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Watershed Resilience: Quantification Methods and Future Perspectives

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ABSTRACT

In recent years, watershed resilience has garnered a substantial interest driven by the need to sustainably manage vital ecosystems in the face of increasing pressures such as climate change and land-use alterations, leading to assortment of definitions and assessment approaches. This overabundance has occasionally manifested in ambiguity and, at times, contributed improper implementations. This review evaluates the capacities, and frameworks employed in quantifying watershed resilience across various geographical contexts. It synthesizes the current state of knowledge to identify trends, limitations, and areas requiring further investigation. Due to the limited number of prior researches synthesizing watershed resilience quantification methods, the primary contribution of this study lies in its consolidation and synthesis of diverse research efforts, shedding light on the evolving landscape of watershed resilience quantification. By critically examining the strengths and weaknesses of existing definitions and adopted frameworks, we aim to provide a roadmap for future research in this field. Additionally, this review emphasizes the importance of developing standardized indicators and frameworks to facilitate more robust and comparative assessments of watershed resilience. A critical research gap is the lack of a universally accepted assessment framework for watershed resilience, hindering comparability and decision-making. We advocate for interdisciplinary collaboration to establish a common framework integrating ecological, hydrological, and social aspects of resilience. In conclusion, this review underscores the urgent need to advance watershed resilience quantification and offers a clear research agenda. Addressing research gaps and fostering interdisciplinary collaboration can significantly contribute to the evolving field of watershed resilience assessment and management.

Keywords: Watershed; resilience; hydrologic resilience; resilience quantification, resilience frameworks

INTRODUCTION

A watershed is an environment that is rich in diversity and complexity. It is widely regarded as a biophysical or socioeconomic unit suitable for managing water resources (Ali Mirchi et al. 2009; Aspinall & Pearson 2000; Chiueh et al. 2012; Farzi et al. 2022; Hazbavi & Sadeghi 2017; Luijten et al. 2001). The watershed is essential in providing humans with potable water, clean air, and food. It also supports various forms of social activity such as flood control, navigation, recreation, and aquatic habitat preservation. Additionally, watersheds play a crucial role in mitigating the risks associated with hazardous materials and pollutants by serving as sites for the storage, transformation, and dilution of these substances. The state of a watershed is determined by its functional and structural traits, as well as the resulting hydrological and biogeochemical processes that involve the storage and movement of various substances such as water. These features are assessed through measurements conducted at the outlet of the watershed (Lane et al. 2022).

Watershed dynamics are affected by a variety of factors, including short-term weather events, long-term climate fluctuations, hydrological conditions, interactions between living and non-living components, and human activities. (Sadeghi & Hazbavi 2017). Which makes it vulnerable to disruptive events, as documented by severe droughts that have occurred in various regions. For example, between 1949 and 1995, China experienced devastating droughts that caused losses of over US$12 billion to the economy (Dai et al. 2020; Qin et al. 2015). In another instance, a drought that occurred in South Africa from 2015 to 2017 resulted in the loss of 30,000 jobs and approximately £320 million in economic damages in the agricultural sector in the Western Cape (Lankford et al. 2023). Hazards, both natural and anthropogenic, can have a significant impact on watershed systems, causing disruption of water supply, increased occurrence of natural disasters, loss of biodiversity, economic losses, and exploitation (Arias et al. 2017; Nemec et al. 2014). It is therefore crucial to study the quality and magnitude of hazards and resilience potential at the watershed scale in order to manage the system more effectively (Farzi et al. 2022).

The concept of resilience has garnered considerable theoretical and practical attention in the management of crises and the mitigation of their impact on different domains. Numerous studies have focused on evaluating the resilience approach in different communities and at various scales worldwide. This is particularly relevant to address the challenges posed by natural disasters, including but not limited to drought and water scarcity, floods, and climate change (Farzi et al. 2022). In this regard, the concept of resilience has been gaining momentum in water management (Wilby 2020).

Throughout the course of its evolution, the concept of resilience has undergone changes in conceptualization and definition, resulting in its expansion into a variety of new areas (Quinlan et al. 2016). There are many definitions of resilience and it is commonly used in various fields in a variety of contexts (Mao et al. 2017). (Patrick Martin-Breen and J. Marty Anderies 2011) conducted a review of research papers related to building resilience in various domains, including engineering, economics, psychology, and complex adaptive systems over a span of 50 years. The researchers used three frameworks, namely the Engineering Resilience, Systems Resilience, and Resilience in Complex-Adaptive Systems frameworks. They highlighted that although each framework has roots in specific disciplines, they can be applied to any domain.

The definition of "resilience" has been given for the first time by (Holling, 1973) as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationship between the population or state variable". In light of the increasing interest in resilience concepts in both theoretical and practical fields, especially in relation to natural hazards, there has been an ambiguity in the definition and application of resilience (Farzi et al. 2022). TABLE 1 presents explanations of resilience in various domains and highlights the emphasis placed on each definition.

In order to understand watershed resilience, it is necessary to consider both the terrestrial and aquatic components of a watershed. In addition, it is necessary to consider their interaction with both the built and natural environments. Including wetlands, streams, rivers, lakes, forests, grasslands, urban areas, and agricultural lands (Lane et al. 2022). The concept of watershed resilience has been defined by several scholars from different perspectives. According to (Neil Adger et al. 2021), it refers to the dynamic capacity of social and ecological elements in a river basin area to cope with and adapt to disruptions and shocks, while (Fraccascia et al. 2018) and (Farzi et al. 2022) added the ability to recover from disruptions and define a resilient watershed that can endure natural and human hazards, prevent some level of damage, and adapt to stressors through interaction with social and human dimensions, as well as recover after shocks to maintain or transform into a sustainable watershed in ecological and social dimensions.

