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The environmental flows implementation challenge: Insights and recommendations across water-limited systems

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Abstract

Environmental flows (e-flows) are powerful tools for sustaining freshwater biodiversity and ecosystem services, but their widespread implementation faces numerous social, political, and economic barriers. These barriers are amplified in water-limited systems where strong trade-offs exist between human water needs and freshwater ecosystem protection. We synthesize the complex, multidisciplinary challenges that exist in these systems to help identify targeted solutions to accelerate the adoption and implementation of environmental flows initiatives. We present case studies from three water-limited systems in North America and synthesize the major barriers to implementing environmental flows. We identify four common barriers: (a) lack of authority to implement e-flows in water governance structures, (b) fragmented water governance in transboundary water systems, (c) declining water availability and increasing variability under climate change, and (d) lack of consideration of non-biophysical factors. We then formulate actionable recommendations for decision makers facing these barriers when working towards implementing environmental flows: (a) modify or establish a water governance framework to recognize or allow e-flows, (b) strive for collaboration across political jurisdictions and social, economic, and environmental sectors, and (c) manage adaptively for climate change in e-flows planning and recommendations.

This article is categorized under:

- Water and Life > Conservation, Management, and Awareness
- Human Water > Water Governance
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KEYWORDS

climate change, coupled-human natural systems, environmental flows, water-limited

1 | INTRODUCTION

Many countries recognize that environmental flows (e-flows) should be implemented and/or incorporated into water management and policy to ensure water sustainability for both humans and ecosystems. The Brisbane Declaration (2007) and the Global Action Agenda on Environmental Flows (2018), which set a common direction and synthesis for international e-flows implementation, were endorsed by 57 countries (Arthington, Bhaduri, et al., 2018; Brisbane Declaration, 2007). Additionally, member states of the United Nations have agreed to work towards simultaneously meeting two freshwater-related Sustainable Development Goal targets (SDG's) by 2030: "Increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater…" (section 6.4), and "protect and restore freshwater ecosystems…" (section 6.6; UN, 2018). Despite this widespread recognition of the need to accelerate the implementation of e-flows globally, in practice, implementation faces numerous barriers with only piecemeal examples of success (Harwood et al., 2018; Kiernan et al., 2012; Le Quesne et al., 2010; Tickner et al., 2020; Twardek et al., 2021). In water-limited regions of the world, these barriers can grow and intensify because of the trade-offs between human water security and freshwater ecosystem protection (Kennen et al., 2018).

Worldwide, freshwater biodiversity and ecosystem function has rapidly declined and deteriorated (He et al., 2019; Tickner et al., 2020; Vörösmarty et al., 2010). Damming rivers for human water security and water extraction for societal uses are the primary impacts that alter freshwater ecosystem structure and function (Mirchi et al., 2014). Consequently, there is increasing pressure to find sustainable approaches to balance the complex trade-offs between human and environmental water needs. The most widely used approach to sustain both human water security and freshwater ecosystems is to establish e-flows—defined as "the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being" (Arthington, Bhaduri, et al., 2018). While there are many frameworks and methodologies that practitioners use to estimate e-flows (Tennant, 1976; Richter et al., 1996; Poff et al., 1997; Hughes & Hannart, 2003; Poff & Zimmerman, 2010; Richter & Thomas, 2007; Acreman et al., 2014; Yarnell et al., 2015; see Poff et al., 2017 for full review of methodologies), there are two main challenges that each approach faces: (a) The assumption of stationarity in flow regimes (i.e., targeting reference conditions for restoration when climate change and human factors are changing flow regimes), and (b) conflicting water needs between ecosystems and human societal uses (Marston et al., 2020; Milly et al., 2008; Poff, 2018).

Hydrologic modification through damming has been shown to homogenize flow regimes and change flow seasonality, altering the magnitude, frequency, and variability of discharge, which can decrease peak flows and flood pulses and increase base flows (Poff et al., 2007). As a result, e-flows implementation often seeks to either restore flow regimes to a pre-dam flow regime (Bednarek & Hart, 2005), establish dynamic, characterization-based flows based on river types and flow–ecology relationships (Poff & Zimmerman, 2010), or design flows to maximize ecological outcomes (Acreman et al., 2014; Chen & Olden, 2017; Poff et al., 2017). These approaches can improve freshwater ecosystem function and biodiversity outcomes by addressing the life cycle needs of aquatic and riparian species (Carlisle et al., 2010; Merritt et al., 2010; Mims & Olden, 2012; Olden et al., 2014), structuring aquatic communities (Bogan & Lytle, 2011; Tonkin et al., 2017), improving water quality (Nilsson & Renöfält, 2008), restoring sediment regimes (Topping et al., 2010), and ecosystem goods and services (Gopal, 2016). Thus, e-flows can both support freshwater ecosystem conservation and provide many socio-economic benefits to human societies (Gilvear et al., 2017).

Despite widespread recognition of the benefits and need to establish e-flows, implementation has been slow (Tickner et al., 2020), with limited examples of broad, systematic success (Harwood et al., 2018; Kiernan et al., 2012; Le

TABLE 1 List of challenges to environmental flows implementation and references illustrating how the challenges were synthesized for this publication based on current literature and the author's regional expertise in water-limited systems

References	Challenges listed
Moore (2004)	Lack of understanding of socio-economic costs and benefits[4]
	Political will[1,2]
	Legal, institutional, and monitoring arrangements[1,2]
	Effective stakeholder involvement[4]
	Financial resources
	Expertise, technical support
	Public acceptance[4]
	Capacity for modeling and scenario development
	Hydrological data
	Other
Hirji and Davis (2009)	Overcoming the misperceptions arising from the term "environmental flows"
	Developing methods for systematically linking biophysical and socioeconomic impacts[4]
	Incorporating the whole water cycle (surface, groundwater, and estuaries) into the assessments
	Applying environmental flow assessments to land use activities that intercept and exacerbate overland flows
	Including climate change in the assessments[3]
	Integrating environmental flow assessments into strategic, sectoral, and project environmental assessments
	Understanding the circumstances in which benefit sharing is a viable approach
Le Quesne et al. (2010)	Lack of political will and stakeholder support[1,2]
	Insufficient resources and capacity
Poff (2018)	Non-stationarity[3]
	Shifting from static to dynamic modeling
	Scaling hydro-ecological relationships in space and time
	Incorporating non-flow environmental factors in e-flows science and assessment[4]
	Broadening the ecological foundation towards a more predictive e-flows science
Wineland et al. (2021, this paper)	1. Lack of authority to implement e-flows in water governance structures
	2. Fragmented water governance in transboundary water systems
	3. Declining water availability and increasing variability under climate change
	4. Lack of consideration of non-biophysical factors

Note: Challenges with numbered superscripts indicate which challenge in the current article the authors synthesized information from.

