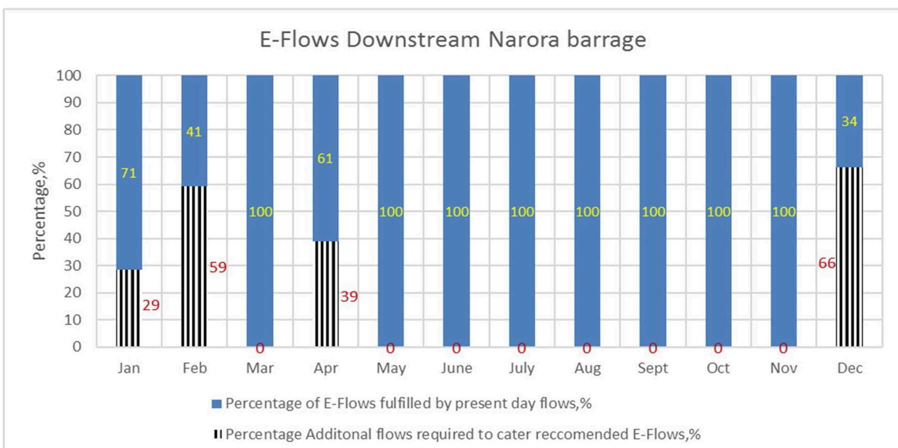


FIGURE 5 | Percentage of E-Flows and its shortfall in comparison to percentage in present day flows from Narora Barrage (headworks of Lower Ganga Canal) (Source: developed by WWF India, based on the information and data from IIT Kanpur).

India) is working with over 2,000 farmers in 40 villages of 8 districts of Uttar Pradesh in Ganga Basin. This work includes the demonstration of Package of Practices (Soil-Health testing, formation and the application of organic fertilizers and pesticides, introduction of drought tolerant varieties etc.), which is helpful for reduction of chemical inputs at the farms along with improving current levels of irrigation water use efficiency.

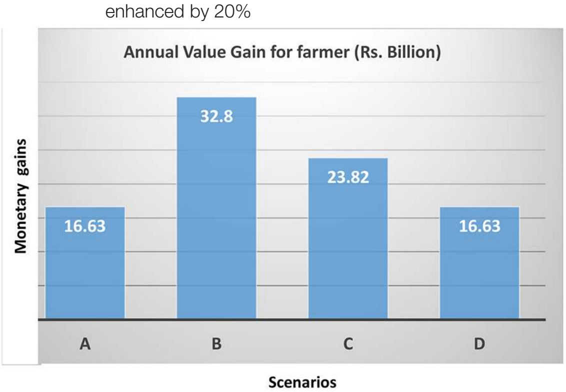
In no way do the authors call for lining of canal systems (as a means of enhancing water use efficiency), because it is recognized that, in this region which is largely alluvial in nature, the ground-water recharge function of canal systems is critical for maintaining ground-water levels and there is no intention to disturb that process, at the moment.

It has been assumed that if current irrigation efficiency levels are increased by varying percentages, then what would be the benefit in terms of water availability at head for maintaining E-Flows. For the purpose of this project, water use efficiency relates to reduction in canal water use for irrigation while maintaining the crop yield, which essentially implies demand management. Under this category, Scenario A–D is presented in **Table 3** for both interventions. It can be inferred from that table that, under Scenario B with achievement of 3% irrigation Water Use Efficiency in the LGC system from current levels, the E-Flows in the Ganga at downstream of Narora Barrage would be realized.

Very recently, the Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India came out with a Notification on E-Flows on 10 October 2018 (Notification on Environmental Flows by Ministry of Water Resources, River Development and Ganga Rejuvenation, 2018). In this Notification, the absolute values of E-Flows for different seasons are given for the locations downstream of different barrages, including both Bhimgoda Barrage and Narora Barrage. However, in the case of the mountainous stretch of Ganga, the required E-Flows are given in percentages.

TABLE 3 | Different WUE scenarios for LGC systems for fulfillment of E-Flows in Ganga.

Scenarios	Description	Whether E-Flows would be achieved	Percentage of E-Flows gap fulfilled, %
NARORA BARRAGE			
	BAU	No	–
A	Water-use-efficiency enhanced by 1%	No	46
B	Water-use-efficiency enhanced by 3%	Yes	137
C	Water-use-efficiency enhanced by 5%	Yes	228
D	Water-use-efficiency enhanced by 20%	Yes	910



A closer comparative analysis of the E-Flows recommendations for lean season (the one recommended as per the Government Notification and the ones recommended as part of this study) informs that the E-Flows recommended as per the Notification cannot meet the E-Flows requirements desired under this study during some of the critical lean months.

The irrigation water use efficiency scenario essentially entails water savings for the purpose of realizing E-Flows, without compromising with agricultural productivity. It is realized that, besides the achievement of E-Flows through irrigation water use efficiency; there would be value gain to farmers as well, because there have been instances of overwatering leading to lesser agricultural productivity, thereby resulting in negative marginal product. Based on this understanding, some broad calculations are completed to estimate monetary gains to the farmers under Scenario A to D and the same is available along with **Table 3**. Thus, it is possible to attain E-Flows without compromising with farm incomes, and rather it would be economically beneficial to farmers. A separate exercise is being conducted to understand economic gains, in a detailed manner, for farmers through irrigation water use efficiency and other means, which is not part of this paper.

Institutional

There are various reforms underway; one is to hand-over operation and maintenance of canal systems at minor canal level to the farmer groups, i.e., Water Users Associations (WUAs) by bringing necessary legislations and executive orders with an objective to empower the farmers in decision-making. There are national and global examples, where the WUAs are able to successfully demonstrate higher levels of irrigation water use efficiency and they have saved lot of water in the system for the respective department. The idea of "buy-back," on the lines of several other countries, is also being looked at.

There is a growing debate within the government that, by extending necessary services to farmers, i.e., Soil-Health Card and pressure irrigation (drip and sprinkler), there is a lot of scope of water use efficiency and this can effectively be run through the WUAs, as it is a group of farmers and the scheme or idea can be implemented in one go.

The Governments, both national and state ones, are implementing programmes and projects, which would help in this larger cause. Notably amongst them include—"*Namami Gange*[10]," *Pradhan Mantri Krishi Sinchai Yojana*[11] (Pradhan Mantri Krishi Sinchai Yojana, 2017-PMKSY), renewed push for improvised District Plans, ongoing Uttar Pradesh Water Sector Restructuring Project (UPWSRP) of the World Bank and so on (Uttar Pradesh Irrigation and Water Resources Department, 2017b).

As part of the "*Namami Gange*" programme, the District Ganga Conservation Committees (DGCCs) are formed under the chairmanship of respective District Magistrate (administrative head of a district) in all the Ganga basin districts. One

[10] *Namami Gange* – name of National Government's flagship programme on Ganga rejuvenation.
[11] English translation – Prime Minister Agriculture Irrigation Scheme.

of the mandates of the DGCCs is about furthering the cause of E-Flows in Ganga, as some of the measures at village-level can be implemented through them, and since these bodies are at local level, the monitoring can also be done effectively. Plus, the "Ganga-*Grams*[12]" (Ganga villages) are identified for furthering the cause of Ganga rejuvenation and conservation. The DGCCs can play a key role in successfully accomplishing the tasks entrusted to Ganga-*Grams*. These Ganga-*Grams* can also implement a package of better management practices in agriculture and irrigation, and can therefore contribute toward enhancing irrigation water use efficiency and reduction of chemical inputs in agriculture.

Under PMKSY, the main aim is "water-to-every-farm" and "more-crop-per-drop." As part of these two aims, one of the objectives is to push for pressure and micro irrigation techniques with an aim to conserve water and doing-away with "flood" irrigation. For this, the Government is extending subsidies to farmers who are willing to adopt these modes of irrigation. If this scheme is enforced properly in the villages falling within the command of LGC, a lot of water saving can be done.

The renewed push for improvised District Plans, in a way, calls for integration of recently announced and enforced governmental schemes into the planning phase; so that the schemes can be smoothly implemented through the district-led processes. The integration of programmes and schemes like *"Namami Gange*" and PMKSY into District Plans can go a long way to help the larger cause of improving the health of river Ganga.

The Government of Uttar Pradesh promulgated Participatory Irrigation Management Act in the year 2009. This Act calls for formation of Water Users Associations with a key mandate of managing the water use within the command of their jurisdiction. There are examples in India (central, southern and western India) where some of the WUAs are doing pioneering work in regards to irrigation water use efficiency and such WUAs are also promoted and incentivized by the concerned governments. Along similar lines, if the WUAs in LGC command are facilitated, then these WUAs can play key role in water savings within their command. In this regard, the UPWSRP is playing a critical role in intensifying the efforts toward formation of WUAs. The WUAs, taking benefit from various governmental schemes (like PMKSY) can save lot of water allocated for irrigation and negotiate with the department and government to incentivize such efforts. Besides this, as per the PIM Act, the WUAs can decide on water charges (higher than the governmental water charges), which are to be collected from the command farmers and incentivize irrigation water use efficiency and discourage water overuse. The Irrigation Department, in a long run, can explore the possibilities of "buying-back" the water from farmers for the cause of enhancing flows in the river; which could be one way of incentivizing the WUAs.

[12]Ganga – *Grams (English meaning Ganga Villages)*: The Central Government in 2016 declared to develop 206 villages located along the main stem of river Ganga which have historic, cultural, and religious and/or tourist importance. The works related to Ganga *Grams* will encompass comprehensive rural sanitation, development of water bodies and river *ghats* (stairs and platforms to facilitate rituals), construction/modernization of crematoria etc. more information can be accessed at: http://pib.nic.in/newsite/PrintRelease.aspx?relid=137672

LIMITATIONS

Whilst this study has been enlightening in many ways, there were some limitations that the team worked with. It is worth capturing those limitations so that the findings in this paper and the way forward is seen in that light.

As mentioned earlier, the flows regime might have changed a bit in view of commissioning of Tehri Dam, but in this study the hydrological data, that the team has used is of pre-Tehri time. This is one of the limitation of the study. One aspect that can be argued is that the team has not explicitly considered the costs associated with each flow regime, the costs associated in moving from one flow regime to other flow regime, and whether the costs would have overturned the benefit figures. While not acknowledging the costs explicitly might be considered as a limitation of this study, one need to note here that the costs are largely non-monetary in nature, and the monetary costs are too negligible even in the forms of capital expenditures.

