Environmental Reviews

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Accelerating environmental flow implementation to bend the curve of global freshwater biodiversity loss

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Abstract

Environmental flows (e-flows) aim to mitigate the threat of altered hydrological regimes in river systems and connected waterbodies and are an important component of integrated strategies to address multiple threats to freshwater biodiversity. Expanding and accelerating implementation of e-flows can support river conservation and help to restore the biodiversity and resilience of hydrologically altered and water-stressed rivers and connected freshwater ecosystems. While there have been significant developments in e-flow science, assessment, and societal acceptance, implementation of e-flows within water resource management has been slower than required and geographically uneven. This review explores critical factors that enable successful e-flow implementation and biodiversity outcomes in particular, drawing on 13 case studies and the literature. It presents e-flow implementation as an adaptive management cycle enabled by 10 factors: legislation and governance, financial and human resourcing, stakeholder engagement and co-production of knowledge, collaborative monitoring of ecological and social-economic outcomes, capacity training and research, exploration of trade-offs among water users, removing or retrofitting water infrastructure to facilitate e-flows and connectivity, and adaptation to climate change. Recognising that there may be barriers and limitations to the full and effective enablement of each factor, the authors have identified corresponding options and generalizable recommendations for actions to overcome prominent constraints, drawing on the case studies and wider literature. The urgency of addressing flow-related freshwater biodiversity loss demands collaborative networks to train and empower a new generation of e-flow practitioners equipped with the latest tools and insights to lead adaptive environmental water management globally. Mainstreaming e-flows within conservation planning, integrated water resource management, river restoration strategies, and adaptations to climate change is imperative. The policy drivers and associated funding commitments of the Kunming–Montreal Global Biodiversity Framework offer crucial opportunities to achieve the human benefits contributed by e-flows as nature-based solutions, such as flood risk management, floodplain fisheries restoration, and increased river resilience to climate change.

Key words: environmental flows, implementation, critical enabling factors

1. Introduction

The Anthropocene is an era of unprecedented pressure on Earth's natural ecosystems. This pressure is particularly acute in freshwater ecosystems where aquatic biota face an extinction crisis caused by a continually growing mix of human-induced threats (Dudgeon 2019; Reid et al. 2019). Calls for action to protect the integrity and biodiversity of freshwater ecosystems—such as rivers and their floodplains, deltas and estuaries, ponds and lakes, and many types of temporary and permanent inland wetlands—have exposed the severity of the problem and stimulated significant conservation and restoration efforts (Speed et al. 2016; van Rees et al. 2021; Lynch et al. 2023). Yet freshwater ecosystem services and the abundance and distribution of numerous aquatic species continue to decline while extinction risks continue to rise (IPBES 2019; WWF 2022). In response to the need for greater recognition of the unique properties and particular requirements of biodiverse freshwater ecosystems, and more effective strategies to mitigate threats to them, Tickner et al. (2020) developed an emergency recovery plan with six key actions to "bend the curve" of freshwater biodiversity loss: (1) accelerate implementation of environmental flows (e-flows); (2) improve water quality to sustain aquatic life; (3) protect and restore critical habitats; (4) manage exploitation of freshwater species and riverine aggregates; (5) prevent and control non-native species invasions in freshwater habitats; and (6) safeguard and restore freshwater connectivity. The recovery plan and its recommendations are aligned with several sustainable development goals and targets of the Kunming–Montreal Global Biodiversity Framework (2022) aiming to restore and recover biodiversity and ensure a world of people living well and in harmony with Mother Earth by 2050.

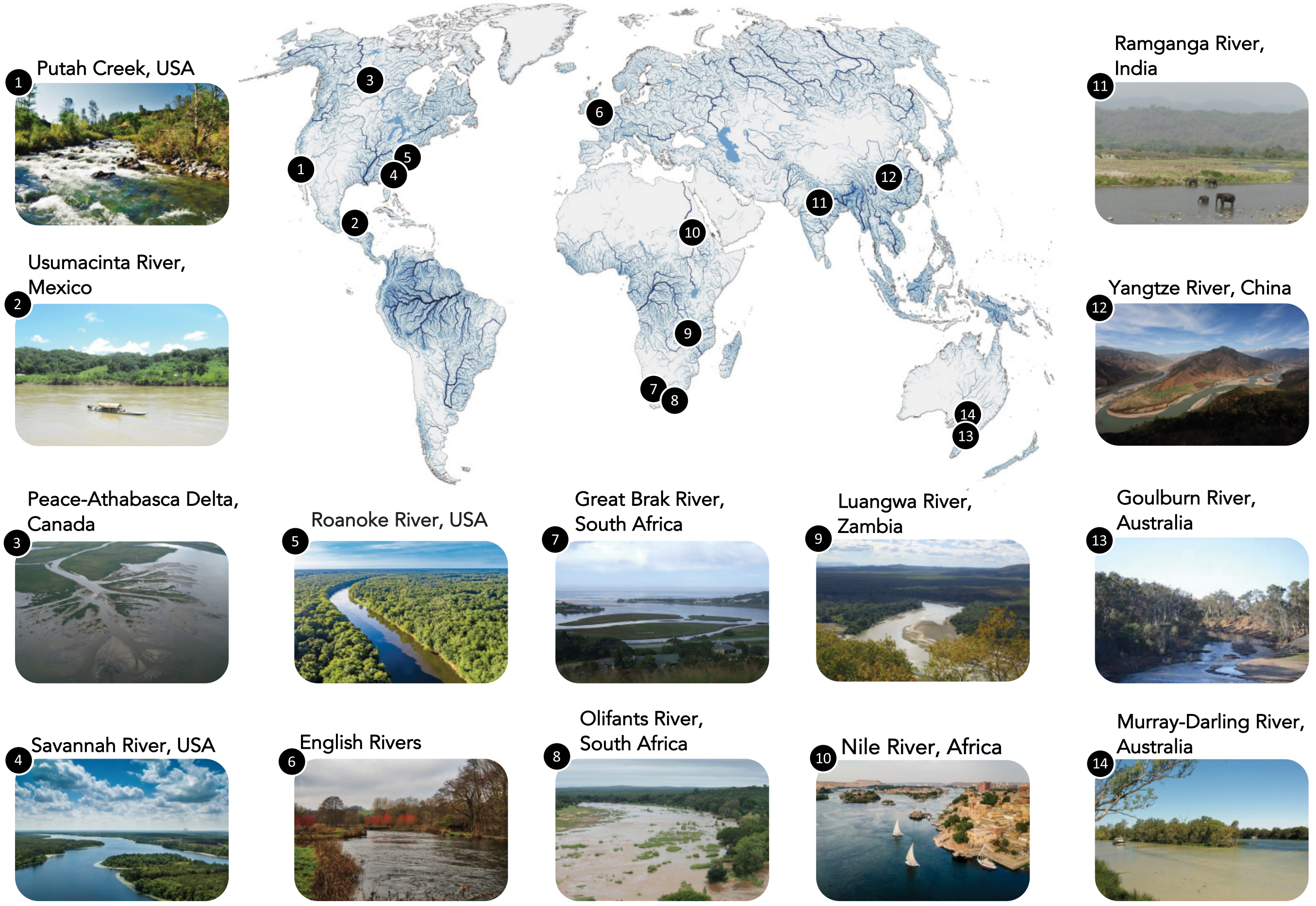
This paper contributes to a Special Section compendium of papers addressing each of the six recovery plan actions. Our focus is *accelerated implementation of e-flows*, an important component of integrated strategies to address multiple threats to freshwater biodiversity (van Rees et al. 2021). E-flows describe "the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems that, in turn, support human cultures, economies, sustainable livelihoods, and well-being" (Arthington et al. 2018). Ecologically appropriate water level regimes for standing or slow-flowing (lentic) systems, such as lakes, wetlands, and aquifers, form part of e-flows principles and relevant practice (Horne et al. 2017; Barchiesi et al. 2018; Kath et al. 2018). However, the majority of e-flow implementations focus on river (lotic) systems and connected waterbodies, including riparian corridors, floodplain wetlands, and estuaries. These ecosystems support a large portion of global freshwater biodiversity, providing services to billions of people (Díaz et al. 2018; Dudgeon 2019), yet remain among the most undervalued, overexploited, and degraded ecosystems worldwide (Reid et al. 2019; Jähnig et al. 2022). Hence, this review is focused on conserving and partially or fully restoring the water regimes of altered rivers and related flow-dependent ecosystems. It is recognised that e-flows may not be the only strategy needed to reduce biodiversity losses in degraded and overutilised river systems but often must be integrated with other recovery actions, such as improving water quality, restoration of habitats and their connectivity (e.g., Abell et al. 2023), preventing/reducing invasive non-native species, and limiting the exploitation of native species (see other reviews in this Special Section). Interactions among these stress factors and e-flows and how to prioritise mitigation options warrant significant attention (Birk et al. 2020) but are beyond the scope of this review.

Many human activities disrupt the hydrology, biogeochemistry, and ecology of river systems and lead to diminished freshwater biodiversity (Dudgeon 2019). Abstraction of water for agricultural, industrial, or domestic uses has risen dramatically in recent decades with significant impacts on river flow regimes, either directly as a result of surface water pumping or storage infrastructure or indirectly where abstraction from aquifers has affected groundwater-dependent river systems (Flörke et al. 2013). Dams fragment river networks and alter biogeochemical processes, often impeding critical fish migrations and reducing recruitment (Stoffels et al. 2022). Only 37% of world rivers > 1000 km long flow freely over their entire length, with just 23% flowing uninterrupted to the sea (Grill et al. 2019). Physical modifications to freshwaters, such as deepening and straightening of rivers, as well as the construction of embankments and levees that divide rivers from their floodplains, also disrupt processes linking hydrology, habitat structure, and biodiversity, and make rivers more vulnerable to changes in flow (Dunbar et al. 2010).

Climate change is intensifying these challenges as the frequency and severity of droughts increase in many parts of the world, leading to greater risk of water insecurity and decreasing capacity to meet the e-flow needs of rivers (Acreman et al. 2014). Evidence is mounting that climate-induced modifications of environmental regimes, including changes in streamflow, water temperature, and habitat connectivity, are driving widespread community shifts and constitute a leading threat to riverine biodiversity (Knouft and Ficklin 2017; Comte et al. 2021).

Expanding the global reach of e-flows and accelerating their implementation have never been more urgent, as hydrological alterations and ecological degradation continue unchecked in numerous rivers, wetlands, and their catchments. E-flows offer an essential strategy to help offset the deleterious effects of altered river hydrology and loss of connectivity by restoring critical functional elements of flow regimes (Yarnell et al. 2020; Stein et al. 2022; Wineland et al. 2022). The science and practice of e-flows have a long history dating from the 1900s, progressing recently through three phases: emergence and synthesis, consolidation and expansion, and globalization and transition towards social–

Fig. 1. Distribution of environmental flow implementation examples included in this review. The map is sourced from HydroRIVERS (Lehner and Gril 2013). All photos are under a Creative Commons license (CC BY-NC-SA 2.0).



ecological sustainability (Poff and Matthews 2013). A rich body of knowledge on methods, flow–ecology response models, and decision-support tools supports e-flow science, assessment, and implementation (Tharme 2003; Poff et al. 2017; Stein et al. 2022). Collectively, this global toolbox enables quantification and implementation of e-flow regimes at reach, river, basin, and regional scales in diverse natural and developed landscapes (Kennen et al. 2018; O'Brien et al. 2018).

Yet globally, while there have been significant developments in e-flow methodologies and increased societal acceptance of the results, implementation of e-flows within water resources management has been slower than required and geographically uneven (LeQuesne et al. 2010; Jähnig et al. 2022; Wineland et al. 2022; Dourado et al. 2023). Moreover, the evidence of positive biodiversity outcomes and ecosystem services delivery is patchy and often poorly documented. The adoption of the Global Biodiversity Framework with its commitment to protect and restore inland waters on an equal footing with terrestrial and marine ecosystems makes this a critical time to act on behalf of the world's degraded and unprotected rivers (Wineland et al. 2022; Cooke et al. 2023).

The purpose of this review is to inform future e-flow implementation by consolidating evidence of the factors and steps that underpin and enable successful applications and beneficial outcomes for freshwater biodiversity. From a combination of case study reviews and published literature, we distil 10 high-potential enabling factors that facilitate the implementation of e-flows and enhance their biodiversity outcomes. We also identify options and generalizable recommendations to overcome prominent limiting factors and constraints, drawing on the case studies and wider literature.