Quesne et al., 2010). Here, we define implementation as either joining, enforcing, or executing an e-flows policy or program (Arthington, Bhaduri, et al., 2018). Previous studies have identified the many challenges that e-flows implementation faces globally (Moore, 2004; Hirji & Davis, 2009; Le Quesne et al., 2010; Poff, 2018; Table 1). Indeed, the lack of widespread adoption of e-flows does not result from a lack of biophysical knowledge, rather it stems from complex socio-political arrangements and uncertainty about future hydrological conditions (Pahl-Wostl et al., 2013; Poff, 2018). Hence, there is a need to better understand the challenges facing e-flows implementation in water-limited systems where biophysical aspects of e-flows are well-studied, but barriers and challenges to implementation are less publicized. Implementing e-flows can be challenging in water-limited systems because of complex water governance structures and a lack of authority for environmental water allocation (Loehman & Charney, 2011; Owen, 2011), extreme spatio-temporal hydrologic variability and projected declines in water availability due to climate change (Arthington & Balcombe, 2011; Tooth, 2000; Young & Kingsford, 2006; Zamani-Sabzi, Rezapour, et al., 2019; Heidari et al., 2020; Larkin et al., 2020), and complex socio-environmental trade-offs resulting from water reallocation or redistribution (Anderson et al., 2019; Lankford et al., 2004; Tickner et al., 2017).

This article synthesizes the major barriers facing e-flows implementation in water limited systems through examining several case studies, and identifies recommendations for overcoming these barriers. We use a hybrid approach, combining a literature review of e-flows implementation challenges with the interdisciplinary, regional expertise of the authors. We first synthesize four major barriers to e-flows implementation in water limited systems based on previous work (Table 1) and our knowledge of the water-limited systems in our region of focus: (a) lack of authority to implement e-flows in water governance structures, (b) fragmented water governance in transboundary water systems, (c) declining water availability and increasing variability under climate change, and (d) lack of consideration of non-biophysical factors. Our synthesis was derived from two river basins, the Red River basin (RRB), the Rio Grande/Rio Bravo River basin (RGB) and one aquifer system, the Edwards aquifer (EA) in the south-central United States (US) and northern Mexico. We then identify three priority recommendations for overcoming barriers to e-flows implementation: (a) Modify or establish a water governance framework to recognize or allow e-flows, (b) strive for collaboration across political jurisdictions and social, economic, and environmental sectors, and (c) manage adaptively for climate change in e-flows planning and recommendations. In doing so, we intend not to be policy-prescriptive for e-flows implementation planning, rather, we aim to summarize specific actionable measures that could help accelerate and extend e-flows implementation planning in water-limited systems.

2 | BARRIERS TO ENVIRONMENTAL FLOWS IMPLEMENTATION IN WATER-LIMITED SYSTEMS

2.1 | Lack of authority to implement e-flows in water governance structures

Water governance establishes the rules, actors, and structures under which water management operates (Nava, 2018). The complexities and challenges of water governance are reflected in its definition by The Global Water Partnership: "the range of political, social, economic, and administrative systems that are in place to develop and manage water resources, and the delivery of water services, at different levels of society" (Rogers & Hall, 2003, p. 16). Water governance and management are inherently multidisciplinary and multidimensional (Pahl-Wostl et al., 2010). Thus, water decision makers and managers navigate and operate under increasingly complex political, social, and economic systems to ensure human water security (Smidt et al., 2016). As a result, incorporating e-flows into water governance and management is often viewed as a disruption to these already challenging human-oriented operations, especially in water-limited river basins (Gawne et al., 2018; Poff & Matthews, 2013).

Water governance can either facilitate or inhibit the development and implementation of e-flows. In the Western US, for example, water rights generally follow the prior appropriation or "first in time, first in right" legal doctrine. This doctrine, which is based on the principles of priority and beneficial use, is a legacy of gold mining camps in California and Colorado that aimed to provide allocation rules in times of water shortages (Tarlock, 2001). Earliest water rights holders obtain priority, and subsequent rights holders are appropriated so long as they do not infringe on the water allotted for prior rights holders (Getches, 2009). Water rights holders must also use water for a beneficial use, which varies from state to state but commonly refers to agricultural, industrial, or municipal uses (Neuman, 1998). Prior appropriations rights are separate from land ownership and can thus be sold and transferred, whereas the riparian rights doctrine, which is more common in the Eastern US, states that water rights result from land ownership. Prior appropriations are also responsible for allowing states to have sovereignty over their water rights, limiting the federal government's role in water governance (Tarrant V. Herrmann, 2013). E-flows are difficult to implement under a prior appropriations system because they have historically not been considered a beneficial use of water in many states. Many states in the western US (e.g., Arizona, California, Colorado, Montana, Nebraska, New Mexico, Oregon, and Idaho) have authorized statutes allowing new appropriations and transfers of water rights for e-flows, but some states still do not legally consider e-flows a beneficial use (e.g., Oklahoma, Kansas, and Texas; Loehman & Charney, 2011).

Because of the limited ability for water to be allocated for environmental purposes in water-limited systems, leveraging the presence of threatened or endangered species or ecosystems often is the only legal and regulatory pathway for allocating water for e-flows (Harwood et al., 2018; Richter, 2010). In the US, for example, the Endangered Species Act (ESA) is the only authority or mechanism to implement e-flows. Many dams are operated by the US Army Corps of Engineers (USACE) for specific purposes enacted by Congress such as flood prevention, water supply, hydropower, navigation, and recreation (USACE, 1992). Consequently, water releases for e-flows are typically not authorized unless dam operations can be modified through federal law like the ESA (Warner et al., 2014). In groundwater aquifer systems, however, e-flows are important for stream baseflows and aquifer recharging through sometimes complex groundwater–surface water interactions (de Graaf et al., 2019). Groundwater resources used for human societal uses like municipal water supplies and irrigation are valuable but are at risk due to overconsumption and lack of aquifer recharge (Famiglietti, 2014). As a result, many springs and streams that rely on groundwater for baseflows have lost this critical flow resulting in habitat loss and fragmentation for groundwater-dependent species (de Graaf et al., 2019; Fan et al., 2013). Because of the intensive reliance on groundwater resources for societal uses and treatment of groundwater as private property in some Western US states, the federal ESA is the only tool to regulate groundwater withdrawal and implement e-flows for groundwater-dependent springs and streams (Devitt et al., 2019).

Establishing a legal basis for e-flows is a global challenge. Global biodiversity treaties and conventions like the Ramsar Convention on Wetlands (UNESCO, 2020) and Convention on Biological Diversity (United Nations, 2020) can provide legal mandates for e-flows. In Australia, for example, these initiatives provided much of the legal grounds for establishing e-flows through the 2007 Australian Water Act (Carmody, 2018; Hart & Doolan, 2017) which established the Murray-Darling Basin Plan that included measures for implementing e-flows (Pittock & Finlayson, 2011). We highlight two examples where the presence of threatened or endangered species resulted in the establishment of e-flows in Box 1. Section "Groundwater: Edwards Aquifer" in Box 1 highlights an example of establishing e-flows from groundwater springs in the Edwards Plateau region of south-central Texas. Section "Surface water: Rio Grande/Rio Bravo" in Box 1 highlights an example of establishing e-flows to support the nearly extinct Rio Grande Silvery Minnow.

