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Emerging themes and future directions in watershed resilience research

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ABSTRACT

A review of ecological, social, engineering, and integrative approaches to define and apply resilience thinking is presented and comparatively discussed in the context of watershed management. Knowledge gaps are identified through an assessment of this literature and compilation of a set of research questions through stakeholder engagement activities. We derive a proposed research agenda describing key areas of inquiry such as watershed resilience variables and their interactions; leveraging watershed natural properties, processes, and dynamics to facilitate and enable resilience; analytical methods and tools including monitoring, modeling, metrics, and scenario planning, and their applications to watersheds at different spatial and temporal scales, and infusing resilience concepts as core values in watershed adaptive management.

1. Introduction

Management of watersheds to provide a wide variety of ecological and human services represents a critical global challenge. Anthropogenic activities have significantly altered rivers, lakes, wetlands and groundwater systems, and the ability of these systems to provide vital watershed services [60,23]. Watersheds have some capacity to absorb and respond to disturbances while maintaining their essential structure and functions [11,15]. However, the capacity of watersheds to absorb and respond without disruption or modification is limited. Research and practice suggest that freshwater systems may evolve towards states with potentially novel structural and functional characteristics caused by endogenous and exogenous forcings acting at various temporal and spatial scales, with implications for the watershed services they provide [36,75,31]. Managing for maintaining some current or "ideal" state, or for restoration to a previous state, which is a traditional approach to resilience, may not always be possible, prompting the need to consider if there are other modes of resilience in watersheds to consider. If more than one mode of resilience exists, how do we know when (or if) we should update management approaches to reflect or anticipate emerging

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conditions?

Stakeholders across sectors and geographies are paying increasing attention to the resilience of their watersheds as they plan and manage the supply of services, economic growth and needed investments. For instance, cities like Cape Town, São Paulo, and Mexico City have recently nearly run out of both surface and groundwater resources [16], revealing resilience challenges and prompting additional action to help secure their water supplies. National agencies in Argentina, Uruguay, and China have invested significantly in policies, initiatives, and projects to increase resilience in watersheds and improve provision of watershed services [46,94].

Watershed resilience is gaining attention in water resources management practice, decision-making, policy, and scholarship [83,84,85,31]. This paper: (i) provides a review of research literature on approaches to define and apply resilience thinking to watersheds; (ii) identifies knowledge gaps through an assessment of this literature and the collection of research questions through a series of stakeholder engagement activities; and (iii) derives a proposed research agenda describing key areas of inquiry on this topic of global importance.

2. Review of approaches towards defining resilience in watersheds

The concept of resilience has been around for centuries (e.g., Hooke's law for compression and deformation of springs), and has been applied across many disciplines: physics, engineering, health, psychology, sociology, disaster studies and ecology, among others [85,97,74,54,1]. Grove et al. [32] define resilience as the capacity to deal with change and continue to develop. The Intergovernmental Panel on Climate Change describes resilience as preserving function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation [43]. Unlike a more commonplace definition of resilience as "bouncing back" to preexisting conditions following a disruption or disturbance, the IPCC definition encompasses the potential reorganization of the system, an insight that also emerges from paleoecology and paleoclimate research into so-called no-analogs [96,71]. Such work observes that quite distinct and stable ecological communities have existed in assemblages that have no analogs to existing communities. Further application of the concept in the life and environmental sciences garnered increased attention in characterizing the ability of an ecological system to self-organize, persist and absorb perturbations [68,67,37,38,53,30,7].

There have been several efforts in the literature on resilience thinking focused specifically on watersheds [97,6,48]. These are complemented with a variety of investigations in related areas such as water systems [85,7], aquatic ecosystems [74,54], water-related disasters [45,72], among others. Most of these efforts tend to pursue the concept of resilience through ecological, social, or engineering approaches. Ecological resilience relates to the magnitude of disturbance(s) that an ecosystem in a relatively stable state can absorb before it shifts into a new presumably stable regime (Holling and Gunderson[39]). Social resilience is the capacity of social systems, such as communities, to withstand and adapt to disturbances that result from social, political, or environmental changes [4]. Engineering approaches to resilience in watersheds focus on optimization and the use of infrastructure to manage watershed system changes, e.g., expansion of supply, disaster recovery, ecosystem restoration [33,73,86,80].