2. Approach

This review explores the factors that both enable and constrain the implementation of e-flows and the resultant strengthening or weakening of biodiversity restoration and conservation. A comprehensive global-scale survey, although ideal, was beyond our remit. Instead, we review 13 examples of e-flow implementations in the diverse water management contexts of 10 countries (Fig. 1). Case study examples were invited from individuals with expertise ranging across e-flow science, practice, and policy; examples range from protection of flows in basins of high conservation importance to the restoration of flow regime characteristics in regulated rivers.

Each respondent completed a tabular description of their e-flow implementation example following the template in

Table 1. Survey used to collect environmental flow (e-flow) implementation details, and the lists of enabling and limiting factors that were ranked by their relative importance to outcomes for freshwater biodiversity.

E-flow implementation details requested

1. Continent, case study basin, and waterbody types/names.
2. Year/s over which implementation happened.
3. What particular issues were affecting flow regimes of waterbodies targeted in this implementation?
4. Strategic framework within which e-flows were implemented.
5. How were e-flows provided and by what agencies?
6. Biodiversity outcomes and evidence base.
7. How was e-flow implementation financed?
8. Who were the most powerful players and what were their roles and activities in this e-flow implementation?
9. Is there anything else you would like to see included in this template?
10. Key references.

Enabling factors

Can you rank the importance of the following factors (high, medium, and low) enabling successful biodiversity outcomes of this e-flow implementation?

1. Clear and effective legislation and regulation of e-flows.
2. Securing sufficient resources and capacity for e-flow implementation.
3. Meaningful communication and engagement with all stakeholders.
4. Using best available science and stakeholder knowledge.
5. Enabling monitoring of ecological, social, and economic outcomes of e-flow implementation.
6. Support for training and research to enhance e-flow implementation and monitoring of outcomes.
7. Enabling some level of flow regime protection as early as possible.
8. Using basin-scale infrastructure planning, design, and operation to enable e-flows, including infrastructure retrofitting and decommissioning.
9. Evaluation of trade-offs, e.g., showing that biodiversity benefits may have low economic costs for other users.
10. Managing water resources adaptively in relation to changing circumstances and climate change.
11. Other?

Limiting factors

Can you rank the importance of the following factors (high, medium, and low) limiting biodiversity outcomes of this e-flow implementation?

1. Lack of legal and governance authority to implement e-flows.
2. Limited resources for e-flow assessments, implementation, and monitoring.
3. Poor scientific understanding of the ecological system and water requirements.
4. Poor community understanding of e-flows and why they are important.
5. Inadequate consideration and uptake of Indigenous values, beliefs, and cultural knowledge.
6. Declining water availability, increasing human demands, or increasing variability under climate change.
7. Fragmented water governance, especially in transboundary water systems.
8. Lack of collaboration across political jurisdictions and social, economic, and environmental sectors.
9. Weak engagement with broader spheres of environmental conservation and restoration.
10. Limited implementation of adaptive management in response to changing circumstances and climate change.
11. Other?

Table 1. They ranked the relative importance of 10 factors that enabled their reported biodiversity outcomes as high, medium, or low, and similarly ranked 10 factors that limited or constrained biodiversity and other outcomes in their case example. The 10 enabling and limiting or constraining factors were consolidated from a review of global e-flow implementation literature and policy advice (Hirji and Davis 2009; Le Quesne et al. 2010; Pahl-Wostl et al. 2013; Horne et al. 2017; Arthington et al. 2018; Harwood et al. 2018; Anderson et al. 2019; Wineland et al. 2022).

3. Summary of e-flow implementation examples

Details about each e-flow example are presented in this section as brief introductory text and a table setting out river names and locations, objectives, biodiversity outcomes, and key references, followed by the enabling factors and constraints ranked as being of high importance to the case study and its outcomes. Table 2 presents an overall summary of the rankings given to each case study. Figure 1 plots their geographic locations.

3.1. Putah Creek, USA

We begin this review of case studies with Putah Creek, a tributary of the Sacramento River, California, USA, where a community council took a water agency to court, citing the Public Trust Doctrine and a California Fish and Game code in their appeal for water rights to meet the flow requirements of fish (Table 3). After years of negotiations and litigation, the Putah Creek Council and the Solano County Water Agency signed the Putah Creek Accord 2000 (https://putahcreekcouncil.org/who-we-are/putah-creek-accord/), which included e-flows for native fishes, a flow schedule for extended periods of drought, and a funding agreement to support creek restoration, monitoring in perpetuity, and a dedicated Streamkeeper program. Partnerships, negotiations, and com-

Table 2. Summary of 13 environmental flow (e-flow) implementations and the ranks assigned to enabling and constraining factors.

Location enabling factors	Putah Creek, CA, USA	Usumacinta River, Mexico	Peace–Athabasca Delta, Canada	Savannah River, USA	Roanoke River, USA	English rivers	Great Brak Estuary, South Africa	Olifants River, South Africa	Luangwa River, Zambia	Nile Basin, Africa	Ramganga River, India	Yangtze River, China	Goulburn River, Australia
Effective legislation and regulation of e-flows	H	H	M	H	H	H	M	H	H	M	H	H	H
Sufficient funding and human resources	H	H	H	H	H	H	M	H	H	M	H	M	M
Engagement with diverse stakeholders	H	H	H	H	H	H	H	M	H	H	H	H	H
Use of best available stakeholder knowledge	H	M	H	H	H	H	H	H	H	H	M	H	H
Monitoring of ecological and social-economic outcomes	H	M	H	H	H	H	H	H	H	M	M	M	H
Support for capacity training and research	H	H	H	M	M	H	M	M	H	H	M	M	M
Protection of some flows as early as possible	H	H	H	H	L	H	H	L	H	H	M	M	M
Planning of infrastructure to enable e-flows	L	M	M	M	M	H	L	M	H	H	H	L	L
Evaluation of trade-offs with other water users	L	H	M	M	M	H	L	M	H	H	H	M	L
Adaptively managing for climate change	L	M	H	M	L	H	L	M	H	M	M	M	L
Constraining factors													
Lack of effective legislation and regulation of e-flows	L	H	L	L	L	L	L	M	H	L	H	–	H
Limited funding and human resources	L	H	L	M	L	L	L	H	H	H	H	–	H
Poor scientific understanding of water requirements	L	H	L	L	L	H	L	L	–	H	H	–	M
Poor community understanding	L	M	L	M	M	L	L	L	–	L	M	L	H
Inadequate uptake of Indigenous knowledge	H	H	L	L	L	L	L	L	L	M	M	L	M
Declining water availability, increasing human demands	H	L	H	M	L	H	H	H	H	M	H	L	M
Fragmentation of governance, especially transboundary	L	H	M	H	L	L	L	M	H	L	M	H	M
Lack of collaboration across jurisdictions and sectors	L	L	L	M	L	L	L	M	H	M	M	–	L
Weak engagement with broad conservation/restoration	L	H	L	L	L	L	L	M	–	L	M	–	M
Limited adaptation to changing circumstances and climate	M	H	L	M	L	L	M	M	–	M	M	–	L

Note: H = High, M = Medium, and L = Low, — rank could not be assigned.

Table 3. Putah Creek environmental flow (e-flow) implementation, with details of highly ranked enabling and constraining factors.

E-flow implementation details	Putah Creek, CA, USA
Location, length, and flow regime modifications	Tributary (112 km) of the Sacramento River. Flow regime modified since 1957 by the Solano Project (dams and lakes).
E-flow objectives	Restore more natural seasonal flows to sustain resident and migratory native fishes and the creek ecosystem.
Biodiversity and other outcomes of e-flows	Native fish populations increased with dominance over non-native species. Increased migration and recruitment of fall-run chinook salmon (*Oncorhynchus tshawytscha).*
References	Kiernan et al. (2012).
Enabling factors	**Ranks and reasons**
Effective legislation and regulation of e-flows	Legal settlement in 2000—the Putah Creek Accord (https://putahcreekcouncil.org/who-we-are/putah-creek-accord/).
Sufficient funding and human resources	Accord enabled a conservation plan, e-flow implementation, fish and wildlife monitoring, and Streamkeeper program.
Engagement with diverse stakeholders	Coalition of Putah Creek Council (NGO), UC Davis, City and County representatives and consultants.
Use of best available stakeholder knowledge	Public, City Council, Solano County Water Agency, and academic knowledge used.
Monitoring of ecological and social-economic outcomes	Ongoing fish and wildlife monitoring and a Streamkeeper program.
Support for capacity training and research	Academic research informed the accord, community training in creek restoration and the Streamkeeper program.
Protection of some flows as early as possible	E-flows implemented after 10 years of litigation and negotiation.
Constraining factors	**Ranks and reasons**
Inadequate uptake of Indigenous knowledge	Wintun native Americans are traditional occupants of catchment, few now speak the language, and much historical knowledge is lost.
Declining water availability	No surface flows during drought 1989–1990 stimulated legal action for e-flows.

munity engagement enabled the accord and continue to support the research, monitoring, and watershed stewardship that have benefited native fish recovery (Kiernan et al. 2012).

3.2. Usumacinta River, Guatemala and Mexico

Between 2014 and 2018, Mexico's Water Reserves for the Environment Program enacted precautionary environmental water reserves (EWRs) in 295 river basins (Salinas-Rodríguez et al. 2021). In the transboundary Usumacinta River, the EWR protects 1000 km of free-flowing river between north-west Guatemala and south-east Mexico (Table 4). River e-flows protect over 50 freshwater species and ensure connectivity with the Ramsar-listed Catazajá Lagoon System, thus enabling movements of manatees (*Trichechus manatus manatus)* to and from the lagoon system. Capacity building processes in e-flows and EWRs have begun in Guatemala, and are expected soon in Honduras, to help establish their national e-flow agendas and support transboundary water governance.

3.3. Peace–Athabasca Delta, Canada

The Peace–Athabasca Delta (PAD), known as Ayapaskaw in Cree, is the world's largest inland boreal delta system, a Ramsar wetland of international importance and a UNESCO World Heritage Site of Outstanding Universal Value (Table 5). Building on deep local experience and early e-flow assessments on the Athabasca River (Candler et al. 2010), present efforts are focused on building partnerships and trust with 11 different First Nation and Métis governments to enable co-production of approaches that, where appropriate, weave together Indigenous knowledge and science with Western research, to help identify, monitor, and adaptively manage the water requirements of the delta-river ecosystems under a changing climate.

3.4. Savannah River, USA

In 2002, The Nature Conservancy (TNC) entered a national (US) partnership with the US Army Corps of Engineers (USACE) called the "Sustainable Rivers Program (SRP)" and focused on opportunities to re-operate USACE dams for ecological benefit as well as meeting basin stakeholder needs (Table 6). As one of the earliest SRP trials, the Savannah River project demonstrated the potential for a collaborative approach to e-flows (Richter et al. 2006). In 2020, however, hydropower interests prevailed and the partnership between the TNC and dam owner operators was terminated for the foreseeable future, this despite the preference of many other stakeholders for the e-flow regime developed over many years of stakeholder consultations.

3.5. Roanoke River, USA

The Roanoke River e-flow implementation involved another SRP partnership led by TNC with the objective of adjusting river flows, regulated by a three-dam cascade for hydropower and flood control, to achieve ecological objectives downstream (Table 7). The new run-of-river e-flow regime promotes floodplain tree recruitment in one of the largest remaining bottomland forests in the U.S., with only a 3% loss in system hydropower generation capacity

Table 4. Usumacinta River environmental flow (e-flow) implementation, with details of highly ranked enabling and constraining factors.

