

# Indicators for assessing socio-ecological vulnerability of water-related ecosystem services: a systematic review

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## Research Article

**Keywords:** vulnerability frameworks, water management, climate change, land use change

**Posted Date:** September 11th, 2026

**DOI:** <https://doi.org/10.21203/rs.3.rs-10898458/v1>

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**Additional Declarations:** No competing interests reported.

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# Abstract

Watersheds function as socio-ecological systems (SES), in which hydrological, ecological, and social processes interact to sustain water-related ecosystem services (WES). These systems are exposed to climate change and land-use changes, which increase vulnerability by altering water availability and quality, as well as ecosystem functioning, with direct consequences for human well-being. Despite a growing body of literature on socio-ecological vulnerability, few studies simultaneously integrate hydrological, ecological, and social dimensions into an integrated assessment to evaluate vulnerability to water-related risks. This study systematizes the indicators used to measure the vulnerability of WES, based on a systematic review of peer-reviewed studies indexed in Scopus. Of the 1,188 indexed articles, 33 studies were selected following full-text analysis. In this review, we identified and categorized the main indicators into three components of vulnerability: (i) exposure indicators, covering climate variability and changes in land use and land cover; (ii) sensitivity indicators, including WES dynamics and social demand for water; and (iii) adaptive capacity indicators, comprising socioeconomic characteristics, institutional and governance mechanisms, substitution capacity, and beneficiaries' perceptions of vulnerability. The analysis also examines methodological approaches, the data used, and gaps in the literature, and we have integrated these elements into recommendations for future assessments that are consistent with the complexity of the socio-ecological system and the components that influence the vulnerability to WES.

## Introduction

Water is an essential resource. It is fundamental to life and ecosystem functioning and is linked to well-being and economic development (De Groot et al., 2002). To understand how socio-ecological systems are vulnerable to pressures relating to the availability, quality and access to water, a perspective is needed that recognizes the inherent complexity of the interactions between society and nature as inseparable dimensions of a single complex system (Liu et al., 2007).

Watersheds function as socio-ecological systems (SES), in which social, ecological, and hydrological aspects are interrelated and cannot be understood in isolation (Bunch et al., 2011; Folke et al., 2016). This concept is linked to socio-hydrology, which studies how the environment and human society interact in water contexts.

Socio-ecological vulnerability refers to a system's propensity to be adversely affected by natural and human-induced drivers, which affect the sensitivity and adaptive capacity of ecosystems and people to external stressors such as climate change and land use changes (He et al., 2018; Li, 2023). Vulnerability is conceptualized through three dimensions: exposure to change, sensitivity to these impacts, and adaptative capacity to cope and recover from disturbances (Adger, 2006). In the context of water-related ecosystem services, it refers to the susceptibility of communities and ecosystems to impacts on water availability, quality, access, and distribution due to environmental and social drivers of change (Reyers et al., 2013; Bolaños-Valencia et al., 2019; Berrouet et al., 2020; Gomez-Jaramillo et al., 2021; Scott et al., 2021).

Evaluating these vulnerabilities is important for estimating how climate and land-use changes can affect the capacity of ecosystems to deliver essential water-related services and, consequently, human well-being (Berrouet et al., 2020; Scott et al., 2021; Peng et al., 2023; Moghadam et al., 2024; Okafor et al., 2025).

Vulnerability assessments allow us to understand, based on biophysical indicators of ecological and hydrological degradation, as well as social, institutional, and political indicators, where and which people and ecosystems are systematically most exposed and unable to respond to water-related stressors. Understanding socio-ecological vulnerability to water stress is essential for developing sustainable management strategies, improving water governance and enhancing communities and ecosystems resilience (Pahl- et al., 2023; Gómez-Jaramillo et al., 2021; López et al., 2020; Gao et al., 2025).

Given the need to understand socio-ecological vulnerability to changes in WES in watersheds, approaches linking hydrological, biophysical, and social dimensions remain incipient state in the literature. This review therefore addresses

the following key questions: What indicators can be used to assess the socio-ecological vulnerability of WES in watersheds? What are the methodologies for each indicator? How well are the biophysical, social, institutional, and cultural dimensions integrated?

To address these questions, this study synthesizes the literature on water-related ecosystem services, tracking their changes and risks, with a particular focus on socio-ecological vulnerabilities. By reviewing and categorizing indicators and methodologies, it aims to develop a framework for assessing the socio-ecological vulnerability of watershed socio-ecological systems. Specifically, this work systematizes the indicators associated with exposure, sensitivity, and adaptive capacity while assessing the methodological scope of existing approaches to identify gaps in the integration of ecological, hydrological and social components and processes of socio-ecological systems that may be vulnerable to changes in water-related ecosystem services.

## Methodology

This systematic review aimed to identify and synthesize studies addressing socio-ecological vulnerability associated with water-related ecosystem services in watershed systems, with emphasis on the indicators and methodological approaches used to assess such vulnerability.

The review followed the PRISMA 2020 guidelines (Page et al., 2021). Study selection followed the sequential stages of identification, screening, eligibility assessment, and inclusion as shown in Fig. 1.