In certain studies, this definition is employed to delineate "watershed health," which denotes the ability of the watershed to withstand, recover from, or adapt to natural and human-made perturbations. Nonetheless, healthy watersheds are inherently dynamic and frequently rely on regular natural disturbances to sustain their well-being (Environmental Protection Agency 2012; Sadeghi & Hazbavi 2017). In recent years, the assessment of the health of the watershed system has gained considerable attention from both hydrologists and ecologists as a hot topic of interest (Hoque et al. 2012a; C. C. Liu et al. 2021).

A system's resilience may be assessed by its ability to recover from shocks or disturbances (Carey et al. 2010), the concept of system resilience has also been linked with the opposite aspect of system vulnerability (Asefa et al. 2014; Ilunga 2017). While some argue that the robustness of a system can be viewed as the opposite of vulnerability, others suggest that resilience may not be the direct opposite of vulnerability, and may instead represent a different aspect of system capacity (Gallopín 2006; Ilunga 2017), the interconnection between vulnerability and resilience implies that systems with low vulnerability, indicating sustainability, are expected to exhibit high resilience (Ilunga 2017; Kjeldsen & Rosbjerg 2004).

It is generally agreed that resilience can be characterized by resistance, adaptability, transformability, and sustainability (Baird & Allyson Quinlan 2021; Gallopín 2006; Müller et al. 2016). Resilience may be viewed as the intended functioning state of the system (Carey et al. 2010) which could go through multiple stable states (Peterson et al. 2014; Peterson & Western 2014) due to transformation in response to the forces acting on the system both internally and externally. Moreover, resilience analyses are influenced both by the choice of indicators and the definitions of reference, which are both subject to great variation (Müller et al. 2016). Thresholds can be used to define the stability space of the system in a relative sense. However, it is a challenging task and subject to variations, and there is no unique way to establish these thresholds (Ilunga 2017; Walker & Meyers 2004). Moreover, the recovery strategy implemented following a disaster such as floods could affect the resilience of a system (Cavallaro et al. 2014).

To our knowledge, only a few review papers have been published on watershed resilience. In the same vein, resilience has been discussed within the context of ecosystem response to perturbations(Yi & Jackson 2021), they also discussed related concepts such as resistance, recovery, sustainability, vulnerability, stability, adaptive capacity, regime shift, and tipping points. Based on their review of current methods of assessing resilience, the authors categorize them into three categories: forest resilience using remote sensing and tree-ring data, soil microbial community resilience using laboratory and field studies, and hydrological resilience of terrestrial biomes using Budyko frameworks and climate data. In their study, the authors note that there is no single measurable variable that can be used as a state variable for analyzing system resilience and that dynamic system theory is a fundamental base of resilience science. In addition, they emphasize the complexity of nonlinear systems and the importance of understanding the structure of feedback loops in order to manage perturbations and avoid catastrophic events. In conclusion, it is recommended that further studies be conducted in order to link practical resilience calculations with feedback loops and to determine which feedback loops affect others. (Wilby 2020) examined resilience in light of climate change and water management. There was a focus on themes associated with persistent and emerging pressures on freshwater; environmental thresholds (or tipping points); 'safe' operating conditions; multiple stable states; regime shifts. As a result, water managers would also benefit from consistent use of resilience terminology, incentives to build better after catastrophes, strategic monitoring of incipient threats, availability of long-term adaptation indicators, coordinated efforts to reduce non-climatic pressures on freshwaters (particularly in headwaters), and practical guidelines for developing resilience through adaptation measures.

While the previous review articles focus on specific system, threat or assessment method adopted, this study is oriented toward conducting a review that centers on the methodologies used to quantify watershed resilience, irrespective of specific threats or geographical locations. This approach broadens our understanding of watershed resilience quantification methods. Consequently, the research questions that follow this aim are:

1. What are the primary capacities of resilience (absorption, recovery, adaptability, transformation) as utilized in the literature related to watershed resilience?
2. Which type of frameworks (as watershed health or as watershed resilience) are involved?

The paper is divided into four sections. Section 2 outlines the research protocol, while Section 3 provides a brief overview of the capacities of watershed resilience. In Section 4, various assessment frameworks for quantifying watershed resilience are presented. Finally, Section 5 offers conclusions, remarks, and future perspectives.

TABLE 1. Resilience definitions in different domains

Resilience	Definition	Emphasis	Reference
Engineering resilience	System's speed of return to equilibrium following a shock	Return time to recover, efficiency, equilibrium	(Pimm, 1984)
Ecological resilience	Ability of a system to withstand shock and maintain critical relationships and functions	Buffer capacity, withstand shock, persistence, robustness	(Hoiling, 1973)
Social resilience	Ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental change	Social dimensions, heuristic device	(Adger 2000)
Social-ecological resilience	(i) Amount of disturbance a system can absorb and remain within a domain of attraction; (ii) capacity for learning and adaptation (iii) degree to which the system is capable of self-organizing	Adaptive capacity, learning, innovation	(Carpenter et al. 2001)

