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Shifting currents: Managing freshwater systems for ecological resilience in a changing climate

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ABSTRACT

Traditional approaches to water resource engineering have sought to maintain a static, optimized state of system performance in providing reliable water supplies, energy, and flood protection. However, delivery of these services has been associated with the disruption of freshwater ecosystem functioning, driving global-scale declines of biodiversity and the loss of ecosystem services. Climate change is presenting new challenges for water and ecosystem managers alike. Yet, climate change is also creating new opportunities to consider ecological resilience in the design and management of water systems. Here, we describe a set of climate-informed ecological resilience principles and associated indicators, which can support integration of ecosystem needs within water resource engineering decision-making. These have the potential to guide climate-adaptive water resource management while also provisioning broad benefits to both people and ecosystems in a shifting operating environment.

1. Introduction

Throughout the 20th century, decisions regarding the design of water management systems have traditionally favored large dams and other forms of long-lasting infrastructure. Generous public financing opportunities and economies-of-scale have promoted the development of large projects intended to maximize water supply reliability, flood control, and power generation benefits. Large water infrastructure is projected to have an equally prominent role in 21st century, especially in developing economies [99]. These investments are widely intended to expand developing economies and alleviate poverty. Yet, climate change is raising new concerns about the performance of water infrastructure under novel and uncertain hydro-climatic conditions. Scientists predict that the frequency and magnitude of extreme events will continue to grow, including storms, floods, and droughts that fall outside observed historical climate variation for which water projects were designed [37,46]. Deep uncertainty about the direction and magnitude of climate change also raises the likelihood of climate-infrastructure mismatches, in which water projects are either over- or under-built [54]. Further, the high cost and significant exposure to climate change greatly increase the risk of investments in large, long-lived infrastructure [16].

Awareness of the negative environmental consequences of water infrastructure has also grown. Construction of dams and ancillary water infrastructure projects has transformed freshwater ecosystems worldwide. Only a third of all rivers longer than 1000 km now flow freely to the ocean [29] and since 1900, it is estimated that over half of the world's wetlands have disappeared [19], in large part a result of flood-control projects that have enabled the "reclamation" of floodplains for agricultural and other human uses. The fragmentation of river networks from dams, flow modification, unsustainable water abstraction, and the conversion of floodplains have collectively reduced the size, simplified the physical structure, and dampened the environmental variability characteristic of healthy freshwater ecosystems. As a consequence, water management activities are now recognized as a principal factor driving freshwater biodiversity declines and the loss of ecosystem services worldwide [22]. At the same time, climate change is expected to interact synergistically with water infrastructure, further compounding stresses on freshwater ecosystems [78].

As climate change amplifies risks to freshwater ecosystems and water infrastructure alike, it is also forcing water managers to explore alternative approaches that are potentially more compatible with freshwater ecosystem needs [69]. Water resources engineers are seeking new design principles to improve infrastructure performance under an uncertain, changing climate [13,84]. There is also a growing appreciation of more holistic water infrastructure design approaches

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that incorporate flexibility [24], the precautionary principle [46], and no-regrets strategies [32]. Such approaches may reduce environmental impacts or even have co-benefits for the environment and traditional water sectors. We are also witnessing the rapid growth in the number and size of investments in natural infrastructure and nature-based solutions by international development banks and national governments [12]. This trend is suggestive of an emerging water management paradigm that integrates the values and services of natural ecosystems and aims to simultaneously enhance both the ecological and engineering resilience of water management systems.

Despite this potential, water resource engineers and planners generally lack the specialized knowledge required to evaluate the consequences of alternative decisions on the resilience of affected freshwater ecosystems. Although much has been written on the relationship of ecological resilience to engineering resilience concepts [35,50,26], as well as general principles for quantifying [1] and enhancing ecological resilience [7], there is limited guidance on how to *operationalize* ecological resilience in water infrastructure design and system planning, particularly within the context of a shifting climate. Building on previous efforts to advance environmentally sustainable water management (e.g., [48,69]), we propose that ecosystem resilience fundamentally relies on the maintenance of interacting dimensions of (1) temporal variability, (2) spatially heterogeneity and (3) hydrologic connectivity. Further, we recognize (4) the basin, or watershed, as the key scale of intervention for management actions that build ecological resilience and mitigate the impacts of other ecosystem stressors, including flow modification, pollution, and invasive species [92,90]. Our understanding of ecological resilience is reflected in Aldo Leopold's observation that ecosystem health depends on its "capacity for self-renewal" [49] and ability to withstand disturbance without losing its characteristic functions [34], which include the maintenance of habitat for constituent plant and animal species, as well as the delivery of valued ecosystem services. Here, we explain how these four principles relate to freshwater ecosystem resilience in the context of a changing climate, and consider how they can be quantified, and managed for, as quantitative indicators by engineers, financers, and practitioners in design, planning, and decision-frameworks.