E-flow implementation details	Usumacinta River, Guatemala and Mexico
Location, length, and flow regime modifications	1000 km river between NW Guatemala and SE Mexico, of which 99% is free flowing. Land-use changes and hydropower threaten connectivity with Ramsar-listed Catazajá Lagoon System.
E-flow objectives	Establish environmental water reserve (EWR) for river management class “A” (ecohydrological integrity and aquatic ecosystem functioning).
Biodiversity and other outcomes of e-flows	E-flow requirements of 57 freshwater species were legally secured by the EWR. Flow connectivity enabled manatee (*Trichechus manatus manatus)* movements to and from Catazajá Lagoon.
References	Salinas-Rodríguez et al. (2021).
Enabling factors	**Ranks and reasons**
Effective legislation and regulation of e-flows	National Water Law and the Mexican Water Reserves for the Environment Program.
Sufficient funding and human resources	Inter-American Development Bank, Mexican National Council for Science and Technology, Gonzalo Río Arronte, and WWF.
Engagement with diverse stakeholders	National Water Commission, National Commission of Natural Protected Areas, National Council for Science and Technology, WWF, academics, and international consultants.
Support for capacity training and research	WWF, consultants, and researcher together strengthened capacities around the e-flow assessment process.
Protection of some flows as early as possible	EWRs set precautionary e-flows.
Evaluation of trade-offs with other water users	Cost–benefit analysis showed low economic costs of biodiversity benefits for other users.
Constraining factors	**Ranks and reasons**
Lack of effective legislation and regulation of e-flows	No specific legal measures to ensure local community and Indigenous participation beyond river basin councils.
Limited funding and human resources	Limited resources for e-flow assessments, implementation, and monitoring.
Poor scientific understanding	Poor scientific understanding of the ecological system and its water requirements.
Inadequate uptake of Indigenous knowledge	Inadequate consideration and uptake of Indigenous values, beliefs, and cultural knowledge.
Fragmentation of governance	Capacity building processes have begun in Guatemala, Bolivia and soon Honduras to help establish their National Environmental Flows Agenda and support transboundary water governance of e-flows and EWRs.
Weak engagement with other conservation sectors	In other Mexican river basins, social NGOs and local stakeholders sued the State alleging omission of free, public, informed participation and violation of human rights to water.
Limited adaptation to climate change	Limited implementation of adaptive management in response to changing circumstances and climate change.

(Opperman et al. 2017). The new regime also gives the impoundments increased flood storage capacity under certain conditions.

3.6. The UK and English rivers

Under the requirements of the European Union’s Water Framework Directive (2000/60/EC) 2000, the UK developed precautionary e-flow standards to support Good Ecological Status (GES) in many waterbodies and High Ecological Status in systems of high conservation value (Table 8). Precautionary default e-flow targets are set by the Environment Agency and adjusted for the type of stream and its sensitivity to flow regime change (Acreman et al. 2008). In English rivers, a water abstractor can undertake investigations to define an alternative e-flow target at their own cost, provided high scientific standards are met. The need to adjust e-flows to fit channel structure modified from natural conditions, or to accommodate other river uses, constrains e-flow implementation, as does declining water availability.

3.7. Great Brak River Estuary, South Africa

The construction of Wolwedans Dam just above this intermittently open/closed Great Brak Estuary, to provide water for municipal and industrial purposes, stimulated community concern, leading to environmental impact assessments and a negotiated e-flow management strategy (Table 9). A combination of annual flushing flows and mechanical mouth-opening has supported biodiversity, fish and mudprawn recruitment, and estuarine processes. However, dense blooms of the macroalga, *Cladophora glomerata*, can develop during spring/summer on occasions when e-flows are insufficient to open and flush the estuary and water quality deteriorates (Human et al. 2016).

3.8. Olifants River, South Africa

The implementation of e-flows in the Olifants River in northern South Africa was the first time that unique components of the 1998 South African National Water Act (Chapter 3), termed Resource Directed Measures (RDM) and their Resource Quality Objectives, were applied (Table 10). Gov-

Table 5. Peace–Athabasca Delta (PAD) environmental flow (e-flow) implementation, with details of enabling and constraining factors.

E-flow implementation details	PAD, Canada
Location, length, and flow regime modifications	Located at the western end of Lake Athabasca, the PAD (Ayapaskaw in Cree) is formed by Peace, Athabasca, and Birch rivers before draining into the Slave River. Hydrological changes and oil-sand mining threaten quantity and quality of delta habitats; climate warming hotspot threatens precipitation patterns and ice processes.
E-flow objectives	E-flows linked to the traditional values, activities, and cultural heritage of the 11 Indigenous governments that have traditional territory in Wood Buffalo National Park. Ecosystem needs (ecological, geomorphological, and hydrological) for the landscape; habitat for waterfowl from four converging intercontinental flyways; water quality improvement.
Biodiversity and other outcomes of e-flows	Base flows have facilitated Indigenous access to important Athabasca River sites.
References	Candler et al. (2010) and Timoney (2013).
Enabling factors	**Ranks and reasons**
Sufficient funding and human resources	E-flows framework (2021) being developed through funding provided by Federal government. Project partnerships among Federal, provincial, territorial, and Indigenous governments.
Engagement with diverse stakeholders	Co-development of e-flows with governments, consultants, stakeholders, and with Rights holders from 11 different First Nations and Métis governments.
Use of best available stakeholder knowledge	Emphasis on braiding of Indigenous knowledge and science with Western research on delta landscape ecosystem needs.
Monitoring of ecological and socio-economic outcomes	In planning. Will be directly linked to co-developed monitoring and science under the Wood Buffalo National Park Action Plan.
Support for capacity training and research	Significant capacity funding, training and research support knowledge co-development.
Protection of some flows as early as possible	Base flows facilitate Indigenous access to important Athabasca River sites.
Adaptively managing for climate change	Implications of climate change for future precipitation patterns and shifting thermal regimes are under consideration.
Constraining factor	**Rank and reasons**
Declining water availability	Hydropower, oil-sand mining, and climate warming threaten water availability and water level variability.

ernment gazette announcements legalise the ecological reserve (e-flows) and include e-flow rules to ensure the protection of water quality, river habitats, and biological communities (Dickens et al. 2011). Drought in the Olifants River and problems with the redistribution of water rights from former owners (including farmers and mining industries) to the Reserve (basic human needs and e-flows) have constrained ecological outcomes.

3.9. Luangwa River, Zambia

The Luangwa River, a tributary of the transboundary Zambezi River system, is one of the last long free-flowing rivers in Zambia facing conflicts over water abstractions and land-use impacts on river health (Table 11). The national Water Resources Management Authority (WARMA) applies between 10% and 30% of the total annual flow as precautionary e-flows in Zambia's water allocation plans. More detailed assessments to refine these early e-flow allocations are intended, but the resources to undertake them can be limited (WWF 2018). Although WARMA is in place, the legal provisions to actualize catchment and sub-catchment councils, and a Water Users Association to drive stakeholder agreements on e-flow scenarios for the basin, are still pending.

3.10. Nile River Basin, Africa

The Nile Basin Initiative (NBI; NBI 2016) is a visionary intergovernmental partnership of 10 riparian countries that collectively aim to achieve sustainable ecological and social-economic development and wise use of the basin's water resources (Table 12). The strategy for the management of e-flows in the Nile Basin is well developed and supported by international funding and expertise (O'Brien et al. 2019). However, a high dependence on local donor funding and limited scientific resources are constraints on e-flow implementation and monitoring of outcomes.

3.11. Ramganga River, India

This e-flow implementation in the Ramganga River has multiple objectives to improve river health and biodiversity, as well as ensure that valuable social–cultural services to the riparian community and visitors (e.g., fishing, holy bathing, and cultural rituals) are sustained by adequate water flows and levels (Table 13). Realisation of the importance of e-flows for healthy river systems, development of new governance arrangements, and the challenges of assessing e-flows while amending international protocols to suit local conditions and conducting trade-off analysis have taken time (Kaushal et al. 2018). General constraints include the existing commitments of water resources to different sectors in the Ramganga River

Table 6. Savannah River environmental flow (e-flow) implementation, with details of highly ranked enabling and constraining factors.

E-flow implementation details	Savannah River, USA
Location, length, and flow regime modifications	Located in south-eastern USA, the Savannah River flows nearly 500 km to its estuary at the Atlantic Ocean. Regulated by three large dams (Thurmond, Russell, and Hartwell), owned and operated largely for flood control and hydropower by the U.S. Army Corps of Engineers (Corps). Flows also impacted by riverbend cut-offs in the lower river, implemented by the Corps to facilitate navigation.
E-flow objectives	Restore magnitude, timing, duration, and frequency of occurrence of river flows downstream of the lowermost dam (Thurmond). Balance ecological requirements of aquatic species with basin stakeholder needs (hydropower, lake levels for recreation, water supply, navigation, and commercial harbour operations).
Biodiversity and other outcomes of e-flows	Improved recruitment of endangered plants and the anadromous Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*). Increased floodplain access and habitat for numerous fish and invertebrate species. Floodplain tree recruitment.
References	Konrad (2010) and Richter et al. (2006).
Enabling factors	**Ranks and reasons**
Effective legislation and regulation of e-flows	Federal legislation (Water Resources Development Act); "Sustainable Rivers Program" partnership between The Nature Conservancy (TNC) and U.S. Army Corps of Engineers (Corps).
Sufficient funding and human resources	TNC organization's funders (corporations, governmental contracts, philanthropic foundations, private individuals, and endowment investments). Georgia and South Carolina Department of Natural Resources very engaged and provided cash match.
Engagement with diverse stakeholders	Regular community outreach, particularly with national Chief of Engineers (typically an Army General), and political leaders in cities of Augusta and Savannah, Georgia. Recreational fishers and fisheries agencies were important supporters.
Use of best available stakeholder knowledge	TNC, agency, stakeholder, and academic knowledge was important.
Monitoring of ecological and socio-economic outcomes	E-flow prescriptions monitored by resource agencies, TNC and academia 2004–2020, when the collaboration ended.
Protection of some flows as early as possible	First high pulse dam release in March 2004.
Constraining factor	**Rank and reasons**
Fragmentation of governance	Fragmented governance arrangements contributed to termination of the Savannah River dam relicensing program in 2020. E-flow recommendations were rejected by hydropower interests.

Basin, and the need to build scientific understanding around the implications of changes in river flow regimes for the ecology of the river.

3.12. Yangtze River, China

The e-flow implementation in the Yangtze, the longest river in Asia, demonstrates how the effects of the massive Three Gorges Dam (TGD) on river health have been mitigated by managing dam operations to mimic the Yangtze's natural flood pulse (Table 14). E-flows have partially restored the spawning of four major commercial Chinese carp species; however, numbers of fish fry below the dam are lower than before the TGD was constructed (Cheng et al. 2018). Complex governance arrangements are a particular challenge for water management in China and were important in the planning and decision-making processes around the design and implementation of e-flows.