Ecological resilience approaches have been employed in watershed conservation and management, with a primary focus on understanding the biophysical processes and structures of terrestrial ecosystems, and how those are impacted by natural disturbances and anthropogenic interventions. These studies have employed both data analysis [22,98,99,36] and process-based model simulations [20,42,52]. Mainstream freshwater conservation approaches are perhaps typical of ecological resilience methodologies, in that they define a baseline or a preferred past stable state as a set of management targets. As such, ecosystem management in practice has come to imply persistence or managing to return to a stable form, one which, according to no-analog research studies, may be overly constrained in its definition (e.g., [74,77]).

A number of researchers have critiqued these "persistence" approaches, however, by demonstrating the evolution of natural systems through a series of states. Hirota et al. [36] recognized forest, savanna, and treeless states arrived at by transitions through tipping points in tropical watersheds and empirically reconstructed a time history of transition between states through analyzing the response of tree abundance to precipitation. Levine et al. [52] predicted the stability and potential transitions of the Amazon watershed to climate change with coupled hydrology-vegetation-climate models. The management implications of these investigations emphasize the importance of the connection between biophysical changes in watershed systems and their ability to provide watershed services. When watersheds transition between states, these services were noted to change as well in reliability, form, and timing. Indeed, these transitions appear to represent ecological reorganization processes, according to no-analog studies.

Social resilience approaches have focused on community and institutional aspects and deriving best practices to build resilience in watersheds [48,5,59,89]. There are several implications for watershed management that emerge from these studies. Resilience building requires collaboration across levels of government, jurisdictional boundaries, and functional sectors (e.g., water supply, energy, food). Governance and regulatory systems can hold implicit resilience definitions, such as mandating specific eco-hydrological conditions as stable (as is common with US Environmental Protection Agency regulations or the US Endangered Species Act) or evolving (such as the European Water Framework Directive, which periodically renormalizes watershed conditions based on recent trends). Resilience building efforts in watersheds must also engage a diversity of nongovernmental actors, particularly those that live and work within the watershed. Thus, building strong networks and enhancing social capital among these actors can strengthen resilience in watersheds, particularly when supported by flexible governance structures that can adapt quickly under strain. For instance, the Colorado River has important water transfers such as the Central Arizona Project to regions outside the watershed, suggesting that actions to increase or define watershed resilience may require interventions within the "management" rather than "hydrological" watershed [48]. This demonstrates the fundamental requirement of taking a systems approach in building resilience in watersheds, as drivers may emerge across different spatial, temporal, and sectoral scales.

In engineering-based approaches, watershed resilience has focused on defining and measuring specific metrics of hydrological and biophysical performance, often facilitated by hydraulic infrastructure. Watershed resilience is evaluated through monitoring and modeling, coupled with the definition of multiple objective functions and optimization analyses for management and decision-making. The selection of objective functions and resilience metrics is dependent on the specific management context and on decision-maker preferences [15,87]. In contrast, socio-ecological resilience approaches have made less emphasis on design and measurement and instead assumed that one system can exist in several alternative stable states rather than a single optimized zone [62,27]. Thus, a strongly engineered watershed may be very resilient from a human services perspective but not from an ecological perspective, while managing a watershed for ecological objectives may have to make compromises on some human services such as flood risk, but provide larger ecological resilience. The potential tradeoffs between engineering and socio-ecological approaches to resilience remains widespread and largely unresolved in practice and can lead to quite different approaches to watershed resilience, i.e., pursuing infrastructure vs social-participatory solutions [44,9,92].

Several recent studies have attempted to integrate across approaches in order to bring a broader perspective into managing watersheds.

Nemec et al. [64] analyzed data on ecological and social resilience using nine watershed properties: ecological variability, diversity, modularity, acknowledgement of slow variables, tight feedbacks, social capital, innovation, overlap in governance, and ecosystem services; the approach used in their analysis is static, using data to create a snapshot of resilience rather than a non-stationary approach. Koebele et al. [48] present a disaster recovery focused program that promotes resilience-building activities in disaster-affected communities through infrastructure planning and replacement efforts carried out by place-based watershed social coalitions. Cosens and Williams [21] analyzed hydropower infrastructure planning, ecosystem health and social-institutional governance mechanisms to improve resilience in the transboundary Columbia River basin, identifying alternative stable resilience states and the need for transitions in management strategies over time.