These principles are not new to freshwater ecosystem managers and the relevance of temporal variability, spatially heterogeneity, hydrologic connectivity, and basin-scale approaches to ecosystem health and biodiversity conservation are well-recognized in the literature (e.g., [72,75,22]). However, these principles have largely been conceived as conservation strategies for preserving or restoring ecosystems to historical baseline-oriented conditions. The relationship of these principles to *ecological resilience* – the capacity of ecosystems to collectively adjust and adapt to shifting and potentially novel environmental conditions while preserving desired functions, species, and services – has not been fully explored. We argue that these principles take on new meaning in an era of rapid environmental change in ways that may be underappreciated by ecologists and engineers. Furthermore, we recognize that environmental needs remain poorly integrated in water management decision-making, with ecosystems often considered as isolated components (e.g., species, habitats) and in *post hoc* assessments once design and/or operational decisions have been finalized. A synthesis of guiding principles and associated metrics for understanding how alternative water infrastructure decisions affect general ecological resilience could enable engineers and managers to more holistically evaluate the system-level effects of management options early in the planning process. Our overall goal is to promote the integration of ecological resilience principles into water system planning, design, and operations to not only improve environmental outcomes, but also to help sustain critical services for human populations and enhance the overall resilience of water management systems in an uncertain, changing world.

2. Principles of ecological resilience for freshwater ecosystems

2.1. Managing for temporal environmental variability

A key principle for promoting ecological resilience is *managing for temporal variability* [72]. Freshwater ecosystems are inherently dynamic systems defined by variation in water quantity and quality, and physical form. The relationship between temporal environmental variability and ecosystem health is well-recognized in traditional approaches to freshwater ecosystem management. For riverine ecosystems, this is expressed by the natural flow regime paradigm [70], which recognizes that predictable patterns of flow variability have a strong influence on aquatic and riparian species adaptations, and that flow-related disturbances, such as floods and droughts, exert a dominant control on ecosystem structure and function [52]. Similar ecological adaptations to the hydroperiod of standing waters have been documented in lakes and wetlands [94]. Hydrologic variability underpins ecological resilience by dynamically altering the distribution of habitats across drainage networks, landscapes, and seasons, enhancing opportunities for some species while limiting opportunities for others, and creating selective pressures that drive local species adaptations at contemporary and evolutionary timescales. When environmental variation in lost, the capacity of ecosystems to support biological diversity at genetic, population, and community levels is predicted to decline, and with it, the loss of adaptive capacity of the ecosystem as a whole to respond to novel environmental conditions, such as are emerging under climate change [88].

The alteration of natural flow variation in freshwater systems is a well-documented consequence of water infrastructure development [71] and a primary driver of freshwater biodiversity loss throughout the world [23,68]. Modification of flow regimes from water infrastructure is also tightly coupled to changes in water quality. For example, the natural delivery of sediment is often reduced by upstream dams, which can accelerate channel down-cutting and floodplain disconnection downstream, adversely affecting riparian vegetation and fish spawning habitat, and limiting potential for habitat regeneration [42]. Similarly, temperature regimes are a key, yet often underappreciated, component of environmental variation in freshwater ecosystems that are affected by flow alteration [66,85]. For example, flow releases from the hypolimnion of a reservoir are colder than would naturally occur, whereas epilimnetic flow releases may be artificially warm [66]. Most freshwater species are sensitive to changes in temperature, which directly influences metabolic rates, physiology, and behavioral characteristics. Temperature also controls important ecological processes, including nutrient cycling, productivity, and respiration. Disruption to temperature regimes can lead to population declines of native species and changes in community assembly [66], and ultimately the loss of ecological resilience. Climate change interacts with human-induced changes in both flow and water-quality regimes, causing an overall rise in water temperatures and driving regional shifts in runoff magnitude [58] and timing [33], and in some regions, a growing frequency of precipitation extremes, including drought and floods [86]. It is also predicted that decreasing streamflow from climate change will shift some perennial streams to an intermittent-flow state [39], with profound consequences for aquatic ecosystems.

