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Environmental flows in the Anthropocence: past progress and future prospects

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Human modification of the global hydrologic cycle through the building and operation of hundreds of thousands of dams and diversions has significantly altered fluvial processes, leading to impairment of river ecosystem function and biodiversity loss worldwide. The concept of environmental flows (e-flows) emerged to mitigate the undesirable hydrological impacts of dams and water diversions, in order to strengthen ecologically informed water management. In this paper, we outline the scientific foundations and progressive development of the current e-flows framework over the last 25 years, identifying three discrete periods in its history: emergence and synthesis, consolidation and expansion, and globalization. We highlight the evolving challenges and audiences that e-flows engages, and discuss the challenges facing the framework during the current period of rapid global change. For e-flows to contribute most effectively to sustainable freshwater management on a global scale, it must, first, move from a focus on restoration to one of adaptation to climate and other environmental change stressors, second, expand its scale from single sites to whole river basins, and third, broaden its audience to embrace social-ecological sustainability that balances freshwater conservation needs with human well-being in both developing and developed economies alike.

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Introduction

The current definition of e-flows is best expressed in the 2007 Brisbane Declaration, which describes 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' (http://www.watercentre.org/news/declaration). The overriding objective of e-flows is to modify the magnitude and timing of flow releases from water infrastructure (e.g. dams) to restore natural [1•] or normative [2] flow regimes that benefit downstream river reaches and their riparian ecosystems [3•,4••]. The general and pragmatic nature of the e-flows concept has allowed for flexibility to encompass a variety of assessment methods and to promote synthesis and convergence of diverse approaches. Arguably, the simple idea of water infrastructure re-operation that is embodied in the e-flows concept must be applied in a scientifically grounded manner and address the realities of complex social-ecological systems, where varied interests compete for limited water sources. A prime motivation for this paper is to describe the origins, consolidation and globalization of the contemporary e-flows framework over the last 25 years, as it has evolved from a relatively narrowly focused aquatic conservation strategy to a rather broad effort toward achieving social and ecological benefits from river management. The challenges facing aquatic ecosystem and biodiversity sustainability are immense, and certainly include factors (e.g. modification of nutrient and sediment flux, thermal pollution, and non-native species) but here we focus solely on hydrologic management and restoration of aquatic systems via the e-flows concept and framework. An additional motivation is to reflect on the challenges that e-flows theory and practice face in a period of rapid socio-economic and environmental change, if it is to be globally implemented and further developed in the future.

A brief history of environmental flows over the last 25 years

The history of e-flows follows closely the rapid expansion of modern dam-building that started to accelerate dramatically in the mid-20th century. Dams are a ubiquitous feature of modern rivers: 45 000 >15 m high in the world [5], with another 75 000 >2 m high in the U.S. alone [6]. These dams modify river ecosystems both locally [7•] and cumulatively at the regional scale [8•]. As more dams have been built, the negative impacts of these structures on riverine ecosystems became increasingly recognized. Advances in scientific understanding and technical tools over this period contributed to shifting conservation and social expectations for how dams might be better designed and operated for diminishing adverse ecological impacts. Here we track this evolution by focusing on the last 25 years as the holistic e-flows concept was developed and applied in practice. We identify three discrete periods of progress. Figure 1 is a simplified illustration of this history, showing approximate timelines, landmark achievements and events, scientific and technical challenges, and participants engaged in the e-flows enterprise during this time span.