2.2 | Fragmented water governance in transboundary water systems

Transboundary water systems (river basins, lakes, aquifers, wetlands, etc., shared by two or more political entities) are complex socio-environmental systems that can exhibit outcomes on a cooperation–conflict spectrum (Munia et al., 2016; Zeitoun & Mirumachi, 2008). With approximately 276 transboundary river basins and 273 transboundary aquifer systems globally, the need for cooperative water management and conflict avoidance to ensure water sustainability for both humans and the environment is a significant global challenge (UNECE/UNESCO, 2015). In water-limited and climate change-impacted transboundary systems, water conflicts can spark easily and create wicked socio-environmental problems (Mianabadi et al., 2020). One of the six statements in the 2018 Brisbane Declaration and Global Action Agenda on Environmental Flows states that: "Implementation of environmental flows requires a complementary suite of policy, legislative, regulatory, financial, scientific, and cultural measures to ensure effective delivery and beneficial outcomes." This can be challenging in the context of transboundary water systems (Arthington, Bhaduri, et al., 2018). In terms of establishing environmental flows in transboundary water systems, coordination can be inhibited by two main factors. First, water management and authority are often distributed across many political jurisdictions and spatial scales, complicating any coordinated efforts to implement and maintain e-flows initiatives at a basin-scale (Brown & King, 2013; Fox & Sneddon, 2007; Porse et al., 2015; van der Zaag, 2007). Second, water resources are often fully allocated for societal uses due to scarcity and competition between entities, making it infeasible to reallocate or redistribute water for e-flows (Arjoon et al., 2016; Brown & King, 2013; Grey & Sadoff, 2007).

The challenges facing e-flows implementation in transboundary basins are global in scale. For example, the construction of the Grand Ethiopian Renaissance Dam on the Blue Nile highlights an emerging water conflict in a transboundary river basin over e-flows. Negotiations on water delivery to Sudan and Egypt through environmental flow

BOX 1 Endangered species as mechanisms of environmental flows implementation

Groundwater: Edwards Aquifer

The Edwards aquifer (EA) system, which covers ~20,000 km^2 in south-central Texas, is one of the most permeable and prolific carbonate aquifers in the US and a primary source of drinking water for the city of San Antonio (Figures 1 and 2). Under the Edwards Aquifer Authority (EAA)'s regulatory jurisdiction, there are eight federally listed threatened and endangered species dwelling in the EA and its major spring outlets, the Comal and San Marcos springs which include three species of macroinvertebrates, the Texas blind and San Marcos salamanders, the Fountain darter, and Texas wild-rice (EARIP-HPC, 2012; US Fish and Wildlife Service, 2015). These endangered species are managed by the EAA under a 15-year US Fish and Wildlife Service issued Incidental Take Permit (ITP) and an associated Habitat Conservation Plan (HCP) expiring in 2028 (US Fish and Wildlife Service, 2015). The HCP contains spring flow protection measures along with recommended minimum environmental flow rates of 30 ft^3/s (0.85 m^3/s) at Comal and San Marcos springs. Additionally, the HCP implements four spring flow protection measures aimed at achieving the 30 ft^3/s environmental flow threshold including a Voluntary Irrigation Suspension Program Option (VISPO), an Aquifer Storage and Recovery (ASR) program, a Regional Water Conservation Program (RWCP), and tiered Critical Period management (CPM) pumping restrictions. This is an example of how the presence of endangered species was effectively used to implement spring flow protection measures that would not be possible due to Texas state law that treats groundwater as private property.

Surface water: Rio Grande/Rio Bravo

The Rio Grande silvery minnow is a small-bodied, pelagic broadcast spawning fish once native to the Rio Grande/Rio Bravo (RGB) and Pecos Rivers in the US and Mexico. It was listed as endangered under the US Endangered Species Act in 1994 after it was only found within 5% of its historical range in one 280 km reach of the RGB between Cochiti and Elephant Butte Reservoirs (Figure 3). Pelagic broadcast spawning fish like the silvery minnow require long, undammed stretches of river with consistent flow to complete their life cycle where eggs passively drift downstream, and juveniles migrate back upstream (Archdeacon et al., 2018). As a result of the intense fragmentation and intermittent flows in the RGB river basin, silvery minnow populations have significantly declined. As part of the recovery plan for the silvery minnow, the US Fish and Wildlife Service (USFWS) focuses on population augmentation through hatchery rearing and rescuing and relocating stranded fish during times of intermittency and stream drying (Archdeacon, 2016; USFWS, 2010). However, some reservoir releases from Cochiti reservoir have been used to help sustain the species. Supporting pelagic broadcast spawning species in water scarce rivers during critical periods like the seasonal spring snowmelt recession could greatly improve conservation outcomes for these species.

releases from Ethiopia are still ongoing (Siddig et al., 2020). Another example of the global importance of e-flows in transboundary water systems is exhibited in the Hirmand river basin, which is shared among Afghanistan, Iran, and Pakistan. There is an ongoing conflict due to the drying of the Lake Hamoun wetland, which was listed as a wetland in danger in 1990 under the Montreaux Record of the Ramsar convention on Wetlands. Iran argues that human activities in the upstream Hirmand river basin have resulted in failed water delivery below treaty amounts, while Afghanistan argues that the flow reduction is attributed to declines in precipitation (Mianabadi et al., 2020). We highlight how sharing water resources across boundaries can produce conflict, inhibit coordinated action, complicate water governance, and inhibit the implementation of e-flows using two case studies in the south-central US and northern Mexico (Box 2). Section "The Red River showdown" in Box 2 highlights a supreme court case between Texas and Oklahoma that set a precedent for the power of states to maintain sovereignty over rivers that

BOX 2 Fragmented water governance in transboundary river basins

The Red River showdown

The Red River Basin (RRB) in the south-central US follows a steep precipitation gradient, rising in intermittent, saline waters in New Mexico and the Texas Panhandle, eventually gaining flow in Oklahoma, Texas, Arkansas, and Louisiana, and emptying into the Mississippi and Atchafalaya rivers (Figures 1 and 4). In 1978, Oklahoma, Texas, Arkansas, and Louisiana signed the Red River Compact which divided the river into five reaches to equally apportion water. In the early 2000s, following droughts and a significant population growth in the Dallas-Fort Worth suburbs, Tarrant Regional Water District (Tarrant) in north Texas repeatedly attempted to purchase water from Oklahoma and the Chickasaw and Choctaw Tribal Nations, all of which were denied because Oklahoma prohibited the sale of out-of-state water at the time. In 2009, Oklahoma approved a statute that authorized sale of out-of-state water with some restrictions (Taylor, 2013). Tarrant then simultaneously applied for water permits to build a dam and pump water from the Kiamichi River, a sub-basin of the RRB entirely within Oklahoma's border and filed suit against Oklahoma anticipating denial. Tarrant settled on this option because transporting and treating water from the Kiamichi would be cheaper than treating the highly saline waters above Lake Texoma on the mainstem of the river. Tarrant claimed that the Red River Compact allowed signatory states to cross state lines to divert water, while Oklahoma argued that each state is entitled to divert its full entitlement within its own boundaries (Johnson, 2013). The suit was taken up by the Supreme Court following appeals by Tarrant. The Supreme Court, in a unanimous decision, concluded that the Red River Compact did not grant signatory states a right to cross state lines to divert water from Oklahoma (Tarrant v. Herrmann, 2013). This decision could inhibit e-flows implementation in the basin because it creates a lack of coordinated effort between the states and a notion of competition to buy water rights. For example, of the 23 river basins in Texas, the RRB is one of four basins that have not adopted e-flows standards under the Texas Instream Flows Program, with no formal plans to pursue e-flows adoption in the basin by the state (TCEQ, 2015).