To date, strategies to restore and preserve variation in flow and water quality regimes have mostly been guided by the natural flow regime paradigm [70] and similar conceptual models (e.g., [95,96]) that rely on historical patterns to define management objectives. These strategies include the re-operation of dams to mimic natural flow variation downstream [45], the installation of variable-depth intake devices in reservoirs to modulate the temperature of water releases below dams [79], and introduction of wood [96] and gravel [43] to stream channels to mitigate lost inputs of these materials from upstream and along river corridors. Given the high cost and persistent effort required artificially replenish wood and gravel, proposed alternatives for sustaining natural inputs include the design of water infrastructure that allow for sediment passage [8]. Siting new infrastructure in locations upstream from major, undammed tributaries is another strategy to maintain natural inputs of flow, sediment, and wood and to buffer the effects of hydromodification on mainstem rivers [43].

It is increasingly recognized that strategies that go "beyond the natural flow regime" [73] are needed to enhance the resilience of freshwater ecosystems in a non-stationary world. Climate impacts on precipitation, especially changes in the timing, form, and intensity of extreme events, are especially likely to alter temporal variability in flows and water quality, which may be difficult to mitigate. Indeed, attempts to maintain historical patterns of variability through management interventions may actually undermine ecological resilience [55]. Recently, river ecosystem scientists have proposed a functional flow approach [98], which recommends that environmental water be strategically allocated to preserve specific functional elements of flow regimes that support biophysical processes upon which native species depend. By focusing on management of ecosystem processes that sustain desired species and services, rather than seeking to configure ecosystems in a static optimal state, a functional flows approach also allows for flexibility in flow management to accommodate shifting conditions. This stands in contrast to traditional approaches that generally define management objectives based on fidelity to historical patterns of biotic and abiotic conditions (Table 1).

A multitude of indicators have been proposed that describe various dimensions of temporal environmental variability in freshwater ecosystems (e.g., [24,66,95]) and selecting a subset most relevant for evaluating ecological resilience in a specific decision context is a challenge. Previous studies (e.g., [14]) have used statistical methods to select metrics based on the strength of the relationship between physical parameters (e.g., flow, hydraulic, and geomorphic variables) and ecological responses (e.g., habitat, species abundance, or community diversity). However, these relationships are often sensitive to data availability and may not be consistent across space and time, making this approach problematic for selecting ecological resilience indicators. In contrast, others have used an approach informed by expert-opinion and literature reviews, in which indicators are selected based on known or hypothesized linkages to process-based drivers of environmental variation. For example, to inform river management decisions in California, USA, Yarnell et al. [98] focused on flow components with documented relationships to key biophysical processes, such as the spring snowmelt recession, winter peak flows, and summer baseflows. Similarly, in an evaluation of management scenarios for the Cache la Poudre in Colorado, USA, Bestgen et al. [6] selected hydrologic indicators for peak flows critical to substrate mobilization, channel formation, and riparian vegetation recruitment. There are few examples in which metrics have explicitly defined in relation to ecological resilience principles. One exception is a study by Bouska et al. [10], who identified a suite of resilience indicators for the Upper Mississippi River Basin (UMRB), USA. They considered temporal variability in water quantity and quality as "controlling variables" and used variation in water surface elevations, total suspended solids, and nutrient concentrations to assess the ecological resilience of mulitple river reaches within the UMRB.

2.2. Managing for spatial heterogeneity

Another important dimension of environmental variation for freshwater ecosystem resilience is *spatial heterogeneity*, which relates to the diversity, redundancy, and spatial configuration of distinct biophysical elements, including species, biotic assemblages, and habitats. Spatial variation in ecosystems is recognized to be hierarchical, in which various processes interact to create and modify patterns of environmental heterogeneity at multiple scales [89,97]. For example, high flows in river channels transport and deposit large amounts of sediment to other parts of the river channel and floodplain, influencing reach scale (100–1000 m) habitat patterns, but also interact with recruitment of large wood and debris from hillslopes to form scour pools and log jams that influence local (1–10 m) habitat complexity. This dynamically changing distribution of "habitat patches" supports a diversity of species, which are able to take advantage of distinct, shifting biophysical environments present in the landscape.