METHODOLOGY

Our study was designed with the main goal of selecting and carefully examining academic works pertaining to the resilience of watersheds and catchment areas within the field of surface water research. The design involved a systematic search of the Web of Science (WOS) database, focusing on papers published between 2000 and 2023. The search string is TS =((“watershed health” AND “RESILIENCE”) OR (“catchment health” AND “resilien*”)) OR TS=(“watershed resilien* “) OR TS= (“catchment resilience”) OR TS=(“hydrological resilien*”). The inclusion criteria were established to select research articles written in English language, Related to surface water and quantify resilience To exclude irrelevant papers, we excluded survey and review papers, studies in languages other than English, papers that mentioned resilience as a future target or for future work, and papers related to groundwater, as these did not align with our research objectives. Following the application of our predefined inclusion and exclusion criteria, a thorough and rigorous examination of the selected papers was conducted to ensure their congruence with the research objectives. Furthermore, we implemented the snowball technique to manually identify and incorporate an additional 12 papers that were considered pertinent to our study, culminating in a total of 43 papers subjected to thorough in-depth analysis.

The data analysis phase encompassed a qualitative assessment of the selected papers. We conducted a detailed review of each paper’s content, focusing on their methodologies, findings, and contributions within the realm of watershed and catchment resilience. This analysis allowed us to synthesize and summarize the key insights and trends in the literature. Furthermore, we opted for thematic analysis as a qualitative methodology to categorize and cluster the chosen papers according to prevalent themes and research methodologies. The aforementioned approach was selected to provide thorough and inclusive portrayal of the state of research in the area of watershed and catchment resilience.

It’s important to note that as a review paper, our primary emphasis was on the consolidation and synthesis of pre-existing research, rather than performing original data analysis. Therefore, the analysis was predominantly qualitative in nature, aimed at providing concise and in-depth overview of the literature in this field.

In summary, our research was meticulously designed, carried out, and analyzed systematically identify, carefully choose, and critically evaluate pertinent research papers related to watershed a resilience. throughout this process, We rigorously adhered to predefined inclusion and exclusion criteria. Subsequently, we conducted a comprehensive examination of 43 selected papers, and our discoveries are comprehensively presented in the review paper. The research protocol is presented in FIGURE 1. TABLE 2 shows the final results, the grey cells are studies that were added using the snowball technique.

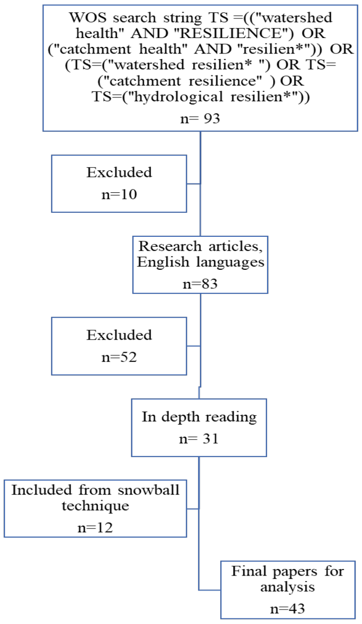

FIGURE 1. Research Protocol

WATERSHED RESILIENCE CAPACITY

Based on the definitions of resilience in the introduction, resilience is primarily assessed in terms of selected capacities. Eco-social systems constitute the core of watersheds, and their adaptability capacity is reflected in their ability to learn, integrate experience and knowledge, adjust responses, and continue developing. The capacity to learn in watersheds refers to the ability of ecosystems to adjust to new environmental conditions, as well as the ability of governance mechanisms to incorporate and adapt to new information and changes that arise. A watershed’s adaptability also refers to its ability to make adjustments and changes to its structure and functionality in order to remain within the SES domain of the watershed. Transformability refers to the capability of creating a fundamentally new stable domain within a watershed. The geomorphology of rivers, the use of riparian areas, and the rules governing floodplain governance can be altered to stabilize flood-prone systems (O. Randhir 2014).

Table 3 has been created to address the initial inquiry: “What are the primary capacities of resilience (absorption, recovery, adaptability, transformation) as utilized in the literature related to watershed resilience?”. This table outlines each capacity, its corresponding definition, and the literature in which it was evaluated.

TABLE 2. Selected literatures

No.	Reference	Framework	Threshold type	Country	No.	Reference	Framework	Threshold type	Country
1	(Schlüter & Pahl-Wostl 2007)	Socio-eco-hydro resilience	Water flow and water use	Amudarya River, Central Asia	11	(Hoque et al. 2016)	RRV	Water quality	USA
2	(Carey et al. 2010)	Hydrological	temperature, precipitation and discharge	Sweden Scotland the United States and Canada	12	(Ilunga 2017)	Catchment resilience	Mean annual runoff	South Africa
3	(Hoque et al. 2012b)	Risk based (RRV)	Water quality	USA	13	(Pires et al. 2017)	Watershed resilience	water quality	Brazil
4	(Silberstein et al. 2013)	Watershed-hydrologic	streamflow	South-West Australia	14	(Sharma & Goyal 2018a)	Eco-hydro	ecosystem water use efficiency	India
5	(Creed et al. 2014)	Hydrologic	Water yield (evapo and prec)	Canada and the United States	15	(Mao et al. 2017)	Socio-hydro resilience	-	-
6	(Chanda et al. 2014)	Risk based	Drought Management Index (DMI) -Permanent Wilting Point (PWP)	India	16	(Sadeghi & Hazbavi 2017)	RRV	SPI	Shazand Watershed in Iran)
7	(Hoque, Hantush, et al. 2014)	Risk based (RRV)	Water quality	USA	17	(Hazbavi & Sadeghi 2017)	RRV	(SPI), low and high flow discharges and suspended sediment concentration (SSC)	Shazand Watershed, Iran
8	(Hoque, Raj, et al. 2014)	Risk based (RRV)	Water quality	USA	18	(Hazbavi, Baartman, et al. 2018)	RRV	rainfall variability SPI	Ireland Portugal Iran
9	(Harder et al. 2015)	Hydrologic resilience	air temperature, precipitation, groundwater levels. snow accumulation streamflow	Canada	19	(Seo et al. 2018)	Watershed resilience	streamflow, groundwater soil moisture	USA
10	(Qi et al. 2016)	Watershed resilience (resilience indicator)	annual river discharge	China	20	(Sharma & Goyal 2018b)	Eco-hydrologic	Ecosystem water use efficiency	India