Fragmented governance in the Rio Grande/Rio Bravo River basin

The Rio Grande/Rio Bravo River basin (RGB) is a large (557,000 km^2) transboundary river basin shared by the US and Mexico with a large population (~10 million people). Water governance is distributed over multiple jurisdictions and political scales (Figures 1 and 3) There are four water governance frameworks that guide water allocation and management in the RGB, including two interstate compacts (Rio Grande Compact and Pecos River Compact), and two binational agreements (1906 Convention and 1944 Water Treaty). Broadly, water infrastructure has altered flow regimes, people view and normalize the river in fragmented reaches rather than a whole, and divided governance greatly complicates water management (Alo & Turner, 2005; Koch et al., 2019; Nava, 2018; Nava et al., 2016; Sandoval-Solis et al., 2019). This fragmentation across legal, biophysical, and sociocultural systems poses significant implications and challenges for implementing e-flows as it requires interstate, binational, and stakeholder cooperation across many political jurisdictions, spatial scales, and use sectors. However, there are few examples of isolated successes with implementing e-flows. In 2014, the National Water Commission (CONAGUA) of Mexico granted water rights for environmental use for the first time to several NGOs for application in Cuatro Ciénegas Valley, an important wetland biodiversity hotspot in the Chihuahuan desert (Ortega, 2020). In 2019, New Mexico issued the first e-flows water right to the Audubon Society (Tashjian, 2019). These actions opened opportunities for private water rights holders to lease or sell their water for e-flows. Despite these isolated successes, for any holistic, integrated e-flows initiative to occur basin-wide, there are many physical, sociocultural, and legal barriers to overcome.

flow entirely within their borders, and section "Fragmented governance in the Rio Grande/Rio Bravo River basin" in Box 2 highlights the challenges of implementing e-flows in a transboundary river basin between the US and Mexico.

FIGURE 1 Our case studies cover two major river basins and one large aquifer in the South-Central United States and Northern Mexico

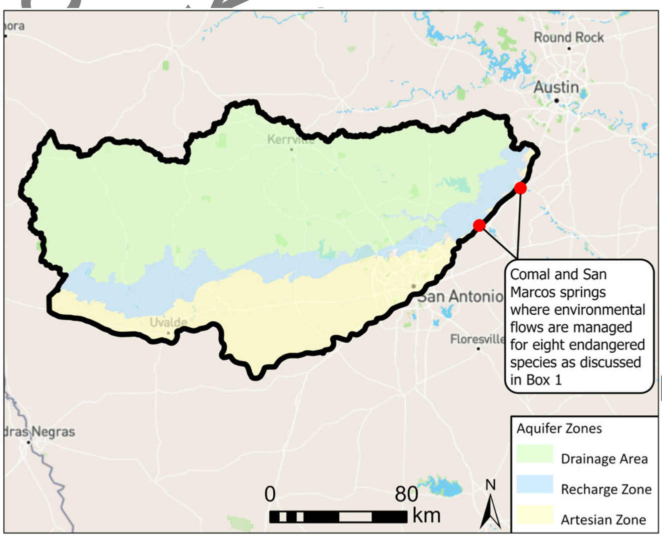

FIGURE 2 Map showing the major features and case study topics in the Edwards aquifer

2.3 | Declining water availability and increasing variability under climate change

Climate change will impact e-flows implementation in water-limited river basins by both decreasing overall water availability and increasing the variability and timing of flows. Global temperatures have increased and are projected to increase further by the end of the 21st century (Vose et al., 2018). Projected increases in temperature could result in increased potential evapotranspiration and decreased runoff, surface water flow, aquifer recharge, groundwater levels, spring flows, and soil moisture. Decreased soil moisture is particularly detrimental to e-flows, as it causes more arid conditions resulting in increasing frequency and intensity of drought conditions (Collins et al., 2013; Das et al., 2011; Fleming et al., 2018; Walsh et al., 2014) and can also shift the rainfall-runoff relationship which is important for regulating the timing and magnitude of e-flows (Saft et al., 2016). Projected temperature increases can also increase the amount of moisture required to reach saturation. As a result, the amount of moisture available for precipitation increases, resulting in an increase in the

FIGURE 3 Map showing the major features and case study topics in the Rio Grande/Rio Bravo river basin

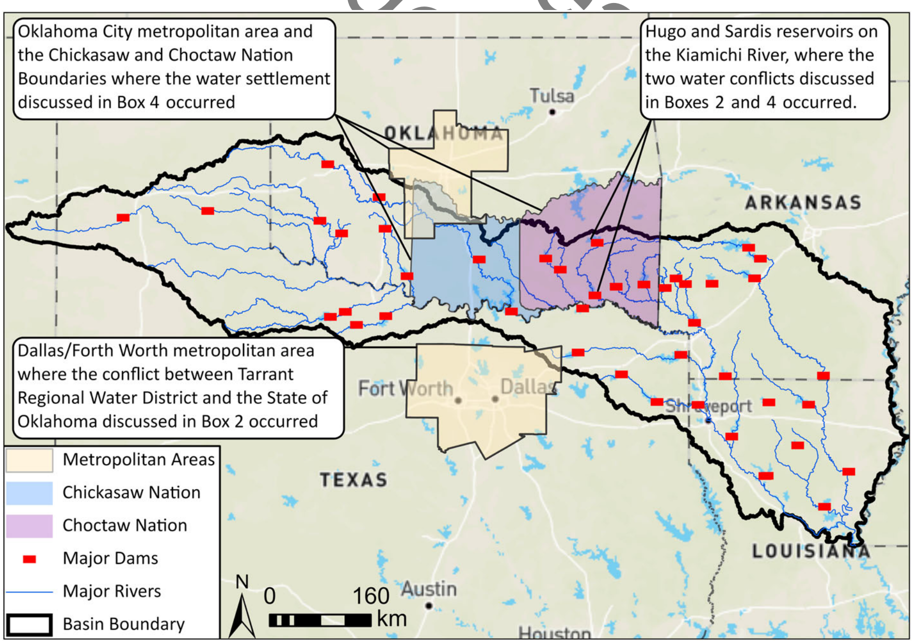

FIGURE 4 Map showing the major features and case study topics in the Red River basin

frequency of heavy rain events (Easterling et al., 2017; Janssen et al., 2014, 2016). Flood events, while related to precipitation extremes, are not solely driven by precipitation. As such, the projected changes in flooding under climate change are much less certain (Walsh et al., 2014; Wehner et al., 2017). However, the projected changes to temperature also indicate a projected increase in the frequency and severity of droughts across North America, with increasing variability in precipitation events. This combination of the potential for both increased droughts and extreme flooding will impact the variability, timing, and magnitude of water available for e-flows.