The presence of redundant, but discontinuous habitat patches in the landscape enhances ecological resilience by buffering freshwater ecosystems from catastrophic change; populations that persist in some locations (i.e., refugia) may subsequently recolonize those affected by a disturbance [82]. The response diversity of organisms to distrubance, coupled with habitat specializations, contributes to the overall stability of biotic communities [1]. Environmental heterogeneity also contributes to the expression of biological diversity within populations (i.e., phenotypic and genotypic variation). Such diversification of subpopulations has been linked to asynchronous ecological dynamics that contribute to the stability of freshwater species populations [81,87] and potentially enhance the ability of species to adapt to changing climate conditions [88].

Anthropogenic water management activities tend to diminish

Table 1
Traditional and resilience-oriented approaches for managing freshwater ecosystems and examples of potential indicators for assessing ecological resilience in water management decision-making.

	Traditional Approaches	Resilience-Oriented Approaches	Example Indicators
Managing for Variability	Preserving environmental variation (e.g., in flow, temperature and sediment, regimes) relative to natural historical conditions that supported native species and services	Adaptively managing for ecosystem functions and processes to support desired species and services	Flow- and water-level variability, extremes, and seasonality (e.g., [10,14,6]), seasonal and sub-seasonal variation in water quality parameters, including temperature [66] and sediment [95]
Managing for Heterogeneity	Preserving "hotspots" of biodiversity and critical habitat for threatened species	Managing landscapes for physical processes that support diverse life histories and buffer desired species and services from change	Diversity, redundancy, and connectivity of landscape patterns [56]; physical habitat complexity: river channel complexity index [65], shoreline complexity index (Kaufman et al. 2014) and Simpson's Index of Diversity (e.g., [10]
Managing for Connectivity	Preserving hydrologic connectivity within aquatic ecosystem networks and between freshwater and terrestrial systems	Managing connectivity to promote fluxes of water, nutrients, sediment, and organisms that sustain desired species and services	Longitudinal connectivity: River Connectivity Index [28] and Dendritic Connectivity Index [18]; lateral connectivity: Hydrologic connectivity index [47] and proportion of floodplain connected to channel [10]; integrated measure of river connectivity: Connectivity Status Index [29]
Managing at the Basin Scale	Basin-scale institutions responsible water accounting, objective-setting and performance monitoring	Adaptive governance, collaborative-stakeholder objective setting, and recognition of environment as legitimate user of water	Self-assessment tool for river basin organization performance [36]; diagnostic framework of river basin governance [10]; water infrastructure governance criteria [17]

spatial heterogeneity in freshwater ecosystems. At local scales, widespread modifications of lakes and rivers, including shoreline embankments, channelization, removal of large woody debris, and clearing of vegetation, collectively reduce the structural complexity of aquatic and riparian habitats. Changes in hydrologic regimes is often the mechanism by which structural complexity is reduced. For example, the reduction in peak flows from large dams has been shown to reduce the frequency of riverbed sediment mobilization, limit natural channel migration, and disrupt the dynamics by which diverse riverine habitats are created and maintained [51]. Expressed at larger scales, the simplification of physical habitat, coupled with the homogenization of flow regimes [71], has been linked to population declines and loss of resilience in communities of native species [61]. Dams can also reduce landscape heterogeneity by restricting access of organisms to historic habitat, potentially synchronizing subpopulations in ways that decrease resilience [60]. For example, Thompson et al. [88] demonstrated how human modifications to salmon-bearing rivers of California have caused the rapid decline of life history diversity expression within Chinook salmon and suggest the loss of genetic diversity could limit the ability of the species to cope with extreme environmental variation in the future.

Strategies for managing for spatial heterogeneity in the context of water planning and decision-making depend on the scale of the project under consideration. Traditional approaches to addressing spatial heterogeneity in freshwater ecosystem management have focused on identification and protection of water bodies or watersheds that support disproportionally high biodiveristy (i.e., hotspots) or critical habitat for threatened species. Although protected areas remain an essential strategy for addressing imminent risks to biodiversity, designing and implementing protected area networks for freshwater ecosystems has proven difficult [62]. Furthermore, protected areas are rarely designed with consideration of the potential changes in environmental conditions and associated shifts in species ranges associated with climate change. Resilience-oriented approaches for managing spatial heterogeneity may still involve the prioritization of management interventions in specific water bodies or watersheds. However, management objectives will shift from the conservation of particular species and assemblages to the management of watershed networks that promote ecological resilience through the maintenance of life history diversity that buffers populations from environmental variability (i.e., portfolio effects [81]) (Table 1). For example, Carlson and Satterthwaite [15] analyzed salmon population dynamics in California's Central Valley and recommended that one of the regions most degraded watersheds be restored to strengthen overall population stability, rather than focusing exclusively on watersheds supporting the most abundant fish runs.