The search strategy identified publications addressing the intersection of ecosystem services, vulnerability, and water-related or watershed systems. The search string was structured for Scopus using Boolean operators (AND, OR) and a truncation operator (\*) to retrieve targeted academic literature, the following search string was used: (ecosystem service\*) AND (vulnerab\*) AND (water\* OR watershed OR basin).

Scopus was selected as the primary bibliographic database because of its broad multidisciplinary coverage and structured metadata, which facilitate the retrieval and systematic screening. No restrictions on publication year or language were applied. Peer-reviewed research and review articles indexed in Scopus were considered eligible. The search was conducted between January and May 2026, retrieving 1,188 records.

Eligibility criteria required studies to: (i) explicitly address water-related ecosystem services; (ii) assess vulnerability within a socio-ecological perspective; (iii) concern watershed, river basin, or hydrologically related systems; and (iv) provide empirical or methodological evidence relevant to the assessment of vulnerability associated with water-related ecosystem services.

Studies were excluded when they: (i) lacked explicit metrics or indicators related to water-related ecosystem services; (ii) assessed vulnerability outside a socio-ecological context; (iii) focused exclusively on marine or coastal systems or (iv) addressed ecosystem services without a direct connection to water, such as studies focused on pollination.

During the first stage, titles and abstracts of all 1,188 records were screened. Records that clearly outside the review scope were excluded, leaving 129 reports for full-text assessment.

The included studies were read in full and categorized by objectives, methodological approaches, and findings. Particular attention was given to identifying and classifying vulnerability indicators and the methods used to measure them in relation to water provision and other water-related ecosystem services within socio-ecological systems.

Of the 129 reports assessed in full text, 96 were excluded for failing to meet the eligibility criteria, and a total of 33 studies met all criteria and were included in the qualitative synthesis.

The review protocol, search strategy, and eligibility criteria were jointly developed by the two authors. Study screening and selection were subsequently conducted by one author, who independently assessed the titles and abstracts of all retrieved records and evaluated the full texts of potentially eligible studies against the predefined eligibility criteria. The final set of included studies was then jointly examined by both authors. Data extraction, categorization, and interpretation were discussed between the authors to reach agreement on the classification of indicators and methodological approaches presented and discussed in the following sessions.

## Results and discussion

### Ecosystem services and trade-offs in watershed systems

Watersheds are hydrological systems where ecological, socioeconomic, and political processes co-occur and interrelate in a complex dynamic across space and time, influencing the provision of ecosystem services (Depietri et al., 2013; Bolaños-Valencia et al., 2019; Peng et al., 2023). The reviewed literature indicates that watersheds provide multiple water-related ecosystem services (WES) that benefit people both within and outside, particularly through the provision of water for human consumption, domestic use, and agricultural production, in both subsistence and large-scale (Notter et al., 2013; Vollmer et al., 2016; Pettinotti et al., 2018; Bidegain et al., 2019; Berrouet et al., 2020; Chen et al., 2021; Zhang et al., 2025). These services depend on hydrological and ecological functions associated with water circulation, storage and yield within watersheds. Water quality and quantity are co-produced by the interaction between social and biophysical processes. There are a multiple range of actors involved in the use, management, and administration of ecosystem services to guarantee water supply (Reyers et al., 2013; Merlo-Galeazzi et al., 2024; Ruiz-Ordóñez et al., 2023).

The literature reviewed identifies four main categories of ecosystem services (provisioning, regulating, supporting, and cultural), with a predominance of provisioning and regulation services related with water quantity and quality (Fig. 2).

Provisioning services primarily included the surface and groundwater supply for human consumption, hydropower generation, and food production (Notter et al., 2013; Rodríguez Osuna et al., 2014; Everard et al., 2018; Hazbavi et al., 2018; Bolaños-Valencia et al., 2019; Ma et al., 2019; Berrouet et al., 2020; Bhattarai et al., 2020; Chen et al., 2021; Duan et al., 2025; Vollmer et al., 2013; Wang et al., 2017; Zakari et al., 2025).

Regulating services contribute to maintaining other water services through flow regulation for flood prevention, water purification via pollutant filtration and dilution, carbon sequestration, erosion and sediment control, climate regulation, and habitat quality maintenance (Nakamura, 2006; Norman et al., 2012; Rodríguez Osuna et al., 2014; Tzilivakis et al., 2019; Bhattarai et al., 2020; Tostes et al., 2020; Sannigrahi et al., 2020; Chen et al., 2021; Moghadam et al., 2024; Saravia-Maldonado et al., 2024; Zhang et al., 2024; Zakari et al., 2025).

Supporting services, although indirect, are necessary for the provision of all other services. These include biodiversity conservation, nutrient cycling, and the maintenance of habitats that sustain both aquatic and terrestrial ecological processes (Granata and Di Nunno, 2024; Zhang et al., 2025).

Cultural services are those associated with water-based recreation and leisure activities, education, scientific research and environmental management, cultural and spiritual values, the preservation of livelihoods, lifestyles, and landscapes, as well as inspirational and aesthetic values linked to water that provide non-material well-being to populations (Bunch et al., 2011; Sannigrahi et al., 2020; Vollmer et al., 2013).