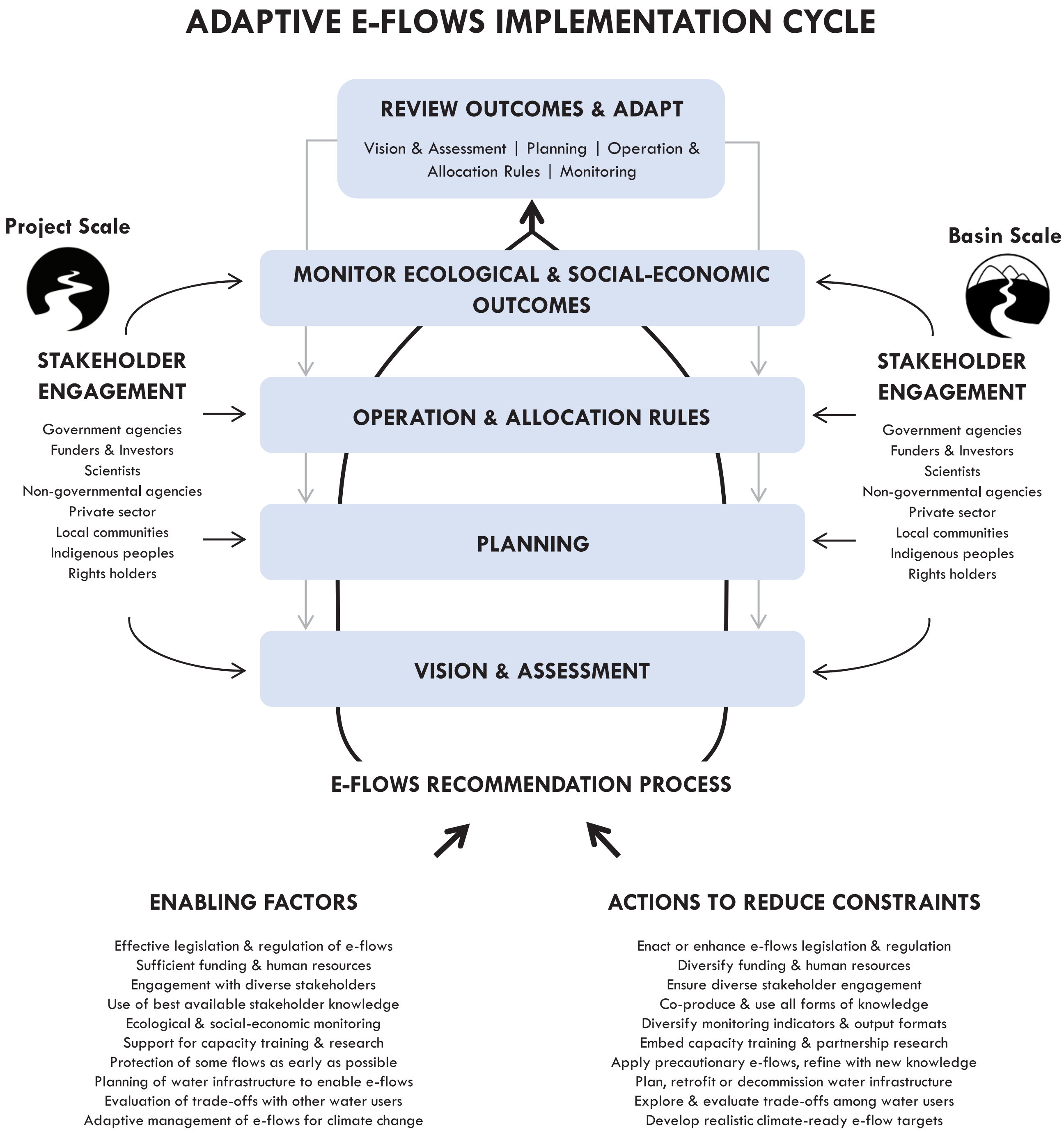
3.13. Lower Goulburn River, Australia

The final case study reviews an example from Australia's Murray–Darling Basin, renowned for efforts to restore overexploited floodplain river systems and recover freshwater biodiversity. The e-flow implementation for the Lower Goulburn River, state of Victoria, is restoring elements of the natural wet–dry season flow pattern of the river below Lake Eildon and Goulburn Weir, where impoundment and flow management for irrigation have reversed the seasonal hydrological regime and impaired river and floodplain functions (Table 15). The provision of more natural seasonal e-flows has reinvigorated channel habitats and low elevation connected wetlands (Lovell and Casanelia 2021). However, a lack of legislation to enable more elevated flows and greater connectivity with floodplains has been a constraint on biodiversity outcomes.

4. Enabling factors and opportunities to enhance e-flow implementation

This review found that the first seven enabling factors listed in Table 2 were highly ranked and important to 6–12 of the e-flow implementation case studies, a finding broadly consistent with previous policy reviews (e.g., Le Quesne et al. 2010; Harwood et al. 2018); diverse stakeholder engagement emerged as particularly important (12 high ranks). This section outlines the significance of all 10 enabling factors to e-flow implementations and outcomes, linking back to details

Fig. 2. Adaptive environmental flow (e-flow) implementation cycle underpinned by 10 enabling factors, showing options to overcome constraints and enhance biodiversity and other outcomes.



provided in Tables 3–15 and supporting literature. We also found that 12 of the 13 e-flow examples were constrained by at least one highly ranked factor (Table 2), with seven implementations affected by declining water availability. We examine each constraint in context and then present options and generalizable recommendations for actions to overcome them, drawing on the wider literature. Figure 2 presents our concept of e-flow implementation as an adaptive management cycle that progresses from a vision for the river and assessment/planning of e-flow requirements, to formulation of operation and water allocation rules, followed by monitoring of ecological and social-economic outcomes and a phase of iterative reviews and adaptation of the e-flow strategy, as required to enhance outcomes. This cycle is informed throughout by stakeholder engagement and co-production of knowledge. Factors enabling successful e-flow implementations are presented in Fig. 2 together with options to overcome the limitations and constraints we encountered during this review.

Fig. 2 Adaptive environmental flow (e-flow) implementation cycle underpinned by 10 enabling factors, showing op-

Table 7. Roanoke River environmental flow (e-flow) implementation, with details of highly ranked enabling factors.

E-flow implementation details	Roanoke River, USA
Location, length, and flow regime modifications	The Roanoke River (660 km) rises in Blue Ridge Mountains, Virginia, flows south-east through large bottomland forests, and discharges into the Atlantic Ocean. A three-dam cascade, managed for hydropower and flood control, changed natural relatively short, high flood peaks into lower magnitude flood pulses with long durations. Extended floodplain inundation occurred when key floodplain tree seedlings would be sprouting, thereby suppressing recruitment.
E-flow objectives	Reoperate hydropower releases on two lower dams (owned by Dominion Power) and revise Water Control Plan on upper U.S. Army Corps of Engineers (Corps) dam (Kerr) towards quasi-run-of-river operation, closer to dynamics of natural floods to support floodplain tree and fish recruitment.
Biodiversity and other outcomes of e-flows	Flow pulses support recruitment of floodplain vegetation; fish migration and spawning.
References	Opperman et al. (2017).
Enabling factors	**Ranks and reasons**
Effective legislation and regulation of e-flows	Sustainable Rivers Partnership between The Nature Conservancy (TNC) and Corps with formal study for Kerr Dam operations under Federal Flood Control Act. Dominion dams renewed their licenses from the Federal Energy Regulatory Commission.
Sufficient funding and human resources	Dam operators funded changes to achieve e-flow regime.
Engagement with diverse stakeholders	Coalition of Dominion Power, Corps, U.S. Fish and Wildlife Service, TNC, Roanoke River Basin, and Lake Gaston associations.
Use of best available stakeholder knowledge	TNC-led hydrological model development, HydroLogics Inc. built the model, TNC and University of North Carolina contributed to monitoring of implementation.
Monitoring of ecological and socio-economic outcomes	New water management regime facilitates flood control, and generates significant revenue from recreation at Kerr Dam, with only 3% loss in system hydropower generation capacity.

tions to overcome constraints and enhance biodiversity and other outcomes.

4.1. Effective legislation and regulation of e-flows

Legislation, participatory governance, and regulatory processes are fundamental enabling factors for effective implementation of e-flow regimes for river, riparian, wetland, and estuarine ecosystems (Pahl-Wostl et al. 2013; Harwood et al. 2018; Dourado et al. 2023). Laws that mandate provision of e-flows create authority, obligations, and momentum to support protection of largely unregulated river ecosystems or to restore features of the hydrological regimes and ecological condition of rivers regulated by storage of water, abstraction, diversion, or land-use changes. This review reveals legislative arrangements that vary in scope and scale, from an international water law (the European Union's WFD) and the collaborative intergovernmental agreements of the NBI (NBI 2016), to national water laws, state/provincial laws, legislated regulations on dam operations, and examples of e-flow implementation achieved by litigation (Tables 3–15). These legislative framings have enabled successful outcomes for freshwater biodiversity in the case studies reviewed herein and elsewhere.

The visionary WFD (2000/60/EC) requires European Union member states to achieve at least "GES" (referenced to biological, hydromorphological, and chemical/physico-chemical "quality elements") in all bodies of surface water and also to prevent deterioration in the status of any waterbody, by 2027. The implementation of e-flows is one of the measures identified as necessary to restore or maintain ecological health in UK and English rivers (Table 8). Similarly, the intergovernmental NBI (NBI 2016) is the only basin-wide and impartial platform for collaboration among the 10 riparian countries to achieve just and sustainable ecological and social-economic development of the basin's shared water resources. The basin's rivers suffer major threats to flow regimes from hydropower and storage dams, water demands for agriculture, urbanization, industry, and mines. The NBI has agreed to policy goals of: (i) supporting the establishment of enabling national policy environments for e-flow management, (ii) building e-flow capacity and awareness among national technical staff and policy makers, and (iii) increasing the number of e-flow assessments carried out in the Nile Basin. The seven-phase e-flow framework has a strong emphasis on maintaining basin-wide biodiversity, ecosystem services, and livelihoods (Table 12).

National (federal) legislation with powers to influence state/provincial laws, policies, and regulations underpins e-flow implementations in Mexico, Canada, the USA, South Africa, Zambia, India, and China (Tables 4–7, 10, 11, and 13). The expression of e-flow policy principles and implementation guidance in national legislation varies from country to country. The South African National Water Act (Act 36 of 1998) is widely regarded as one of the most progressive pieces of water legislation in the world, serving to inform implementation of integrated water resource management (IWRM) and e-flows in other countries, e.g., Zambia (Table 11) and China (Table 14). The Olifants River case study was the first to legalise the basic human needs reserve, the ecological reserve (e-flows), and e-flow rules to ensure the protec-

Table 8. English river environmental flow (e-flow) implementation, with details of highly ranked enabling and constraining factors.

E-flow implementation details	English rivers
Location, length, and flow regime modifications	Many English rivers are affected by pumping and diversion of surface and groundwater (e.g., distinctive chalk streams).
E-flow objectives	Sustain aquatic communities, fishing, recreation.
Biodiversity and other outcomes of e-flows	Macro-invertebrates, fish, plants, and algae; recreational fishing; aesthetics; historical weirs and bridges that are protected monuments.
References	Acreman et al. (2008, 2011) and UKTAG (2008).
Enabling factors	**Ranks and reasons**
Effective legislation and regulation of e-flows	European Union's Water Framework Directive (2000/60/EC) 2000 applies in the UK, to maintain or restore most surface waterbodies to Good Ecological Status (GES) or High Ecological Status (HES). The Environment Agency issues abstraction licences and defines dam flow releases.
Sufficient funding and human resources	A screening tool applied by Environment Agency uses public funding to set default e-flow targets. Water abstractors can propose and fund alternative flow regimes if underpinned by science.
Engagement with diverse stakeholders	Stakeholders include water supply companies, industrial companies, land farmers, fish farmers, and hydropower companies.
Use of best available stakeholder knowledge	Precautionary e-flow standards support GES. The e-flow indicator determines where abstraction and flow regulation might harm river habitats and species, depending on river's ecological sensitivity to flow changes.
Monitoring of ecological and social-economic outcomes	Ongoing by Environment Agency and NGOs.
Support for capacity training and research	Environment Agency, environmental organisations (WWF), and academics support training and research.
Protection of some flows as early as possible	Precautionary e-flow standards support GES and HES, followed by adjustments as required.
Planning of infrastructure to enable e-flows	E-flows are adjusted to channel conditions and hard and soft infrastructure.
Evaluation of trade-offs with other water users	Environmental organisations, e.g., WWF and local river groups, can campaign to protect or restore rivers and stimulate e-flow allocations.
Adaptively managing for climate change	Declining water availability and increasing variability under climate change are concerns.
Constraining factors	**Ranks and reasons**
Poor scientific understanding	Defining e-flows for rivers with channel modifications, levees, etc. requires site-specific studies and understanding.
Declining water availability	Government is granting permission for new urban development even where water resources are not sufficient to meet human needs and e-flows.

tion of water quality, river habitats, and biological communities in South Africa's rivers (Dickens et al. 2011). Water reserves for the environment also have legal status in Mexico under the National Water Law and the Mexican Water Reserves for the Environment Program (Salinas-Rodríguez et al. 2021). The Usumacinta basin was identified as a potential water reserve given the basin's low pressure on water resources and the exceptional levels of biodiversity and conservation values (Table 4).

In the USA, the federal Endangered Species Act of 1973 (ESA) is the primary means for federal agencies to protect threatened and endangered invertebrates, fish, wildlife and plant species, and the ecosystems upon which they depend. The legal and regulatory powers of the ESA have enabled restoration of e-flows through adaptation of reservoir release rules (Warner et al. 2014) and e-flows to protect groundwater resources upon which springs and baseflow streams and their endemic species depend (Devitt et al. 2019). By building public concern about threatened species, and encouraging state, local, and tribal stakeholders to resolve water resource issues related to conservation of endangered species and their habitats, the federal ESA offers a powerful model for community contributions to water allocation planning and e-flow practice.

Legislated regulations on dam operations offer further opportunities to implement e-flows in the USA by reassessing water storage and release regimes to balance ecological and stakeholder needs in regulated rivers. Non-federal hydropower dams must undergo a periodic review process to renew their licenses from the Federal Energy Regulatory Commission. This process includes an assessment of flow regimes and the new license often requires shifts in operations to improve downstream flows for river, riparian, and floodplain ecosystems (Tables 6 and 7).