Resilience-oriented strategies also include interventions that protect or restore natural disturbance processes that create structural complexity in freshwater ecosystems, such as floods. Siting or configuring water projects to avoid impacts to tributary streams is one approach for allowing natural river processes to maintain the natural delivery of flow, sediment, and wood downstream. Providing "room for the river" is another example, in which human settlements and infrastructure are set back from the river channel, giving the river sufficient space to move, erode banks, and flood and thereby perform hydrologic, water quality, and habitat functions [44]. These types of passive management interventions designed to enhance environmental heterogeneity may also confer substantial benefits to people through reduced flood risk and costs [44].

The spatial heterogeneity of freshwater ecosystems can be quantified at multiple scales. As with the selection of metrics that relate to temporal variability, resilience indicators related to environmental heterogeneity should be based on known or hypothesized linkages with biophysical processes within the system of interest. For example, Bouska et al. [10] identified several resilience indicators corresponding to the spatial heterogeneity of the Upper Mississippi River System. These included metrics related to aquatic habitat diversity and redundancy as well as floodplain inundation diversity. At small to moderate spatial scales (1–1000 m), heterogeneity can be measured by indicators of structural complexity, such as variation in river channel morphology, bedforms and substrate [65] and shoreline complexity [40], as well as by indicators of biological complexity, such as the diversity and distribution of distinct habitat types present [80]. At larger spatial scales (1–1000 km), heterogeneity can be assessed by the diversity and spatial configuration of distinct landscape features, defined by geology, vegetation, hydro-climate, and other biophysical characteristics, using readily available geospatial tools (e.g., FRAGSTATS, [56]). However, for these and other descriptors of spatial patterning, indicators representative of conditions at a single point in time will be less meaningful assess for assessing ecological resilience than if state changes are tracked over time.

2.3. Managing for hydrologic connectivity

Freshwater ecosystems are characterized by the dynamic movement and exchange of water, across components of the hydrologic cycle and at interfaces with adjacent terrestrial systems. Transfers of matter, energy, and organisms resulting from these processes, herein referred to as *hydrologic connectivity*, are a fundamental control on freshwater ecosystem functions and integrity [75]. Freshwater ecologists have identified four relevant dimensions of hydrologic connectivity: longitudinal (upstream–downstream linkages between habitats), lateral (connectivity between a river channel or lake and adjacent floodplains and riparian areas), vertical (connectivity with the hyporheic zone, groundwater, and the atmosphere), and temporal (seasonal interactions among the three spatial dimensions) [93]. Connectivity of heterogeneous habitat types contributes to resilience by sustaining a diverse pool of species that use a variety of habitats for feeding, reproduction, resting, rearing, refuge, and migrating [91]. Connectivity also enhances resilience by allowing biota to recolonize disturbed areas or replenish depleted populations, and in the context of climate change, is essential for facilitating range shifts of organisms to areas of remaining suitable habitat.

Water infrastructure projects affect multiple dimensions of hydrologic connectivity. Dams interrupt the longitudinal connectivity of river networks directly as physical barriers, or indirectly by reducing flows and drying channels downstream, thereby impeding or eliminating the movement and dispersion of sediment, nutrients, and organisms. Lateral connectivity between aquatic ecosystems and adjacent floodplains and riparian areas are also disrupted by physical structures such as dikes and levees. Flow alteration can further reduce lateral connectivity, especially from the loss of high flows from upstream dams or diversions that alter the frequency, duration, and timing of floodplain inundation along rivers or lakeshores. Climate-induced shifts in flow regimes may act synergistically with water infrastructure to intensify interruptions to connectivity. For example, the combination of dam development and increasing drought risk threatens the Tonle Sap in Cambodia, the largest wetland ecosystem in the Mekong River Basin, known to support one of the worlds' largest freshwater fisheries that feeds millions of people [2]. Groundwater pumping from aquifers can alter the timing and direction of groundwater-surface water interactions with rivers and lakes, directly affecting vertical hydrologic connectivity, but potentially reducing longitudinal and lateral connectivity through declining surface water flow and elevations [20]. The loss of geomorphic complexity from channelization, levee construction, and wood removal also reduces hyporheic exchange in river channels, which can negatively affect nutrient processing and habitat quality for a variety of freshwater species. While human activities tend to reduce connectivity, in some cases, connectivity may be artificially enhanced via inter-basin transfers, canals, elevated flows, potentially altering water quality conditions and creating pathways for non-native species invasions [76].