TABLE 2. (continued): selected literatures

No.	Reference	Framework	Threshold type	Country	No.	Reference	Framework	Threshold type	Country
21	(Sinha et al. 2018)	Hydrologic resilience	partitioning of precipitation to ET and streamflow	India	33	(Xue et al. 2020)	Hydrological resilience	water use efficiency.	Global
22	(Ilunga 2018)	Hydrologic resilience	Mean annual runoff	South Africa	34	(J. F. Liu et al. 2020)	Hydrological resilience	Runoff and runoff rainfall ration	China
23	(Krogh & Pomeroy 2018)	Hydrologic resilience	streamflow response	Canada	35	(Zeng et al. 2020)	RRV	3 and 12 month standard precipitation evapotranspiration index (SPEI)	China
24	(Mallya et al. 2018)	RRV	Water quality	USA	36	(Xue et al. 2021)	Hydrologic resilience	Tolerance and plasticity	China
25	(Hazbavi, Keesstra, et al. 2018)	RRV	standardized precipitation index (SPI), flow discharge, suspended sediment concentration (SSC), total nitrogen (TN) and total phosphorus (TP).	Ireland Portugal Iran	37	(Jha et al. 2021)	Watershed resilience	Spi-12	India
26	(W. Liu et al. 2019)	Eco-hydrological resilience	Standard Evapotranspiration Deficit Index satellite-retrieved evapotranspiration (ET) and net primary production (NPP).	China	38	(C. C. Liu et al. 2021)	Watershed resilience	seasonal runoff	China
27	(Sadeghi et al. 2019)	RRV	standardized precipitation index (SPI), normalized difference vegetation index (NDVI), soil erosion, and low and high flow discharges	Iran.	39	(Garza-Díaz & Sandoval-Solis 2022)	Watershed resilience	streamflow drought index.	USA and Mexico
28	(Ervinia et al. 2019)	RRV	Standardized precipitation index (SPI), Low flow discharge, High flow discharge, Ammonium-N Nitrate-N	China	40	(Domingues & da Rocha 2022)	Hydrologic resilience	rainfall, flow, soil moisture, and water storage	Brazil
29	(Ahn & Kim 2019)	RRV	watershed landscape, stream geomorphology, hydrology, water quality, aquatic habitat conditions, and biological conditions	South Korea	41	(Vazquez & Muneepeerakul 2022)	social-ecological-hydro	water availability variation	--
30	(Spence et al. 2020)	Hydrological resilience	Water budget components-streamflow, water chmestry	Canada	42	(Lankford et al. 2023)	Drought resilience (SOCI-ECO-HYDR)	water accounts AND Days to Day Zero (DDZ).	South Africa
31	(Lees et al. 2020)	Hydrological resilience	soil moisture	Scotland, Britain, and England	43	(Wang et al. 2023)	Catchment resilience	rainfall and runoff	Germany
32	(Dai et al. 2020)	RRV	SPI	China					

TABLE 3. Resilience Capacities

Capacity	Definition	Source of definition	Capacity in literature
Persistence	(the ability of a system to change by absorbing disturbances and reorganize while undergoing changes to retain essentially the same identity and set of functions).	(Baird & Allyson Quinlan 2021; Lankford et al. 2023)	(Carey et al. 2010; Creed et al. 2011; Domínguez-Tuda & Gutiérrez-Jurado 2021; Farzi et al. 2022; Harder et al. 2015; Ilunga 2017; Krogh & Pomeroy 2018; Lankford et al. 2023; C. Liu et al. 2021; J. F. Liu et al. 2020; W. Liu et al. 2019; Luijten et al. 2001; Mao et al. 2017; Schlüter & Pahl-Wostl 2007; Seo et al. 2018; Sharma & Goyal 2018a 2018b; Sinha et al. 2018; Spence et al. 2020; Vazquez & Muneepeerakul 2022; Wang et al. 2023; Xue et al. 2020 2021)
Adaptive	the capacity to learn, adjust and adapt in response to a shock or series of shocks. Adaptation is generally linked to on-going	(Baird & Allyson Quinlan 2021; Lankford et al. 2023; O. Randhir 2014)	(Farzi et al. 2022; Lankford et al. 2023; Mao et al. 2017)
Anticipative	the capacity to anticipate, prepare and plan for unexpected changes and disturbances.	(Lankford et al. 2023)	(Lankford et al. 2023)
Transformative	the capability to become a different kind of system when the present system is untenable	(Baird & Allyson Quinlan 2021; Lankford et al. 2023; O. Randhir 2014)	(Farzi et al. 2022; Lankford et al. 2023; Mao et al. 2017; Park & Rao 2014)
Recover	the rate at which a system recovers from perturbation describes how quickly a system will recover from failure state once failure has occurred	(Lees et al. 2020)	(Chanda et al. 2014; Domingues & da Rocha 2022; Farzi et al. 2022; Hazbavi, Baartman, et al. 2018; Hazbavi & Sadeghi 2017; Hoque et al. 2012b; Hoque, Hantush, et al. 2014; Hoque, Raj, et al. 2014; Lees et al. 2020; Mallya et al. 2018; Sadeghi et al. 2019; Sadeghi & Hazbavi 2017; Xue et al. 2020; Zeng et al. 2020)