On the other hand, there are certain datasets that are "classified" in nature, and hence cannot be shared in this paper; however the team ensured that validation of information generated through standard models is done with the actual data.

Both the UGC and LGC are fairly large irrigation systems and a statistically viable sample number (in terms of farmers) is difficult to consider, however, the team ensured that all the sections of head-middle-tail reaches of canal systems are taken care of.

It is recognized that, since there is substantial surface-ground water interaction happening in the gangetic plains, long term E-Flows implementation across the river system would call for better understanding of "loosing" and "gaining" streams/stretches in the Ganga, which would therefore call for regulation of ground-water use for irrigation. There is currently a "knowledge-gap" existing in this respect, and thus it can be a forthcoming research opportunity.

Besides this, it is understood that there would be "return-flows" from agriculture to the river, however its estimation in specific terms has not been done on current agricultural practices in this region, and thus the team refrained from doing any general broad estimation of "return-flows" through standard modeling exercises. In view of this, the "return-flows" phenomena have been kept aside; however, it is a crucial research question that should be taken up by researchers.

Whilst it is recognized that issues like—domestic and industrial pollution, urbanization and floodplains encroachment are other critical challenges the river Ganga faces, and thus addressing these issues are critical to improving the overall health of river Ganga, it is equally pertinent that the desired freshwater flows in the river are maintained. Together, with all these aspects, a basin-wide approach is required for ensuring a healthy state of river Ganga and that has been the thrust of GRBMP; however, this paper deals with the specific aspect of flows in the river Ganga.

CONCLUSION: CHALLENGES AND OPPORTUNITIES AHEAD

When water resources are allocated to economic uses and water needs to be recovered for the environment, this is always difficult. There are various options for obtaining this water, one of the main options is:

- Instituting water efficiency improvements in the economic uses through technical improvements, with some of the "saved" water being used for the environment (Hirji and Davis, 2007).

Whilst this argument holds true for Ganga, without required support the desirable results would be difficult to achieve. On the other hand, given the scale of challenges the river and the basin face, the implementation of E-Flows in the Ganga is a long-drawn and highly complex process. Right from growing population, and thus the need to have more agricultural produce, coupled with growing economy leading to changing food habits, improved life-styles and individual expectations; all this pushes the boundaries and limits of existing facilities and infrastructures. The current irrigation and agricultural practices, aging canal and associated facilities further aggravates the scenario.

There has been a feeling amongst a section of policy makers and the water managers that there would be widespread dissatisfaction amongst the farming community if the allocation of surface water resources for irrigation are rationalized to accommodate E-Flows requirement of the Ganga. In many ways, this study attempted to burst this myth about potential dissatisfaction amongst the farmers; however, it is to be noted that the path toward E-Flows implementation is going to be complex due to various reasons, some of which are as follows –

a. **Promotion of Efficient Irrigation and Agriculture Practices**—Starting with furrow, similar easy-to-adopt better management practices in irrigation and the gradual movement toward micro-irrigation techniques. This approach also needs to be coupled with marginal change in cropping pattern (in terms of using less-water intensive crops) in the command area based on soil health improvement, as this marginal change would mean substantial water savings. This is going to be a slow process, mainly because of the scale (major perennial irrigation systems feeding about 2 million hectare of agricultural land), which is a big challenge as the change "at-scale" would be a long, complex and persuasive process.

b. **Hand-Holding and Incentivizing the Farmers**—Whilst there is a huge "reverence-value" amongst the farmers, as about 90% of them visit the banks of river Ganga for various socio-cultural festivities and they are supportive to compromise part of the water (allocated to them) for raising water levels in the Ganga for improvement of Ganga's health. However, this needs to be done with proper "hand-holding" of the farmers (in terms of institutional support, adequate knowledge of BMPs in irrigation and agriculture, effective extension services, pilot demonstrations). The Water Users Association can play crucial role here.

c. **Overcoming Technical Challenges**—The existing irrigation systems are designed to take certain designed discharges and any reduction in discharges would mean reduction in hydraulic head that is required to transfer water to tail ends. This will essentially lead to inequitable distribution of water; therefore, some level of technological intervention would be required. The ongoing UPWSRP and PMKSY could be a useful medium for looking at technical upgradation of some sort and may be on pilot basis in a small command area, to start with.

d. **Clear Understanding About Influent and Effluent Streams**—One of the critical research questions or rather a "gap," is about the understanding of "influent" (a stream located above the water table and discharges into the underlying groundwater system) and "effluent" (a stream that get their water from the groundwater) nature of streams in the Ganga basin or even for the Ganga river itself. In absence of this understanding, the additional waters from the barrages into the river may not bear desired results in totality; such an understanding can extend long-lasting support for maintaining E-Flows in the Ganga. Parallel to this, conjunctive use of surface water and ground water is required to be thoroughly promoted in irrigation, as this will significantly help in ground water recharge as well. At the moment, this is something farmers are practicing based on their needs, and thus its uptake is inadequate.

The ongoing dialogue within the government, researchers and civil society to secure water resources for E-Flows in Ganga by looking at withdrawals for irrigation is a positive sign. This study strengthens the hypothesis that, in current agricultural scenario where there are ample technical-social-institutional opportunities to push for savings of water in the irrigation sector, E-Flows for the river Ganga are achievable. On the other hand, the farmers are going to benefit toward the end, after resolving initial challenges. This narrative needs to find place in the policy discourse and thereby lead to translation of this idea into some concrete steps at the ground level.

With renewed impetus and some fresh thinking in approach, the current scenario appears to be "a hopeful" one. The coming 5–10 years, would be the testimony of the applicability and efficacy of the measures the governments and civil society are putting forth for the conservation of river Ganga to transform it into a healthy river, throughout its entire length!

ETHICS STATEMENT

Does the study presented in the manuscript involve human or animal subjects: No.

An ethics approval for this research was not required, as per organizational guidelines and national regulations; however, necessary project approvals were sought from Competent Authorities at an organizational level.

Before the start of the interview/survey/Focused Group Discussion with the respondents (farmers and departmental field officers/functionaries); they were informed about the project and once they were adequately briefed; afterwards further interactions took place. An informed verbal consent was obtained from research participants. No written consent was required as per the project requirement; however, all the questionnaires were filled and duly signed by the recording researcher, as most of the farmers do not have a tertiary level education background, so writing the responses and then signing the same was not possible for them.

AUTHOR CONTRIBUTIONS

NK conceived, structured, and drafted the paper. SB did an overall review of the paper and provided inputs. He also made suggestions on structural aspects of the paper. He also played key role in designing the work around trade-offs and in selecting the Management Scenarios with NG. AM supported with water use efficiency scenario and refinement of figures. He also conducted individual interviews with field functionaries of Irrigation Department, hence provided inputs in appropriate section. NG conducted the water use efficiency scenario, economic valuation exercise and he contributed the appropriate section. Besides this, he also did an overall review of the paper from an academic perspective. VT and his team conducted E-Flows assessment and provided inputs to the appropriate section. PS reviewed and analyzed the farmer data and developed top-line messages emerging out of the mammoth data that was generated as part of farmer surveys and he provided inputs to appropriate section. RK did an overall review of the paper and provided contextual inputs and suggestions related to irrigation projects and related aspects. RV and his team conducted farmer surveys across two irrigation systems and the farmer's arguments are built on that data.

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Securing Environmental Flows Through System Reoperation and Management: Lessons From Case Studies of Implementation

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Water-management infrastructure, such as dams, diversions, and levees, provides important benefits to society, including energy, flood management, and water supply, but this infrastructure is a primary cause of the decline of freshwater ecosystems and the services they provide. Due to these declines, recent attention has focused on improving the environmental performance of water infrastructure, such as modifying the location, design, or operation of infrastructure to maintain or restore environmental flows. Despite growing attention to the importance of environmental flows, and continued advancement in flow assessment methods, implementation of flow protection or restoration has lagged expectations. In this paper we describe how pursuing environmental flows at the scale of infrastructure systems, rather than individual sites, such as a dam, offers two pathways to increased implementation of environmental flows. First, policy and management mechanisms that apply to large areas—river basins or political jurisdictions—can catalyze large-scale implementation of flow protection or restoration. We provide two examples of system-scale policy and management mechanisms: flow protection policies and system-scale hydropower planning and management. Although system-scale policy and management offer a clear path to large-scale implementation, there will continue to be a need for flow implementation that occurs at smaller scales, such as a high priority river reach. The second pathway focuses on implementation at that scale—such as environmental flow releases from a dam or small set of dams—but embeds dam reoperation or site-scale flow implementation within reoperation of the larger systems of resource management within which the dam or ecosystem is located. These systems of resource management can encompass various sectors and here we provide examples of dam reoperation or flow implementation facilitated by solutions that included changes to the management of (1) water supply systems; (2) floodplains; and (3) irrigation systems. We illustrate both of these system-scale pathways through a set of case studies, drawn primarily from North America, each of which includes an example of current implementation.

Keywords: river restoration, water management, environmental flows, hydropower, dam removal

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INTRODUCTION

Rivers and river-dependent ecosystems, such as floodplains and estuaries, support immense biological diversity and productivity. They also are among the most important ecosystems for providing economically and socially important services to people, such as fisheries, flood-recession agriculture, regulation of water quality and quantity, and attenuation of floods (Costanza et al., 1997; Opperman et al., 2017b). Although water infrastructure, such as dams and levees, provides important benefits such as hydroelectric energy, flood management, and water supply, this infrastructure can also degrade freshwater ecosystems by disrupting connectivity and altering the movement of water, sediment and organisms through river basins. Due to this fragmentation, river-floodplain disconnection, and flow alteration, water infrastructure is one of the primary contributors to the dramatic global declines in freshwater biodiversity and the loss of ecosystem services such as fisheries (Tockner and Stanford, 2002; UNEP, 2010; McDonald et al., 2012).