Other efforts to integrate and reconcile these different and complementary approaches to resilience in watersheds have been pursued through applying principles of resilience thinking in hydrology and ecohydrology [28,93,29], and more broadly to water systems [85,7]. These efforts integrate the ecological, social, and engineering perspectives discussed above, and broaden the scope of resilience to encompass different possible watershed trajectories of change. This literature incorporates three key and complementary concepts: *persistence* (the ability of a watershed to change by absorbing disturbances and reorganize while undergoing changes to retain the same identity and function), *adaptation* or adaptability (the ability of a watershed to adjust its responses to more gradual, incremental, and/or predictable external drivers and internal change), and *transformation* or transformability (the ability to reorganize as a different kind of watershed when structures, e.g., ecological, economic, social, make the present one untenable).

A conceptual depiction of this framework that integrates approaches to resilience in watersheds is shown on Fig. 1. Persistence, adaptation, and transformation can be thought of as *resilience modes* that apply to the various variables in a watershed system, e.g., hydrological, ecological, social, institutional/governance, cultural, engineering/infrastructure, among others. In this framework, resilience can be thought of as a vector where each component of the vector is a watershed system variable, each at its own position in the cycle. Durations over time of each resilience mode for a given watershed variable will vary of course depending on the specifics of the watershed and the variable. Further, one can think of a watershed transitioning between more than one of each resilience mode (i.e., more than one range of the watershed variable for persistence, adaptation, or transformation). If, for instance, the variable depicted is the persistent flow regime of a natural stream, the first adaptation period could correspond to progressive increases in stormflow runoff due to urbanization within the stream’s watershed; this continues until the stream is transformed into an urban drainage flowway. In a possible additional transition, the river could adapt to increases in discharge due to additional runoff generated by land use change in upstream watersheds and may transform into a major river or an increasingly inundated floodplain. A similar rationale could apply if the watershed variable is evapotranspiration fluxes which could increase due to forcings such as agricultural expansion and climate