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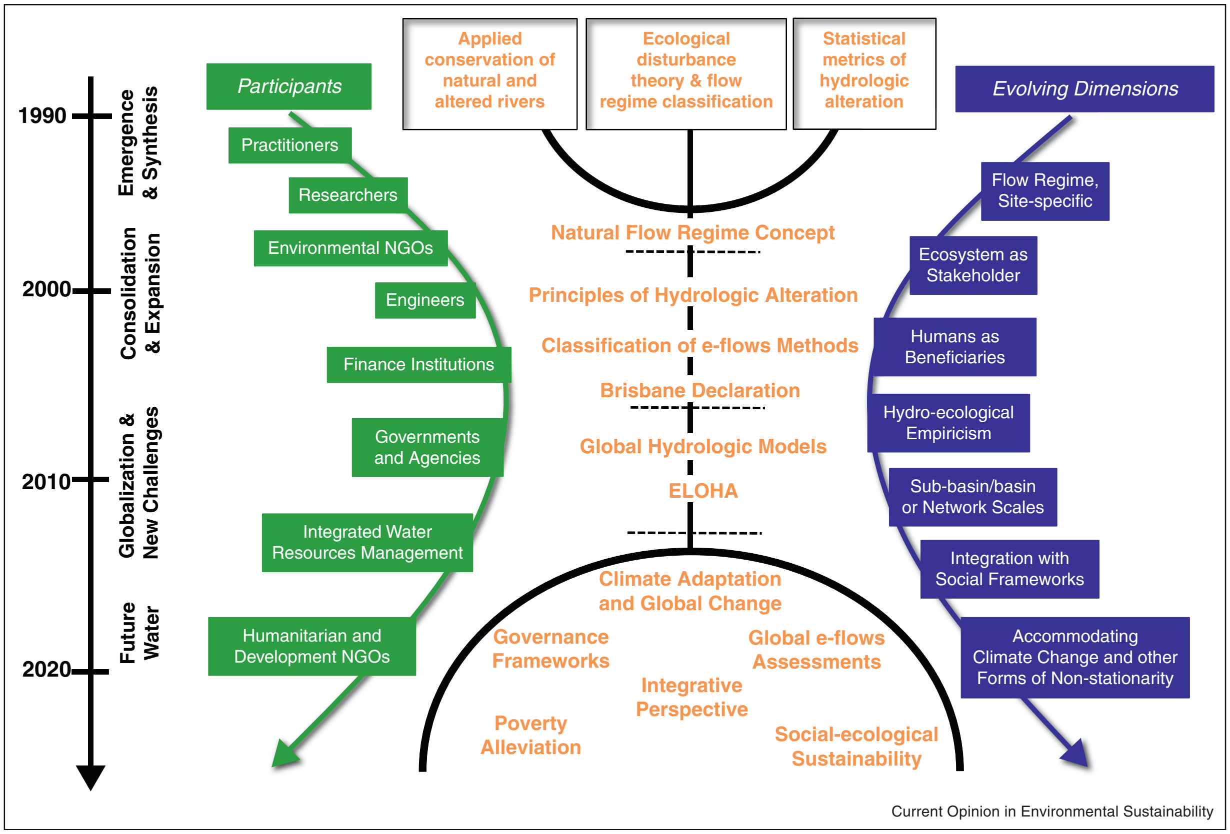
Figure 1



A synoptic history of the environmental flows concept and its application from its emergence in the late 1980s. Timelines are shown that fall into relatively discrete periods of types of activities. Participants engaged in e-flows over time are shown in green, benchmark achievements are indicated in orange, and evolving dimensions of e-flows are shown in blue. NGO = Non-Governmental Organization and ELOHA = Ecological Limits of Hydrologic Alteration.

Emergence and synthesis: late-1980s through mid-1990s

Prior to the 1980s, e-flows was practiced in a 'reductionist' mode of aiming to secure minimum flows for singles species (usually a valued game fish) below individual large dams, mostly in the U.S.A. and western Europe [9,10]. Around this time, ecological theory began to inform resource management generally about the importance of hydrologic dynamics in maintaining ecosystem structure and functions, and how individual species were embedded in webs of interactions mediated by environmental conditions [9,10]. This whole-community and ecosystem perspective developed into the foundation of today's e-flows framework. It can be traced to at least three discrete sources of scientific and conservation activity.

First, applied river conservation by e-flows practitioners in Australia [11] and South Africa [12] began to focus on multiple ecological targets, not just individual species of fish valued by society. These efforts were guided by ecological principles and informed largely by expert opinion. They focused on particular sites requiring restoration or conservation. They contributed fundamentally to the development of e-flows principles and assessment approaches that are still widely used today.

A second source was grounded in academic interest in characterizing the natural flow regime and its role in ecosystems of largely unmodified, free-flowing rivers. This grew from the increasingly recognized role that natural disturbance plays in regulating the structure and function of riverine ecosystems from both ecological [13] and geomorphic [14] perspectives. These principles were then explored in a comparative context to examine how ecosystem structure might vary across broad hydro-climatic and geographic extents. For example, Poff and Ward [15] developed a stream classification system based on multi-site analysis of long-term hydrographs that were decomposed into ecologically relevant flow metrics such as the magnitude, frequency, timing and predictability of extreme flow events (i.e. floods and droughts) that act as natural disturbances critical to maintaining functioning

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riverine ecosystems and native biodiversity. This approach informed theoretical expectations about spatial variation in hydro-ecological relationships and potential evolutionary adaptations of species in rivers differing in disturbance regimes (e.g. snowmelt-dominated versus groundwater-dominated streams). Similar hydrologic classification efforts motivated by ecological considerations developed simultaneously in Australia [16] and New Zealand [17].