The co-occurrence of multiple WES is linked to the multifunctionality of ecosystems. These ecosystem services are interconnected through their water dependence, which can result in either reinforcement or conflict, leading to dynamic interactions that manifest as synergies and trade-offs (Akbar et al., 2023; Zhang et al., 2025). Synergies occur when different services mutually reinforce each other (Tomscha and Gergel, 2016; Sannigrahi et al. 2020). For instance, flood

regulation, erosion control, and soil moisture retention often exhibit synergistic relationships, as improved vegetation cover simultaneously enhances all three services.

Conversely, trade-offs represent situations where the provision of one service reduces another (Wang et al., 2026). In watersheds, there are often trade-offs between provisioning and regulating services (Bennett et al., 2009). The literature reviewed indicates that, in most cases, these trade-offs occur between agricultural food production and water quality regulation. The conversion of native vegetation to cropland, intensive irrigation, and agrochemical use increase food provisioning but simultaneously degrade water purification capacity, nutrient cycling, and flood regulation (Quintas-Soriano et al., 2016). Consequently, this dynamic reduces water quality, thereby compromising agricultural sustainability and the livelihoods of people who live in and/or depend on the goods provided by the watershed (Postel & Thompson Jr., 2005; Pérez-Silos et al., 2021; Wu et al., 2021; Assis et al., 2023).

The combined effects of land use change and climate change on socio-ecological systems can affect ecosystem functions, threatening the capacity to provide and maintain ecosystem services consequences for human well-being (De Groot et al., 2002; Adger, 2006; Armatas et al., 2017; Bolaños-Valencia et al., 2019). These pressures are particularly evident in river basins where human activities interact with hydrological and ecological processes.

In the Las Piedras River basin, southwestern Colombia, Ruiz-Ordóñez et al. (2023) showed that conventional agricultural practices including agrochemicals use, monoculture and crop expansion in strategic ecosystems, increased nutrient inputs to rivers and contributing to their degradation. In the northern Colombian Andes, Bolaños-Valencia et al. (2019) and Berrouet et al. (2018) found that land-use changes have increased socio-ecological risk to ecosystem service provision in the Riogrande basin, which is critical for water supply and hydropower. Khan et al. (2019) reported that land-use change progressively degraded the ecological functions of the Kagera river basin, Eastern Africa, a regional hotspot for multiple ecosystem services. Similarly, Everard et al. (2018) described the Banas catchment in northwestern India as being trapped in a cycle of ecosystem and socioeconomic degradation associated with population growth and water exploitation exceeding the ecosystem's capacity to regenerate and provide WES.

These studies indicate that changes in hydrological regimes caused by land-use and climate change can simultaneously affect water quantity, water quality, ecosystem functions, and the benefits derived by dependent populations. Such interactions become particularly important when pressures reduce the capacity of watersheds to sustain multiple uses and when communities have limited alternatives for accessing or substituting the services on which their well-being depends.

## **Socio-ecological vulnerability to water-related ecosystem services**

Vulnerability emerges from the interaction between exposure to pressures, sensitivity to changes in WES, and the capacity of communities and ecosystems to adapt to or cope with these changes (Berrouet et al., 2020; Ma et al., 2019). In watershed systems, vulnerability is therefore multidimensional, reflecting not only changes in ecosystem functions and service provision but also the degree to which populations depend on these services and their ability to adapt or substitute them.

Vulnerability is dynamic and variable over time, as well as being context-specific and dependent on culturally and institutionally determined boundaries that are difficult to discern (Turner et al. 2003; Adger, 2006; Adger et al. 2009; Bennett et al. 2016; Armatas et al., 2017; Vieira et al., 2023).

Assessing vulnerability in these socio-ecological systems is a challenge, as it requires consideration of multiple environmental and social dimensions that interact with one another. Consequently, vulnerability assessments require that vulnerability indicators be selected based on their ability to measure exposure, sensitivity, dependence, adaptive capacity,

and changes in the provision of ecosystem services. This requires the integration of hydrological, ecological, biophysical, and social indicators to obtain reliable and valid assessments.

Despite these limitations, vulnerability assessments have become crucial for water resources management, especially in the face of pressures arising from climate change, changes in land use, and increased demand on water.

## Identified indicators in the literature

The reviewed studies have explored different dimensions of socio-ecological vulnerability using multiple indicators. These indicators are analyzed within the common framework of three vulnerability components (Adger, 2006): exposure, sensitivity, and adaptive capacity. Table 1 presents the selected vulnerability indicators, followed by an analysis of their applicability across the reviewed literature.

Table 1

Relevant indicators to measure the socio-ecological vulnerability of water-related ecosystem services in river basins, based on the literature review.