Changes to precipitation patterns because of climate change will also impact e-flows. For example, annual precipitation across the US has increased, but there is significant regional variation to the observed changes in seasonal precipitation (Easterling et al., 2017). General patterns for changes in precipitation suggest that precipitation across northern areas of the US will increase in spring, fall, and winter. In the south-central US, precipitation is projected to decrease across all seasons, especially during summer (Easterling et al., 2017). Observed declines in overall snow cover and a projected northward shift in the rain/snow transition zone across the US, combined with increasing temperatures that result in earlier spring snowmelt will alter the quantity and timing of e-flows in snowmelt-driven rivers (Elias et al., 2015; Fleming et al., 2018; Fyfe et al., 2017; Klos et al., 2014; Luce et al., 2014; Rhoades et al., 2017). Together, these changes to temperature and precipitation will cause increased variability in the frequency and severity of droughts and the quantity and timing of seasonal flows, which could have detrimental impacts on aquatic biota such as fish, macroinvertebrates, and freshwater mussels that rely on specific temporal flows for their life histories (Hain et al., 2018). Additionally, this increased variation in flows and extremes will cause changes to temperature and dissolved oxygen regimes in rivers and increase salinity in tidewater rivers (Gonzalez et al., 2018; Thompson et al., 2012; Zhao et al., 2018).

Climate change is a global issue that is and will continue to alter the availability and variability of water in river basins around the world (Grantham et al., 2019). For example, the Murray Darling Basin of Australia now ceases flow to sea at its mouth 40% of the time compared with 1% under previous natural flows and often fails to meet e-flows targets due to ongoing climate-driven droughts like the Millennium Drought and 2016–2020 drought (Ryan et al., 2021). One of the six statements in the 2018 Brisbane Declaration and Global Action Agenda states that: "Climate change increases the risk of aquatic ecosystem degradation and intensifies the urgency for action to implement environmental flows," highlighting the global context and importance of climate impacts on e-flows (Arthington, Bhaduri, et al., 2018). Implementing e-flows requires incorporating, allowing, and adapting to variability and non-stationarity in hydrologic regimes (Horne et al., 2019; Poff, 2018). Box 3 highlights examples of climate impacts on e-flows in two river basins in the south-central and south-western US and northern Mexico. Section "Red River basin" in Box 3 highlights climate impacts on water resources in the RRB, and section "Rio Grande/Rio Bravo River basin" in Box 3 highlights climate impacts on seasonal snow melt in the RGB.

2.4 | Lack of consideration of non-biophysical factors

Humans and freshwater ecosystems have complex, interdependent relationships, and e-flows research continues to advance our understanding of these complex socio-hydrological systems (Anderson et al., 2019; Wesselink et al., 2017). Implementing e-flows effectively requires considering the social, political, and economic factors (i.e., local/cultural water use, knowledge, and traditions; public and political support; funding, etc.) in concert with traditional biophysical aspects (i.e., hydrographs, flow-ecology relationships, etc.; Arthington, Kennen, et al., 2018; Jackson et al., 2015). However, despite this recognition of the need to incorporate social, political, and economic factors in e-flows frameworks, integration is still lacking (Anderson et al., 2019; Chappell et al., 2020). In water-limited systems, the challenge of addressing these factors is exacerbated because it involves balancing complex trade-offs between supporting freshwater ecosystem function through e-flows while not disrupting societal water needs. These trade-offs can drive a pervasive notion of conflict among the public, stakeholders, and water managers driven by water scarcity, which can create a separation of social and environmental factors. This separation is also reinforced by water governance frameworks that delineate environmental water uses as separate from water with a "beneficial" or "productive" use (see Section 2.1), further inhibiting socio-hydrological integration (Davies et al., 2014; Koch et al., 2019; Tickner et al., 2017; Wineland, Fovargue, York, et al., 2021).

Just as water scarcity drives conflict among competing water users, e-flows are often viewed as a rival water "user" to societal water uses in water-limited systems because e-flows approaches that seek to redistribute water or re-operate water infrastructure effectively construct the environment as another water "user" (Meza & Scott, 2016; O'Donnell & Talbot-Jones, 2018; Parker & Oates, 2016). While these approaches often are the only mechanism to implement e-flows due to the limitations of water governance frameworks (i.e., labeling e-flows as a beneficial or productive use,

BOX 3 Climate impacts on environmental flows

Red River basin

The impacts of climate change on water resources have been studied extensively in the Red River basin (RRB). Downscaled climate projections indicate considerable spatial variation in climate outcomes across future scenarios. While there is significant uncertainty in climate projections across different scenarios, some consistent patterns suggest that eastern portions of the basin in Oklahoma, Arkansas, and Louisiana could see an increase in mean daily precipitation, while western portions of the basin in Texas and Oklahoma could see a 15% decline by 2100 (Bertrand & McPherson, 2018, 2019; Xue et al., 2016). Additionally, across future climate scenarios, mean daily minimum temperature is expected to increase by as much as 6°C–7°C by 2100. These potentially hotter and drier conditions across the basin will likely increase the frequency and severity of droughts and significantly complicate water resources management. For example, under current estimates of water availability, a 21% reduction in societal (i.e., agricultural, industrial, and municipal) uses is necessary to allocate sufficient water to e-flows (Zamani-Sabzi, Rezapour, et al., 2019). A growing population in the basin also highlights increased areas of water demand and water stress across different future climate scenarios (Zamani-Sabzi, Moreno, et al., 2019). Despite these challenges though, it can be feasible to implement e-flows at a subset of locations across the basin under future climate uncertainty if biodiversity conservation is a priority objective (Wineland, Fovargue, Gill, et al., 2021). Additionally, by jointly considering how water scarcity and future climate uncertainty vary independently by location, sites can be prioritized for strategic water investments to boost water availability (Fovargue et al., 2021). By incorporating climate uncertainty into e-flows planning and conservation prioritization frameworks, feasible targets can be identified as a preamble to broader-scale e-flows adoption approaches.

Rio Grande/Rio Bravo River basin

The upper branch of the Rio Grande/Rio Bravo River basin (RGB) largely depends on seasonal snowmelt from the Sangre de Cristo mountains in southern Colorado and northern New Mexico and contributes over 60% of flows to the Rio Grande. Climate change has already significantly impacted e-flows in the Rio Grande. Decreased streamflow trends were observed from 1980 to 2015 because of decreased snow accumulation in the Rio Grande headwaters (Rumsey et al., 2020, Figure 3). Future projections indicate that this declining trend will continue through the end of the century. While there is significant variability and uncertainty in climate projections, most projections indicate declining annual streamflow in the upper Rio Grande, with some estimates showing up to a 72% reduction relative to historical baselines (Elias et al., 2015; Townsend & Gutzler, 2020). Similarly, in the middle Rio Grande (south-eastern New Mexico and west Texas), streamflow projections indicate significant uncertainty, including wet and dry extremes (Samimi et al., 2020). However, decreasing water quantity is only one factor. The timing of 7-day peak runoff is estimated to be 14–24 days earlier under future climate scenarios (Elias et al., 2015). Since some aquatic biota depend on the timing of seasonal events like peak runoff, earlier and lower magnitude e-flows could significantly impact these species. Overall, climate change has already decreased overall flows in the Rio Grande where increasing water demand will continue to stress aquatic ecosystems.