Due to these declines, growing attention has focused on improving the environmental performance of water infrastructure, such as implementing environmental flows that maintain or restore the flow regime of a river or other aquatic ecosystem (Poff et al., 2017). The flow regime has a strong influence on freshwater ecosystem processes and consists of the pattern of water discharge or level over time including events such as low flows, small floods, and large floods (Poff et al., 1997; Postel and Richter, 2003). Environmental flows can be implemented by managing water withdrawals or diversions, changing operations of a dam, or by other changes to the design or siting of infrastructure, including policies or decisions that maintain free-flowing conditions on a river.

Despite growing attention to the importance of environmental flows, and continued advancement in flow assessment methods, implementation of flow protection or restoration has lagged expectations (Horne et al., 2017). This paper reviews the potential for system-scale approaches to increase the rate and geographic scope of implementation of environmental flows. We consider two system-scale pathways. First, policy and management mechanisms that apply to large areas—river basins or political jurisdictions—can catalyze widespread implementation of flow protection or restoration (Duane and Opperman, 2010; Poff et al., 2010). Examples of these mechanisms include regional flow protection policies and system-scale hydropower planning and management. Although system-scale policy and management mechanisms can promote large-scale implementation of flow management, there will continue to be a need for environmental flow implementation that occurs at smaller scales, such as a high priority river reach. The second pathway focuses on implementation at that scale—such as environmental flow releases from a dam or small set of dams—but embeds flow implementation within reoperation of the larger systems of resource management within which the dam operates and/or the ecosystem is located (Richter and Thomas, 2007). These systems of resource management can encompass various sectors including water supply, flood, and floodplain management and irrigation.

We illustrate both of these system-scale pathways through 10 case studies, drawn primarily from North America, each of which includes an example of current implementation.

SYSTEM-SCALE POLICY AND MANAGEMENT

Implementation of Regional Flow Protection Standards

Poff et al. (2010) noted that only a small fraction of river kilometers worldwide has environmental flow protections in place. Given the rapid development of water infrastructure and growing extraction of water, they asserted that regional approaches to setting environmental flow standards (e.g., for scales ranging from large river basins to countries) would accelerate the designation of these flow standards at a pace and geographic scope commensurate with the management need. The Ecological Limits of Hydrologic Alteration framework (ELOHA; Poff et al., 2010) is a flexible framework for determining scientifically based environmental flow recommendations at a regional scale. ELOHA draws on existing hydrologic and biological information and rests on the premise that, although each river is distinct, many exhibit similar environmental responses to flow alteration. Therefore, scientists can determine flow-ecology relationships for groups of ecologically similar rivers, rather than for one river at a time.

Translating these regional flow recommendations into implementation requires corresponding policies to establish flow standards for specific river reaches based on their ecological condition goals, similar to how many water quality programs regulate contaminant concentrations according to water quality attainment goals. Below we provide two case studies of system-scale flow protection policies (one at a sub-national level and one at a national level) that have implemented flow protection based on regionally determined flow standards.

Connecticut—Regionalized Dam Operating Rules

Regionalizing environmental flow management has the potential to minimize environmental impacts of new developments, direct development to less sensitive areas, and prioritize flow restoration efforts (Poff et al., 2010). Several states within the United States are accomplishing these objectives through new streamflow criteria or standards, expressed as limits on hydrologic alteration (Kendy et al., 2012). Streamflow standards, which apply to water bodies, are implemented as operating rules that apply to dams or as withdrawal permits that apply to water users (Kendy et al., 2012).

Generally, water withdrawal limits protect existing streamflow from future development. In contrast, restoring depleted flows may require additional policies, such as Oregon's Conserved Water Statute, which explicitly re-allocates water saved through conservation measures to environmental flow (Aylward, 2008; Kendy et al., 2018).

Streamflow standards that regulate dam operating rules can both protect and restore streamflow. A 2005 statute required the Connecticut Department of Energy and Environmental

Protection (DEEP) to develop environmental flow regulations for all 4,386 kilometers of rivers and streams in the state while also providing for secure water use. The process was informed by a policy advisory committee, a Commissioner's advisory committee and a technical advisory committee, along with formal public comments. The process was accompanied by high-visibility advocacy campaigns and culminated in 2011 with the issuance of final regulations (Smith, 2012).

The regulations contain three primary components: (1) narrative streamflow standards that apply to all rivers and streams; (2) a goal classification process, which associates every stream segment in the state with one of four environmental flow standards that it must meet; and (3) detailed reservoir operating rules, called release requirements, associated with each goal class (Connecticut Department of Energy Environmental Protection, 2017). The regulated reservoirs primarily store domestic water supplies.

Narrative streamflow standards describe four stream condition classes ranging from Class 1, which is free-flowing, to Class 4, which is substantially altered to meet human water needs. Dams on Class 4 river reaches are required to achieve Class 3 conditions to the best of their ability. A stream condition goal classification is assigned to each stream and river reach by DEEP through a detailed public process, accounting for 18 specific factors, such as the presence of sensitive species, existing water withdrawals, and existing and planned development upstream of the reach. To date, two of the state's five river basins have formally adopted stream condition goal classifications.

Reservoir release requirements mimic natural conditions. The advisory committees adapted the ELOHA framework to develop the requirements, using flow-response curves for fluvial-dependent species in the northeastern United States (Vokoun and Kanno, 2009, 2010; Armstrong et al., 2010, 2011). Water suppliers used a Safe Yield Wizard (Vogel et al., 2007) to calculate impacts of proposed release requirements on the amount of water available to supply customers. Dams on Class 1 streams may not actively manipulate reservoir storage. Dams on class 2 streams must release at least 75% of their reservoir inflows at all times, thereby maintaining some degree of natural flow variability. Release requirements for dams on class 3 streams, which include almost all dams of any significant size, depend on the time of year (bioperiod, or biologically based season lasting from 1 to 4 months) and whether inflows are low or high. Inflow levels are defined as a function of average inflows over the preceding 2 weeks (Smith, 2012).

Release requirements are expressed as bioperiod exceedance probabilities, rather than as volumetric discharge, so they apply consistently to the entire regulated community, while acknowledging that different types of streams vary in their flow characteristics. For example, the relative volume of a Q95 flow (discharge that is exceeded 95% of the time) of a high-baseflow river differs substantially from that of a flashy river (Smith, 2012).

Exceptions to the regulations ensure water reliability for communities and flexibility during drought. For example, the regulations allow for time-limited release reductions to ensure that public water suppliers maintain an adequate margin of safety. Release requirements also can be reduced during drought, in concert with implementation of water-use restrictions. Critical to the regulations' acceptance was a provision that dam operators have 10 years from the time from which a stream is classified until they must fully comply with the regulations (Smith, 2012). This gives water providers sufficient time to make structural modifications to dams and/or to find additional supplies if necessary.

In practice, about 23 major dams and reservoirs are changing their operations because of the regulations (David Sutherland, The Nature Conservancy (TNC), personal communication). Just as importantly, the regulations ensure that thousands of river kilometers will always have environmental flows.

Despite progress in the science and practice of environmental flows, the vast majority of global rivers remain unprotected from flow alteration (Poff et al., 2010). Meanwhile, pressure on rivers from water infrastructure and extraction is increasing. Through a transparent, inclusive policy process, Connecticut has implemented environmental flows for every river and stream in the state in a timeframe and at a cost comparable to environmental flow implementation for some individual river reaches.

Environmental Water Reserves in Mexico

Mexico's National Water Law was passed in 1992 and has language requiring "sustainable extraction." However, for the first 15 years following its passage, the Water Law did not translate into formal management of river flows in Mexico. At the start of the last decade the National Water Commission (CONAGUA) sought to clarify water availability and water rights, finding that water consumption exceeded 40% of mean annual flow in eight of CONAGUA's 13 hydrological administrative regions, an area representing 75% of Mexico's Gross Domestic Product (Barrios et al., 2015).

In 2005, the Gonzalo Río Arronte Foundation (FGRA) and WWF-Mexico formed an alliance to explore new water management models for Mexico, including an assessment of how environmental flows could be determined and managed at the national scale. Pilot studies were conducted in three basins that spanned the range of hydrological conditions in Mexico: the Conchos, San Pedro-Mezquital, and Copolita-Zimatan-Huatuculco basins. From this project, FGRA and WWF proposed to CONAGUA a "norm," or standard, for determining environmental flows (Barrios et al., 2015).

The environmental flow standard emphasized a set of scientific principles rather than requiring specific methods for determining environmental flow levels. The standard also recommended a three-level hierarchical approach to match the intensity of methods to the degree of certainty required. Further, the standard was based on a concept of maintaining balance between flow protection and water use, with the balance set along a continuum determined by the value of environmental resources and the level of demand for water (Barrios et al., 2015). The Mexican environmental flow standard was published in 2012 and ratified in 2017.

To translate environmental flow determinations into improved water management and protection of flows, FGRA and WWF joined with CONAGUA and the National Commission of Natural Protected Areas (CONANP) to launch a National Water Reserves Program (NWRP). The goals of the NWRP were to: (1) establish a national system of water reserves; (2) demonstrate that water reserves could support healthy river functions; and (3) build capacity in Mexico to implement environmental flows (Barrios et al., 2015). The concept of "water reserves"—a set volume of water dedicated to a specific use such as urban water supply—was used to establish an "environmental water reserve" (EWR), defined as an annual volume of water that must be left in the river to support ecological function and not available for allocation to any other purpose, similar to the 'ecological reserve' concept pioneered in South African water law (King and Brown, 2006).

Under the NWRP, a team of scientists conducted a study of Mexico's 730 river basins to identify candidate basins where an EWR could be established relatively quickly and where government and stakeholders could develop experience implementing environmental flows. Further, the early establishment of an EWR in these basins could allow these basins to avoid the overallocated condition common to many regions in Mexico. Criteria included the proportion of water still available, water demands, the presence of infrastructure projects and the presence of natural protected areas and Ramsar sites (Barrios et al., 2015). Through this process, 189 candidate basins were identified in 2011 (**Figure 1**; Harwood et al., 2017).