Connectivity has long been a focus of traditional ecosystem management approaches. The removal or modification of dams and other barriers has been a primary strategy for restoring connectivity within river networks [25]. Dam reoperation experiments involving pulse flow releases have also effectively reconnected downstream habitats [41]. Lateral connectivity has been enhanced through managed flood-flow release and by removing or setting back artificial channel constraints, such as levees [67]. While these strategies for restoring or enhancing connectivity likely promote ecological resilience, their potential benefits are dependent on the spatial and temporal dimensions of connectivity and dynamics of transferred matter; previous studies have attempted to quantify the temporal patterns of hydrologic connectivity in stream networks (e.g., [5]), but more research is needed to understand how fluxes of water, nutrients, and organisms within and between freshwater and terrestrial systems contribute to resilience (Table 1).

Several indicators have been developed to describe the ecologically relevant dimensions of hydrologic connectivity in freshwater ecosystems. Human influence on longitudinal connectivity have typically been evaluated by river network fragmentation indices (e.g., [18]). Changes in lateral connectivity in river and wetland ecosystems have been assessed by indices that describe the spatial configuration of connected hydrologic units [47]. Recently, Grill et al. [29] proposed an integrated connectivity status index that incorporates all four dimensions of hydrologic connectivity for assessing alteration to free-flowing rivers. Connectivity metrics have also been applied in studies aimed at explicitly enhancing the resilience of river ecosystems, including the prioritization of barrier removal to restore ecosystem functions [11] and evaluation of connectivity indicators as part of an ecological resilience assessment of the Upper Mississippi River [10].

2.4. Managing freshwater ecosystems at the basin scale

The scale of water management decision-making dictates how challenges, opportunities, and solutions are identified, negotiated, and implemented. Basin-scale management has long been identified as critical for managing water resources [74], and in recent decades basin planning has taken on increasing significance in adapting to climate change [83,90]. For ecosystems, basin-scale governance is often necessary to manage for ecological needs that span jurisdictions, administrative and political boundaries, sectors, and distinct biotic communities. A basin perspective also underscores the importance of managing threats to freshwater ecosystems that may be distant from a receiving freshwater body, including the effects of land- or water-management activities that propagate or amplify downstream [22], and is required for addressing cumulative watershed impacts, such as from nonpoint source pollution [53].

The transition towards basin-scale management has been marked by the ratification of global policy conventions (e.g., the Ramsar Convention, the Brisbane Declaration [3]), transboundary water-sharing conventions [92], and empowerment of basin institutions to facilitate planning and decision-making among interacting management entities that may each have narrow jurisdictional authorities. Through their role in convening a diverse set of actors, basin-scale organizations are also viewed as a promising governance strategy for advancing a common vision of human-ecological resilience in a changing climate, illustrated by basin-scale climate adaptation interventions in regions as diverse as the North American Great Lakes [59], Tanzania's Pangani basin [38], and Europe's Danube River [23].

From an ecological resilience perspective, adaptive governance is a critical feature of basin management, which describes the set of institutions and policies that facilitate and foster adaptive decision-making (Gunderson et al 2016). Adaptive governance also facilitates the co-production and dissemination of knowledge among communities of resource users, scientists, regulators, and managers. Importantly, adaptive governance recognizes the importance of collaborative stakeholder processes in determining management goals for ecosystems, which may change over time (Table 1). The recognition of environmental water needs is another important feature of basin-scale governance that relates to the resilience of freshwater ecosystems. Environmental flow protections vary widely in scope and efficacy, but formally defining ecosystem needs as a stakeholder in basin-scale water allocation decisions is essential [27]. However, securing the environmental water needed for ecological resilience strategies will likely require broad societal support, built through collaborative stakeholder engagement and institutional capacity building [9].