WATERSHED RESILIENCE EVALUATION FRAMEWORKS

Identifying how one stressor influences the interconnected social-ecological system is one challenge in enhancing resilience to desired system states (Adger et al. 2011). In TABLE 3 the selected literatures were analysed as (Reference, framework, threshold type and country).

We divided the frameworks based on how they are mentioned in the study. Those are: i) a framework for risk-based indicators (RRV), and ii) a framework for watershed resilience (eco-hydro resilience, socio-hydro resilience, and hydrologic resilience). The analysis of these frameworks is explained in the next paragraphs, 42 out of 43 papers have been published in the last ten years, indicating the increasing interest in the resilience concept. These methods targeted diverse regions around the world recommendations.

RISK BASED INDICATORS FRAMEWORK

Watershed health has been compromised by persistent environmental degradation, resulting in decreased ecosystem services for organisms (Aju 2017; H. Liao et al. 2018), it is important to note that the degree of damage to watersheds depends upon a variety of factors, such as the existing land use, topography, soil, and vegetation within the watershed (Hazbavi, Baartman, et al. 2018; Hazbavi, Keesstra, et al. 2018; K. Liao et al. 2018).

As part of its efforts to evaluate the health of watersheds, the Environmental Protection Agency (EPA) in the United States has suggested the use of integrated assessments. Using this approach, managers will be able to identify healthy watersheds and prioritise those that should be protected or restored. A significant aspect of watershed health is the ability to withstand, recover from, or adapt to natural and human-caused disturbances. However, in order to maintain their health, healthy watersheds often rely on recurrent natural disturbances. Therefore, watershed health assessment (WHA) is considered as a useful tool for bridging the gap between watershed research and management (EPA 2014; Hazbavi & Sadeghi 2017; Sadeghi & Hazbavi 2017). In the realm of environmental management, identifying and mitigating potential threats to watersheds is a complex and challenging task. This is due to the fact that environmental impairment is typically not attributable to a single source, and can be difficult to predict or prevent altogether (Johnston 2016) . As a result, it is necessary to develop and utilize a range of indicators that can effectively monitor the health and functionality of a given watershed (An et al. 2002; Li et al. 2013; H. Liao et al. 2018; Sadeghi et al. 2019). Towards this end, scientists and researchers are becoming increasingly aware of the importance of quantifying indicators and methods to assess the health of watersheds in order to achieve this goal (Ahn & Kim 2019).

Some standards have therefore been proposed for selecting the appropriate health assessment indicators. These standards are sensitivity to environmental changes, convenience and affordability, as well as the ability to provide a predictive understanding of ecosystem function (Li et al. 2013; Mantyka-Pringle et al. 2017; Sadeghi et al. 2019). Risk based indicators approach developed by (Hashimoto et al. 1982), This framework involves reliability, resilience and vulnerability (RRV) indicators to assess a reservoir operation as one of the evolving approaches dealing with human-coupled ecosystems. (Hashimoto et al. 1982) defined the three indicators as reliability is defined as the probability of the system being in a non-failing state at any given time, resilience is defined as the probability of a system recovering from a state of failure given that a violation has occurred and vulnerability refers to the likelihood that a system will suffer damage in the event of a system failure.

The RRV analysis has the potential to identify areas within watersheds that are more likely to encounter violations, thereby contributing to the overall degrading health of the watershed (Hoque et al. 2012b). In this regard, it is imperative to conduct a comprehensive assessment of WH. Watershed health assessments have been conducted using this approach, for example: (Hazbavi, Baartman, et al. 2018; Hazbavi, Keesstra, et al. 2018; Hazbavi & Sadeghi 2017; Hoque et al. 2012b 2016; Hoque, Hantush, et al. 2014; Hoque, Raj, et al. 2014; Mallya et al. 2018; Sadeghi & Hazbavi 2017). Although these studies typically focused on one aspect of the watershed system. For example, (Hoque et al. 2012b 2016; Hoque, Hantush, et al. 2014; Hoque, Raj, et al. 2014) and (Mallya et al. 2018) assessed the health of some watersheds in Indiana, USA, solely in terms of water quality criteria. (Hazbavi, Baartman, et al. 2018; Sadeghi & Hazbavi 2017) assessed watershed health from the viewpoint of drought criterion, i.e., standardized precipitation index (SPI). In (Ahn & Kim 2019), six representative indicators (watershed landscape, stream geomorphology, hydrology, water quality, aquatic habitat, and biology) were combined to assess the vulnerability of the Han River basin's watershed to artificial stressors. Back to our question (how has resilience been quantified?). Although the final result in this framework incorporates all aspects of resilience definition from (Fraccascia et al. 2018) and (Farzi et al. 2022), in this context, resilience is utilized as a metric to indicate the duration it takes for the system to recover (i.e., the time it takes for the system to return to a desirable state), and the desirable state is denoted by a specific threshold value.