A system was established to formalize EWRs. An environmental flow proposal is developed at the basin scale following the environmental flow standard. The flow proposal is then evaluated and discussed through formal consultations with water management entities and the general public, resulting in a Technical Justification Study that CONAGUA provides to the Executive Branch as a recommendation. Based on this recommendation, an Executive Decree can formally establish an EWR (Barrios et al., 2015). In September 2014, the first EWR was formally established for 11 basins that are sub-basins within the San Pedro-Mezquital Basin. Demonstrating that the EWR can influence decisions about infrastructure and flow management, the environmental review process for a hydropower dam on the San Pedro was halted because it would not have been able to be operated in a manner consistent with the EWR (Harwood et al., 2017).

The Government of Mexico is now pursuing one of the largest programs to establish environmental flow protections in the world. The Mexico National Water Plan 2013–2018 calls for the establishment of 189 water reserves that, due to hydrological connectivity, could reach up to 356 basins that represent 40% of the national territory. WWF is now presenting the Environmental Water Reserve concept as a model and is working with partners to promote water reserve policies in other countries in Latin America (Bolivia, Colombia, Ecuador, Guatemala, and Peru; Harwood et al., 2017).

System-Scale Planning and Management of Hydropower

Hydropower currently provides 16% of global electricity generation and global hydropower capacity is projected to increase by at least 50% by 2050 (International Energy Association, 2014). Although hydropower provides low-carbon energy, representing the majority of renewable electricity generation, the dams associated with hydropower can cause substantial negative impacts to the environmental and social resources of rivers (World Commission on Dams, 2000; Scudder, 2012). For example, hydropower dams can alter the flow regime of rivers and serve as barriers to migratory aquatic species.

In the context of hydropower, environmental flows can be protected or restored through a range of mechanisms, including: (1) planning for new hydropower that incorporates flow standards into decisions about siting and operation to ensure that new dams and reservoirs are consistent with the standard. In terms of siting, this can include requirements that a river, or section of river, remain free-flowing (i.e., free of dams); (2) reoperation of existing reservoirs to reduce hydrological alteration and release environmental flows; (3) strategic removal of dams to restore free-flowing conditions to a river. Below we review system-scale approaches to hydropower planning and management that can be used to implement environmental flow management across large areas (e.g., the scale of a country).

National Relicensing Policy to Implement Environmental Flows From Existing Dams

In the United States, non-federal hydropower dams (i.e., those owned by a state government or private company) are regulated by the Federal Energy Regulatory Commission (FERC), created by the Federal Power Act of 1920. FERC issues 30–50 year licenses to hydropower projects and, prior to license expiration, projects must undergo a relicensing process. The FPA was amended in 1986 with the Electric Consumers Protection Act (ECPA) which required FERC to give "equal consideration" to conservation and recreational uses of rivers alongside hydropower production (Gillilan and Brown, 1997). Following passage of ECPA, the periodic relicensing of projects provides an opportunity to reassess their impacts and benefits and to ensure that projects comply with new regulatory requirements issued since the previous license was granted, such as the Clean Water Act (CWA) and Endangered Species Act (ESA). During relicensing processes, other Federal agencies, such as the U.S. Fish and Wildlife Service, have "conditioning authority" through which they can issue conditions that FERC must incorporate into a license (Pollak, 2007), including conditions that require changes to project design (e.g., a retrofit to include a fish passage structure) or to its operation (e.g., the release of environmental flows).

In addition to this legal role for agencies, relicensing processes also provide a formal role for consultation with stakeholders including non-governmental organizations (NGOs) that represent environmental, cultural, or recreational interests (e.g., NGOs that represent anglers and boaters). The FERC licensing process has continued to evolve, and dam operators now generally pursue a new license through the Integrated Licensing Process (ILP), which is structured to promote consistent engagement of agencies and stakeholders throughout the process. Under the ILP, most relicensing processes now culminate in a settlement agreement—a legally binding instrument that is negotiated and signed by a licensee and parties that generally include federal, tribal and/or state agencies and NGOs. A settlement agreement describes the terms for the

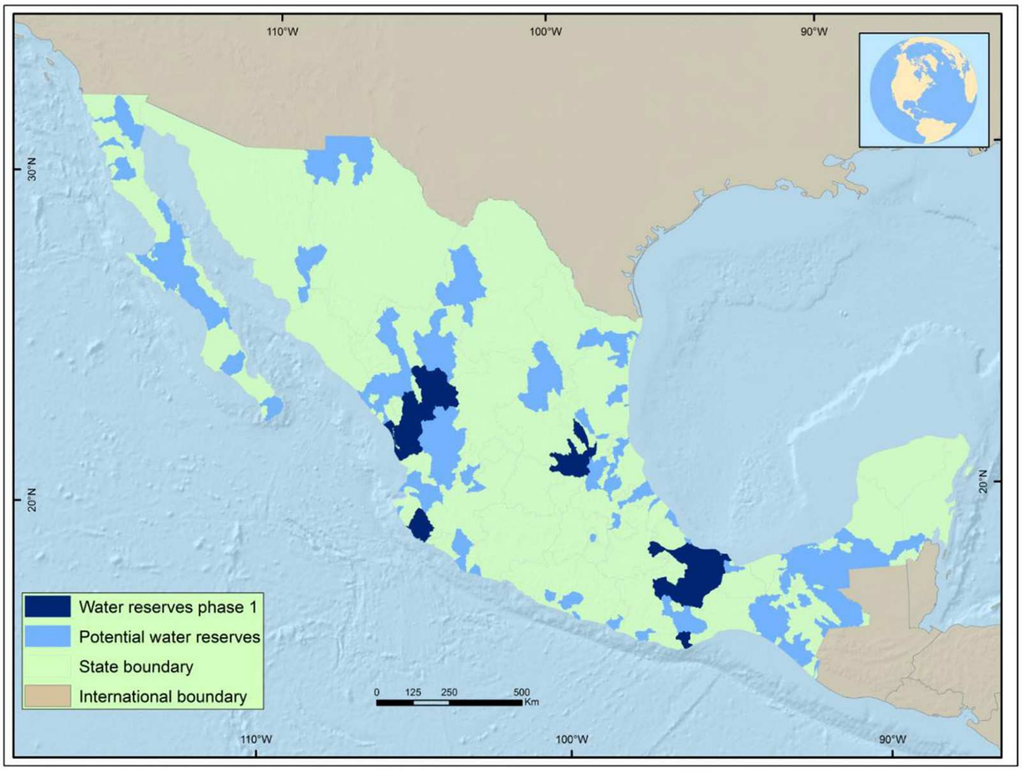

FIGURE 1 | Initial and potential water reserves in Mexico.

license, including components such as required dam operations and environmental flows (Hydropower Reform Coalition, 2005).

Environmental flows are a common mitigation requirement of renewed FERC licenses. Schramm et al. (2016) reviewed 309 licenses issued between 1998 and 2013 and found that the most common category of mitigation focused on how projects manage hydrology, with 82% of the licenses requiring environmental flows (most of the exceptions were projects for which an environmental flow would not be appropriate, such as projects within an irrigation canal or projects added to a federally owned dam where the flow regime is set by the federal agency, not by the licensee). Nearly 40% of the licenses stipulated that the project would be operated as "run of river" (outflow equals inflow), though note that some definitions of run of river allow for within-day storage and peaking operations. Among the projects not categorized as run of river, most of the environmental flow requirements were for minimum flows with relatively few requirements to manage ramping rates (∼11% of licenses) or for flood or "flushing" flows (∼6% of projects).

Through the FERC relicensing process, nearly all non-federal hydropower projects in the United States will have some degree of environmental flow management, and that management will continue to be revisited every few decades. Although studies do not yet exist to provide general results or trends on the environmental performance of flow requirements under FERC licenses, a number of individual results show the potential for improved environmental and social outcomes. For example, on the Roanoke River (Virginia and North Carolina, USA), a settlement agreement for a FERC license was signed in 2017 that formalized a new flow regime, based on the results of an adaptive management research program (Pearsall et al., 2005), to improve ecosystem conditions in the river and floodplain. In the Skagit River (Washington, USA), FERC conditions for license renewal required adjustments to hydropower dam operations to improve spawning habitat for salmon, resulting in a significant increase in successful spawning (Connor and Pflug, 2004). Nationally, a number of projects that previously were operated for peaking were moved to run of river operations following relicensing; Jager and Bevelhimer (2007) review 28 cases of this change.

Finally, evidence suggests that these are not isolated examples. The Hydropower Reform Coalition (HRC) is an umbrella organization for NGOs that engage in relicensing processes across the U.S. According to the HRC's website, they have signed on to 200 settlement agreements, representing 20,000 MW of hydropower capacity. Through these settlement agreements, HRC-member NGOs have pursued improvements to flow regimes, fish passage, and other environmental improvements. As described below, the FERC relicensing process has been used to catalyze dam removal and some projects show the potential of relicensing being used to trigger system-scale management of a river basin.

Dam Removal to Restore Free-Flowing Rivers

The United States Federal Energy Regulatory Commission has asserted the right to require a dam to be removed if it is in the public interest (Bowman, 2002), with the prominent example of Edwards Dam on the Kennebec River (Maine, USA). In other cases, dam owners have decided that the mitigation conditions required for license renewal, particularly for fish passage, were too expensive and so they pursued options for dam removal; examples include the Sandy River (Oregon, USA) and the Klamath River (California, USA). On the Penobscot River (Maine, USA) the FERC relicensing process was used to implement a basin-scale solution to balancing hydropower generation with dam removal to restore free-flowing river conditions. This section explores how the FERC relicensing process can be applied at a system scale to catalyze dam removal and restoration of free-flowing rivers.

The Penobscot River basin (22.3 million hectares) is the largest in Maine and second largest in the Northeastern United States. Migratory fish—including Atlantic salmon and American shad—provided the primary source of protein for the Penobscot Indian Nation and, following European settlement, supported a large commercial fishing industry. Beginning in the 1820s, dams began to be developed on the Penobscot with observers recording immediate negative impacts on migratory fish: "a great many shad and alewives lingered about the dam and died there, until the air was loaded with the stench" (Foster and Atkins, 1869). In 2000, the National Marine Fisheries Service listed the Penobscot River run of Atlantic salmon as endangered under the U.S. Endangered Species Act.