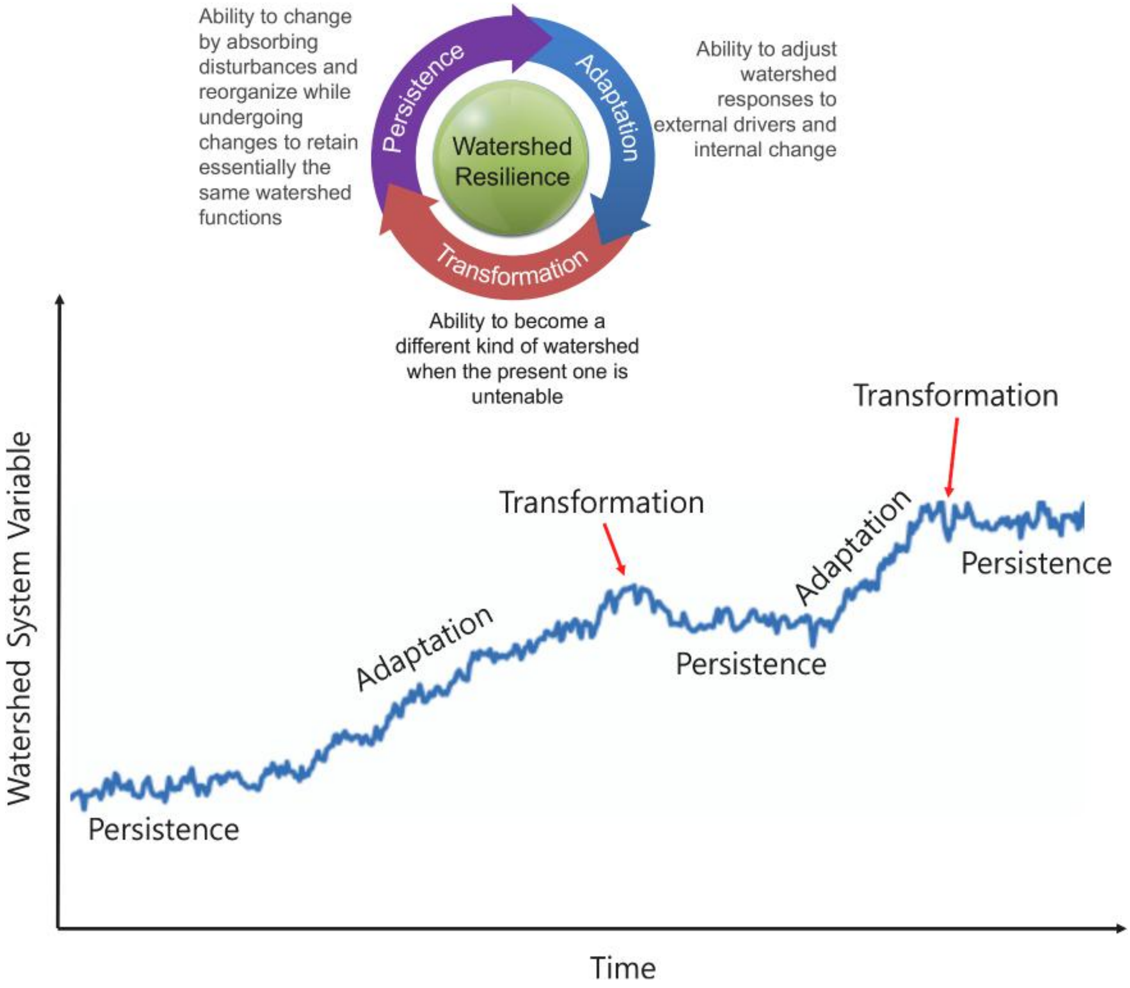

Fig. 1. Conceptual depiction of watershed resilience based on a persistence-adaptation-transformation framework (upper panel, adapted from [7]). The lower panel shows a time series of a hypothetical watershed system variable (e.g., water flow, water depth, land cover, population, water demand), illustrating the transitions between resilience modes.

change, generating one or more cycles of persistence, adaptation, and transformation in the watershed. Other examples of watershed trajectories through resilience modes can be driven by extreme events (e.g., hurricanes), policy (e.g., water management) or infrastructure (e.g., reservoirs) interventions for water supply, flood protection, drought mitigation and other transitions, each of these resulting in the variation over time of a given watershed system variable.

An illustrative example of a watershed system transitioning through these resilience modes is the Everglades wetlands. Over time, the discharge flow rate of these wetlands to Florida Bay and the salinity of the water in the wetlands have changed significantly. During the second half of the 20th century, large scale efforts to drain these wetlands to make land available for agriculture and urban development and protect from flooding led to alteration of flow rates and salinity throughout the watersheds in this ecosystem. Prior to this period (at least throughout the 19th century), the Everglades persisted in a state significantly wetter with freshwater discharge rates of 2–3 times those post-drainage, and salinity levels about 20 times lower [63,57] than present values. The anthropogenic interventions, consisting of building hydraulic infrastructure (canals, levees, pumps) to modify the physical configuration of Everglades watersheds and their drainage/connectivity pattern, forced the system over decades to adapt to the new hydraulics and water quality, and transform to its current version. It is worth noting that a valid question would be whether the Everglades are still adapting or have completely transformed and may now be persisting again in their current state. Another question would be whether these transitions have made the Everglades inherently less or more resilient. And another question is whether the Everglades have undergone more cycles through resilience modes through their history (e.g., sea level rise during the last deglaciation). Answering these questions would merit further analysis of this watershed system under this resilience framework.

3. Knowledge gaps and a potential research agenda in watershed resilience

The study of resilience in watersheds presents an important opportunity for the convergence of research in related areas such as social-ecological-hydrological systems, water resources engineering and management, resilience thinking applied to water systems, nature-based solutions, and water security, among others. Knowledge gaps derived through our review of the literature on resilience thinking approaches to watersheds were complemented and reconciled with a set of research questions collected through a series of stakeholder engagement activities (see Section 4). We mapped the results of this analysis into the following proposed areas of research need: (i) defining and characterizing resilience for a given watershed, i.e., resilience modes and transition durations, resilience variables, their interactions and thresholds; (ii) leveraging watershed natural properties, processes and dynamics to facilitate and enable resilience; (iii) analytical methods and tools including monitoring, modeling, metrics, and scenario planning, and their applications to watersheds at different spatial and temporal scales and (iv) infusing resilience concepts in watershed adaptive management, particularly focusing on understanding different trajectories of change in a watershed and avoiding undesired outcomes. A potential agenda covering these areas of research and describing key topics of inquiry in these areas is presented in the discussion that follows, while emphasizing that these areas are not mutually exclusive nor disconnected silos of knowledge, but rather intersecting and interdisciplinary areas of investigation illustrating examples of cross-cutting topics that should be advanced.