The terms "threshold" and "tipping point" are interchangeable, as they both refer to the level of stress that propels a watershed ecosystem into a different state. The concept of a threshold is used in watershed ecology to describe a stress level or disturbance that can cause the ecosystem to shift into a new state or regime. The new state can either be stable or unstable, depending on whether it is above or below the threshold level. During a stable state, the ecosystem exhibits certain physical and biological characteristics. However, when the system is pushed beyond the threshold level, it may become unstable, and the physical and biological features of the ecosystem may change. The change may occur suddenly, as in the case of a tipping point, or it may occur gradually without any apparent tipping points.

When an ecosystem reaches a new stable state, it is likely to self-perpetuate, and feedback mechanisms stabilize the new state. This type of feedback mechanism has the potential to reinforce the new state, making it difficult to return to the previous state. Thus, it is important to identify and monitor the threshold levels within a watershed ecosystem in order to prevent the ecosystem from tipping into an undesirable state.

However, it is important to note that changes to watershed ecosystems can also be gradual, without any apparent tipping points. The ecosystem can therefore change slowly over time without sudden changes. It is still important to monitor the ecosystem's health and identify any gradual changes that could affect its stability and function in the long term (Hazbavi, Keesstra, et al. 2018). The fundamental aspect of evaluating the health of a watershed is based on selecting a specific type and degree of threshold. Previous research has utilized the Standard Precipitation Index (SPI) to measure the impact of hydrology on the Watershed health assessment to quantify the impact of hydrology on the Watershed health assessment. The SPI is a commonly used index in hydrology that measures precipitation anomalies over time. This index enables researchers to determine whether a particular watershed is experiencing a drought or a surplus of water, which can help in assessing its overall health. (Hazbavi, Baartman, et al. 2018; Hazbavi & Sadeghi 2017; Sadeghi & Hazbavi 2017) , (Hazbavi & Sadeghi 2017) used SPI with streamflow, sediment yield to assess the effects of climate change and a range of human activities on the watershed response. (Sadeghi et al. 2019) used five criteria of standardized precipitation index (SPI), normalized difference vegetation index (NDVI), soil erosion, and low and high flow discharges to assess watershed health by developing an integrated watershed health index (IWHI) to conceptualize and develop RRV-based WH with varieties of climatic, hydrologic and human conditions.

In order to develop the Drought Management Index (DMI), (Chanda et al. 2014) utilized the permanent wilting point PWP for soil moisture in India. While using standardized SPI, low flow, high flow, and sediment yield assessments for Shazand Watershed, Iran, (Hazbavi & Sadeghi 2017) developed a Hydrologic Watershed Health Index (HWHI). These indices are probabilistic ranges between 0 and 1 used for characterizing the long-term, spatiotemporal variation of drought propensity. Only (Zeng et al. 2020) utilized a combination of two tools, namely the 3- and 12-month Standardized Precipitation Evapotranspiration Index (SPEI) and the Reliability, Resilience, Vulnerability framework (RRV), to create a projection of future river basin health. They base their projection on an analysis of how various basins in China have responded to diverse degrees of dryness in the period from 2021 to 2050.

Overall, the selection of an appropriate threshold type and magnitude is a critical step in the watershed health assessment process. It is essential to choose a threshold that is relevant to the specific watershed being evaluated and that can effectively capture the key indicators of its health. By doing so, researchers and practitioners can obtain a comprehensive understanding of the state of a watershed and develop effective strategies to protect and improve its health.

To gain a more comprehensive understanding of watershed health, future research could expand the use of the SPI index to different scales and scenarios related to climate and water management. This expansion can offer insights into the impact of various factors on the health of the watershed, such as agricultural, water resources, and meteorological factors. By utilizing the SPI index at different scales, researchers can evaluate the health of a watershed in different contexts, which can be useful in developing more targeted strategies for its management and protection.

Furthermore, it is essential to select appropriate indices and thresholds that are relevant to the specific watershed being evaluated and can effectively capture the key indicators of its health. These indicators may include water quality, biodiversity, ecosystem services, and overall sustainability. By accurately assessing the state of the watershed, researchers and practitioners can develop effective plans for its management and protection that address the unique challenges and opportunities of that particular watershed.

WATERSHED RESILIENCE ASSESSMENT

In this section, we describe another approach to quantifying the resilience of watersheds. In this section, the focus has been shifted from a risk-based framework to a quantitative approach which enables a better understanding of the resilience of watersheds. In this approach, the resilience of watersheds is evaluated across three distinct domains: hydrological, eco-hydrological, and socio-hydrological. As each of these domains depends on the others, they are crucial to assessing a watershed's overall resilience.

There are various ways in which the term "resilience" is used in relation to humans and water. These include hydrological resilience, aquatic ecological resilience, the resilience of communities and cities to water-related disasters, and the resilience of water cycles (Mao et al. 2017). In situations involving the management of complex ecosystems or resources, the interactions between social and ecological or resource systems often determine the system's ability to adjust to changes (Schlüter & Pahl-Wostl 2007). The term hydrological resilience refers to the capacity of a system to maintain its form and function in the presence of both natural and anthropogenic pressures. This includes the ability to withstand changes and retain its stability over time. This definition has been proposed by (Creed et al. 2011; Harder et al. 2015). It is important to note that hydrological resilience is not a one-size-fits-all concept, and its degree may vary depending on the dominant hydrological processes and their interaction with the climatic and biological characteristics of the catchment.