Individual dams on the Penobscot underwent numerous relicensing processes in the twentieth century but these were contentious and failed to resolve conflicts between migratory fish and hydropower generation. Early in the twenty-first century, PPL Corporation acquired the major dams on the Penobscot mainstem and, by replacing multiple dam owners with a single owner, creating the enabling conditions for a broader solution. Diverse parties negotiated the major conservation and energy issues; these included PPL Corporation, the Penobscot Indian Nation, the state of Maine, the Department of the Interior (Bureau of Indian Affairs, US Fish and Wildlife Service, National Park Service), and five non-profit conservation organizations (American Rivers, Atlantic Salmon Federation, Maine Audubon, Natural Resources Council of Maine, and Trout Unlimited). In October 2003, the parties reached a conceptual agreement to balance hydropower generation and restoration of migratory fish habitat, and a year later, filed the Lower Penobscot River Comprehensive Settlement Accord with FERC. The major components of the accord included dam removal and fish passage projects to restore free-flowing rivers and fish habitat, changes to the design, and/or operation of remaining dams to maintain hydropower generation, and new licenses for PPL's dams. Under the Accord, PPL granted to the newly formed Penobscot River Restoration Trust ("the Trust") a 5-year option to purchase three dams for ∼US$25 million and the Trust subsequently exercised that option. The Trust is composed of the Penobscot Indian Nation and the five conservation NGOs involved in the negotiation, with TNC joining the Trust in 2006.

By 2013 two mainstem dams had been removed (**Figure 2**). The power plant at a third dam was decommissioned and, in 2016, a "nature-like" fish bypass, which physically mimics a stream, was completed to allow even weak-swimming fish to move both upstream and downstream past the dam (the dam remained because the local community preferred current river levels above the dam). PPL also committed to improving fish passage at other remaining dams in the basin. Following completion of dam removal and fish passage improvements, the accessible network of large river and stream channels will increase by an order of magnitude: from 60 to 615 km (**Figure 2**; Opperman et al., 2017a). Some fish populations have shown an immediate response to the increased habitat with river herring numbers increasing to 600,000 in 2015 and 1.8 million in 2016, 135 times greater than before the dam removals (Miller, 2015). Species such as salmon will require greater time to respond to the new habitat but, based on the increase in connected habitat, biologists estimate that Atlantic salmon will increase from a few thousand to 12,000 (Opperman et al., 2011).

In addition to these dramatic increases in fish and fish habitat, the agreement will at least maintain the previous level of power generation from the Penobscot and PPL's projections indicate that total generation from the basin may increase after the project (Opperman et al., 2017a). The generation lost due to dam removal will be offset through several changes to design and operation of remaining dams that were approved under the new licenses.

In the section "National Relicensing Policy to Implement Environmental Flows From Existing Dams", we characterized FERC relicensing, a national policy, as a system-scale mechanism to promote widespread implementation of environmental flows. FERC relicensing was the national policy context for the Penobscot restoration. However, by addressing most of the major infrastructure within a river basins, the Penobscot project showed the potential for FERC relicensing to also function as a mechanism to promote reoperation of a system, such as a river basin, similar to mechanisms described in section "Implementing Environmental Flows by Reoperating A System." To date, the Penobscot is one of the few examples of where FERC relicensing has been applied to multiple projects in a coordinated manner to achieve results at a basin scale. Opperman et al. (2011) and Opperman et al. (2017a) offer a range of recommendations for how FERC relicensing can be adapted to promote basin-scale solutions. Owen and Apse (2014) describe how policies for environmental trading could be applied to allow system-scale solutions that balance power generation with dam removal and restoration of free-flowing rivers.

The potential gains, in terms of protecting or restoring environmental flows, from system-scale mechanisms to reoperate basins (e.g., through FERC relicensing or environmental trading) are quite large. For example, Kuby et al. (2005) investigated the potential to expand salmon habitat in the Willamette River basin (Oregon, USA) through dam removal. They modeled various removal options from among 150 dams in the basin and quantified tradeoffs between power generation, water storage and the length of connected channel network accessible to salmon. They reported that removal of only 12 dams could reconnect 52 percent of channel length in the basin with a loss of <2 percent of the basin's hydropower and water-storage capacity. This situation—in which a relatively small proportion of hydropower capacity causes a high proportion of the fragmentation of a basin's channel network—is likely common in many basins

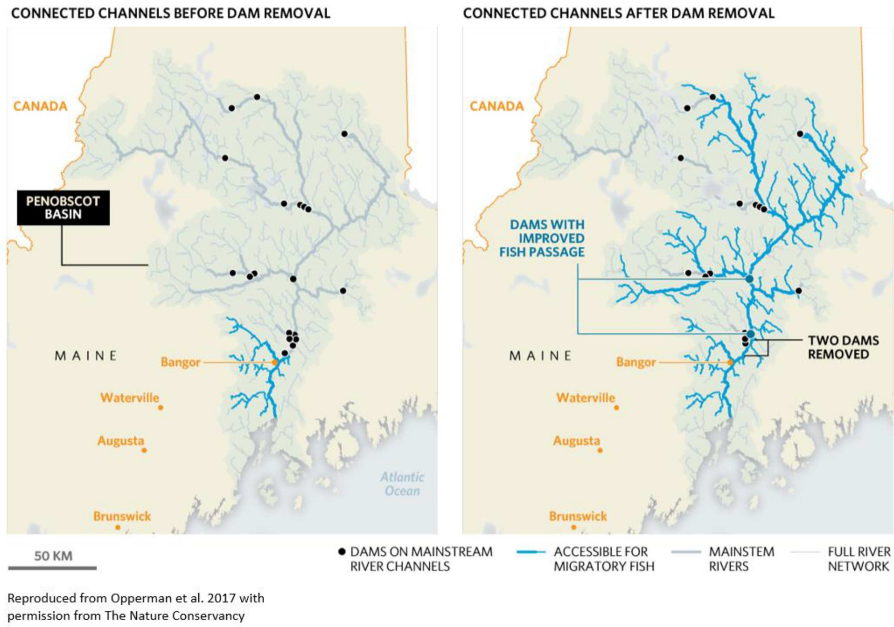

FIGURE 2 | The Penobscot River (Maine USA) and the length of channel accessible to migratory fish before and after dam removal. Reproduced from Opperman et al. (2017a) with permission from The Nature Conservancy.

around the world, particularly those with a legacy of smaller and older dams. In the Duero basin (Spain), small hydropower dams are responsible for most of the disconnection while contributing very little to the total generation from the basin (Mayor et al., 2017). The data from these basins suggest that considerably large restoration gains could be achieved through strategic dam removal with relatively small losses in generation and/or water storage and thus that policy mechanisms that promote dam removal through system-scale relicensing, mitigation, or environmental trading could produce large benefits in terms of restoring free-flowing conditions in rivers.

Planning for New Hydropower to Incorporate Environmental Flow Protections

Economic growth is driving an increase in dam construction in the later-developing world including a rapid expansion of hydropower (Zarfl et al., 2015). Although development of water-management infrastructure can help countries meet important objectives for water and energy, a proliferation of new dams could lead to significant negative impacts to river ecosystems and people that depend on them, particularly because the current expansion of dams is occurring primarily in those river basins with the greatest diversity of aquatic species and highest productivity of fish harvests (Opperman et al., 2015, 2017a) which provide livelihoods and food security to millions of rural people (Richter et al., 2010). Opperman et al. (2015) found that the projected hydropower development by 2050 could fragment or alter flows, or both, on 300,000 km of river channel worldwide.

Policies that promote system-scale planning of hydropower could reduce impacts on rivers while achieving targets for renewable energy. Opperman et al. (2015, 2017a) describe a framework for system-scale planning, Hydropower by Design (HbD), which is defined as "a comprehensive and system-scale approach to hydropower planning and management that fully integrates other economic priorities and environmental and social issues from the earliest stages to promote sustainability and optimize delivery of benefits." HbD influences environmental flow management by guiding decisions on siting (where future dams are developed and where free-flowing conditions are maintained) and design and operation. Opperman et al. (2015) conducted global modeling of projected hydropower development to 2040 and found that widespread application of HbD could reduce impacts on connectivity and flow on approximately 100,000 km of river channel globally. Opperman et al. (2017a) provide more detail on the technical, policy, and planning mechanisms that can be used within HbD and a set of case studies that show how application of HbD can result in greater length of free-flowing rivers or implementation of environmental flows during dam development within a basin. Several of the case studies demonstrate that these balanced outcomes for energy and environmental benefits can also produce economic benefits for countries, through better coordination of infrastructure investments, and financial benefits for developers and investors, primarily through improved risk management.

There are few applied examples of this comprehensive approach to system planning. The Mexican Environmental Water Reserves program (described in "Environmental Water Reserves in Mexico") illustrates how a regional to national environmental flow management scheme can provide some of the outcomes associated with hydropower system planning. For example, where relevant, new infrastructure proposals, such as a hydropower dam, must demonstrate that the construction and operation of the proposed project can be consistent with a designated Environmental Water Reserve (EWR). In some cases, the EWR may influence license conditions (e.g., design or operation requirement to ensure consistency) for a project that goes forward. If a project cannot be managed in a way consistent with the EWR it may be halted, such as was the case for the proposed dam on the San Pedro, described in the section "Environmental Water Reserves in Mexico". In this way, application of the EWR can influence infrastructure siting and operation decisions, illustrating that incorporation of flow standards into infrastructure planning and licensing could be a vehicle for widespread implementation of environmental flow management.

National policies for hydropower planning and development in Norway illustrate several of the mechanisms and potential benefits and outcomes of system-scale planning for hydropower. Hydropower provides nearly all (99%) of Norway's electricity and most of its large rivers have been dammed. By the 1970s, Norway had developed approximately half of its estimated hydropower potential and proposals to construct new hydropower projects began to generate opposition from environmental organizations, indigenous groups, and other stakeholders. Managers and political leaders recognized that a project-by-project approach to hydropower development could not effectively resolve conflicts and identify options that balanced the diverse values of the country's rivers (Huse, 1987). In response, Norway passed a set of policies encompassing river protection and hydropower site selection that collectively created a system-scale framework that guides how hydropower is developed and managed.