A third source reflected an explicit focus on how humans alter natural flows. This activity began in the early to mid-1990s and represented a move toward a unifying approach that bridged academic and pragmatic approaches. In particular, The Nature Conservancy (TNC) in the U.S.A. developed a framework for classifying the *alteration* by dams of ecologically relevant flow variability at individual sites of interest. A pre-impact (pre-dam) flow period representing a benchmark, or reference condition, could be compared to a post-impact time series of flow to quantify the extent of alteration of ecologically relevant flow metrics and thus provide an index of ecological risk [7•,18].

These three perspectives converged during a synthesis period in the mid-1990s with the publication of the natural flow regime concept [1•,18], the normative flows concept [2], and the indicators of hydrologic alteration method [7•], which together encapsulate the basic idea that a range of flows with characteristic magnitude, frequency, duration, timing, predictability and rate of change are required to sustain native biodiversity and ecosystem functions, and that alteration in these key flow regime components leads to ecological modification. These publications established the principle that natural (i.e. recent historical) flow variability is a cornerstone to river restoration. Streamflow was argued to be the 'master variable' (in concordance with ecological disturbance theory). Other factors are well known to be ecologically significant (e.g. sediment transport, thermal regime, geomorphic setting (e.g. [19]) but not so much under the control of managers of water infrastructure and thus less subject to immediate management interventions that could restore downstream ecosystems. Already explicit in the e-flows concept at this stage was the notion that hydrologic alteration impaired ecosystem functions, and hydrologic indices of alteration could be used as proxies of ecological impairment [18].

During this period in the mid-1990s the focus was largely scientific and technical, involving conceptualization and measurement of natural flow variability and dam-induced alteration. The audiences for this effort had been those explicitly engaged in river conservation and ecology, such as academic researchers, restoration practitioners, and environmental NGOs. Most of the activity occurred in developed countries with high scientific capacity and significant water management capacity, such as the U.S.A., western Europe, South Africa and Australia.

Consolidation and expansion: mid-1990s through mid-2000s

Armed with a solid conceptual basis and readily accessible statistical tools to characterize natural and altered flow regimes [7•], scientists and practitioners working on e-flows began to focus on how to manage rivers in an ecologically sustainable fashion. Among the key contributions of this period was the articulation of principles of flow alteration, combined with documented examples of ecological effects that could be understood by water infrastructure managers [3•]. The argument was advanced that ecosystems should be represented as legitimate 'stakeholders' deserving ethical consideration on par with human sectors and livelihoods with ethical 'rights' to legitimate water needs [20,21]. While often not realized in practice, this philosophical position was an important benchmark in advocating for the conservation status of freshwaters. Given the large human imprint on natural systems, sustainability began to be viewed in terms of tradeoffs or the balancing of competing needs of humans and ecosystems [22,23]. Moreover, the audience for e-flows was expanded through popular writing, notably the book by Postel and Richter [24•] that helped elevate public and broad scientific awareness about the loss of freshwater ecosystem integrity and biodiversity globally.

Another extension was the growing engagement of conservation NGOs. For example, new research ties were forged by TNC to engage academics and scientists at federal agencies to collaborate on large site-based river restoration projects through collaboration with the U.S. Army Corps of Engineers. Adaptive management experiments were conducted on the Savannah River in the southeastern United States [25] and the Bill Williams River in Arizona [26]. These efforts built on the ground-breaking experimental releases on the Colorado River in 1996 [27]. TNC also engaged the U.S. Army Corps of Engineers in a national plan to re-operate large dams for environmental benefit (see http://www.nature.org/ourinitiatives/habitats/riverslakes/sustainable-rivers-project.xml). Other international NGOs and conservation organizations, such as the International Union for Conservation of Nature (IUCN), began to embrace the concept of e-flows, particularly through application in emerging economies [28]. The World Wildlife Fund (WWF) and Conservation International (CI), by increasingly developing expertise in aquatic conservation and sustainable freshwater management (including climate adaptation [29]), also helped to expand the reach of e-flows [30].