Section 2.1), they reinforce competition between societal and environmental water needs. In most water-limited systems, water scarcity/supply drives trade-offs between societal water uses and e-flows (Batchelor et al., 2014; Pittock & Lankford, 2010; Porse et al., 2015; Zamani-Sabzi, Rezapour, et al., 2019), but in some contexts, establishing e-flows has been shown to rarely encroach on societal water uses (Chen & Olden, 2017; Owusu et al., 2021). Ultimately, e-flows approaches should seek to integrate social, political, economic, and environmental factors to benefit both freshwater ecosystems and societal water users in a manner that does not separate social factors or construct e-flows as just another water user. This need is reflected in two of the six statements in the renewed 2018 Brisbane Declaration and Global Action Agenda: "Implementation of environmental flows requires a complementary suite of policy, legislative, regulatory, financial, scientific, and cultural measures to ensure effective delivery and beneficial outcomes." and "Local knowledge and customary water management practices can strengthen environmental flow planning, implementation, and sustainable outcomes" (Arthington, Bhaduri, et al., 2018).

Regardless of whether water supply/consumption or distribution/management drive e-flows trade-offs in water limited basins, there remain significant social, political, and economic barriers to implementing e-flows (Hirji & Davis, 2009; Le Quesne et al., 2010; Moore, 2004; Poff et al., 2017). For example, in the Red River basin, a lack of understanding of what e-flows are, their benefits to society, funding, and communication, and pervasive views that societal water needs should take priority over environmental water needs among the public, water users, and water managers were all identified as barriers to implementing e-flows (Wineland, Fovargue, York, et al., 2021). Similar e-flows barriers related to social, political, and economic factors were identified in previous efforts (Harwood et al., 2018; Horne et al., 2017; Le Quesne et al., 2010; Moore, 2004). These barriers include a lack of communication, coordination, and public support; the absence of political will; insufficient funds, capacity, and expertise; multijurisdictional complications; complicated regulatory frameworks; and institutional and regulatory mandates that can create conflicts of interest and shared resource conflicts (Hirji & Davis, 2009; Horne et al., 2017; Moore, 2004; Opperman et al., 2018). Ultimately, barriers to e-flows implementation are context-specific, dependent on the social, political, and economic setting of the system of interest (Harwood et al., 2018).

For water-limited systems, the social, political, and economic challenges facing e-flows implementation can also intensify due to shared resource conflicts driven by increasing populations and water demand. While supply augmentation strategies and river engineering through infrastructure and diversion projects has allowed populations to thrive in water-limited systems, the long-term sustainability of these river systems and the populations that depend on them is uncertain (Kibaroglu et al., 2017; Mekonnen & Hoekstra, 2016). For example, the states of Texas and Oklahoma expect an overall 22% and 33% increase in water demand under an expected 82% and 32% increase in population by 2060, respectively (Oklahoma Water Resources Board, 2012; Texas Water Development Board, 2012). In Mexico, the population living in the RGB basin is expected to increase by 12% by 2030. This means reducing renewable water availability per capita from 1019 m^3/year to 894 m^3/year, putting the population of the basin under water scarcity conditions (Estadísticas del agua en México, 2018). Because of these large increases in water demand driven by population growth, it is likely that less water will be allocated or available for e-flows based on existing water shortages. While there are many other factors that contribute to the feasibility of implementing e-flows, water availability can largely drive conflicts. Box 4 highlights how a failure to consider non-biophysical factors can drive complex social perceptions of rivers and drive water conflicts. Section "Compact cognition in the Rio Grande/Rio Bravo basin" in Box 4 displays how different models of the social perceptions of water issues can be used to conceptualize complex socio-environmental water systems in the RGB basin. Section "Tribal water settlement in the Red River basin" in Box 4 discusses a water conflict in the RRB between the State of Oklahoma and several Tribal Nations to highlight the complexities of shared resource conflicts in water-limited systems and the cultural importance of e-flows.

3 | ACTIONABLE RECOMMENDATIONS

We developed three actionable recommendations for implementing e-flows in water-limited systems following our synthesis and building on previous work: *(1) Modify or establish a water governance framework to recognize or allow e-flows*. This is a necessary step to secure water rights or allocations for e-flows or ensure that e-flows can be considered a beneficial or productive use of water. *(2) Strive for collaboration across political jurisdictions and social, economic, and environmental sectors*. This is essential because e-flows initiatives that fail to involve all relevant parties or gain sufficient support risk being perceived as illegitimate by those who were side-lined. *(3) Manage adaptively for climate change in e-flows planning and recommendations*. This is necessary to ensure that e-flows implementation can successfully adapt to changing water availability under future climate conditions. These recommendations are actionable steps that decision makers, conservation practitioners, stakeholders, and policymakers can incorporate into e-flows assessments and implementation plans.

BOX 4 **Environmental flows in complex socio-environmental systems**

Compact cognition in the Rio Grande/Rio Bravo basin

Because of the complexity of water management challenges like implementing e-flows, conceptualizing how social and environmental components link in these systems can help better understand the challenges and opportunities facing social–environmental systems. Koch et al. (2019) developed a conceptual model and an integrative geodatabase (Plassin et al., 2020) for the Rio Grande/Rio Bravo basin (RGB) to document and contextualize "the social" in the RGB socio-environmental system. Through extensive ethnographic fieldwork, Koch et al. (2019) found that human perceptions of water issues in the RGB largely followed "compact cognition," where individuals tend to ascribe water issues to water governance frameworks rather than the collective impacts of agricultural practices. Their work also highlights a conceptualization of the river as highly fragmented segments between major dams, which has important implications for understanding the context and complexity of water issues in the RGB. Overall, their work is an important first step in developing further socio-environmental models of the RGB and has important implications for implementing e-flows through gaining a better understanding of how humans conceptualize water governance and fragmentation of the RGB socio-environmental system. For example, an implementation approach might try to focus on hotspots for agricultural water use along specific river segments rather than a basin-scale approach due to perceptions of fragmentation and tendency to attribute water issues to governance frameworks rather than the collective actions of agricultural water users.