Through several legislative actions in the 1970s and 1980s, Norway established a national Protection Plan for Watercourses and a Master Plan for Water Resources. The Master Plan incorporated economic, social, and environmental criteria into a method for ranking individual hydropower projects with a goal of minimizing impacts on other resources for a given generation target. Based on these rankings, the Master Plan included a category for high impact projects that would not receive regulatory approval. The Protection Plan for Watercourses identified a set of rivers to be protected that, along with the Master Plan's identification of areas that could not be developed, has grown to include nearly 400 rivers or parts of rivers. The basins of these protected rivers encompass 40% of Norway's area and represent ∼25% of Norway's hydropower potential (Stensby and Pedersen, 2007). Norway's national policies that govern hydropower planning have reduced conflict over hydropower and illustrate how a system-scale approach to infrastructure planning and licensing can catalyze large-scale protection of free-flowing rivers.

IMPLEMENTING ENVIRONMENTAL FLOWS BY REOPERATING A SYSTEM

Although national policies can promote widespread implementation of environmental flows, flow management at the site-scale, such as a river with high conservation values or competing economic sectors, will remain necessary in many places. A wide variety of constraints can limit the ability to achieve environmental flow implementation at a site, such as reoperating a single dam to restore flow to a section of river (Konrad, 2010). The range of environmental flows that a dam can release can be limited by the economic purposes for which the dam was built; for example, if implementation would impact existing water rights or power purchase agreements. Overcoming constraints for implementation at a site may thus require moving beyond reoperation of a dam and/or site-scale flow implementation to "reoperation" of the larger management systems in which the dam or ecosystem is located (Richter and Thomas, 2007). In the case studies below, we explore how reoperation of systems of water storage, irrigation, and flood and floodplain management can facilitate the implementation of environmental flows.

Coordination of Multiple Dam Operations

Expanding beyond a single dam to a cascade or system of dams can increase the likelihood of overcoming constraints to environmental flow implementation. By considering more than one dam, water managers can take advantage of a greater range of options and synergies. This case study (summarized from Konrad, 2010) examines how coordination of dam operations on the Yakima River (Washington state, USA) facilitated environmentally beneficial reoperation without impacting water-management objectives in a way that would not have been possible with a single dam (Konrad, 2010).

The Yakima River is a tributary to the Columbia River that supports endangered salmon populations. Spring snowmelt runoff in the Yakima River basin is stored in dams operated by the U.S. Bureau of Reclamation (the Bureau), such as the Cle Elum Reservoir, for release during the irrigation season. These irrigation releases result in elevated flows through the summer and early fall. Salmon begin to spawn toward the end of the irrigation season and the elevated flows induce salmon to build redds (sites where eggs are buried in gravel for incubation) along channel margins that will become dry as soon as the flows drop at the end of the irrigation season. Preventing the de-watering of redds would require dropping flows to their stable, fall low-flow levels before salmon begin to spawn and prior to the end of the irrigation season, interfering with the primary purpose of the Yakima system of water storage and delivery.

To prevent redd de-watering while maintaining irrigation deliveries, the Bureau developed an approach that required coordinated operations of two dams. Just prior to salmon spawning in the Upper Yakima, the Cle Elum Dam drops its release of water to stable low-flow levels that can sustain spawning throughout the incubation period. As releases from the Cle Elum drop, Tieton Dam on the Tieton River, a tributary to the Yakima, greatly increases its flow release level to meet irrigation demand in the lower Yakima. This so-called "flip-flop" coordinated operation achieves the fulfillment of both environmental and water-supply goals with a solution that could not have been achieved at a single dam (**Figure 3**). The Bureau developed this solution in response to a Federal court decision in 1980 that supported the treaty rights of the Yakima tribe to retain access to salmon for harvest (MacDonnell, 1999).

Modeling results from other basins provide further support that moving from a single dam to a system of dams increases

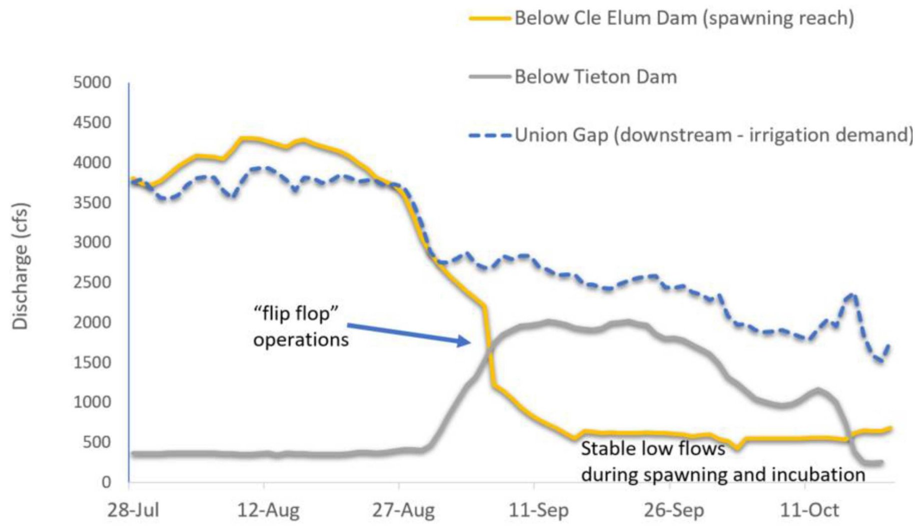

FIGURE 3 | The “flip-flop” hydrograph produced by coordinated management of reservoirs in the Yakima River basin (Washington, USA). Chinook salmon spawn in the upper reaches of the Yakima River, below Cle Elum Dam, beginning in early September. Under previous management, flow below Cle Elum Dam would remain high in September, to support irrigation in the lower river, and then begin to decline as irrigation demand declines. However, this pattern of flows would expose and dry out salmon redds along the river margin that were laid in September. Under the new coordinated management, the Cle Elum reservoir rapidly reduces discharge (beginning late August) to reach a stable flow level that can persist throughout the spawning season (mid-September to mid-October for the year shown, 2012). At the same time, discharge from the Tieton Dam increases so that the flows in the downstream section with irrigation demand can remain higher through September, before declining in October [Flow data from USGS gage 12500450 (Union Gap) and US Bureau of Reclamation: Yakima River at Cle Elum and Tieton River below Tieton Diversion Canal].

management flexibility and can increase the likelihood of implementing environmental flows while maintaining, or even improving, the primary designated purposes of the dam system. Lee et al. (2010) investigated optimization of hydropower and flood control within the system of dams on the Colombia River, including modeled changes to hydrology from climate change. They found that, compared to fixed *status quo* flood control release curves, optimized release curves for a system of dams could allow for increased generation while maintaining equivalent levels of flood-risk management. Further, under these optimized release curves, more water would be available in the system in the later summer for flows to maintain fish habitat. Modeling reoperation options for a cascade of dams on the Tana River (Kenya) identified options that could increase hydropower generation and the release of flood flows that could benefit downstream floodplain fisheries and livestock grazing (Opperman et al., 2017a; McCartney, in preparation).

Integration of Water Management Sectors: Dam Operation, Water Allocation, and Irrigation Supply

Dams are not the only cause of flow alteration, nor is dam re-operation the only solution. In over-allocated systems, environmental flow implementation means reducing water withdrawals, potentially at the expense of water-dependent economic production. Case studies are emerging, however, which demonstrate that win-win solutions can be found by integrating water management sectors. In our first example, environmental flows were secured for the Colorado River Delta (Sonora and Baja California, Mexico) through a combination of water markets and international diplomacy and delivered through a combination of dam and irrigation infrastructure re-operation. In our second example, Whychus Creek in Oregon, USA, irrigation infrastructure upgrades benefited farmers while providing environmental flows.

Colorado River Delta

Diversions from the Colorado River and its tributaries irrigate more than 50 million acres (20 million hectares) of cropland and supply water for 40 million people in the US and Mexico, most of whom reside outside the basin. As a result, the river rarely reaches its once-productive delta and estuary. What remains of the delta’s riparian corridor is a dry, sandy channel flanked by desert, punctuated by patches of remnant riparian habitat maintained by irrigation drainage (**Figure 4**).

In the late 1990s, a coalition of NGOs mobilized to restore riparian habitat along the corridor, which is a critical stopover for migratory birds along the Pacific Flyway (Pitt, 2001). Restoring the riparian habitat would require delivering more water to the channel and riparian corridor. But, with climate change exacerbating water shortages in the already over-allocated basin, water users and managers did not support dedicating scarce water to ecosystem restoration. A system-scale approach was required both to acquire the necessary water and to deliver it to the river and delta.

By the 2000s, water levels in Lake Mead, the largest reservoir in the United States, were declining rapidly, raising concerns among water users and decision makers across the basin. Mexico,

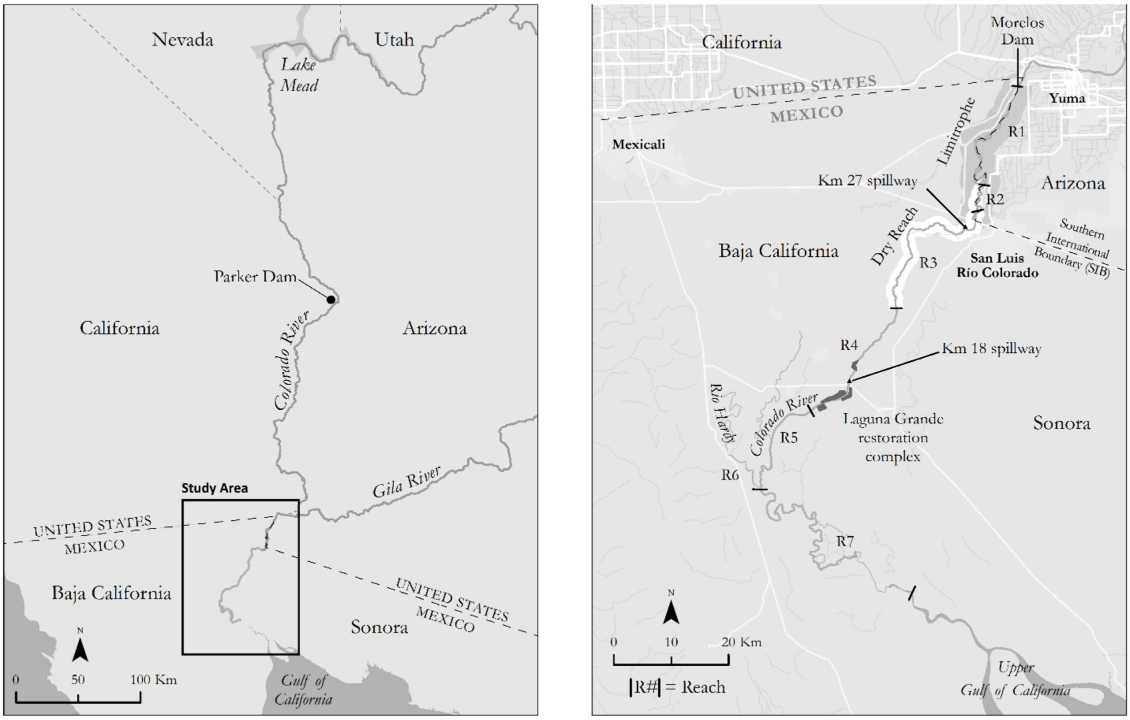

FIGURE 4 | Riparian corridor in the Colorado River delta. Under Minute 319, environmental water was delivered to the river via Morelos Dam and Kms 18 and 27 canal spillways. Modified from Pitt and Kendy (2017) and used with permission from the authors.