3.1. Characterization of watershed resilience variables and their interactions

The water cycle, globally and for any given watershed, is not stationary and increasingly influenced by climate change and other stressors such as urban growth, land use and socioeconomic changes. This poses the challenge of identifying, both quantitatively and qualitatively, variables, modes and transitions, and characterizing conditions that can enable resilience in a given watershed [47,2,90]. Research in this area can focus on consolidating and analyzing historical data, as well as developing new data sources and analytical approaches to define the persistence, adaptation and transformation modes, their range of values for the numerous resilience variables, and conditions that may lead to transitions between modes.

A salient example of a watershed variable that continues to be the focus of attention in characterizing resilience is the flow regime [75,79,51,78]. Seasonal cues in the flow regime have been linked to specific ecological or livelihood outcomes, such as the initiation of fish spawning with late-spring flows. However, the flow regime is also climate-sensitive, and limited guidance has been developed to suggest how the range of choices presented by a shifting climate might guide management of flows in a watershed.

This is inherently interdisciplinary work. For instance, technological innovation has been a key driver of human development and adaptation to social and environmental challenges and will continue to be fundamental to watershed resilience. Engineering solutions such as dams, reservoirs, canals, and water transfers have dramatically altered the water cycle and transformed watersheds for human use. Social feedback mechanisms can mediate transitions and build resilience, i.e., social norms, cultural values, institutions, markets, technology, knowledge, and learning all serve to inform our approach to managing natural and human systems such as watersheds in general terms [26,83,84]; institutional structures and arrangements are needed to consolidate this. In a persistence mode, approaches towards conservation of the biophysical attributes and functions of watersheds can help preserve their productive capacities and resilience, but these same approaches may not be successful in conditions approaching an adaptation and transformation mode. Indeed, as suggested above, restoration-centric efforts may hinder the system reorganization and cause unintended side effects without actually slowing or reducing the impacts of drivers such as climate change.

Efforts at watershed restoration may be thus reframed. In a persistence mode, restoration of ecological communities to some baseline may be useful and important, as should be restoration of ecological function. For adaptation and transformation mode conditions, however, restoration of ecological communities may have limited and even adverse impacts as the eco-hydrological system reorganizes under a new, emerging set of physical and biotic conditions. Restoration of hydrological functions, however, would likely remain relevant and useful.

Whether best efforts should be made to restore watersheds, noting that a full community or hydrological restoration is rarely possible, allow them to adapt to changing conditions, or transform to a new flow regime is a question of practical importance affecting long-term planning and management. A noteworthy example of this is the Yongding river basin in China, commonly referred to as the “mother” river of Beijing. This river was a threat to the old city of Beijing due to frequent floods. However, increasing water use largely because of population and economic growth has led to the river running dry. Certainly, it is not an aim to restore the river ecosystem towards a flooding status. Stepwise ecological restoration was proposed to drive towards an alternative resilience mode rather than attempt to return to flow conditions similar to the past [55]. Similar approaches can be implemented to deal with watershed changes due to climate change or relatively irreversible human activity impacts.

3.2. Leveraging watershed natural properties and processes towards resilience

While most of the world’s watersheds are dominated by traditional engineering (grey) infrastructure, there is a growing body of literature that has documented the feasibility of implementing approaches to manage water through leveraging the watershed's natural infrastructure. In this literature, terms such as green infrastructure, green solutions, and nature-based solutions (NbS) are used somewhat interchangeably [17]. In this review, we use NbS as a representative way to capture the utilization of natural infrastructure to complement grey infrastructure in addressing water challenges such as water security, biodiversity conservation and helping communities mitigate and adapt to climate change.

In theory, NbS or hybrid grey-NbS approaches can address multiple modes of watershed resilience while providing co-benefits to communities and nature. Although the general biogeophysical mechanisms by which NbS impact key variables, such as water quantity and quality are well understood, the empirical experience of implementing NbS towards watershed resilience at the times, places, and scales of interest require further investigation. For example, NbS interventions are usually localized, and it is unclear how local impacts might propagate and route downstream along the watershed. Resulting benefits from NbS may shift from one set of beneficiaries to another set, perhaps keeping the overall resilience at a similar level, but making a difference to internal distribution and equity. Similarly, it is unclear when the watershed impacts of NbS will become detectable or will surpass a certain threshold, and for how long these impacts will be sustained.