Tribal water settlement in the Red River basin

The Oklahoma City metropolitan area's (OKC) growing population and water demand is highlighted through its complex water footprint across seven reservoirs and two pipelines spanning the Canadian and Red River basins. Aiming to increase its water security, OKC sought to tap water from an eighth reservoir, Sardis, on the Kiamichi River in Southeast Oklahoma (Figure 4). In 2011, the Chickasaw and Choctaw Tribal Nations filed a federal lawsuit against this proposed pipeline citing their treaty rights to control and sustainably manage the water within their boundaries. After years of conflict and litigation, all parties (OKC, State of Oklahoma, Chickasaw Nation, and Choctaw Nation) came to an agreement in 2016. The overall outcomes under the agreement follow that the State of Oklahoma was granted the administrative and statutory authority over water in south-eastern Oklahoma, and in return agreed that the Chickasaw and Choctaw Nations have preferential water rights and management protections. These standards include measures regarding water conservation, lake levels, and e-flows to sustain streams of significant cultural, ecological, and recreational values (Oklahoma Water Unity Settlement, 2016). The agreement was described as an "acceptable compromise," but it does highlight a historic and successful resolution to a long-standing water conflict that preserves the cultural and ecological importance of e-flows for the Chickasaw and Choctaw Nations. Most of all, the agreement highlights successful cooperation between parties that have been at odds for many years.

3.1 | Modify or establish a water governance framework to recognize or allow e-flows

Understanding the types of water policy instruments available for implementing e-flows is key for addressing the barriers and facilitating factors to their implementation. There are four types of water policy instruments. The first is command and control, where a national regulator enforces control over water resources. This water policy is currently implemented in Israel, where water scarcity has largely driven this institutional arrangement (Marin et al., 2017). The second is water markets (Coase, 1960), where water rights are privatized and can be transferred, leased, and traded. This water policy is currently implemented in Australia, Chile, and other countries (Bauer, 2004; Docker & Robinson, 2014). The third is water pricing (Pigou & Aslanbeigui, 2017), where water extractions are taxed to minimize negative environmental externalities. This water policy instrument is currently implemented in the European Water Framework Directive (Albiac et al., 2020). The fourth is collective action based on stakeholder cooperation, where rules and enforcement mechanisms are designed by stakeholders (Ostrom, 2010). When water is managed as a common good, stakeholders' cooperation seems to be the inescapable driver for achieving the collective action of implementing e-flows in basins, where command and control and economic instruments could be only ancillary tools for more sustainable water management. To achieve this "institutional" cooperation, Ostrom (2010) provides several design principles that enhance collective action outcomes. Four of these design principles seem essential for the sustainable management of e-flows: user and resource boundaries, user monitoring, system-wide monitoring, and minimum rights for local self-organization (Ma'Mun et al., 2020).

Reflecting the recommendation of Harwood et al. (2018) to "Enact clear and effective legislation and regulation…" to facilitate e-flows implementation, we suggest that e-flows planners seek to identify, modify, or establish a water governance framework to recognize or allow e-flows. In water-limited systems, water governance frameworks often inhibit e-flows implementation through priority given to human uses, lack of a legal basis to allocate water for the environment, and institutional and regulatory mandates that prevent dam re-operations or the purchase of water for e-flows (Opperman et al., 2019; Pahl-Wostl et al., 2013). To facilitate e-flows implementation, e-flows planners should work with stakeholders and policymakers to modify or establish water governance frameworks to facilitate e-flows allocations. A clear mandate within the water governance framework or goals for a target program could provide practitioners with the structures and tools to successfully implement e-flows. In our focal region, a water market or collective action-based approach could be most feasible to achieve wider e-flows implementation. For example, water markets exist in Texas in the EA, where permanent transfers and lease markets exist and in the Texas portion of the RGB, where this market has facilitated a shift from low to high-value crops (Debaere & Li, 2020; Montginoul et al., 2016). However, water purchases for environmental flows are not considered in these markets. In the Red River basin, collective action might be the most feasible approach to achieving e-flows implementation because of the complex socio-political factors that have inhibited progress towards e-flows implementation (Boxes 2 and 4, Ostrom, 2010; Wineland, Fovargue, York, et al., 2021). Ultimately, the barriers, challenges, and implementation success of e-flows will depend on the unique social, political, economic, and environmental context of each system—there is no catch-all approach (Harwood et al., 2018; Le Quesne et al., 2010).

While attempting to legitimize e-flows in water governance frameworks is difficult and challenging, there are few examples of successes and hardships highlighting the difficulties of this implementation route. In all three of our case studies, a clear lack of authority or legitimacy to establish e-flows was/is present. In the RRB, for example, there remains no authority to implement e-flows except for base flow requirements at one reservoir sparked by the Oklahoma Water Unity Agreement (Box 4). Here, failure to legitimize e-flows can be traced to the legacy of the prior appropriations water doctrine, and socio-political views that water for humans is more important than water for the environment (Wineland, Fovargue, York, et al., 2021). However, in Oklahoma, a senate bill was recently introduced that calls for studies to establish e-flows in a select few rivers and streams in the eastern portion of the state to "maintain the functions and resilience of freshwater stream systems and the needs of communities that depend on the healthy ecosystems" (SB109, 2021). This bill shows promise for the possibility of establishing e-flows in the basin, and even calls for voluntary and incentive-based mechanisms to facilitate water re-allocation from water rights holders. However, an older version of this bill died in the state legislature in 2019, highlighting the socio-political hurdles e-flows implementation faces in this river basin (H.B. 1403, 2019). In the RGB, e-flows legitimacy emerged through several different routes. For example, in the Mexican portion of the basin, e-flows authority emerged from modifying the role of CONAGUA, Mexico's National Water Commission (Box 2). In New Mexico, the legislature enacted the Strategic Water Reserve (SWR) which "allows water or water rights to be designated for public purposes" (New Mexico Office of the State Engineer, 2020). As of January 2018, three leases were signed and four purchase agreements were executed for a total of 1,355,595 cubic-meters of water above Elephant Butte and 1,952,599 cubic-meter for the Pecos River, largely to protect endangered species like the Rio Grande Silvery Minnow discussed in Box 2 and the Pecos Bluntnose Shiner (New Mexico Office of the State Engineer, 2018). In the EA, low flows from springs resulted in "take" of listed species under the federal Endangered Species Act. This sparked the transition from "rule of capture" water law, where groundwater can be withdrawn infinitely by property owners, to a hybrid permit system governed by the Edwards Aquifer Authority (Box 1; Votteler, 2001). However, this water law transition faced significant legal hurdles, first by Sierra Club v. Babbitt (1993), and then through the last-minute creation of the Edwards Aquifer Authority by the Texas Legislature to avoid federal intervention (EAA Enabling Act, 1993).

3.2 | Strive for collaboration across political jurisdictions and social, economic, and environmental sectors

Implementing e-flows requires collaboration among all relevant parties—policymakers, water managers, water users, natural resource managers, scientists, and populations—and across political jurisdictions and spatial scales (Arthington, Bhaduri, et al., 2018; Pahl-Wostl et al., 2013). Indeed, previous work has identified a lack of communication and collaboration among stakeholders as a major barrier (Hirji & Davis, 2009; Le Quesne et al., 2010; Moore, 2004), and collaboration and leadership as a critical enabling factor that supports successful e-flows implementation (Harwood et al., 2018). Water management in water-limited systems can be fragmented among entities that fail to communicate and collaborate effectively. As a result, basin-scale approaches that cross jurisdictional boundaries will require stakeholder and interagency collaboration or non-governmental organizations that can bridge these coordination barriers (Opperman et al., 2019). For other types of conservation actions (e.g., terrestrial preserve design and dam removal), large-scale coordination of investments has been shown to be dramatically more cost-effective than local-scale, piecemeal decision-making (Kark et al., 2009; Neeson et al., 2015; Roy et al., 2018). At times, local conservation organizations can even receive the greatest benefit within their region by allocating resources beyond their focal area (Milt et al., 2017). These examples underscore the potential economic and environmental benefits of large-scale coordination of investments in e-flows.