| Vulnerability                | Indicators                                                                                                                                                                                                                                                        | Context (Reference)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Exposure</b>              | Climatic variation and change<br><br>Precipitation; Temperature;<br>Flood/drought frequency;<br>Climate scenarios                                                                                                                                                 | Pangani River basin, between Kenya and Tanzania (Notter et al., 2013); Sasumua watershed, Kenya (Van de Sand et al., 2014); Riogrande basin, Colombia (Berrouet et al., 2020; Bolaños-Valencia et al., 2019); Wami-Ruvu and Rufiji basins, Tanzania (Macharia et al., 2020); Vanajavesi River Basin, Finland (Rankinen et al., 2021); Las Piedras basin, Colombia (Ruiz-Ordóñez et al., 2023); Taleghan Watershed, Iran (Moghadam et al., 2024); Talgua River watershed, Honduras (Saravia-Maldonado et al., 2024).                                                                                                                                                                                                    |
|                              | Anthropogenic<br><br>Land use/land cover change<br>(May include: Vegetation<br>fragmentation; Population<br>growth, density, or total;<br>Pollution, contaminants and<br>decreased water quality)                                                                 | Yangtze River basin, China (Nakamura, 2006); Riogrande basin, Colombia (Berrouet et al., 2020); Monongahela River basin, USA (Merriam et al., 2020); Tietê-Jacaré Hydrographic Basin, Brazil (Trevisan et al., 2020); Fazenda Glória watershed, Brazil (Pissarra et al., 2021); Vanajavesi River Basin, Finland (Rankinen et al., 2021); Yellow River basin, China (Niu et al., 2024); Talgua River watershed, Honduras (Saravia-Maldonado et al., 2024); Kulpawn River Basin, Ghana (Zakari et al., 2025).                                                                                                                                                                                                            |
|                              | <b>Sensitivity</b><br><br>Ecosystem services<br><br>Water-related ecosystem<br>services                                                                                                                                                                           | Omerli Watershed, Turkey (Tezer et al., 2012); Guapi-Macacu watershed, Brazil (Osuna et al., 2014); Kagera basin, Eastern Africa (Khan et al., 2019); Miyun Reservoir watershed, China (Ma et al., 2019); Riogrande basin, Colombia (Berrouet et al., 2020); Fazenda Glória watershed, Brazil (Pissarra et al., 2021); Xiangjiang watershed, China (Chen et al., 2021); Manas River Basin, China (Zhang et al., 2024); Taleghan Watershed, Iran (Moghadam et al., 2024); Xijiang River basin, China (Zhang et al., 2025); Yangtze basin, China (Duan et al., 2025); Huailai mountain-basin, China (Wang et al., 2017); Yellow River basin, China (Fan et al., 2026); Kulpawn River Basin, Ghana (Zakari et al., 2025). |
|                              | Social demand<br><br>Population dependence and<br>demand on water; water<br>resource availability per capita,<br>and beneficiary characteristics                                                                                                                  | Guapi-Macacu watershed, Brazil (Osuna et al., 2014); Miyun Reservoir watershed, China (Ma et al., 2019); Riogrande basin, Colombia (Bolaños-Valencia et al., 2019; Berrouet et al., 2020); and Yangtze basin, China (Duan et al., 2025).                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| <b>Adaptive<br/>Capacity</b> | Socio-economic<br><br>Demographic characteristics<br>(income, age, ethnicity, gender,<br>diseases, etc.); access to<br>public water services,<br>infrastructures, and<br>technology; traditional/local<br>knowledge; community<br>organization and participation; | Riogrande basin, Colombia (Bolaños-Valencia et al., 2019; Berrouet et al., 2020); Banas catchment, India (Everard et al., 2018); Kagera basin, Eastern Africa (Khan et al., 2019); Wami-Ruvu and Rufiji River basins, Tanzania (Macharia et al., 2020); Yangtze River basin, China (Nakamura, 2006); Santa Cruz River, USA-Mexico Border (Norman et al., 2012); Pangani River basin, between Kenya and Tanzania (Notter et al., 2013); Talgua River watershed, Honduras (Saravia-Maldonado et al., 2024); Omerli Watershed, Turkey (Tezer et al., 2012); Quiroz River Basin, Peru (Tostes et al., 2020);                                                                                                               |
|                              | Institutional and governance<br><br>Distribution and access to<br>water information; access to<br>programs, subsidies,<br>incentives, and financial<br>support mechanisms;                                                                                        | Riogrande basin, Colombia (Bolaños-Valencia et al., 2019; Berrouet et al., 2020); Indrawati, Trisuli, Bagmati, and Melamchi basins (Bhattarai et al., 2020); Banas catchment, India (Everard et al., 2018); Yangtze River basin, China (Nakamura, 2006); Guapi-Macacu watershed, Brazil (Osuna et al., 2014); Sasumua watershed, Kenya (van de Sand et al., 2014); Omerli                                                                                                                                                                                                                                                                                                                                              |

|                                                                                                                                                                                                                                                                         |                                                                                                               |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|
| collaborative and multiscale governance; establishment of protected areas, payments for ecosystem services, and other conservation practices;                                                                                                                           | Watershed, Turkey (Tezer et al., 2012); Quiroz River Basin, Peru (Tostes et al., 2020).                       |
| Substitution capacity                                                                                                                                                                                                                                                   | Riogrande basin, Colombia (Berrouet et al., 2020).                                                            |
| Possibility of relocation or abandonment of the area or property; relocation or abandonment of water-dependent productive activities; access to other water sources (in other areas, or, in the case of surface water abstraction, switching to the use of groundwater) |                                                                                                               |
| Perceptions of the vulnerability by the beneficiaries                                                                                                                                                                                                                   | Huailai mountain-basin, China (Wang et al., 2017); Riogrande basin, Colombia (Bolaños-Valencia et al., 2019). |
| Subjective perception of human well-being based on ecosystem service availability or not.                                                                                                                                                                               |                                                                                                               |

## Exposure

Watershed systems are exposed to climate-related pressures such as rising temperatures, changing precipitation patterns, and increasing variability and frequency of extreme events, which can alter freshwater supply and hydrological dynamics (Macharia et al., 2020; Rankinen et al., 2021; Saravia-Maldonado et al., 2024). Accordingly, climate-related exposure was commonly operationalized through indicators of changes in precipitation and temperature and through the occurrence, intensity, and frequency of floods and droughts.