The NGO interest in e-flows facilitated engagement with institutions involved at national, sectorial, and global applications of water resources development and operation. This in turn facilitated incorporation of the

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e-flows concept into policy statements around the financing of large dams in the developing world (e.g. [5,31,32]). Academics began to see e-flows as a new and potentially powerful policy tool that could be formally incorporated into established approaches to watershed management, such as Integrated Water Resources Management [33].

As the momentum of the e-flows concept grew, new research and management interests were engaged. Water resources engineers began to explore how dam operation schemes might be modified based on flow alteration principles to allow for downstream ecological benefit beyond minimum flows [34–37]. Scientists at U.S.A. federal agencies began to engage in research on flow alteration. For example, the U.S. Geological Survey invested resources in research embracing the e-flows-concept [38–40], suggesting a growing profile for the science underlying sustainable management at the governmental institutional level in the U.S.A. Governments began to apply e-flows principles to large, complex river systems, such as the Murray-Darling in southeastern Australia [41]. Concerns over water shortage and environmental sustainability in Australia gave rise to the eWater Cooperative Research Centre (CRD) in 2005 with 'the backing of the Australian Government, and leading water industry and research organizations through the CRC Program' (http://www.ewater.com.au/uploads/files/2011-eWater-brochure.pdf). This program continues to address water allocation problems in arid Australia.

The consolidation and expansion period culminated with the 2007 Brisbane Declaration. This event, held at the 10th annual Brisbane *RiverSymposium*, brought together more than 800 scientists, engineers, resource managers, economists and policy makers from 57 countries. A declaration of the principles of e-flows was ratified, noteworthy for its articulating the linkages between ecological sustainability and social well-being. Thus, e-flows had expanded beyond a relatively narrow conservation agenda to a broad social-ecological sustainability perspective that could be applied in a range of governance settings. Indeed, initial applications of e-flows moved beyond developed countries into emerging economies despite their more limited institutional capacity [42,43].

Globalization and new challenges: mid-2000s to present

With global awareness of e-flows growing, major new audiences were engaged, such as global hydrologic modelers and regulatory institutions. New challenges arose as well, including expanding the scale of e-flows from individual dams to regional and basin-wide planning scales and infusing more ecological empiricism in the science.

The understanding that the global hydrologic cycle is markedly influenced by humans [44,45] facilitated new ecohydrologic activities through hydrologic models used to evaluate integrated environmental threats on a global scale. These models were employed to address questions of water stress and the tradeoffs between water supply for agricultural water demand and supply to natural ecosystems [46], the implications of climate change and human population growth for management of regulated versus unregulated rivers [47], and the implications of multiple stressors on human water security and biodiversity conservation in the world's rivers [48•]. A few models explicitly evaluated climate and water management alteration of ecologically important flow components such as timing and duration of peak flows [49••], thus laying a foundation for future global-scale assessments of flow alteration that integrate hydrologic and ecological information. During this period, databases were assembled that allowed assessing the effects of dams on global river flow [50], sediment capture [51], and river ecosystem fragmentation [52]. These efforts culminated in the assembly of global databases of the world's large dams (e.g. [53]).

A major scientific challenge during this period arose as academics and practitioners began to re-examine some of the basic scientific assumptions used in e-flows practice, such as the strength of evidence for ecological response to specific types of hydrologic alteration [54,55] and biological adaptations to historic flow variability [56]. A need for solid empirical grounding behind the assumed ecological impairments associated with degrees of flow alteration was recognized. Developing explicit relationships between ecological responses to flow alteration was deemed necessary to enhance the scientific credibility of the enterprise. Arthington *et al.* [57••] articulated this position and proposed a method to classify flow regimes based on natural patterns of historic variation (cf. [15]). This approach allows for a scientifically rigorous method to support flow standards for streams and rivers that lack extensive historical hydrologic and ecological data.

This perspective captured a large cross-section of the global e-flows community (academics, NGOs, agency scientists) who collaborated to produce a synthesis on e-flows science and practice, dubbed the Ecological Limits of Hydrologic Alteration (ELOHA) [4]. The ELOHA framework called for hydrologic modeling of entire river networks, classifying river segments into ecologically relevant types based on flow metrics, hypothesizing testable ecological responses to flow alteration for river types (defined by flow regime and geomorphic setting), and explicitly considering societal preferences for ecological conditions as part of flow management strategies. This framework was intended to be applied at the regional (multiple river) scale in a variety of governance contexts. Applications have been growing, especially in the U.S.A. [58] and usefulness of the framework is also tested in Spain [59], China [60], and

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Australia [61]. However, the data demands for empirical grounding of the framework and the challenges and perceived costs of implementing e-flows based on empirical data have revived some interest in promoting prescriptive flow standards that reflect allowable flow deviations, based on historical (pre-impact) conditions and presumed ecological alteration that modifies ecological function or biodiversity (cf. [18,62]). The firm establishment of the global reach of e-flows theory and practice was documented in this period by special journal issues [63••,64•] and an academic book [65].