which by treaty receives a set 1.5 million acre-feet (1.85 cubic kilometers) of Colorado River annually, was critical to a solution, but historical distrust between the US and Mexico precluded productive negotiations. The NGOs conducted shuttle diplomacy in exchange for a seat at the negotiating table (King et al., 2014). Ultimately, in 2012, the two federal governments signed Minute 319, a binational agreement that established a set of measures to share both shortages and surpluses. Among these measures, the Minute allowed Mexico to store water in Lake Mead and allocated environmental water to restore riparian habitat in the delta (International Boundary and Waters Commission (IBWC), 2012). By addressing system-scale water shortages, delta restoration became part of a basinwide solution instead of an isolated problem.

Because the Colorado River is over-allocated, simply re-operating a dam would not procure new water for the environment. The environmental water had to be acquired from existing users. Minute 319 identified two sources. First, the NGO coalition established a water trust, which purchases water rights from willing sellers in the irrigated Mexicali Valley surrounding the riparian corridor. This water is delivered to the riparian corridor as "base flows" to sustain native habitat. Second, the US and Mexican governments invested in irrigation efficiency projects in the Mexicali Valley, enabling Mexico to reduce its water demands. The water conserved through these projects is stored in Lake Mead; in 2014, some of this water was released as an environmental pulse flow into the delta. Thus, the integration of two water management approaches—water markets and irrigation efficiency improvements—freed up the water for environmental flows.

Finally, delivering the environmental water required a system-scale approach. Minute 319 negotiators envisioned the pulse flow being released from Morelos Dam, on the US-Mexico border. However, the binational science team, which designed and monitored the pulse flow, predicted that releases from Morelos would be too small to traverse a 40 km (25-mile) dry river reach without seeping into the depleted aquifer below. In order for the water to reach targeted restoration sites and to recede slowly enough to maintain growth of riparian seedlings, a portion of it was delivered through irrigation canals that bypassed the dry reach (**Figure 4**; Pitt and Kendy, 2017). In the end, this novel combination of water deliveries via irrigation infrastructure and dam releases was crucial to the pulse flow's success in restoring riparian habitat (Kendy et al., 2017). Improving environmental performance meant re-operating a system; not just a dam.

The benefits of restoring flows to the Colorado River delta ranged from local to binational. Locally, residents in riverside towns enjoyed seeing water in their river, many for the first time in their lives. Surveys indicated resounding support for the pulse flow across genders, age groups, educational levels, and socioeconomic conditions (Kendy et al., 2017). Mexicali farmers, who previously viewed any water in the river as wasted, saw that the river and the farms could share the water. In the US, Mexico's stored water in Lake Mead forestalled a water crisis, giving the

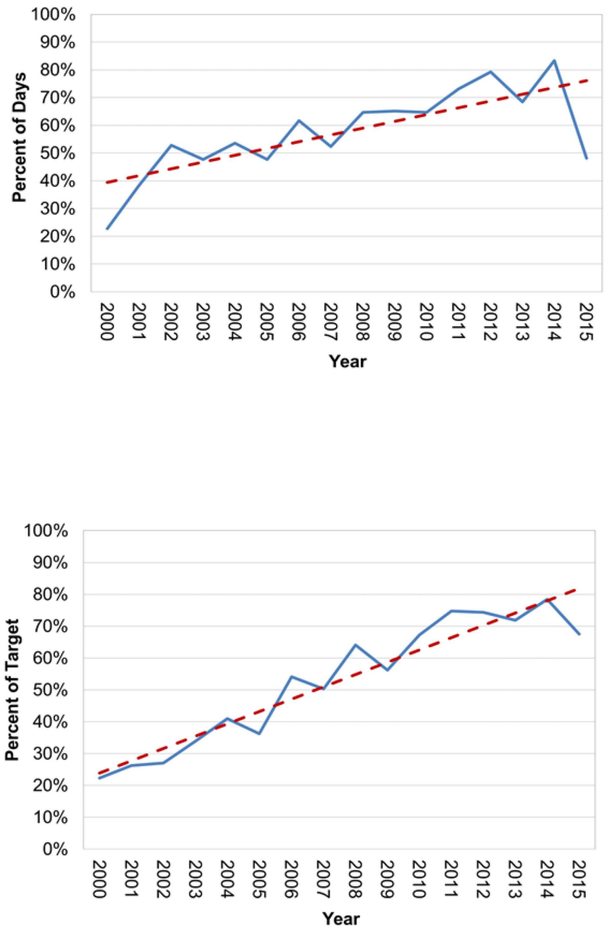

FIGURE 5 | Attainment of the environmental flow target in Whychus Creek, Oregon, expressed as a percent of days per year (above) and as a percent of the target volume (below). Stakeholders established the flow target of 33 cfs (0.93 m^3/s) based on ecological criteria. Dashed lines are linear regressions. Modified from Kendy et al. (2018) and used with permission of the authors.

lower basin states more time to develop comprehensive drought contingency plans.

Whychus Creek

From its glacial headwaters in Cascade Range of Oregon (USA), Whychus Creek flows 35 miles through forested mountains and sagebrush steppe before joining the Deschutes River, a tributary to the Columbia River. Prior to development, natural flows in Whychus Creek supported a diverse assemblage of riverine species, including steelhead trout (*Oncorhynchus mykiss*), now listed as a threatened species under the U.S. Endangered Species Act. However, by 1913, irrigators were granted water rights to divert more than 200 cubic feet per second (cfs) (5.7 m^3/s), exceeding the natural streamflow in dry and normal years. As a result, a 5-mile (8 km) reach of Whychus Creek often ran dry (Aylward and O'Connor, 2017).

Beginning in the 1990s, conservationists engaged local water users in a water transaction program to restore environmental flows. As the largest water right holder on the creek, Three Sisters Irrigation District (TSID) has been an active participant in the program. From 2000 through 2015 the program secured approximately 30 cfs (0.85 m^3/s) of water rights by shifting agricultural diversions to environmental flows in Whychus Creek, at a total cost of USD $17 million. Two-thirds of the water was acquired through collaborations with the TSID to eliminate water conveyance losses by installing pipes in place of ditches and canals and upgrading other irrigation infrastructure, and legally transferring the saved water to instream water rights.

As a result, the attainment of environmental flow goals has increased markedly (**Figure 5**), improving aquatic health in Whychus Creek (Mazzacano, 2015), while simultaneously benefitting irrigators. The conserved water projects upgraded the irrigation district's infrastructure, reducing transmission losses, thereby increasing the reliability of its water deliveries and allowing farmers to maintain crop production while diverting less water. Furthermore, the irrigation district has retained a portion of the water saved by water use efficiency projects, enhancing the security of the remaining irrigation rights.

Several conditions unique to Whychus Creek enabled this win-win solution. First, the physical configuration of the hydrologic system allowed flows to be restored without reducing agricultural water consumption. Historically, irrigation water conveyance losses returned to the creek *downstream* from the dewatered reach of concern to a consistently perennial reach. Therefore, the irrigation conveyance improvements financed by the transaction program enabled irrigators to reduce withdrawals without simultaneously reducing return flows to the dewatered reach. Reducing withdrawals from Whychus Creek left more water in the dewatered reach when it was most needed, without reducing crop production.

Second, Oregon law supports water transaction strategies for restoring instream flow. Unlike most western United States, Oregon allows water users to reduce return flows, even if downstream water users rely upon them. Additionally, Oregon's Conserved Water Statute stipulates that a portion of the water saved through irrigation efficiency improvements must go the environment. Finally, Oregon law allows the rights to saved water to be transferred to high-priority instream flow rights, thereby preventing other users from diverting it for their own use.

Restoring 30 cfs to Whychus Creek came at a relatively high cost ($17 million USD); as in much of the western US there are few opportunities for restoration using low-cost water. By working together, conservationists and irrigators achieved both of their objectives—environmental flow restoration for the environment, and irrigation-supply reliability and economic sustainability for farmers. Although neither sector alone could afford to pay $17 million, the multi-sector, multi-objective nature of the transactions attracted the funding from both private and government sources.

Integrating Environmental Flows With Flood and Floodplain Management

While most cases in this paper focus on various aspects of water management, system reoperation can also encompass land management, incorporating interventions such as increasing irrigation efficiency or groundwater recharge. In this section, we examine how management of floodplains and multipurpose reservoirs can be integrated to enable environmental flow management.

Floodplains are among the most diverse and productive ecosystems on the planet (Opperman et al., 2017b) and floodplain productivity and diversity is influenced strongly by river flows (Opperman et al., 2010). The Brisbane Declaration emphasized that environmental flows can be used to restore floodplains and that implementation of environmental flows may require coordination with floodplain management (Brisbane Declaration, 2007; Arthington et al., 2018).

Opperman et al. (2017a) describe an approach to enable environmental flows, and other benefits, through the reoperation of flood management, including floodplains. Key components of the approach include: (1) reduce reservoir storage allocated to flood management; (2) compensate for the reduction of flood-management storage through investments on the floodplain that will maintain or improve flood safety, relative to the *status quo*; and (3) apply the increased reservoir storage, made available through reduction of flood storage, to produce additional economic and environmental benefits. These economic benefits can include water supply, hydropower generation, or recreation. The environmental benefits can include increasing the frequency of meeting environmental flow objectives.