Macharia et al. (2020), for example, used the long-term coefficient of variation in annual precipitation, flood frequency (events/year), and the long-term mean of annual maximum temperature to assess the effects of climate variability on water production and availability for ecosystems and populations. Moghadam et al. (2024) combined current climate indicators with scenario modeling to project water vulnerability under changing climate and land-use conditions. Berrouet et al. (2020) and Bolaños-Valencia et al. (2019) incorporated beneficiaries' perceptions of climate change and climatic conditions into vulnerability indices, including perceived effects on water supply and erosion control.

Anthropogenic pressures were also widely represented through land-use and land-cover change, which directly affects ecosystem functions and the provision of WES (Bolaños-Valencia et al., 2019; Moghadam et al., 2024; Zakari et al., 2025). Changes associated with agricultural expansion, industrialization, urbanization, vegetation loss, and forest fragmentation can increase erosion, sedimentation, and surface runoff and reduce the capacity of ecosystems to regulate water quality (Niu et al., 2024; Peruchi Trevisan et al., 2020; Ruiz-Ordóñez et al., 2023; Saravia-Maldonado et al., 2024).

Niu et al. (2024) used temporal changes in land-cover distribution as an indicator of ecological vulnerability in the Yellow River Basin, showing that changes in land use influenced the capacity of ecosystems to provide WES. Zakari et al. (2025) similarly found that agricultural and built-up expansion in the Kulpawn River Basin reduced forest areas and water bodies, contributing to declining ecosystem services and increasing risks to livelihoods and water security.

Land-use change may also modify local climatic conditions and thereby reinforce exposure. Moghadam et al. (2024) showed that extensive conversion of forest to urban areas can reduce the capacity of ecosystems to regulate local

climate, while Vieira et al. (2023) found that deforestation associated with agricultural expansion in the São Francisco and Parnaíba river basins altered evapotranspiration and local rainfall patterns, exacerbating water stress.

These two indicators are often assessed together in the reviewed literature. Thus, climate variability and change, combined with the influence of anthropogenic land use, determine exposure to socio-ecological vulnerability and directly affect the watershed's capacity to provide water-related ecosystem services.

## Sensitivity

Sensitivity refers to the degree to which a system is predisposed to be affected by external stressors and pressures, reflecting its vulnerability to disturbances (Álamos et al., 2025). In the reviewed literature, sensitivity was primarily represented through changes in the availability and condition of WES and through the degree of social demand and dependence on these services.

In Ma et al. (2019), to identify which communities were most vulnerable to changes in water-related ecosystem services, the authors estimated the water supply and the amount of water demanded, comparing trends in supply and demand, and considering the vulnerability of ecosystem services to be fundamentally linked to the dynamics of changes in the supply of ecosystem services.

In watersheds systems, sensitivity is directly associated with ecosystem integrity and the capacity to provide water-related ecosystem services. Significant changes in the availability or conditions of the WES indicate greater sensitivity to additional stress factors, as they reduce the system's ability to absorb new disturbances (Niu et al., 2024).

The spatiotemporal dynamics of WES can serve as indicators of sensitivity, particularly when decline service provision affects population and their productive activities that depend on these services (Bolaños-Valencia et al., 2019).

## Adaptive Capacity

Adaptive capacity is the ability to cope with, recover from, adapt to, or maintain ecosystem service despite system stresses.

Socioeconomic characteristics, such as income, age, ethnicity, and gender, directly affect people's ability to adapt in watersheds (Norman et al., 2012; Bolaños-Valencia et al., 2019; Vieira et al., 2023). These conditions increase exposure to ecosystem service degradation, particularly due to limited access to water, dependence on vulnerable water sources, and an inability to cope with water scarcity (Bereciartua, 2005; Hernandez-Delgado, 2015; Caretta et al., 2022). They also affect these populations' economic dynamics, especially their livelihoods and economic and productive activities (Collins & Bolin, 2007).

Norman et al. (2012) argue that the most vulnerable people do not always live in the most vulnerable environments but may coexist with declining ecosystem services within a watershed. The poorest populations consistently and disproportionately experience declines in ecosystem service provision, exacerbating social inequalities and conflicts over water because they tend to depend more heavily on ecosystem services.

Therefore, investigating socioeconomic characteristics and public policies that strengthen them can promote greater resilience within watershed communities.

Access to public infrastructure and technology also strengthens community resilience by ensuring reliable water supplies and expanding the technical options available during stress events (Macharia et al., 2020; Tostes et al., 2020).

Local and traditional knowledge systems incorporate generations of adaptive experience, contributing to water conservation and sustainable management (Everard et al., 2018; Tostes et al., 2020). Community organizations and social participation networks are essential for adaptation, enabling communities to influence resource governance and access external support. These networks facilitate risk management, coordinated responses to ecosystem service degradation, and responsible management of shared ecosystems (Berrouet et al., 2020; Khan et al., 2019; Macharia et al., 2020).