Some literature reports how NbS can become an important tool to mitigate water security pressures [65,69,1]. For instance, restoration of native vegetation, changing to sustainable and extensive land-use, wetland creation, re-meandering, and floodplain reconnection, have a buffering effect on river flow and sediment control, and enhance groundwater storage. As such, they may be able to moderate the impact of increasingly variable rainfall patterns. NbS may also be instrumental in maintaining ecosystem integrity, e.g., through watershed restoration and conservation, which can increase the ecosystem's resilience to climate change. NbS that protect natural vegetation from future conversion are maintaining hydrologic functions that might otherwise be lost. Further, some interventions classed as NbS reduce the exposure of people to water-related risks, for example, by zoning to restrict development and maintain vegetation in floodplains. The effectiveness of these types of NbS are driven as much by reducing exposure to flood risk as by avoiding changes in vegetation and ecosystem presence that could alter hydrologic flows.

There is also an opportunity to investigate approaches to move towards a more widespread use of hybrid solutions that integrate NbS with traditional engineering solutions for current and future watershed resilience [70]. Although some functions of NbS can be fulfilled by built infrastructure, the high flexibility and adaptive capacity of NbS are specific advantages for resilience [58]. Uncertainties created by climate change and an unpredictable future render static solutions with high sunk costs and low adaptive capacity, such as large reservoirs and similar gray infrastructure, increasingly risky investments. NbS are often smaller, more affordable, more flexible, and more multipurpose than conventional interventions [66]. As such, NbS are compatible with the type of adaptive solutions and no-regret strategies that are advocated in the context of uncertain future change.

Despite their potential, rigorous studies of the effectiveness of NbS with a focus on specific aspects of watershed resilience are scarce in the literature. This is driven in part because those impacts take time to manifest, and most projects are young. In other cases, projects are not yet implemented at the scale needed to see watershed-scale impacts. Much of our current understanding about the impact of NbS comes from comparing healthy and degraded watersheds, often with a focus on forests, e.g., the Hubbard Brook Ecosystem study [40], from evaluations of agricultural best management practices and from limited studies of ecological restoration projects, e.g., wetland restoration [3]. There is also a need to better understand the costs and uncertainty in investments associated with the operation and maintenance of these projects compared to engineering infrastructure. A body of evidence derived directly from NbS applications should allow for improved understanding of their effectiveness in delivering targeted resilience outcomes.

Other gaps in the evidence of NbS applicability to watershed resilience relate to drylands and floodplains, which feature prominently in the climate adaptation literature [24,41,88] because of their potential to attenuate the impacts of drought and reduce risk to extreme events. For instance, persistent droughts, land degradation and desertification in drylands are often slow-onset processes that, over time, may well lead to disaster. More attention should also be given to evidence-based studies of NbS in promoting resilience in these cases, particularly in rapidly growing urban coastal areas around the world, where large populations depend on ecosystem services for protection and livelihoods.

3.3. *Integrative monitoring, modeling, and data analysis*

The study of watershed resilience offers opportunities for development and application of integrative monitoring, modeling and data analysis approaches that contribute to advance our understanding of the topics such as coupling and feedbacks between resilience variables (e.g., physical, biological, engineering, social), thresholds, and rates of transitions between resilience modes and overall dynamics of the watershed resilience problem. Integrative modeling approaches are intended to address the nexus of human and natural systems (e.g., water supply and demand, energy, agriculture and land use, climate, socioeconomics). By achieving this integration, such models can focus on the feedbacks between these systems along with the evolution of the systems themselves, and the interactions between these systems and other key forcers such as climate change, socioeconomic and technological change, and policy interventions. They can be used to explore large ranges of key parameter spaces, which is ideal for interactions with decision makers and stakeholders [46,94].

As recognition of the importance of complexity of human-natural systems such as watersheds has grown, the focus of integrative models has shifted from studying the interactions of a limited number of systems (energy-economy-climate) at the global level to consideration of multiple interactions (energy-water-land-economy-climate) and at greater temporal, spatial, and process resolution scales. Recent research has explored the effects of climate on watersheds and their connections to energy, agriculture, and climate [10,34,35] and bioenergy and agricultural watershed systems [91,49].