Indeed, existing partnerships illustrate how cross-sector collaboration can facilitate e-flows implementation. For example, the EA's Habitat Conservation Plan highlighted in Box 2 was a collaborative effort among three cities, two water management agencies, and a stakeholder group representing 23 public, private, and non-profit interests. With growing interest and recognition of the need to implement e-flows, overcoming coordination challenges is necessary to facilitate this shift in water management. Another example of collaboration among public and private institutions is the Sustainable Rivers Program (SRP), a partnership between The Nature Conservancy and the US Army Corps of Engineers (USACE). The SRP is arguably the largest cooperative e-flows program in the US, with e-flows successfully implemented at 24 federal dams in 13 rivers as of 2020, and 71 additional sites advancing through the program's process (John Hickey, personal communication, April 23, 2021). These include two advancing proposed sites (Pecos River in New Mexico, Kiamichi River in Oklahoma) and one incorporated site (Big Cypress Bayou/Caddo Lake) within our focal region (TNC, 2019). The SRP focuses on identifying flow requirements and modifying USACE dam operations procedures to implement e-flows. Despite USACE dams having strict federal mandates authorized by the US Congress (i.e., flood prevention, water storage, hydropower, etc.), with limited ability to re-allocate water, the SRP has been successful at implementing e-flows across river basins in the US within the operational flexibility of each dam (Warner et al., 2014). In Mexico, the Rio Bravo Basin Council (RBBC), which started in 1999 as a public venue for discussing water management challenges in the Mexican portion of the RGB, is a central entity for guiding e-flows adoption. The RBBC is comprised of many stakeholders across many sectors and is now currently planning to incorporate e-flows in a new water allocation framework for Mexican water users (Sandoval-Solis et al., 2019b). However, stakeholder inclusion is not always successful, and can be difficult to garner adequate support and achieve equitable outcomes. For example, in the RGB, because water demand often exceeds supply and intended water deliveries can face uncertainty, there is low motivation among stakeholders to support e-flows. Indeed, the International Boundary and Water Commission (IBWC), which applies the boundary and water treaties of the US and Mexico, notes that stakeholder perspectives drastically differ between the US and Mexico. Stakeholders in the US, particularly those in Texas, argue that the timing and uncertainty of Mexico's water delivery has resulted in ineffective use and management of water, whereas Mexican stakeholders argue that they are complying with the cycle provided for in the 1944 Water Treaty (CRS, 2018). These divergent perspectives have perpetuated notions of conflict and inequity, inhibiting coordination on e-flows.

3.3 | Manage adaptively for climate change in e-flows planning and recommendations

Climate change uncertainty and variability greatly complicates water management planning and hinders e-flows implementation. An additional dimension of this challenge involves planning for uncertainty and non-stationarity in climate conditions, hydrologic flow regimes, and socio-economic conditions (Cosgrove & Loucks, 2015; Poff, 2018; Riahi et al., 2017; Rissman & Wardropper, 2021). Previous work has identified an overreliance in water policy and decision making on assumptions of stationary reference hydrologic or climate conditions that are no longer relevant (Kopf et al., 2015; Milly et al., 2008; Radeloff et al., 2015). Reflecting the recommendations of Harwood et al. (2018) to

"Monitor ecological, social and economic outcomes of e-flow implementation and manage adaptively", and Arthington, Bhaduri, et al. (2018) to "...adapt existing approaches to maintain/restore ecological resilience and societal benefits", we recommend e-flows planners manage adaptively for climate change as they seek to expand and accelerate e-flows implementation. Balancing the trade-offs between human water security and e-flows under climate uncertainty and non-stationarity is a significant challenge (Crespo et al., 2019). However, these risks can be minimized by taking an adaptive management approach to e-flows (Sordo-Ward et al., 2019; Watts et al., 2020; Webb et al., 2018). Adaptive management allows practitioners to be inclusive of climate and, subsequently, water resources uncertainty and respond to these changes in resource availability (Webb et al., 2017). Broadly, adaptive management follows a cyclical process consisting of four steps: plan, do, monitor, and learn (Allan & Watts, 2018). However, implementing an adaptive management plan that adequately incorporates climate change and minimizes political risks can be a significant challenge, as Australia's Murray-Darling Basin Plan exemplifies. Here, water and public policy professionals indicate that hostile climate politics, particularly climate change denialism and overstating uncertainty, shaped water policy options that were adopted (Alexandra, 2020). Ultimately, this contributed to the Basin Plan relying on assumptions of stationarity that fails to appropriately address future climate risks (Alexandra, 2018).

With the considerable impacts and uncertainties associated with water management in the case studies presented here and across water-limited systems, e-flows assessments, and adaptive management plans could ultimately reveal that it might not be feasible to implement e-flows at large spatial scales across water-limited systems (Zamani-Sabzi, Rezapour, et al., 2019). Rather, smaller-scale projects that target specific river reaches or catchments with high conservation priority like those in TNC's Sustainable Rivers Program or other dam re-operation projects might be more appropriate and feasible to implement (Opperman et al., 2019; Warner et al., 2014; Wineland, Fovargue, Gill, et al., 2021). Further, adaptive management approaches could reveal trade-offs between short-term agreements and long-term ecosystem protection. For example, if adaptive management creates short-term agreements based on projections of water availability, this could potentially break down some socio-political barriers because involved parties are not locked into long-term agreements. However, these short-term agreements could threaten long-term conservation goals if climate change alters water availability or consumptive demand increases due to population growth. With few studies on how climate change and adaptive management influences the successful implementation, monitoring, and management of e-flows, future research should seek to study these factors and the trade-offs presented by adaptive management.

4 | CONCLUSION

The recommendations and examples across the presented case studies highlight both the importance and challenge of implementing e-flows in water-limited systems. Many intersecting social, political, economic, and environmental factors act as significant barriers to e-flows implementation. Trade-offs between human water security and freshwater biodiversity will be a persistent challenge in water-limited systems with growing populations and decreasing water availability. While our case studies present few examples of successful implementation through piecemeal, ad hoc approaches, these small successes highlight a growing interest and recognition of the importance of e-flows while displaying the importance of self-organization for finding sustainable management strategies. Transitioning to larger-scale strategic conservation frameworks is necessary to slow the dramatic decline of freshwater biodiversity, but conservation practitioners must also consider the contexts in which environmental flow recommendations are being made by considering the trade-offs between human and environmental water needs and where it is most feasible to implement e-flows. Accordingly, we reflect and build on existing work to provide three recommendations for conservation practitioners and policymakers aiming to implement e-flows initiatives in water-limited systems around the world. These recommendations draw from lessons in three water-limited systems but can be scaled up to water-limited systems globally as they face similar challenges.

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CONFLICT OF INTEREST

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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