The future of environmental flows

Over the last 25 years e-flows has unfolded to encompass a wide range of ecological, social and economic goals. Speculation about the future of e-flows in the coming decades is enticing, if necessarily selective and risky. What seems clear is that e-flows is now expanding and transitioning from an era of aquatic conservation and ecological integrity to a period of explicit 'social-ecological sustainability.' This transition is attended by new challenges and emerging audiences and users, with contrasts made stark both by future management constraints in the face of continuing large-scale environmental and societal change and by the emerging center of water resources development and activity in countries with rapidly developing economies. Here, we identify four challenges that are already being addressed and that appear to be most significant to ensure future success of e-flows.

Global environmental change and climate adaptation — the scientific challenge for e-flows

Changes in flow in the future, whether from climate-mediated hydrologic change or increasing human demands and management of water systems, will require adaptation by society to attain desirable and economically acceptable ecological endpoints. Research on adaptation is just beginning but suggests that climate change is likely to drive future water infrastructure development and could soon play a globally significant role on modifying freshwater ecosystems, primarily through further alterations of flow regime [66•,67,68].

The basic scientific principles underlying the current e-flows framework, as now widely used, are rooted in two fundamental assumptions. First, from a hydrologic and water-management perspective, the belief in a stationary climate (i.e. statistically repeatable properties of the Holocene) has ruled water-resources management for decades, but this assumption has been undermined by the realization of rapid climate change [69,70]. Second, the view among conservation ecologists that natural systems persist within a range of variation in ecological states and process rates (effectively, a dynamic equilibrium) may be giving way to the perspective that restoration to some 'reference' or 'natural' state is problematic [71], due to rapid global environmental change and the spread of non-native species, resulting in both cases in a sense that restoration limited value as a management target. Together, these perspectives deeply challenge the validity of using historical data to predict future hydrologic and ecological conditions.

In short, the historic hydrologic foundations and conservation or restoration goals at the heart of the e-flows concept need to accommodate a new set of targets that reflect a non-stationary world of shifting hydro-ecological baselines. A goal of hydrologic restoration to achieve past reference ecological states risks failure. In practical terms, e-flows as a management strategy will need to become more attentive to how *a priori* flow prescriptions are determined, given that natural hydrology is changing, due to global change agents such as land use change and urbanization, consumptive water uses such as agricultural diversion, and hydrograph modification through river regulation by dams. Setting meaningful hydrologic targets for conservation purposes will require sound and perhaps new scientific underpinnings of how resistant and resilient different ecosystem states and ecological processes are to changing combinations of flow alteration. The e-flows framework needs to evolve to consider a range of potential future hydro-ecological conditions (i.e. a set of scenarios) rather than defining achievement of a single future situation as success. Climate change presents society with choices about how to respond with management and operations — retarding or buffering impacts, tracking change through time, or anticipating and facilitating transitions to new ecological states and adaptively updating management actions through time. A strong, flexible, and vigorous scientific framework is needed to best navigate between these alternative decisions.

This is most pressing in the developing world, where new construction of water management infrastructure is proceeding at a pace comparable to that in western Europe and North America during the mid-twentieth century. The Mekong basin alone has more than 80 dams in process [72•], while the Himalayas have over 300 [73] and the Andes more than 150 [74]. Here, and elsewhere, there may be options for *designing* or *staging* infrastructure for multiple e-flows regimes rather than developing these regimes through the lens of re-operation. This will require the e-flows framework to expand its limited site-specific focus to a broader spatial context of whole basins [75•,76], where tradeoffs relevant to freshwater biodiversity conservation and direct human water use can be evaluated in a more sophisticated spatial and connectivity context. Some early efforts toward basin-scale approach are already under way [68,72•,77–79]. The e-flows approach must find credibility in these new contexts with policy makers and stakeholders.