Hydrological characteristics, such as geology, topography, soil texture, and vegetation cover, may have a significant effect on the response of a basin to various environmental changes. For example, the way streamflow responds to alterations in the distribution of precipitation phases may vary greatly across basins with diverse hydrological and environmental features. As a result, it is essential to consider the specific attributes of each catchment when assessing its hydrological resilience (Harder et al. 2015).

Watershed hydrological resilience was assessed using elasticity and deviation indicators based on the Budyko framework (Creed et al. 2014; Sinha et al. 2018; Xue et al. 2020 2021). This conceptual framework outlines the correlation between a catchment's potential evapotranspiration (PET) and actual evapotranspiration (AET), both normalized by precipitation (P). Specifically, the framework illustrates the relationship between AET/P (evaporative index, EI) and PET/P (dryness index, DI). By utilizing this framework, researchers can evaluate the catchment's capacity to withstand changes in the climate, and according to (Sinha et al. 2018), anthropogenic stress as well, who applied this framework to India to examine its resilience to climate and anthropogenic pressures. In their study, (Wang et al. 2023) employ a probabilistic model of hydrologic response that utilizes daily observations of rainfall and streamflow from 175 catchments across Germany.

As humans have developed increasingly sophisticated methods and resources for controlling the dynamics of the water cycle, there is currently a growing interest in understanding the relationships between humans and water from a complexity perspective. Therefore, (Sivapalan et al. 2012) proposed the concept of "socio-hydrology," which distinguishes itself from Integrated Water Resources Management (IWRM) by focusing on observing, understanding, and predicting the interconnected and co-evolving ways in which human and water systems interact over time. In light of this, while IWRM primarily aims to manage water systems to achieve desirable environmental and societal outcomes, socio-hydrology provides a foundational scientific understanding of the complex interactions between these systems, which is essential for managing water resources sustainably. Consequently, the socio-hydrology concept acknowledges the non-linear nature of these interactions, where fast processes interact with slow processes to produce complex and rich dynamics in the system.

In a study conducted by (Mao et al. 2017), they utilized the "socio-hydro" concept to create a theoretical structure that encompasses various facets of socio-hydrological systems. These facets include: (1) the water subsystem, which pertains to the resilience of hydrological processes in the face of human-made changes; (2) the human subsystem, which relates to the capacity of society to cope with hydrological risks and pressures; and (3) the combination of human and water systems, which was investigated using the strengths, weaknesses, opportunities, and threats analysis as a tool to improve socio-hydrological resilience.

Research into the resilience of watersheds or catchment scale as a unifying concept for water management is difficult to find (Wilby 2020). Watershed resilience described in most selected researches refer to the capacity of a watershed to absorb and recover from perturbations or disturbances (Folke et al. 2010; Hoque et al. 2012b; O. Randhir 2014). Consequently, there has been a growing focus on watershed resilience and the transitions that occur in watershed systems, particularly in the context of river basin conservation and management (Davidson et al. 2012; Qi et al. 2016).

The identification of thresholds in rivers, similar to the risk-based method, would provide valuable information about the carrying capacity of river basins and the maximum number of anthropogenic disturbances a hydrologic area can withstand before it deteriorates and becomes untenable. When a threshold is crossed, a stressed system may remain in the current state or shift (smoothly or abruptly) to another state, depending on the relative strength and severity of the disturbances. The transition to this new possible state is referred to as a regime shift, a long-term reorganization of a system (Garza-Díaz & Sandoval-Solis 2022; Park & Rao 2014). Regime shift mechanisms, as well as the types of regimes shifts that occur in a system, provide insight into the relationship between the response (e.g., flow regime) and control variables (e.g., flow regulation) (Collie et al. 2004).

In the case of abrupt regime shifts, the relationship between the response variable and the control variable will be nonlinear or have a positive feedback effect. The cascading regime shift occurs when one system undergoes a shift that changes key variables in another system (Rocha et al. 2018). In order to adapt to a new state after a regime shift, variables in the system will likely go through significant changes, tipping into a new equilibrium. It is becoming increasingly important for river basin resilience, conservation, and management to understand and identify regime shifts in natural ecosystems, as well as the ability of rivers to absorb and recover from perturbations as research continues to progress (Davidson et al. 2012; Garza-Díaz & Sandoval-Solis 2022; Qi et al. 2016). There have been many studies conducted to improve our understanding of the changes in river basin regimes, such as (C. Liu et al. 2021; Qi et al. 2016) who investigated the resilience of the Yangtze River Basin by applying the concept of the stability fate of a ball in a landscape of hills and valleys. (Garza-Díaz & Sandoval-Solis 2022) used streamflow drought index and critical slowdown principle. Others have cited differences between observed and simulated streamflow records as evidence of a change in catchment state (i.e., a shift to a new equilibrium). Such transitions have been reported for diverse climates following decades of drought in South-West Australia (Silberstein et al. 2013). Some studies have investigated the use of chaos (or entropy - the degree of disorder, or randomness in a system) as a proxy for catchment resilience (Ilunga 2017 2018) As a result of the literature review discussed above, this paper presented a framework for quantifying watershed resilience, as shown in Figure 2.