Australia has drawn upon biodiversity conservation legislation and conventions to build legal provisions for the provision of e-flows. The CBD, the Ramsar Convention, and international migratory species conventions underpin Aus-

Table 9. Great Brak River Estuary environmental flow (e-flow) implementation, with details of highly ranked enabling and constraining factors.

E-flow implementation details	Great Brak River Estuary
Location, length, and flow regime modifications	This 6.2 km estuary is an intermittently open/closed system in the Warm Temperate, South Africa. Wolwedans Dam upstream reduced freshwater inflows by 56%, shifting it to persistent mouth-closure and poor ecosystem condition.
E-flow objectives	Release of a flushing flow, timed to follow artificial breaching of the mouth (by bulldozer) during the spring and summer of every year to maintain water quality, estuarine biodiversity and functions.
Biodiversity and other outcomes of e-flows	Rapid freshwater outflows scour mouth and channel, enabling fish and mudprawn recruitment into estuary and saltmarsh growth. The estuary experiences dense blooms of the macroalga, *Cladophora glomerata*, in spring/summer during periods when e-flows are insufficient to open the estuary mouth and water quality deteriorates.
References	Human et al. (2016) and Adams and van Niekerk (2020).
Enabling factors	**Ranks and reasons**
Engagement with diverse stakeholders	Great Brak River Environmental Committee with stakeholders from Department of Water Affairs and Forestry, Cape Nature and Environmental Conservation, CSIR, Island Residents' Association, and local community.
Use of best available stakeholder knowledge	Academics contributed to environmental impact assessment, monitoring, and experiments and reported results to public meetings.
Monitoring of ecological and socio-economic outcomes	Annual monitoring of estuary condition; mouth breaching experiments.
Protection of some flows as early as possible	Great Brak town residents and landowners lobbied for a review of the initial Environmental Impact Assessment and water allocation of 1 × 106 m^3 per year.
Constraining factor	**Rank and reasons**
Declining water availability	E-flows to the estuary can be insufficient to replicate pre-dam estuary mouth-opening conditions that support good water quality, prevent algal blooms, and enable ecological functions.

Table 10. Olifants River environmental flow (e-flow) implementation, with highly ranked enabling and constraining factors.

E-flow implementation details	Olifants River, South Africa
Location, length, and flow regime modifications	This 600 km perennial river flows from highly developed, mining region of South African Highveld plateau, through Kruger National Park into Mozambique. Flows are regulated by 30 large and many smaller dams. Power generation, agriculture, urban centres, and coal mines impair river quality and quantity.
E-flow objectives	Determine river management class and the ecological reserve (e-flows) to maintain water quality, quantity, habitat, and biodiversity.
Biodiversity and other outcomes of e-flows	Drought and lack of compliance with the ecological reserve in terms of water quantity and quality have impaired river condition.
References	Dickens et al. (2011) and O'Brien et al. (2022).
Enabling factors	**Ranks and reasons**
Effective legislation and regulation of e-flows	Legislated Resource Directed Measures (RDM) component of South Africa's 1998 National Water Act protects water resources through river classification, the Reserve (basic human needs and e-flows) and Resource Quality Objectives (water quality, quantity, habitat, and biota).
Sufficient funding and human resources	Department of Water and Sanitation (formerly the Department of Water Affairs and Forestry) fully funds analysis and implementation of RDM.
Use of best available stakeholder knowledge	Integrated water resource management plan for the Olifants Basin involves all users and interested/affected stakeholders including Indigenous people, who contribute to establishing RDM measures and e-flows.
Monitoring of ecological and socio-economic outcomes	Monitoring focuses on ecological responses.
Constraining factors	**Ranks and reasons**
Limited funding and human resources	Insufficient funding available for the implementation of full RDM process, e-flow implementation, and monitoring.
Declining water availability	Overdevelopment occurs in the basin where allocations of water are prioritised to farmers and mining ahead of the Reserve (basic human needs and e-flows) contrary to the requirements of the Act.

Table 11. Luangwa River environmental flow (e-flow) implementation, with highly ranked enabling and constraining factors.

E-flow implementation details	Luangwa River, Zambia
Location, length, and flow regime modifications	This 850 km tributary of Zambezi River is threatened by water abstraction, severe deforestation, sand mining, and riverbank cultivation.
E-flow objectives	Evaluation of scenarios for the river from A (pristine) to E (severely modified) ecological state.
Biodiversity and other outcomes of e-flows	The basin records at least 400 bird species and rich fisheries. A detailed biodiversity study is pending.
References	WWF (2018).
Enabling factors	**Ranks and reasons**
Effective legislation and regulation of e-flows	Zambian Water Resource Management Act 2011 requires integrated water resource management (IWRM) with water for the environment second to water for domestic use.
Sufficient funding and human resources	WWF and in-kind support from Water Resources Management Authority (WARMA). Precautionary e-flows were necessary due to limited funding for detailed studies.
Engagement with diverse stakeholders	WWF, WARMA hydrologists and catchment managers, Department of Water Affairs, Department of Wildlife, Lunsemfwa Hydropower Company, Luangwa Catchment Office, and Lukanga Water and Sewerage Company were involved.
Use of best available stakeholder knowledge	Stakeholder knowledge was used in e-flow assessment and helped to build ownership of recommendations.
Monitoring of ecological and socio-economic outcomes	WWF developed an e-flow monitoring and evaluation system for the adaptive management of the Zambezi River system.
Support for capacity training and research	WWF provided training in international best practice.
Protection of some flows as early as possible	WARMA applies between 10% and 30% of the total annual flow as the precautionary e-flow in Zambia's water allocation plans.
Planning of infrastructure to enable e-flows	Important but retrofitting or decommissioning of existing infrastructure may not be feasible.
Evaluation of trade-offs with other water users	IWRM promotes water sharing. Zambia is moving towards a system to value its natural resources.
Adaptively managing for climate change	In planning.
Constraining factors	**Ranks and reasons**
Lack of effective legislation and regulation of e-flows	Legal provisions are pending to actualize catchment and sub-catchment councils and a Water Users Association to drive consultative process around e-flow scenarios for the basin.
Limited funding and human resources	Precautionary e-flows are necessary due to limited funding for detailed studies.
Declining water availability	Increased conflicts over water use and low e-flows have been detrimental to river's ecosystem.
Fragmentation of governance	The lack of a Statutory Instrument on the formation of catchment/sub-catchment councils and Water Users Associations hampers effective management of water resources.
Lack of sector collaboration	Strong competition for water among river users.

tralia's Commonwealth (Federal) Water Act 2007, which provides the legislative framework to ensure the return to environmentally sustainable levels of water extraction in the Murray–Darling Basin (Table 15; Bunn 2017). Constitutional powers for managing the rest of the country's water resources lie with the states and territories. For example, the state of Queensland's e-flow programs and plans are governed by The Water Act 2000 supported by the Environmental Protection Act 1994 and related policies. The basin-wide environmental watering strategy brings the jurisdictions and water management bodies together in concerted efforts to restore e-flows to throughout the river basin.

In spite of various legal, governance, and regulatory arrangements, four of our e-flow case studies were affected by legislative constraints (Table 2). In India, National Water Policy dating from 2012, the Ganga Authority Notification 2016, and the Ganga E-Flows Order 2018, as well as judiciary and local efforts to bridge knowledge gaps around e-flow requirements, all enabled the Ramganga River implementation. However, development of new governance arrangements at national and state levels, including support for wide stakeholder engagement, slightly prolonged the actual e-flow implementation (Table 13). In the Luangwa River, Zambia, legal provisions to establish catchment and subcatchment councils and a Water Users Association are still pending (Table 11). In contrast, in the Usumacinta and other Mexican rivers, river basin councils were in place but there were no specific legal measures to ensure broader community and Indigenous participation (Table 4). We expand on "Engagement with diverse stakeholders" below. A different legislative weakness arose in the instance of the Lower Goulburn River, where legal control of floodplain flows and wetland connectivity were constrained by the risk of flooding to private property (Table 15). Under natural (unregulated) conditions in this river, both the winter and spring flows would have been large enough to generate significant overbank floods and floodplain connection (Lovell and Casanelia 2021). Legislation and governance arrangements to enable e-flows onto floodplains present special challenges where in-

Table 12. Nile River Basin environmental flow (e-flow) implementation with highly ranked enabling and constraining factors.

E-flow implementation details	Nile River Basin, Africa
Location, length, and flow regime modifications	The 6650 km Nile River has two major tributaries, the White Nile arising at Lake Victoria, Uganda, and the Blue Nile arising at Lake Tana, Ethiopia. Riparian states of the Nile Basin include 10 countries. River flows are threatened by major hydropower and storage dams and water demands for agriculture, urbanization, industrial development, and mines.
E-flow objectives	To determine e-flows for vulnerable ecosystems, processes and consequences of altered flows in the Nile Basin.
Biodiversity and other outcomes of e-flows	The 5–10 year audit will report on policies, e-flow allocations, and outcomes across the basin.
References	NBI—Nile Basin Initiative (2016) and O'Brien et al. (2019).
Enabling factors	**Ranks and reasons**
Engagement with diverse stakeholders	Nile Council of Ministers, Nile Technical Advisory Committee (Nile-TAC), consultants from the International Water Management Institute, Delft IHE, HYDROC, and academics.
Use of best available stakeholder knowledge	"Strategy for the Management of Environmental Flows in the Nile Basin" involves international best practice in e-flows.
Support for capacity training and research	Numerous strategies informed by local and international education stakeholders and national development programs, supported by the Nile Basin Initiative (NBI).
Protection of some flows as early as possible	Controls are in place to provide e-flows in the basin.
Planning of infrastructure to enable e-flows	Infrastructure planning for water supply and hydropower is well informed by the NBI and NILE-TAC.
Evaluation of trade-offs with other water users	Demands for water in the basin are contentious; many stakeholders have unsustainable water demands for provisioning and regulatory services.
Constraining factors	**Ranks and reasons**
Limited funding and human resources	International funding dominates, but there is minimal support from within the basin. Donors are willing but resources are limited.
Poor scientific understanding	Indicators are established for e-flow determination, implementation, and monitoring, yet poor knowledge of biodiversity, ecosystem processes, and services are constraints.

frastructure, private property, and livelihoods may be threatened. Solutions are canvassed under "Planning of infrastructure to enable e-flows" (below).

We recommend that national and provincial governments, water managers, and other stakeholders seeking to enact new e-flow legislation, or to galvanise existing legislation and governance in new ways, consider the kinds of opportunities outlined above, among others. Building national, state, or provincial water legislation can draw upon multilateral environmental and global river agreements, regional river agreements, binding provisions in treaties and customary law, recent international water policy documents, constitutional provisions to environment and water, and national and sub-national laws and agreements on water and natural resources (Dyson et al. 2008; Harwood et al. 2018). Legislated relicensing of existing water infrastructure to meet ecohydrological objectives is an effective strategy at project and basin scales (Tables 6 and 7), often supported by modelling to evaluate trade-offs (Poff et al. 2016; Widén et al. 2022; Willis et al. 2022). The momentum of public concerns around environmental protection and urgent water crises (overallocation, drought, algal blooms, or fish kills) can be marshalled to reinforce the case for water reforms and new legislation (Bunn 2017). Where legislation is lacking, litigation offers another powerful option (e.g., the Putah Creek Accord, Table 3). However, terminating unsustainable water use, developing alternative water resources, and allowing water users to adapt to new legislation and tighter e-flow constraints can be a long-term process, as exemplified in Australia (Bunn 2017) and Spain (Acreman et al. 2022).

4.2. Sufficient funding and human resources

Legislation and participatory governance set the stage for technical management of e-flows at project, basin, or regional scales (Pahl-Wostl et al. 2013). They must be supported by secure and sustained funding arrangements and sufficient human resources. Both can be significant, depending on context: geography, basin versus project scale, scope of e-flow objectives, available expertise and river system knowledge, urgency and time scale.