Hooper [36] developed a list of performance indicators for evaluating the efficacy of river basin management in the United States. Guidelines for evaluating the efficacy of basin-scale management have also been developed by the OECD [64]. Although these were not designed for engineering or ecological resilience concerns per se, they identify governance features required for ecological resilience management, including the need for a basin-scale authority that spans levels of governance, water sectors and political boundaries; accurate and functional water accounting and allocation systems; and robust planning and dispute-resolution processes. Elements of the OECD guidelines have recently been refined into a checklist for evaluating the investments in green, or nature-based, water projects that assess the level of climate-informed basin-level governance [17]. To date, these criteria have been applied across five continents, representing several billion USD investments in large-scale resilient gray and nature-based solutions that embody aspects of flexible governance, legal frameworks, regulation, and allocation systems.

3. Discussion

Water resources engineering is at a critical juncture as the profession endeavors to move beyond myopic economic considerations that have driven project development in the past [4]. In recent decades, decision makers and water managers have transitioned from a narrow focus on cost minimization under an assumed future state towards a more holistic and precautionary approach that addresses long-term needs in supporting a broad range of social, environmental, and economic benefits. However, for designers and operators of water infrastructure, managing for resilience represents a fundamentally new perspective that presents a broad array of risks and uncertainty [13]. Given the widespread operational challenges associated with balancing numerous economic and social objectives while accommodating growing hydroclimatic variability, it is perhaps unsurprising that ecological resilience criteria have not been considered in decision-making. We recognize two other factors that may be impeding management of freshwater systems for resilience. First, although there is a rich body of scientific literature on ecological principles that support the health of freshwater ecosystems, the relationship of these principles to ecological resilience has not previously been described in a single source for water management practitioners. Second, engineering decision analysis and operations require metrics and criteria that are quantifiable, but a set of practical general resilience indicators for utilization by water resources engineers and managers remains elusive. This initial evaluation of ecological resilience indicators, which reinforce the capacity of freshwater systems to maintain ecological functions while adapting to a wide range of conditions and changing operating environments, is a step towards that end.

Decision-making aligned with ecological resilience principles is not only new to engineering. It also represents a significant departure from traditional ecosystem management approaches, which are retrospective in nature. However, ongoing climate impacts coupled with other forms of global change may render historically-oriented management targets constrictive, irrelevant, or even damaging [55]. This perspective is reinforced by paleoecological studies that recognize the dynamism of eco-hydrological systems over longer evolutionary-ecological timescales and the problematic nature of defining management benchmarks in relation to recent historical conditions. Management under an ecological resilience paradigm suggests a more dynamic, interactive form of engagement with ecosystems, whereby they are adaptively managed for desired conditions and services, but potentially with physical and biological characteristics that bear limited resemblance to their recent historical state. This represents a new frontier for ecologists and conservation scientists and will inevitably require novel and more intensive forms of stakeholder engagement and collaborative decision-making to define ecosystem objectives and management actions.

Despite these challenges, there are immediate opportunities for advancing ecological resilience-oriented strategies in water management. For example, approaches for addressing flood hazards are moving away from large, structural control measures to more passive designs that expand the flood inundation capacity of the landscape, lowering the velocity and water level of flood flows and thereby reducing risk to property and life [67]. By restoring lateral hydrologic connectivity with the landscape and accommodating ecologically beneficial high flows, this approach has the potential to recover lost floodplain ecosystem functions [67] and is highly compatible with the ecological resilience principles described here. The multitude of water infrastructure projects (e.g., dams, levees, and canals) at the end of their functional lifespan and/or requiring relicensing represents another opportunity to infuse ecological principles in decision-making [21]. Evaluating the potential ecological resilience benefits of removing water infrastructure against potential costs and risks would be a valuable exercise for prioritizing projects for strategic removal in the future (e.g., [63]).