Institutional and governance indicators can reveal how effectively adaptive capacity is mobilized and sustained over time by shaping the distribution of information, resources, subsidies, and incentives, thereby promoting sustainable water resource management (Tostes et al., 2020). Nakamura (2006) and Khan et al. (2019) demonstrate that collaborative, multiscale governance further enhances adaptive capacity by integrating sectors, jurisdictional levels, and stakeholder groups into environmental decision-making, reducing fragmentation and promoting shared watershed management.

Financial mechanisms, such as payment for ecosystem services (PES) programs, support conservation practices, local livelihoods, and sustainable resource management (Rodríguez Osuna et al., 2014; Van de Sand et al., 2014). Similarly, protected areas and ecological conservation policies contribute to the long-term maintenance and security of ecosystems (Chen et al., 2021; Zhang et al., 2025).

Van de Sand et al. (2014) examined whether Payments for Ecosystem Services (PES) contribute to safeguarding or improving ecosystem service (ES) provision under climate change. In African river basins, they found that these incentives tend to produce more effective adaptation outcomes when combined with vulnerability assessments and climate scenarios, helping realize their benefits and minimize potential conflicts between PES and adaptation measures. Pissarra et al. (2021) evaluated the feasibility of applying the Agriculture for Clean Water Yield (ACWY) model to reconcile agriculture with drinking water production through incentives and financial compensation. They argued that these incentives could contribute to water supply and reduce related vulnerabilities.

Water is an essential and irreplaceable resource for human survival, ecological processes, and economic activities (Vörösmarty et al., 2010). However, Berrouet et al. (2020) demonstrate how beneficiaries can maintain ecosystem service benefits when supply changes or declines by measuring substitution capacity, the ability to replace ecosystem services through access to alternative natural sources or technological solutions. This capacity varies considerably among social groups and production systems. Populations with limited substitution options are more vulnerable, particularly when they depend heavily on WES without viable alternatives.

Its non-substitutability increases the vulnerability of social-ecological systems dependent on water provisioning, particularly under water scarcity or quality degradation. Access to alternative water sources, such as nearby surface water bodies or groundwater, can mitigate water scarcity and sustain productive activities during severe droughts or changes in water quality (Berrouet et al., 2020).

Wang et al. (2017) emphasize the importance of integrating sociocultural perspectives into vulnerability assessments to understand the relationships between humans and nature. Social perceptions and preferences regarding ecosystem services and human well-being reveal both the demand for these services and the perceived vulnerabilities associated with their loss. Capturing these dynamics in watersheds can support adaptation practices that address water users' perceptions of climate and land-use impacts that compromise access to water-related ecosystem services, thereby creating alternatives to reduce vulnerability.

## **Selection of indicators, data availability, and methodological approaches**

The reviewed studies assessing vulnerability reveal fragmentation in existing approaches and assessments regarding the integration of the system's ecological, hydrological, and social components and their influence on the WES. Although the literature addresses climate variability, land-use change, ecosystem service dynamics, social demand, and institutional

capacity individually, it rarely integrates them into one assessment. This fragmentation limits assessments' ability to capture the full complexity of socio-ecological systems, where hydrological, ecological, biophysical, and social dimensions interact dynamically.

Vulnerability depends on exposure to climatic and anthropogenic stressors, sensitivity, and adaptive capacity, requiring an integrated, systemic assessment based on the indicators in Table 1. Selecting and implementing these indicators depends on data availability, accessibility, and quality, requiring existing data and, when necessary, producing and collecting primary data to address dimensions relevant to a systemic understanding of vulnerability.

Table 2 summarizes the key indicators, data types, methodological instruments, and primary data sources used to assess socio-ecological vulnerability dimensions.

Table 2

Key data and methodologies used to conduct socio-ecological vulnerability assessments, categorized by methodological tools and access to public data.

| Component   | Dimension                  | Key indicator                                       | Data type and viability                                                                                                                                                                                                              | Primary data sources and methodological instruments                      | References                                                                                                                  |
|-------------|----------------------------|-----------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|
| Exposure    | Climate change/variability | Precipitation/temperature fluctuations and extremes | Data are obtained by records in tabular format and raster grids, derived from meteorological stations, satellite products, and climate reanalysis - <i>high viability</i>                                                            | Meteorological stations, reanalysis (CHIRPS, ERA5), IPCC models          | Macharia et al. (2020); Moghadam et al. (2024)                                                                              |
|             | Land use and cover         | LULC conversion rates and forest fragmentation      | Data obtained by multispectral satellite imagery and classified raster layers, including land-use/land-cover maps and forest-fragmentation metrics derived through remote sensing and GIS spatial/geographic - <i>high viability</i> | Satellite imagery (Landsat, Sentinel), global products                   | Niu et al. (2024); Zakari et al. (2025)                                                                                     |
| Sensitivity | WES Provisioning           | Water yield and sediment/nutrient retention         | Data obtained by raster datasets of water yield, runoff, sediment, and nutrient retention generated by hydrological/eco-hydrological models and calibrated with field or monitoring data - <i>medium viability</i>                   | Ecohydrological modeling (SWAT, InVEST) + <i>in situ</i> monitoring data | Notter et al. (2013); Ma et al. (2019); Chen et al. (2021); Zhang et al. (2024); Moghadam et al. (2024); Duan et al. (2025) |