Funding models varied among our case studies, ranging from financial support from international banks and grants to national, state/provincial, and local sources, all with positive biodiversity outcomes achieved for both the protection and restoration of river flow regimes. Financial arrangements authorised and distributed under national or state/provincial legislation offer a particularly reliable model, enabling river management programs to be supported (and audited) from planning and design to e-flow provisions and monitoring of outcomes. For example, in 2012, the Australian Commonwealth and state governments committed to an AUS$13 billion program to balance environmental and consumptive water use in the Murray–Darling Basin (14% of the country's land area) by 2026 (https://www.mdba.gov.au/basin-plan-roll-out). The costs of e-flow implementation including monitoring and research are shared between the Commonwealth and the in-

Table 13. Ramganga River environmental flow (e-flow) implementation, with highly ranked enabling and constraining factors.

E-flow implementation details	Ramganga River, India
Location, length, and flow regime modifications	This 596 km river is a northern tributary of the Ganga (Ganges) River. Flows are regulated by Kalagarh/Ramganga Dam that provides irrigation water, flood control, and hydropower.
E-flow objectives	To protect aquatic biodiversity, channel morphology, connectivity, river health, and socio-cultural values, rituals and services.
Biodiversity and other outcomes of e-flows	Improvements have occurred or are expected in river flows, water levels, longitudinal connectivity, water quality, improved hydraulic habitat conditions for freshwater species, fish diversity, populations, and social–cultural rituals.
References	Kaushal et al. (2018), Kaushal et al. (2022).
Enabling factors	**Ranks and reasons**
Effective legislation and regulation of e-flows	National Water Policy 2012 considers e-flow requirements while developing water resources infrastructure on river systems. The government's National Mission for Clean Ganga set the stage for e-flows in the Ganga River through Ganga Authority Notification 2016 and Ganga E-Flows Order 2018. Now the stage is set for e-flow implementation in Ganga's tributaries.
Sufficient funding and human resources	Securing sufficient resources and required capacity for e-flow assessment and implementation has been a primary issue.
Engagement with diverse stakeholders	E-flows led by WWF-India and national partners, the Indian Institute of Technology—Kanpur, Indian Institute of Technology—Varanasi, Indian Council for Agricultural Research—Central Inland Fisheries Research Institute Prayagraj, Uttar Pradesh State Water Resources Agency, Uttar Pradesh Irrigation & Water Resources Department, INRM Consultants Delhi, People's Science Institute Dehradun, university academics, and individual water resources experts.
Planning of infrastructure to enable e-flows	Influencing operational guidelines of water resources infrastructure to enable e-flows is important.
Evaluation of trade-offs with other water users	Work with local farmers, district authorities, and water managers demonstrated potential to enhance e-flows in the Ramganga system while enhancing farm yields through improved agricultural practices.
Constraining factors	**Ranks and reasons**
Lack of effective legislation and regulation of e-flows	Development of new water governance arrangements has taken time.
Limited funding and human resources	Limited funding is an issue.
Poor scientific understanding	Need for deeper scientific understanding of the implications of changes in river flow regimes for the ecology of the river.
Declining water availability	Ramganga water resources are largely committed for irrigation purposes.

dividual jurisdictions (Table 15). At project scale, the SRP in the Savannah River brought together funding from the states of Georgia and South Carolina and an international NGO (TNC) in a cost-sharing agreement (Table 6).

When such government-led and partnership funding models are not feasible or fall short, other sources of funding can be considered, including boating and fishing licence fees, hydropower compensation funds, agency or community support for endangered species protection plans, research grants, donations, and water markets (Le Quesne et al. 2010; Bunn 2017).

The human resources and capacity needed to assess e-flows can also be demanding. Typically, an e-flow implementation requires sound knowledge of the subject system's hydrology and ecological systems (Tharme 2003; Poff et al. 2017) as well as its history, social context, infrastructure, commitments to off-stream uses, and water management arrangements. The range of expertise expands when social and cultural considerations and flow-related outcomes (e.g., treaty rights, Indigenous cultural values, and recreational benefits) are included (Harwood et al. 2018; Anderson et al. 2019). This review revealed a range of approaches to securing scientific, technical, and other essential capabilities. Most e-flow implementations acquired such expertise by appointing multi-institutional interdisciplinary technical, management, or advisory groups composed of government agencies, water managers, research institutes, consultants, NGOs, conservation groups, and community representatives. Advisory groups may include Indigenous peoples and other Rights holders, many of whom are also important knowledge holders (e.g., PAD, Canada, Table 5; and Ramganga River, Table 13).

In spite of effective legislation and institutional support, six e-flow implementations ranked constraints on financial and (or) human resource highly (Table 2)—the Usumacinta River (Table 4), Olifants River (Table 10), Luangwa River (Table 11), Nile Basin (Table 12), Ramganga River (Table 13), and the Goulburn River (Table 15). These shortfalls relate primarily to the time-consuming, resource-hungry action areas of the implementation cycle, when experienced people and operational funds are needed to undertake e-flow assessments and to lead e-flow trials, experiments, and monitoring (e.g., the full South African RDM process, Table 10). There is evidence of high reliance on the interest and goodwill of NGOs (e.g., TNC and WWF) and university groups as initiators, facilitators, and fund raisers, in planning and fostering engagement with stakeholders, leading research, teaching assessment methods, and publishing results (O'Keeffe 2018). While these engagements are valuable and applauded, they

Table 14. Yangtze River environmental flow (e-flow) implementation, with highly ranked enabling and constraining factors.

E-flow implementation details	Yangtze River, China
Location, length, and flow regime modifications	The Yangtze River rises in the Tanggula Mountains and flows 6300 km to the East China Sea. It supports 36% of China's freshwater fish species and its services underpin the Chinese economy. The Three Gorges Dam (TGD) on the Upper Yangtze River (installed capacity 22 500 MW) began impounding the river in 2003.
E-flow objectives	To mimic the river's natural flood pulse and thereby promote spawning of four Chinese carp species of commercial importance.
Biodiversity and other outcomes of e-flows	Carp reproduction has increased with pulsed e-flow releases; however, numbers below the dam are considerably lower than before the TGD was constructed.
References	Cheng et al. (2018), Harwood et al. (2018), and Xu et al. (2020).
Enabling factors	**Ranks and reasons**
Effective legislation and regulation of e-flows	State Environmental Protection Administration (now Ministry of Environmental Protection) requires hydropower projects to release e-flows according to economic production, human needs, and environmental and landscape requirements. The Optimised Operation Scheme of TGD and the Operation Guideline of TGD and Gezhouba Dam were approved by Ministry of Water Resources (MWR).
Engagement with diverse stakeholders	Stakeholders included China Three Gorges Corporation (CTG), the Changjiang (Yangtze) Water Resources Commission under MWR, the Yangtze River Basin Fishery Administrative Office (under the Ministry of Agriculture and Rural Affairs (MARA)), and representatives of the power grid.
Use of best available stakeholder knowledge	MARA's Office of Fisheries Law Enforcement for the Yangtze River Basin actively promoted the e-flow implementation. A multi-institutional interdisciplinary team funded by the CTG contributed to the development of e-flow plans and a science and monitoring program. International conservation organizations (WWF, The Nature Conservancy) supported the TGD e-flow program.
Constraining factor	**Rank and reasons**
Fragmentation of governance	Fragmented governance might have played a role in decision-making processes around the design and implementation of e-flows.

may not compensate for limited institutional support and may be particularly difficult for developing nations. Among other unsatisfactory scenarios, initial water allocations may be delivered by institutional resources, but the follow-up monitoring so important to learning and adaptive management may fail to materialise or is short-term and poorly documented.

In consequence, we suggest that e-flow implementations would benefit from more realistic and reliable financial and human resourcing arrangements commensurate with objectives, spatial and temporal scales, and urgency. Mainstreaming e-flows within watershed and river conservation and restoration initiatives (e.g., IWRM) is an immediate opportunity (van Rees et al. 2021). The 2022 Global Biodiversity Framework has been accompanied by substantial on-paper commitments to close the "biodiversity finance gap", particularly in low-income countries. Cohesive action is recommended to access these and other funding sources in support of e-flows, and to use them in ways integrated with other actions to "bend the curve of freshwater biodiversity loss" (Tickner et al. 2020).

4.3. Engagement with diverse stakeholders

The importance of stakeholder engagement is widely recognised in natural resource management. Meaningful, effective, and enduring partnerships among stakeholders and co-production of knowledge (Djenontin and Meadow 2018) are crucial to the success of river conservation and restoration programs (Nel et al. 2016), the sustainable development goals (United Nations 2022), and nature-based solutions (NBS) that aim to address biodiversity loss and climate change adaptation or mitigation (Brill et al. 2022). Noting that the term stakeholder is becoming questionable, we are still not aware of a widely accepted alternative word. This review has endeavoured to respect and apply the language of different cultures in the following text and in Fig. 2 but maintains the use of stakeholder in the interest of broad understanding until a new term emerges in the common lexicon of freshwater science.

Emphasis on stakeholder collaboration in e-flow implementation reflects growing appreciation of rivers as complex, adaptive social–ecological systems (Ostrom 2009). Broad stakeholder participation can achieve shared visions, agreed decisions about the desired future state of a given river system within its societal context, and hence, alignment of e-flow objectives (Conallin et al. 2018). Working together for a common cause also helps to build trust and the sharing of different forms of knowledge as well as maintaining legitimacy (O'Donnell et al. 2019). Identifying stakeholders is usually an iterative process involving several methods, such as interest–influence matrices, expert opinion, semistructured interviews, snow-ball sampling, or a combination of approaches (Reed et al. 2009). Recent e-flow framings recognise many categories of stakeholders—government agencies, water managers, the private sector (e.g., food sector businesses and hydropower generators), researchers, NGOs, local communities, Indigenous peoples, and Rights holders (Fig. 2). Each grouping contributes individual context-specific per-

Table 15. Lower Goulburn River environmental flow (e-flow) implementation, with highly ranked enabling and constraining factors.

E-flow implementation details	Lower Goulburn River, Australia
Location, length, and flow regime modifications	The 570 km Goulburn River in the Murray–Darling Basin is Victoria's largest basin. Lake Eildon and Goulburn Weir store wet season flows and release water during dry periods to service irrigation. This regime reverses the natural wet–dry seasonal flow pattern. Elevated water levels in summer–autumn damage bank vegetation and reduce shallow riffle habitat for invertebrates and fish; regime reduces flows to floodplain wetlands.
E-flow objectives	Restore natural wet–dry seasonal flow pattern of the river, enhance channel and floodplain flows, river health and biodiversity.
Biodiversity and other outcomes of e-flows	Winter and spring e-flows deposit sediment and seeds on riverbanks with minimal erosion. Spring flows support water-dependent vegetation. Late spring/early summer flows trigger fish spawning.
References	Bunn (2017), Lovell and Casanelia (2021), and Horne et al. (2022).
Enabling factors	**Ranks and reasons**
Effective legislation and regulation of e-flows	Water Act 2007 (Cth) and the 2012 Murray–Darling Basin Plan set limits on water use and regulate e-flow releases from storage. Rules are set by Victoria's Department of Environment, Land, Water and Planning (DELWP), and implemented by Goulburn Murray Water, the storage operator.
Engagement with diverse stakeholders	Murray Darling Basin Authority, Goulburn Broken Catchment Authority, Victorian and Commonwealth Environmental Water Holders, and DELWP enable e-flows. Academics informed e-flow assessment, design and implementation of monitoring program. Environmental Water Advisory Group facilitated engagement of landowners, Indigenous owners, and business owners.
Use of best available stakeholder knowledge	Diverse stakeholder contributions were used via new stakeholder engagement method (Horne et al. 2022).
Monitoring of ecological and socio-economic outcomes	Monitoring, Evaluation and Research program reports annually on e-flow outcomes. Continual long-term monitoring informs biodiversity outcomes against program objectives.
Constraining factors	**Ranks and reasons**
Lack of effective legislation and regulation of e-flows	Limited legislative control of floodplain flows and wetland connectivity due to potential flooding of private property. Planning is in progress to address these constraints.
Limited funding and human resources	E-flows are funded by Victorian Government (through an Environmental Levy) and the Commonwealth Government.

spectives and often unique experience and knowledge of river history, ecohydrology, and governance (Musсehl et al. 2022). A framework that defines these stakeholder groups, delineates their roles, and incorporates multiple knowledge sources with scenario modelling has been tested to good effect in the Goulburn River e-flow implementation (Horne et al. 2022; Table 15).