In this increasingly system complexity context, the design of resilience strategies in watersheds can be approached through combined modeling scenarios and data analytics. This combination can be approached through the interaction between ensembles of data and models with varied parameters. Stakeholder input is important so that scenarios can approximately describe interactions between natural and human systems given limited observations, imperfect assumptions, and finite model choices. For instance, approaches such as digital twinning allow simulation of multiple scenarios and possible interventions in a digital environment and is a promising route for watershed resilience [8,81]. Stakeholder input is also important so that decision-makers understand and have confidence in the model outputs and are willing to use them in their decision making [14,13].

An existing challenge in modeling and data approaches is to provide results at appropriate spatial and temporal scales that allow assessment of the effectiveness of interventions towards watershed resilience. For example, a recent study shows that many models can simulate the hydrological processes of sponge city practices; however, the use of these modeling results in decision support tools is relatively poor and ineffective due to lack of stakeholder involvement [56]. In such contexts, decision support tools and systems need to be tailored to meet diverse user requirements to ensure that it provides useful, usable, and used information for decision support for a diverse audience [100].

An increasingly important research topic in human-natural modeling towards watershed resilience is to develop visual analytics methods for cross-scale comparison of outputs from integrative models with a focus on the impact of spatial and temporal scales and variations on scenarios and maximizing knowledge transfer that underpins evidence-based decision making. This is critical for assessing interactions/feedbacks between watershed system variables as well as the dynamics of resilience modes, e.g., rates of change, reversibility, and hysteresis [50,95]. Intercomparison of model simulations is helpful to provide insight into uncertainty of an ensemble analysis and the impact of model structure on outputs.

3.4. Developing a resilience focus in adaptive watershed management

Management of a watershed aligned with resilience principles such as those discussed in this paper represents an evolution from traditional approaches used in water resources engineering and ecosystem-based management. Ongoing climate impacts coupled with other forms of global change may render historical management targets constrictive, irrelevant, or even damaging. Managing watersheds under a resilience paradigm suggests a more dynamic, interactive form of engagement, whereby watersheds may be managed for desired conditions and services (either persistence or adaptation), but potentially with physical and biological characteristics that exhibit limited resemblance to their recent historical state (transformation). The development of holistic management strategies from headwaters to floodplain to groundwater may be necessary as single system approaches are not sufficient [77,18]. This represents a new frontier for hydrologists, ecologists and social scientists and will inevitably require novel and more intensive forms of stakeholder engagement, community-based collaborative decision-making to define watershed objectives and management actions. The science of watershed resilience will need to combine insights from these disciplines into a new, forward-looking framework that is only beginning to emerge operationally [19].

Despite these challenges, there are immediate opportunities for advancing resilience-oriented strategies in watershed management. For example, approaches for addressing flood hazards are moving away from large, structural control measures to NbS or hybrid 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 [69,66]. By restoring lateral hydrologic connectivity with the landscape and accommodating ecologically beneficial high flows, this approach has the potential to recover lost watershed floodplain functions and is compatible with the resilience principles described here. The multitude of water infrastructure projects (e.g., dams, levees, and canals) at the end of their functional lifespan or requiring relicensing represents another opportunity to infuse resilience principles in watershed management [25,65]. Evaluating the potential watershed 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, as well as identifying new projects that are more flexible and effective.

Additional work is needed to define both general and specific indicators of resilience [64,12] and to demonstrate how they can be incorporated in watershed management approaches. Recently, Poff et al. [76] explored a quantitative approach to evaluate trade-offs between ecological and engineering objectives in an integrated vulnerability assessment method. This approach has been applied to a wide range of cases across economic development contexts. It has already been integrated within new approaches to non-stationary watershed planning and design methodologies [61], while also serving as a complement to established approaches to assessing climate risk in watershed decision-making [82]. These and other climate-informed risk assessment approaches hold promise for identifying novel solutions for building resilience in managed watersheds and communicating options and building stakeholder consensus through environmental governance mechanisms.

4. Watershed resilience – An initial set of research questions

As part of this review, we conducted several workshops, surveys, and consultations with various stakeholder groups: watershed and conservation managers, scientists, practitioners, and decision-makers, to elicit input on knowledge gaps that could be assembled into an initial list of research questions around watershed resilience. These questions also informed the proposed areas of research described in Section 3. We have paired this list of questions with the proposed research areas, with the understanding that a given question may cut across more than one area of inquiry. The table below summarizes this initial set of research questions, further tuned by the identification of knowledge gaps in the reviewed literature and additional discussions while preparing this paper. These questions can be thought of as future lines of investigation on watershed resilience.