Note on data viability criteria: High viability refers to open-access spatial and climate datasets available globally or nationally (e.g., remote sensing, reanalysis data, censuses) requiring minimal primary sampling. Medium feasibility refers to data accessible through specialized institutional monitoring or secondary modeling results (e.g., SWAT, InVEST biophysical simulations, water quality monitoring networks, or municipal utility records), which may require parameterization, downscaling, or data-sharing agreements. Low feasibility indicates high resource intensity: scarce public data and a need for primary field data collection, empirical sampling, or participatory methods (e.g., household surveys, stakeholder interviews, or mapping of local perceptions).

| Component                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Dimension                   | Key indicator                                                | Data type and viability                                                                                                                                                                                                         | Primary data sources and methodological instruments                                      | References                                                                                   |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|--------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Social Demand               | Water use profiles, population density, and water dependence | Data obtained by census tables, administrative databases, water-consumption records, water-use permits, and population statistics in tabular/database formats<br><br><i>- medium viability</i>                                  | Population censuses, water permit registries, consumption statistics                     | Chen et al. (2021); Duan et al. (2025)                                                       |
| Adaptive Capacity                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | Governance and Institutions | PES coverage, protection networks, and regulatory frameworks | Data obtained by regulatory documents, management plans, institutional records, GIS layers of protection networks, and stakeholder information, complemented by interview-based data - <i>low viability</i>                     | Official documents, stakeholder mapping, semi-structured interviews                      | Khan et al. (2018); Van de Sand et al. (2014); Tostes et al. (2020); Bhattarai et al. (2020) |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Substitution and Technology | Access to alternative water sources (groundwater/reuse)      | Data obtained by household survey records, groundwater-well inventories, infrastructure databases, and spatial locations of alternative water sources, combining field-collected and administrative data - <i>low viability</i> | Population surveys, household surveys, groundwater well data, and infrastructure records | Berrouet et al. (2020); Everard et al. (2018)                                                |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Perception and Knowledge    | Risk perception and local/traditional knowledge              | Data obtained by structured questionnaires, semi-structured interviews, focus-group records, and participatory mapping generated through primary fieldwork - <i>low viability</i>                                               | Participatory appraisals (PRA), focus groups, perception surveys                         | Wang et al. (2017); Bolaños-Valencia et al. (2019)                                           |
| <p>Note on data viability criteria: High viability refers to open-access spatial and climate datasets available globally or nationally (e.g., remote sensing, reanalysis data, censuses) requiring minimal primary sampling. Medium feasibility refers to data accessible through specialized institutional monitoring or secondary modeling results (e.g., SWAT, InVEST biophysical simulations, water quality monitoring networks, or municipal utility records), which may require parameterization, downscaling, or data-sharing agreements. Low feasibility indicates high resource intensity: scarce public data and a need for primary field data collection, empirical sampling, or participatory methods (e.g., household surveys, stakeholder interviews, or mapping of local perceptions).</p> |                             |                                                              |                                                                                                                                                                                                                                 |                                                                                          |                                                                                              |

The indicators are further categorized by data viability, reflecting accessibility, spatial and temporal coverage, and the primary data collection required for operationalization. High-viability indicators rely mainly on globally or nationally available open-access datasets, remote sensing products, climate reanalysis, census data, and therefore need limited field data. Medium-viability indicators generally depend on specialized monitoring networks, institutional databases, or modeled outputs that may require additional parameterization, validation, or data-sharing arrangements. Low-viability indicators, in contrast, require substantial primary data collection and participatory approaches, including household surveys, stakeholder interviews, and assessments of local perceptions and knowledge. This classification highlights the methodological diversity of socio-ecological vulnerability assessments and the practical data requirements and constraints of each indicator.

Indicators related to the social dimension of vulnerability in socio-ecological systems, as defined by the WES, governance effectiveness, legislation, substitution options, and perceptions of vulnerability, generally come from interviews, questionnaires, and fieldwork. At the local level, readily available, spatially detailed data on these aspects are often lacking, except for socioeconomic and demographic information from official statistical agencies, as in Vieira et al. (2023), Pissarra et al. (2021), and Trevisan et al. (2020), which used IBGE (Brazilian Institute of Geography and Statistics) data.

Validated, geospatially mappable data and information are essential for accurately understanding vulnerability within a watershed, covering all dimensions of the socio-ecological system, biophysical, ecological, hydrological, or social. Such data provide a more realistic basis for watershed management.

Identifying relevant indicators and data is as important as the methodologies to measure or analyze them, the ability of existing approaches to integrate biophysical, social, institutional, and cultural dimensions, and the meaningful combination of qualitative and quantitative data in vulnerability assessments. Each study uses a specific methodology, but indicators can be measured quantitatively, qualitatively, or both.