Looking ahead, integration of ecological resilience principles in decision-making has the potential to reorient water management towards strategies that allow ecosystems to adapt to novel conditions. However, it is important to recognize that there are also important social factors, including the diversity, trust, and social networks of stakeholders, as well as the capacity of governing institutions, that will enable (or impede) a transition towards such resilient management approaches [30]. Additional work is needed to quantify both general and specific resilience indicators of socio-ecological systems [10] and to demonstrate how they can be incorporated in water management decision frameworks, such as in multi-criterion decision analysis [31]. Recently, Poff et al. [69] explored a quantitative approach to evaluate trade-offs between ecological and engineering objectives in an integrated vulnerability assessment method. Referred to as Eco-Engineering Decision Scaling (EEDS), the approach was initially applied to evaluate flood management alternatives that could reduce flood risk, while improving floodplain ecosystem functions. EEDS has already been integrated within new approaches to non-stationary water resources planning and design methodologies [57], while also serving as a complement to established approaches to assessing climate risk in water resources decision-making (e.g., [77]). These and other climate-informed risk assessment approaches hold promise for identifying novel solutions for building ecological and engineering resilience in managed water systems. We suggest that as water system designers and managers plan for new infrastructure, as well as for re-operating and retrofitting existing infrastructure, considering ecological resilience principles described here early in the planning process can provide new opportunities for ecosystem improvement with modest management adjustments, fewer unintended negative environmental consequences, and more cost-effective outcomes over the long term.

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Erratum

Erratum regarding missing Declaration of Competing Interest statements in previously published articles

Declaration of Competing Interest statements were not included in published version of the following articles that appeared in previous issues of "Water Security". Hence, the authors of the below articles were contacted after publication to request a Declaration of Interest statement:

1. "Water transfers between agricultural and urban users in the region of Valencia (Spain). A case of weak governance?" [Water Security, 2019; Volume 7: 100030] https://doi.org/10.1016/j.wasec.2019.100030.

   Declaration of competing interest: The Authors have no interests to declare.
2. "Water availability on the Third Pole: A review" [Water Security, 2019; Volume 7: 100033] https://doi.org/10.1016/j.wasec.2019.100033

   Declaration of competing interest: The Authors have no interests to declare.
3. "Planning for sustained water-electricity resilience over the U.S.: Persistence of current water-electricity operations and long-term transformative plans" [Water Security, 2019; Volume 7: 100035] https://doi.org/10.1016/j.wasec.2019.100035

   Declaration of competing interest: The Authors have no interests to declare.
4. "Water reallocation, benefit sharing, and compensation in northeastern Mexico: A retrospective assessment of El Cuchillo Dam" [Water Security, 2019; Volume 8: 100036] https://doi.org/10.1016/j.wasec.2019.100036

   Declaration of competing interest: The Authors have no interests to declare.
5. "Invisible water security: Moisture recycling and water resilience" [Water Security, 2019; Volume 8: 100046] https://doi.org/10.1016/j.wasec.2019.100046

   Declaration of competing interest: The Authors have no interests to declare.
6. "Water access transformations: Metrics, infrastructure, and inequities" [Water Security, 2019; Volume 8: 100047] https://doi.org/10.1016/j.wasec.2019.100047

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7. "Shifting currents: Managing freshwater systems for ecological resilience in a changing climate" [Water Security, 2019; Volume 8: 100049] https://doi.org/10.1016/j.wasec.2019.100049

   Declaration of competing interest: The Authors have no interests to declare.
8. "Water is a master variable: Solving for resilience in the modern era" [Water Security, 2019; Volume 8: 100048] https://doi.org/10.1016/j.wasec.2019.100048

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9. "Resilience of Water Resource Systems: Lessons from England" [Water Security, 2019; Volume 8: 100052] https://doi.org/10.1016/j.wasec.2019.100052
10. "Resilience by design in Mexico City: A participatory human-hydrologic systems approach" [Water Security, 2019; Volume 9: 100053] https://doi.org/10.1016/j.wasec.2019.100053

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11. "Resilience by design: A deep uncertainty approach for water systems in a changing world" [Water Security, 2020; Volume 9: 100051] https://doi.org/10.1016/j.wasec.2019.100051

    Declaration of competing interest: The Authors have no interests to declare.
12. "Are intra- and inter-basin water transfers a sustainable policy intervention for addressing water scarcity?" [Water Security, 2020; Volume 9: 100058] https://doi.org/10.1016/j.wasec.2019.100058

    Declaration of competing interest: The Authors have no interests to declare.
13. "Exploring the relation between flood risk management and flood resilience" [Water Security, 2020; Volume 9: 100059] https://doi.org/10.1016/j.wasec.2020.100059

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14. "Human dimensions of urban water resilience: Perspectives from Cape Town, Kingston upon Hull, Mexico City and Miami" [Water

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