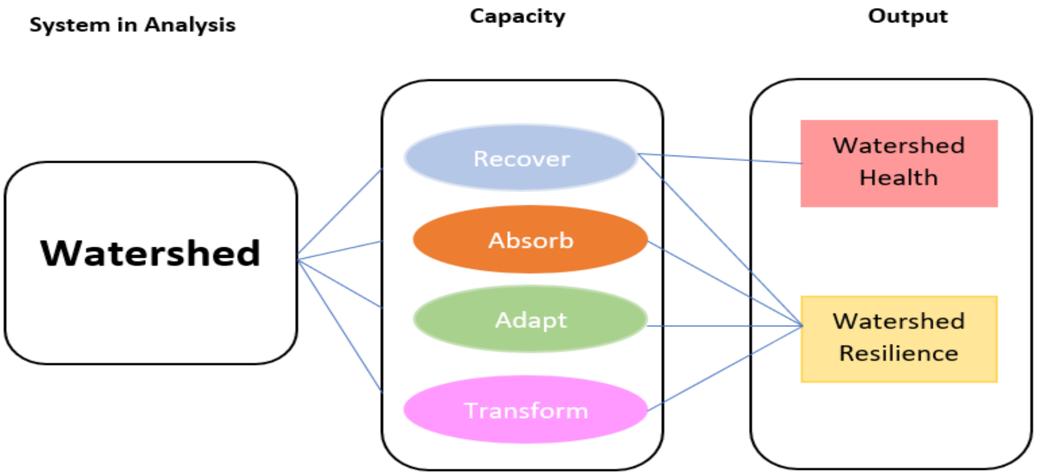

FIGURE 2. Resilience from the watershed point of view

CONCLUSION

The concept of resilience depicts the response of a system to external disruptions or alterations. Quantifying the resilience of watersheds is a crucial measure for promoting the durability and resilience of our water resources and ecosystems, as well as securing the continued prosperity of our communities. The article presented here provides an in-depth examination of 43 frameworks pertaining to watershed resilience published between 2007 and 2023. The key contribution of this study is its amalgamation and synthesis of a variety of research endeavors, which elucidates the developing landscape of quantifying watershed resilience. This study scrutinizes the capacities and aspects encompassed in the identified frameworks and proposes future research prospects.

Despite the growing interest in resilience, there is still considerable scope for improving its conceptual clarity and practical relevance in socio-hydrological and eco-hydrological contexts. For example, it is critical to understand the different factors that contribute to watershed resilience. Among these factors are the physical characteristics of the watershed, the diversity of species and habitats, as well as the social and economic systems dependent on the watershed. Additionally, it is necessary to examine the impacts of climate change, land use changes, and other anthropogenic activities on the resilience of watersheds. This is in order to develop effective strategies for improving watershed resilience. Consequently, further research and investigation are required to enhance the conceptual clarity and practical relevance of watershed resilience in eco-hydrological and socio-hydrological contexts. This will help us to better assess and manage our water resources, thereby Nmaintaining the health and sustainability of our ecosystems and communities.

In parallel, information dissemination is essential for sharing knowledge and data among various stakeholders, including government officials, scientists, and the general public. In this way, awareness will be raised regarding potential hazards, such as climate change and its impact on watersheds. In the context of climate change and its impact on watersheds, decision support systems may provide stakeholders with valuable information and resources to assist them in making informed decisions. Achieving a resilient watershed may require the development of strategies for mitigating damage from natural disasters, adapting to changing conditions, and protecting ecosystems.

The watershed resilience framework's use for evaluating the state of watersheds in relation to climate change and other drivers and stressors is still in its infancy in terms of theoretical understanding and practical implementation. Although the mentioned frameworks hold promise for regional assessment, several aspects of the framework require more exploration, such as defining goals, developing efficient strategies, identifying appropriate standards and limits, allocating resources, managing and evaluating uncertainty, and accounting for ecological and social complexities. These areas need to be explored to ensure the effectiveness and applicability of the framework in enhancing the resilience of watersheds.

The main limitation of the resilience framework is selecting the threshold for the assessment (specifically for RRV). It is recommended to select different thresholds for different subregions. Furthermore, river basin health includes many aspects, e.g., ecology, flora and fauna, climate, socio-economics, etc. In some basins, human activities may play a major role in determining the health of the basin. To conduct a comprehensive health assessment, it is necessary to include land use, water quality, and economics in the adopted framework. Different thresholds will lead to different outcomes, and further research is needed to identify appropriate threshold levels for different hydroclimatic regions. By choosing indicators that fulfil these requirements, researchers and managers can effectively track changes in ecosystem health and make informed decisions about how to address emerging threats. It is imperative to note, however, that selecting appropriate indicators can be a challenging and iterative process, and it requires careful consideration of several factors such as the local context, available resources, and the specific objectives of the assessment. Through a rigorous and thoughtful approach to indicator selection, it is possible to enhance our ability to assess ecosystem health and respond promptly and effectively to emerging challenges. This study primarily emphasizes research concerning surface water quantity, with a potential future extension to encompass water quality and groundwater investigations. Additionally, future research may intend to investigate the examination of strategies and decisions and their influence on watershed resilience.

As a conclusion, this review article has clarified theoretical contributions as well as highlighted the gaps in the body of existing knowledge. It highlights opportunities for further study and emphasizes the value of a comprehensive strategy for improving watershed resilience. In the end, it contributes to new knowledge in the field by delivering a thorough synthesis of current theoretical frameworks and a research plan for the future.

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DECLARATION OF COMPETING INTEREST

None

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