Research Area	Research Questions
Characterization of watershed resilience variables and their interactions	• How can watershed resilience modes be effectively identified and measured using comparable and transferable metrics? • To what degree can resilience be managed as past conditions, tracking change through time, or for potential future states? • How can we react to climate and impacts of other stressors and shocks, or can we redefine growth and prosperity for times of ongoing change? • Should we maintain existing flows despite climate change? Revert to past flows? Anticipate or track emerging trends? • What are the trigger points and the associated risk of actions (or inaction) on the resilience of a watershed?
Leveraging watershed natural properties and processes towards resilience	• How do we deliver on outcomes for watershed resilience both from biodiversity/ecosystems and human wellbeing standpoints, measured by delivery of services to people? • What are the characteristics of watershed resilience that can be strengthened through NbS? • What is the effectiveness of NbS in watersheds on multiple scales in time and space? • What do we know about trade-offs, externalities, uncertainties, and potential negative impacts of NbS on other ecosystem services and specific communities? • How do we quantitatively assess co-benefits and enhancements on ecosystem services and community/social outcomes influenced by NbS?
Integrative monitoring, modeling, and data analysis	• What are new methods in data-driven and physically based modeling that are needed to delineate resilience modes in a watershed and quantify outcomes across the wide variety of resilience variables? • How can watershed modelling help quantify changes in watershed variables in space and time and linkages to persistence, adaptation, and transformation modes of resilience? • How can we advance modeling methods to better integrate biophysical and socioeconomic systems in assessing watershed interventions and their impacts on resilience? • How can future scenarios (e.g., climate, socioeconomic, land use) be effectively

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Research Area	Research Questions
	integrated into watershed resilience assessments, and to what extent might they result in better long-term outcomes? • How can data and scenarios best inform decision-making in watersheds where decision-making authority is fragmented among several institutions and regulations?
Developing a resilience focus in adaptive watershed management	• How can watershed services for nature and people be improved through resilience thinking compared to planning conducted with traditional engineering or ecological management approaches? • What are the underlying social processes or driving forces, such as attitudes, behavior, and standard institutional processes, that create barriers to resilience planning in watersheds; how do they function to prevent such planning? • What are the linkages between the levels of alteration to watershed processes in space and time that are commonly used to assess watershed resilience and the ability of watersheds to sustain nature and provide services to people? • How can monitoring, evaluation and learning be conducted to demonstrate that resilience planning is progressing towards improved provision of watershed services benefits to people and nature? • What can be learned, scaled, and transferred between watersheds towards more established and sustainable pathways to resilience?

5. Concluding remarks

Resilience has emerged as a standard for evaluating the sustainability of watershed management, much in the same way that cost, benefits, and ecological flow maintenance have served as standards in the past. Progress towards increased resilience in watersheds is hindered by conflicting management objectives, interests, existing policies, inflexible infrastructure design and a lack of quantitative tools and data to facilitate critical decision-making. Resilience modes are heuristic for decision makers such as resource managers, infrastructure operators, and watershed planners because matching resilience actions to the correct trajectory of change can determine the success and failure of projects and policies. Aligning decisions to the appropriate trajectory of change can define the options for successful and context-sensitive interventions, what we monitor for progress against targets, and how we evaluate success. Indeed, actions that are not aligned with the appropriate trajectory of change may even be counterproductive. Ideally, monitoring systems should aim to detect potential shifts in trajectory, such as transitions from persistence to adaptation to transformation. Actions that are intended to support a persistence mode may be inappropriate or even counterproductive for a context where adaptation or transformation are in play. Resilience mode mismatches may have important ramifications, inducing fragility rather than building resilience. Efforts to keep a watershed in a persistence mode when external drivers are forcing adaptation or transformation may have quite perverse consequences as ecological communities and populations try to adjust behaviors, range, and phenologies in spite of resource management planning.

As society looks forward to a future with changing physical and socioeconomic drivers, resilience in watersheds needs to be better understood as a set of informed choices that can be shaped towards implementation. The research agenda summarized in this paper, consisting of proposed areas of inquiry and research questions, can be useful for generating discussion and guiding future research in characterizing resilience in a watershed, how nature can play a role in its successful operationalization, the integrative monitoring, modeling tools and data that are required to understand, conceptualize, design, and implement effective resilience solutions in watersheds, and the infusion of resilience thinking in watershed adaptive management approaches.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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