The e-flow cases reviewed herein typically involved diverse stakeholder groups from the categories identified above, usually with government water management agencies, research groups, or NGOs leading the process (Tables 6–13). We found that community stakeholders can have a direct role in stimulating and establishing an e-flow program or influencing the details of an environmental water regime. For example, the "*Ramganga Mitras*" (friends of Ramganga, a voluntary group of people coming from different walks of life) were engaged throughout the Ramganga e-flow assessment. A Rights holder petition to UNESCO's World Heritage Committee enabled novel e-flow initiatives for the PAD and its rivers (Table 5). The Putah Creek Accord on e-flows was initiated and achieved by a coalition of citizens, city council officials, and academics who challenged the way water was allocated by the regional water agency and won (Table 3).

Nevertheless, this review of case studies revealed two instances where agreements over e-flow decisions made by diverse communities of stakeholders were subject to shifts in context and power structure and were unable to persist. In Mexico, the national Water Reserves for the Environment Program enacted environmental water requirements in numerous river basins (Table 4). However, elements of the program generated opposition from local stakeholders, rural communities, and social NGOs who sued the state alleging omission of free, public, and informed participation and violation of human rights to water access. As a consequence, e-flow reserves for around 30 basins were invalidated in 2022 under Presidential decree (https://www.dof.gob.mx/nota_detalle.php?codigo=5652171&fecha=17/05/2022#gsc.tab=0). The Savannah River project team (Table 6) spent years developing and monitoring a collaborative and ecologically beneficial e-flow implementation until the partnership between the TNC and hydropower operators was terminated by powerful hydropower interests (https://tnc.box.com/s/9z4463oa880gsx9r02cghqk7ckk08tth).

Accordingly, recognising the importance of effective stakeholder teams and partnership processes in natural resource management, we recommend comparative studies of stakeholder participation models and modes of interaction to inform e-flow practice and avoid or reduce disagreements over visions, objectives, and final decisions. We note that stakeholders' views, positions, and power dynamics can change over time; thus, recognizing and planning for such change (and stakeholder fatigue) are as important to achieving e-flows as effective engagement of stakeholders at the start. Djenontin and Meadow (2018) provide methodological guidance on designs for supporting and achieving stakeholder co-production of knowledge to inform shared visions, processes, and decisions. Van Rees et al. (2019) promote the ecological stakeholder analogue (ESA) concept as a means to give ecological phenomena (e.g., species and processes) and ecological information (e.g., flow–ecology relationships and models) an equal "voice" in stakeholder negotiations among human parties. Strang (2023) explores rivers as active partners in human–non-human relations, proposing that it is "only by "listening to the river", and upholding the needs and interests of all of its human and non-human communities that we can hope to co-create the flourishing lifeworlds that will sustain all living kinds in the future". Further developments of the stakeholder concept, terminology, and effective engagement processes seem likely and could be transformative.

4.4. Use of best available stakeholder knowledge

Using the "best available science" is a stated or implicit principle of e-flow implementation and there is a wealth of information on the biophysical aspects of e-flow assessment at river, basin, and regional scales (Poff et al. 2017; Kennen et al. 2018). Deciding which assessment method to apply can seem challenging (Hirji and Davis 2009) especially to new practitioners, but many resources are available, such as introductory guidelines, method reviews, and books; guidance can be sought to identify and make use of the most recent science.

Co-production and inclusion of broad stakeholder knowledge are also essential for effective e-flow implementations, as discussed above, and as the majority of e-flow case studies indicate (Table 2). Here, we give emphasis to Indigenous knowledge and the concept of Two-Eyed Seeing as "learning to see from one eye with the strengths of Indigenous knowledge and ways of knowing, and from the other eye with the strengths of mainstream knowledge and ways of knowing, and to use both these eyes together, for the benefit of all" (Bartlett et al. 2012). The two forms of knowledge and perspective are regarded as being of equal importance, and rather than "blending, weaving, and merging" knowledge, the process should be a "thoughtful integration of the best each perspective has to offer to solve problems and benefit others" (Wright et al. 2019).

Our review includes two instances of particular efforts to safeguard Indigenous values, knowledge, ways of life, and spiritual practices. In the Ramganga River (Table 13), one of the motivations to maintain e-flows is to facilitate adequate water levels and velocities to protect social–cultural services valued by riparian communities and visitors (e.g., fishing, holy bathing, and *aachman*—the ritual taking of a few drops of river water and consuming them from the right palm). The PAD e-flow project (Table 5) has a particular focus on co-production to meet the social–ecological needs of the delta landscape, linked to the traditional values, ways of life, and cultural heritage of the 11 First Nations and Métis governments that have traditional territories traversing the Wood Buffalo National Park and World Heritage Site, Canada. For delta communities, the PAD is "their home, their grocery store, their classroom, their medicine cabinet, their church, their highway, their photo album, and the place where their happiest memories live" (IEC—Independent Environmental Consultants 2018).

Two of our case studies recorded inadequate uptake of Indigenous knowledge (Table 2). Putah Creek lies within the traditional territory of the Wintun Native Americans whose subsistence economy included acorns ground to make mush and bread, various plants and berries, communal deer and rabbit hunts, and fish drives to catch salmon and trout. The Lacandon are Mayans who have hunted, raised crops and some livestock, gathered roots and plants, and fished within their homeland along the Usumacinta River and its tributaries. In both cases, we are not aware of any interactions with members of these groups during e-flow implementation.

In these contexts, we recommend using best available Indigenous and Western knowledge as foundational in e-flow implementation by means of inclusive partnerships and co-production of knowledge following the principles of Two-Eyed Seeing (Wright et al. 2019). In accordance with the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP 2008) and recent developments in Canada, Australia, and New Zealand (Conallin et al. 2018; Crow et al. 2018; Anderson et al. 2019), we also recommend further historical and methodological investigations to enrich and inform respectful, safe, and just e-flow implementation (Rockström et al. 2023) and stewardship of riverine systems through full stakeholder participation and sharing of knowledge.

4.5. Monitoring of ecological and socio-economic outcomes

Monitoring the outcomes associated with every e-flow implementation is essential to demonstrate the environmental and societal benefits for governing agencies and operators, the private sector, the broader public, and politicians, all of whom need to know that major investments of taxpayer or private funds are used to best effect (Dyson et al. 2008; Wineland et al. 2021). Ideally, monitoring programs should be embedded in an adaptive management framework to ensure that the outcomes of e-flows can inform all stages of the implementation cycle (e.g., Fig. 2), including modifying objectives, adjusting water release patterns, or making other adjustments that support e-flows (King et al. 2015; Mussehl et al. 2022). Where there are critical biophysical knowledge gaps, some aspects of monitoring should be designed as hypothesis-driven research projects framed to inform adaptive management of e-flows (Olden et al. 2014; Nelson et al. 2020). In some cases, Indigenous knowledge may offer related insights gleaned over generations of lived experience.

In England, a national river condition monitoring program based on macro-invertebrates and fish is used to assess the appropriateness of flow regimes and to adjust any found to be inappropriate; this is particularly important where e-flows are initially set by default generalised standards (Table 8). Monitoring strategies should also capture human perceptions of the benefits or limitations of e-flow implementations (Bennett 2016). Citizen science and Indigenous-led initiatives are encouraged to widen perspectives on what is monitored and to fill gaps in spatial and temporal observations and measurement (GEO BON and FWBON 2022). Decisions about the ecological and socio-economic indicators to be monitored and where and how often are particular to each circumstance. However, all e-flow monitoring programs should include dedicated human and financial resources and clear lines of responsibility for data analysis, reporting, and the communication of results in suitable formats to all stakeholders and the wider public.

E-flow examples we reviewed varied considerably in the availability of information about their monitoring programs. Two models emerged, both of which are valuable. Regular reporting required by funding agencies provided detailed accounts of some e-flow outcomes (e.g., Lovell and Casanelia 2021; Table 15). In other cases, researchers, consultants, and NGOs led the reporting process and published monitoring designs and outcomes in scientific journals and technical reports. For example, regular sampling of carp eggs and larval fish below the TGD showed that reproduction of Chinese carp species has increased with pulsed water releases (Cheng et al. 2018; Xu et al. 2020; Table 14). Monitoring of ecological outcomes in Putah Creek established that a more natural flow regime resulted in the recovery of resident native fish populations (Kiernan et al. 2012; Table 3). User-friendly outputs from all forms of e-flows monitoring (such as River Health Scorecards or similar devices, social media posts, mainstream media stories, and policy briefs) are needed to build understanding and knowledge exchange with participant stakeholders and broader communities (Djenontin and Meadow 2018; Horne et al. 2022). A well-structured engagement and communication strategy can help convey important messages, exchange knowledge, and help shift the mindsets of a wide range of stakeholders, notably community groups and decision makers, towards e-flow protection.

Accordingly, we recommend greater institutional commitment and support of rigorous long-term monitoring and reporting of biophysical and societal outcomes of e-flows in an adaptive management framework tailored towards continuous learning (van Rees et al. 2022). The growing applications of flow-related NBS to river degradation and biodiversity loss warrant system-level monitoring to evaluate their benefits for ecosystems, species, and society (van Rees et al. 2023). We recommend involving stakeholder agencies, research groups, citizens, Indigenous peoples, and other Rights holders in monitoring (GEO BON and FWBON 2022) and the packaging of e-flow results and outcomes into accessible formats and bundles that target, inform, and empower diverse audiences.

4.6. Support for capacity training and research

Support for capacity training and research can be embedded at every step of an adaptive e-flow implementation cycle (Mussehl et al. 2022). Informative workshops and "training-by-doing" during e-flow implementations can enable progressive building of stakeholder understanding and technical capacity (O'Keeffe 2018), as well as facilitating contributions to e-flow visions, objectives, and decision-making processes. The identification and filling of critical knowledge gaps will often require hypothesis-based research (Olden et al. 2014; Irving et al. 2022), as well as careful analysis of ecological responses revealed through monitoring. Six of our e-flow examples ranked support for capacity training and research highly (Table 2). Academic research informed the Putah Creek Accord, which funded community training in creek restoration and the Streamkeeper program (Table 3). The WWF, consultants, and researchers together led and strengthened stakeholder capacities around the e-flow assessment process in the Usumacinta River and Mexico's national EWRs program (Table 4). The PAD program has a significant focus on capacity building for co-production to ensure that the e-flow framework is led by and developed with the participating communities and supported by all available expertise and systems of knowledge (Table 5). Other examples engaged significantly with NGOs and research groups to support training in e-flow assessment and river-specific knowledge generation. Even so, four examples (Ramganga River, Mexican and English rivers, and the Nile Basin (Table 2)) ranked poor scientific understanding as an important limiting factor, indicating the need for place-based biophysical surveys and research on flow-related river processes to inform e-flow assessments at these river, country, and multijurisdictional scales.

Consequently, we acknowledge that there can be significant demand for biophysical and social-economic research and knowledge generation as well as practical training and experience to inform e-flow assessments and effective implementations (O'Keeffe 2018). We recommend concerted efforts to train a new generation of e-flow practitioners equipped to lead and empower environmental water management globally. At the time of writing, the Instream Flow Council (a joint enterprise between US and Canadian resource scientists and managers; https://www.instreamflowcouncil.org/about/ and the American Fisheries Society) is working to establish a new national e-flow training centre. Its mission is to synthesize emerging research and to develop and provide uniform interdisciplinary training in support of conserving ecological water flows and levels. We recommend extending this concept towards a global network of training centres with strong agency, research, NGO, and Indigenous and Rights holder partnerships to service developing countries and other regions.

4.7. Protection of some flows as early as possible

Setting aside water for the environment as early as possible has particular advantages when there are existing or imminent pressures on the resource and future opportunities to conserve water may be limited (Harwood et al. 2018). Water managers can then set limits on further water abstraction or examine the operational flexibility of releasing e-flows from existing dams or consider e-flow recommendations in the design of new water infrastructure. In Australia, an early step in water reforms was to establish the Murray–Darling Basin "Cap" designed to set limits on overall water extractions from the basin's rivers (Bunn 2017), followed later by tailored e-flows in each major catchment (e.g., the Goulburn River, Table 15). Other countries have established precautionary EWRs to ensure the conservation or partial restoration of riverine ecosystems while more detailed studies are in progress (Mexico, Table 4; England, Table 8; South Africa, Tables 9 and 10; Zambia, Table 11). In this context, it is important to keep open the option to undertake further investigations and refine the precautionary e-flow regime as further information becomes available, as is required in the Mexican and English e-flow process. Opperman et al. (2018) offer a staged approach to developing precautionary ecohydrological rules followed later by more tailored, comprehensive holistic e-flow assessments.