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Global modeling of e-flows

As global hydrologic models become increasingly sophisticated, progressively finer spatial and temporal resolution of river flow will become available. These hydrologic simulations can be used to address questions of flow alteration in streams and rivers around the world and to guide the development of basin-specific environmental flow requirements [80••]. These simulated flows will be directly useful for application in an e-flows context if they capture the seasonal and short-term variation in the hydrology of ungauged rivers. We need to evaluate the sensitivity of different components of the flow regime to projected climate change and to particular kinds of human interventions in the hydrologic cycle. Attention must also be paid to other sources (beyond climate change) of non-stationarity, such as land use practices and increasing human demand for freshwater and other resources.

Modeling these responses will allow for mapping river vulnerability to climate change and other human-derived environmental change. Hydrologic models linked to other global databases, such as floodplain extent and fish species diversity [81,82], can provide insights into how future flows will be translated into ecological responses and human well-being, across a range of governance contexts [83].

Global analyses that show the intersection of water stress; agricultural, industrial and personal human demand; ecosystem services; management of dams; regional vulnerability to climate change; *et cetera* can be used to inform water infrastructure planning and development. They can also be used to show where ecosystem service provision is greatest or where aquatic and riparian biodiversity is likely to find refuge. This kind of information can guide global conservation efforts and inform what kinds of management interventions or infrastructure design are needed. The e-flows framework can act in these contexts to integrate on-the-ground planning efforts with global biodiversity conservation strategies.

Incorporating e-flows in governance context

During the 20th century, public concern in the developed countries grew with increasing awareness of the ecological changes associated with dam construction. A key question has been (and remains) whether the transition to public concern over environmental tradeoffs associated with dam construction in the developing world will be sufficient to lead to a widespread implementation of e-flows. In regions such as the Mekong, for instance, transboundary issues are negotiated politically (e.g. Mekong River Commission: http://www.mrcmekong.org/) but much of the environmental voice is currently carried by international NGOs. Application of an e-flows framework can play an important role in helping the transition to local and regional advocacy for social-ecological sustainability to enable economic development and maintain livelihoods in such regions. An additional challenge is that the funding sources for infrastructure commonly used in the 20th century (e.g. the World Bank) have provided at least some safeguard mechanisms on environmental constraints on these investments in the past as part of procurement requirements, but whether these will persist in the future with new investors is unclear.

One of the means of gaining broader societal understanding of the importance of and acceptance of e-flows may be to shift the focus to a more integrative perspective on issues surrounding the water-food-energy planning and policy discussions [84]. This can help develop river basin (network) scale approaches to balancing demands, environmental needs, and infrastructure implementation through an e-flows lens.

E-flows as vehicle for poverty alleviation and social-ecological sustainability

A critical hurdle for e-flows to become implemented in much of the developing world will be transforming the framing of e-flows practice beyond a perceived focus on narrow environmental issues to an approach that supports the poor. A clearer articulation of the co-benefits of e-flows in simultaneously supporting economic development while protecting biodiversity and key ecosystem functions should underpin national development strategies. In part, these transitions in perspective and justification for applying e-flows also reflect an extension of the e-flows concept to new audiences, similar to the transitions of many conservation groups toward sustainable development through the valuing of fisheries [72] and various ecosystem services [85]. E-flows theory and practice will likely be most successful if integrated with social and economic metrics such as the Millennium Development Goals [86] and subsequent Sustainable Development Goals [87] to reduce poverty and create a sustainable future. Importantly, the Sustainable Development Goals include targets for fresh water security and biodiversity conservation that can be regionally calibrated within an e-flows framework. Thus, NGOs and government agencies concerned with humanitarian, health, and sustainability objectives may well be the next major advocates for e-flows.

Conclusion

Since its emergence as a holistic perspective, the e-flows concept has shown a remarkable track record of consolidation, expansion, globalization and now transition. Managing rivers, their floodplains and entire watersheds for balanced human and ecological goals is a principle that has become embraced globally by scientists, NGOs, water managers and various policy and government institutions. The broad aspirations of the e-flows enterprise make it a complex undertaking, to which spatial variation in climatic and physiographic settings, in human-environment

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interactions and governance contexts, and in projected changes in water supply and demand all contribute. One size cannot fit all, but the guiding principle of flexible water resources management to sustain ecosystems and people alike, as embodied in the e-flows framework, should continue to resonate. The Anthropocene poses monumental and growing management challenges to achieve meaningful aquatic conservation targets along with social-ecological sustainability, but the energy and creativity that has characterized the last 25 years of developing the e-flows framework suggests that it can carry forward into the coming decades as the ecohydrological status and services of the world's river ecosystems will increasingly depend on how humans make decisions about their value and use.

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