In 1998, TNC and the U.S. Army Corps of Engineers began collaborating on an environmental flow program for the Green River (Kentucky, USA), a tributary to the Ohio River notable for its high richness of freshwater species, including 151 fish species (12 endemic), and 71 mussel species. Through collaboration of scientists and dam operators, the Corps began implementing a new flow regime that improved habitat conditions, particularly to promote spawning of fish and mussels. To implement environmental flows, reservoir operations at Green River Dam were modified to include (1) a reduction of the flood pool; (2) delaying the drawdown that occurred each autumn, prior to season of higher flood risk; and (3) extending the period of reservoir refilling in the spring. After a program of experimental flow releases, the Corps formalized the new reservoir operation, including environmental flows, through a revision to the dam's water control plan. In addition to environmental benefits, the new operation would extend the recreation season on the reservoir by 6 weeks (Warner et al., 2014).

The integration of floodplain management with reservoir management played a role in the implementation of environmental flows. The Green River Dam's primary purpose was flood-risk management and, to implement the environmental flow regime, reservoir operations needed to change in a way that reduced flood storage. The flood pool was reduced by 1.3 m (meaning the reservoir surface is 1.3 m higher during the season focused on flood management), reducing the flood storage volume by 5%. Further, the new flow regime allowed an increase in the maximum allowed discharge by 20–30% (depending on season) (Warner et al., 2014). Through modeling of reservoir operations and downstream hydraulics, managers realized that a limited number of properties would be affected by the changed reservoir operations. To maintain equivalent levels of flood protection, the Corps, TNC, and partners carried out targeted and voluntary floodplain acquisitions and easements downstream of the reservoir, through a mix of public and private funding. Through this process, changing the management of specific floodplain parcels increased the operational flexibility of the dam and facilitated the release of environmental flows (Warner et al., 2011).

The Green River example illustrates how changed management on a floodplain can facilitate reservoir reoperation. In that case, the change in floodplain management was relatively simple, involving only a few properties. Implementation at larger scales would require considerably more complex and extensive changes in floodplain management. Opperman et al. (2017a) and The Nature Conservancy (2012) summarize research on potential large-scale implementation of this concept for the Yangtze (China), Savannah (Georgia and South Carolina, USA), and Mokelumne (California, USA) rivers.

RECOMMENDATIONS AND CONCLUSIONS

In the developed world, nearly all large rivers have been affected by water-management infrastructure (Nilsson et al., 2005) and infrastructure is expanding rapidly in parts of the later-developing world (Zarfl et al., 2015). While infrastructure is an important foundation of modern economies and poverty reduction, it is also a primary contributor to the decline of freshwater ecosystems and the services they provide to society. Vörösmarty et al. (2010) demonstrated that water security for people increases, and freshwater biodiversity decreases, in direct proportion to the investment in water-management infrastructure. Thus, to achieve economic development that is sustainable, society must find solutions to reduce the environmental impacts of existing infrastructure and to ensure that new infrastructure is built in a way that is as compatible as possible with healthy rivers and the provision of services, such as fisheries.

Maintaining or restoring environmental flows provides a specific example of this challenge. In this paper, we propose that this challenge can best be met by pursuing solutions at the scale of systems rather than the scale of individual projects. System-scale approaches include policies and practices that integrate flow protection into planning and regulatory and management regimes. Through these policies and practices, environmental flow management can be implemented through management (e.g., the release of environmental flows from dams or restrictions on diversions) or by directing new development away from rivers with natural flow regimes (e.g., free-flowing rivers). Mexico's Environmental Water Reserves and national hydropower planning in Norway both illustrate how environmental objectives can be integrated into infrastructure planning, environmental review, and licensing to protect the natural flow regime in undammed rivers.

In addition to policies and practices that can achieve impact at large scales, there will remain a need for strategies focused on managing flow regimes at specific high priority sites. System-scale solutions can also catalyze implementation at the site scale, such as securing flow releases from an individual dam, through strategies that look for solutions at the scale of the overarching management systems within which an individual dam operates. For example, improving flood-risk management within a floodplain can increase the management flexibility of an upstream reservoir and improve its ability to release environmental flows. Management focused on irrigation efficiency or the trading of water allocations can also free up water that can then be used to achieve a flow restoration objective.

The case studies presented here share several themes. First, the system scale affords a broader set of potential solutions than could have been achieved at a single project such as a dam. Not only does this allow for more meaningful environmental restoration, these solutions also often achieve conservation outcomes without compromising the management purposes of the infrastructure.

Second, these balanced outcomes are often possible through spatial partitioning within a river basin, with some locations supporting conservation objectives and some supporting more intense management. For example, Konrad (2010) notes that the "flip flop" flow management within the Yakima system increases flow distortions on the Tieton River. However, this flow distortion in one location of the basin allows a more beneficial flow regime in the upper Yakima, which supports the most valuable spawning habitat in the basin. The Penobscot Project resulted in removal of the dams that posed the greatest challenge to fish migration, leaving these areas as unfragmented rivers that prioritize natural flow and fish habitat, while a dam on a side channel, with much lower impacts on migratory fish habitat, emphasizes hydropower and increases energy generation. The conceptual foundation of hydropower by design supports this spatial partitioning by identifying those locations that should be avoided and those locations where dam development is more appropriate.

Although this paper features a number of applied examples, implementation of environmental flows—at site or system scales—lags expectations and objectives, due to a variety of constraints. Below we describe these constraints while offering several recommendations to overcome them and to promote broader implementation.

Recommendations

Tailor Technical Requirements and Level of Data Needed for the Specific Context

One of the constraints to broader uptake of regional flow protection standards (see section "Implementation of Regional Flow Protection Standards") is that these processes are viewed as being data intensive and overly complicated. However, as demonstrated by the case study on environmental water reserves in Mexico (Environmental Water Reserves in Mexico) and an application of ELOHA that guided flow policy for the Susquehana River Basin Commission (DePhilip and Moberg, 2010), regional flow protection standards can be based on relatively simple approaches, where appropriate. Another article in this special issue (Opperman et al., 2018) focuses on how implementation of environmental flows can be facilitated by processes that tailor the methods and level of data required to the specific context.

System-Scale Approaches Require Conveners Who Can Overcome Siloed River Management

River management is often characterized by fragmented authority of agencies or other parties that do not communicate or collaborate effectively. Processes to explore and implement new system-scale approaches will require an organization, or organizations, that can overcome this fragmentation and convene the necessary agencies and stakeholders. This convening role can be played by non-governmental organizations, as demonstrated by WWF for environmental water reserves and TNC for state flow protection standards (section "Implementation of Regional Flow Protection Standards").

Embed System-Scale Approaches Within the Policy and Regulatory Framework for Water Resource Management

A clear mandate within the water resource regulatory framework provides managers with the tools and structures to implement system-scale approaches for environmental flow implementation, such as water allocation rules that require protection of environmental flows. As demonstrated with water reserves in Mexico, integrating these protections into allocation rules and then implementing them in places that are not yet in conflict over allocation provides a path to proactive and widespread uptake of flow protections.

Implement Periodic Relicensing of Existing Hydropower Projects to Integrate Environmental Flows Into Existing Hydropower Projects

In most countries with mature systems of hydropower, there is little opportunity to revise operations, other than through litigation or specific legislation. Periodic relicensing, such as that administered by FERC in the U.S., is an example of a policy that can compel widespread reoperation of existing facilities, including implementation of environmental flows (see section "System-Scale Planning and Management of Hydropower"). In certain cases, relicensing can trigger dam removal and the restoration of free-flowing conditions on rivers. Overall, relicensing allows for a rebalancing of river management objectives within systems that have already been developed, and, though generally focused on individual projects, relicensing has the potential to achieve system-scale objectives (Opperman et al., 2011). However, relatively few countries currently require periodic relicensing of hydropower projects. Pittock and Hartmann (2011) recommend broader uptake of relicensing to increase the sustainability of hydropower and to increase dams' resilience to climate change.

Multilateral Institutions Can Promote System Planning for New Infrastructure

The regions of the world undergoing rapid development of water-management infrastructure, including dams, encompass many countries in which the governments have relatively low capacity for planning or regulating. In these situations, development generally occurs on a project-by-project basis, with projects selected by developers based on their access to a site and financing. With limited government capacity for planning and licensing, other mechanisms are needed to promote system-scale and strategic infrastructure planning and development. For example, multilateral financial institutions can fund mechanisms such as an early planning facility or Strategic Environmental Assessment (SEA) to provide a system-scale framework which can inform the selection of individual projects, both to achieve sustainable development and to reduce investment risk (Opperman et al., 2017a).

Innovative Financial Mechanisms Can Help Achieve System-Scale Outcomes by Sharing Costs and Benefits Across Stakeholders

Implementing environmental flows by reoperating components of a larger system (section "Implementing Environmental Flows by Reoperating a System") will generally require changes to how costs and benefits are distributed across stakeholders in a system; in other words, there may be winners and losers under the new arrangement, creating barriers to implementation. Overcoming these barriers may require innovative financial mechanisms that can compensate those who will incur costs, potentially paid in part by those who will experience benefits. For example, the environmental flow program at Wychus Creek (Whychus Creek) was facilitated by a mechanism that funded irrigation upgrades for farmers linked to requirements that the saved water would remain in the creek.

The science and practice of environmental flows has recognized the need to move beyond site-specific flow management and toward management of appropriate flow regimes across broad spatial areas, as articulated in the concept of ELOHA (Poff et al., 2010). Ultimately, the best opportunities for meeting demands for energy and water while maintaining healthy rivers and the services they provide will arise through system-scale approaches that coordinate infrastructure location, operations, and the integration of green and engineered infrastructure.

AUTHOR CONTRIBUTIONS

JO conceptualized the paper, was lead author on the Introduction and Conclusions and wrote the case studies on relicensing, dam removal, hydropower planning, the Yakima River, and floodplain management. EK helped conceptualize and edit the paper and wrote the case studies on ELOHA, Connecticut, Colorado River Delta, and Whychus Creek. EB wrote the case study on Water Reserves in Mexico and contributed to the Conclusions.

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