Legislated conservation of free-flowing rivers or parts thereof can help to safeguard them from future dams, water infrastructure developments, and major water withdrawals (Thieme et al. 2021). Systematic conservation and system-scale infrastructure planning tools offer data-driven methods for prioritizing protected areas that maximise river–wetland connectivity and biodiversity (Reis et al. 2019; Nel et al. 2011). These tools can also identify instances where infrastructure could be modified or removed for ecological benefit and enhanced delivery of riverine ecosystem services. We discuss the latter options under "Planning of infrastructure to enable e-flows" (below).

We urge global efforts to protect river flows as early as possible, as precautionary e-flow allocations or EWRs (Salinas-Rodríguez et al. 2021), particularly in regions of high and poorly protected lotic biodiversity where intensive water infrastructure developments are planned. We recommend exploration of opportunities for e-flows to inform and support the conservation of largely free-flowing rivers and neglected freshwater biodiversity hotspots (Nel et al. 2011). Ensuring that river reaches and tributaries upstream of protected area boundaries have minimally altered flows, or adequate e-flow regimes, can enhance the conservation effectiveness of downstream protected areas. Limiting water infrastructure and abstraction within protected areas, and if necessary securing e-flow provisions in those areas, is also a necessity.

4.8. Planning of infrastructure to enable e-flows

The provision of e-flows is most often enabled by modifying the water release rules of individual dams or dam cascades using existing infrastructure (Richter et al. 2006; Widen et al. 2022). In other cases, retrofitting or removing water infrastructure could facilitate and enhance e-flow implementation (Thieme et al. 2021). A great deal of global water infrastructure is ageing or no longer fit for purpose, with increasing calls for dams and weirs to be upgraded to accommodate extreme flood and drought risks and to ensure sufficient storage to meet human water needs (Duda and Bellmore 2022). The World Commission on Dams (2000) concluded that decommissioning should always be an option when the operations and management of a dam are being evaluated. Optimizing dam removals and water infrastructure adjustments is increasing in many countries despite associated risks and uncertainties about outcomes (Roy et al. 2020; O'Hanley et al. 2020). The removal of four dams in the lower Klamath River in California (the largest dam removal project in US history) will reopen more than 640 km of spawning and rearing habitat for five species of salmon using the river and its headwaters (https://www.fisheries.noaa.gov/feature-story/building-network-restored-habitat-klamath-river-watershed).

Climate change is bringing more extreme floods in many countries but building more and larger dams and massive levees that sever connections between river channels and their floodplains are no longer an acceptable solution. The perception of flooding as a threat is shifting towards appreciation that inundated floodplains are a shared resource with many ecosystem, social-economic, and cultural benefits (Serra-Llobet et al. 2022), as are floodplains in their dry phases. E-flows can be integrated with other NBS to restore channel structure (such as meanders) and to reconnect riparian zones, rivers, and floodplains by removing or modifying levee banks, weirs, and large barrier infrastructure (Curry et al. 2020; Morandi et al. 2021). Projects and programs that create "room for the river" by widening dynamic river–wetland corridors and their "process space", while simultaneously addressing present and anticipated flood risks, offer promising solutions (Ciotti et al. 2021; Wohl et al. 2021).

In this review, the importance of using basin-scale infrastructure planning, design, and operation to enable e-flows was rated highly in four e-flow implementations (Table 2). In England, e-flows are designed to complement channel morphology modified for flood defence, navigation, fisheries, and hydropower (Table 8). The Nile Basin Initiative has major infrastructure projects for water supply and hydropower under development, with e-flows an integral part of planning and design (Table 12). However, the challenges of decommissioning infrastructure were of concern in the Luangwa River (Table 11).

We recommend consideration of options to modify or decommission infrastructure as an integral part of e-flow implementation in regulated rivers, and during reviews of aging dams and weirs. This intervention is also a primary strategy underpinning another of the six key actions under the Emergency Recovery Plan: safeguard and restore freshwater connectivity (Thieme et al. 2023). Novel indices of longitudinal river fragmentation can be used to quantify the impacts of individual dams and assess a range of development scenarios even in data-deficit environments (Jumani et al. 2022). We recommend comprehensive assessments of the ecological and social implications of new hydropower cascades or other large dam developments to minimize impacts of infrastructure, maximize connectivity, and optimize retention of biodiversity and ecosystem services (Flecker et al. 2022). We advocate wider consideration of blended green–grey water infrastructure (Vörösmarty et al. 2021) and NBS that can address flood risk and floodplain management while simultaneously improving aquatic habitat, biodiversity, and ecosystem services (Acreman et al. 2021; van Rees et al. 2023).

4.9. Evaluation of trade-offs with other water users

Making best use of available water requires the evaluation of priorities and identification of practical opportunities and constraints. Declining water availability and water scarcity both underpin and impede many e-flow implementations in the sense that scarcity motivates initiatives to protect e-flows, but often much of the available water is deemed to be needed for other uses of the resource (Wineland et al. 2022). Optimisation tools, regional-scale risk assessments, and trade-off and cost–benefit analysis play important roles in deciding how to share water with other users, such as hydropower generation and agriculture (Chen and Olden 2017; Linstead 2018; O'Brien et al. 2018). Solutions for implementing e-flows may emerge at the basin scale, such as coordinated operations between dams or reducing irrigation losses in one part of a system to allow increased flow levels in another area (O'Brien et al. 2019; Opperman et al. 2023). With increasing concerns for water availability, there may be an opportunity to align e-flow goals with water security goals; for example, by implementing strategies to lessen upstream consumption, more water can flow to downstream water users, benefitting e-flows along the way. Framed appropriately within resource constraints, e-flows can be implemented so that the needs of multiple water users can be met or minimally disrupted (Poff et al. 2016; Widen et al. 2022).

Five of our e-flow case studies ranked trade-off analysis as an important enabling factor (Table 2). In the Usumacinta River, cost–benefit analysis revealed low economic costs of biodiversity benefits for other users (Table 4). In England, high river and wetland water levels conserve peat soils, enhance biodiversity, and reduce CO_2 emissions, but they also reduce grazing nutrition for cattle and increase methane releases (Acreman et al. 2011). In Zambia, environmental water requirements are secondary to water for domestic use; however, the country is moving towards a system to value its natural resources (Table 11). In the Nile Basin, regional-scale ecological risk assessment demonstrated the cost–benefit value of supporting services and e-flows compared to stakeholder demands for provisioning and regulatory services (Table 12). Work with local farmers, district authorities, and water managers has demonstrated the potential to enhance e-flows in the Ramganga River system while enhancing farm yields through improved agricultural practices (Table 13).

Recognising the need for trade-offs in social–ecological water requirements and water allocation management for other purposes (e.g., agriculture, hydropower, and flood management), we recommend stakeholder-driven processes that are transparent, inclusive, and based on the best available quantitative and qualitative evidence. We further recommend the development of a freely available toolbox of frameworks for water trade-off analysis (e.g., IWRM, Water Diplomacy and Mediation), including software such as eco-engineering decision scaling (Poff et al. 2016) and multi-objective optimisation (Thieme et al. 2021), and a training program to guide e-flow implementation through trade-off and cost–benefit analysis.

4.10. Adaptively managing for climate change

The provision of e-flows is often challenged by declining water availability, as this review of examples has revealed in seven instances (Table 2). Water managers and e-flow practitioners will also have to cope with more frequent flow extremes (drought and floods) and shifting temporal patterns associated with climate change (Sabater et al. 2022). These regime changes can exacerbate the effects of river impoundment and diversion on riverine hydrology and further endanger freshwater ecosystems and biodiversity (Poff 2018; Oberdorff 2022). Climate change challenges the setting of e-flow objectives, their technical management, and societal expectations of benefits (Knouft and Ficklin 2017; Tonkin et al. 2019). Recent studies promote "climate ready" targets for e-flow implementation that consider plausible scenarios of changes in water availability and in temporal flow patterns (John et al. 2021; Judd et al. 2022). They emphasise the need for processes to support trade-off decisions and adaptation of e-flow designs according to particular future conditions and stakeholder visions. Maintaining ecological resilience, adaptability and the potential for recovery of valued ecosystem services, or support of different services under novel hydrological regimes, are key goals of climate-ready e-flow designs and management (Poff 2018; Grantham et al. 2019; Tonkin et al. 2019).

Three e-flow examples assigned a high rank to risks associated with climate change in their study areas (PAD, Table 5; English rivers, Table 8; Luangwa River, Table 11), and one case commented that implementation of adaptive management in response to changing circumstances and climate change was limited (Usumacinta River, Table 4). A systematic review of a much larger sample of e-flow implementations would be needed to assess how often (and in which regions) the risks associated with climate change are being considered and incorporated in e-flow assessments and environmental water management (e.g., Dourado et al. 2023).

The implications of climate change may require significant conceptual and practical changes to how we approach e-flow assessments (Tonkin et al. 2019). Accordingly, we recommend development of methodologies to incorporate the implications of climate change as a routine element of e-flow assessment (Grantham et al. 2019). We propose a systematic review of case studies and the assembly of a dossier of examples, methods, modelling tools, and other resources to support climate-ready e-flow practice. This could be combined with the toolbox of methods, software, and a training program to guide e-flow implementations through climate-related trade-off and cost–benefit analysis (see "Evaluation of trade-offs with other water users", above). These resources could support the training centres proposed above, as well as assisting global agencies, such as the Food and Agriculture Organisation of the United Nations, which currently guides and collates country information on the Sustainable Development Goal water stress indicator 6.4.2, including e-flow allocations (FAO 2019).

5. Conclusions

E-flows are gaining traction internationally as a key tool for sustainable water resource management. Expanding and accelerating their implementation can help to restore the biodiversity and resilience of hydrologically altered and water-stressed rivers and connected water-dependent ecosystems. Our review of diverse e-flow case studies and literature demonstrates this and identifies 10 critical factors that enable effective e-flow implementations. These factors are broadly consistent with previous evaluations of success in e-flow implementation and reinforce the need for a wide vision and solid foundation of enabling conditions to maximize ecological and social-economic benefits from e-flows. The implementation of e-flows is most effective where it is treated as an adaptive management cycle that incorporates ongoing engagement, co-production of knowledge, and learning with all stakeholders. Contributions of knowledge and perspectives from diverse cultures and stakeholders, including agencies, industries, local communities, Indigenous peoples, and other Rights holder groups, are as important for successful implementation and outcomes as an understanding of hydrology, ecology, and other biophysical aspects.

The 13 real-world examples of e-flow implementation we reviewed achieved beneficial outcomes for rivers, floodplains, and connected wetlands. They include increased channel habitat, improved recruitment of many plants and animals, increased floodplain access and habitat for numerous fish and invertebrate species, improved floodplain tree recruitment, and the protection of freshwater-dependent species listed as endangered by conservation agencies. In addition, significant social-economic benefits arose from e-flows and beneficial ecological outcomes, ranging from access to and use of river sites and freshwater resources of importance to Indigenous, local, and visitor communities, improvements in fisheries production, flood control and recreation, and the protection of cultural heritage, including built infrastructure and sacred rituals.

While significant practical progress is being made, e-flow implementation is often challenging and can be constrained by factors operating at different stages of the adaptive management cycle. We show that it is often possible to overcome such constraints—partially or fully—through thoughtful, concerted, and timely actions. These range from strengthening e-flow legislation and participatory governance, to exploration of trade-offs between social–ecological water requirements and other uses of water (e.g., agriculture and hydropower generation). In each instance, we provide options, and generalizable recommendations to overcome constraints, as well as examples of where this has happened in practice. We emphasize the need for trade-off analysis and the implications of climate change to be incorporated as routine elements of e-flow assessment. We advocate support for a collaborative global network of training centres to educate and empower e-flow practitioners as leaders of adaptive environmental water management globally. If the world is to bend the curve of freshwater biodiversity loss, strengthen river resilience, and promote safe and just human benefits from nature-base solutions, it will need e-flows as a key tool. The implementation of e-flows can be challenging, but it is feasible, and the ecological and societal benefits justify and necessitate far more effort.

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