Climate and land-use indicators commonly serve as inputs to quantitative biophysical models rather than as vulnerability indicators themselves. Models such as InVEST and SWAT use climate, hydrological, and land-use data to estimate ecosystem service provision. Macharia et al. (2020), however, directly considered precipitation, temperature, and flood frequency as climate exposure indicators. When treated as indicators, land use and land cover are generally classified as pressures or exposure. Saravia-Maldonado (2024) qualitatively analyzed cause-and-effect interactions within the basin and identified land-use change and deforestation as pressures on aquatic ecosystem functions. Khan et al. (2019) combined participant observation, key-informant interviews, focus groups, GIS, and remote sensing to assess land-use change and identify synergies and trade-offs among ecosystem services. Treating climate and land-use dynamics only as secondary inputs may therefore underestimate their effects on ecosystems and water-dependent societies.

Quantitative methods also predominate in WES assessment. Duan et al. (2025) assessed water supply and demand risks and quantified ecosystem services—including soil conservation, carbon storage, and habitat quality—using InVEST and the Soil Conservation Service Curve Number (SCS-CN) model. Moghadam et al. (2024) used InVEST and SWAT to assess water flow regulation, erosion control, and local climate regulation under different land-use and climate scenarios. Zhang et al. (2024, 2025) similarly used InVEST to assess water yield, water conservation, food supply, soil retention, carbon sequestration, and habitat quality. Census and sociodemographic data also commonly quantify population water demand, as in Chen et al. (2021) and Ma et al. (2019), who assessed water provision alongside human consumption for domestic and productive activities.

These models rely on secondary data describing climate, hydrology, land use, and other physical characteristics and can also support economic valuation of ecosystem services (Zhang et al., 2024; Niu et al., 2024; Zakari et al., 2025). However, inconsistent data, generalized land-cover representations, limited parameterization, and uncertainty in ecosystem service dynamics and quantification may constrain their application (Rodríguez Osuna et al., 2014; Vollmer et al., 2016; Zhang et al., 2024). Despite these limitations, they remain operationally feasible and scientifically robust for quantifying ecosystem

services at the watershed scale because the methodology is highly replicable and results can be validated using monitoring point data. This allows estimating water-related ecosystem service production across space and time. However, biophysical modeling alone is insufficient for systemic socio-ecological vulnerability assessment because changes in ecosystem services are intrinsically linked to human well-being.

Given the paradigmatic nature of socio-ecological studies, a biophysical approach to water production alone may be insufficient to systematically explain its vulnerability. Changes in ecosystem services are intrinsically linked to human well-being and the population's dependence on or demand for water. Census data and sociodemographic statistics quantitatively assess this demand to map water consumption, as calculated by Chen et al. (2021) and Ma et al. (2019), calculating water supply services alongside demand and referring to human consumption of water resources for subsistence and production activities within watersheds.

The literature further shows that spatial scale strongly influences methodological choices. The scale of both the study area and available data determines which vulnerability dimensions can be represented.

Local studies can capture social and governance characteristics that broader assessments may overlook. Vollmer et al. (2016) note that global assessments can disconnect decision-making from locations where impacts occur, limiting their ability to capture differences in needs and response capacities. Berrouet et al. (2020) similarly emphasize local-scale assessment based on beneficiary-level dependence on ecosystem services and adaptive capacity, particularly where spatially disaggregated data are scarce. However, locally developed frameworks may be difficult to transfer to national or global scales.

For biophysical and hydrological analyses, Duan et al. (2025) recommend integrating macro- and microscale approaches to better represent relationships between land use and ecosystem service provision, while Zhang et al. (2025) show that finer spatial scales can better represent heterogeneity and spatial differences in ecosystem service trade-offs and synergies. Thus, no single spatial scale can systematically characterize socio-ecological vulnerability. Watershed size influences data availability, spatial resolution, and the processes that may be represented, suppressed, or overlooked. Indicator weighting and data resolution should therefore match the assessment's objectives.

In contrast to predominantly quantitative biophysical assessments, studies addressing social and adaptive capacity frequently employ mixed methods. Berrouet et al. (2020) combined semi-structured interviews, focus groups, and field research with a quantitative vulnerability index incorporating socioeconomic, institutional, governance, technology, economic diversification, public infrastructure, and ecological knowledge variables. They also assessed substitution capacity based on the availability and accessibility of alternative natural sources, technological barriers, and beneficiaries' perceptions of their ability to implement replacement measures.

Bolaños-Valencia et al. (2019) combined qualitative analysis of open-ended responses and focus groups with quantitative econometric models to assess social risk perception, defined as the combination of perceived threat and vulnerability. Wang et al. (2017) integrated face-to-face interviews and questionnaires on human well-being and ecosystem service importance with meteorological data, satellite imagery, and spatial modeling. These studies demonstrate the value of incorporating perceptions of ecosystem service importance and risk into adaptive capacity assessments.

Zakari et al. (2025) similarly combined biophysical assessment of ecosystem service values with questionnaires, household surveys, key-informant interviews, and focus groups to investigate perceived causes of ecosystem service changes in the Kulpawn River Basin, Ghana. Their approach illustrates how beneficiary characteristics and relationships with ecosystems can inform sensitivity and adaptive capacity assessments.

Qualitative approaches were less common in the reviewed studies and included literature reviews, document analysis, interviews, focus groups, participant observation, and text coding without mathematical, statistical, or geoprocessing models. Bhattarai et al. (2020) used interviews, policy workshops, document review, and direct observation to examine

how collaborative governance supports source-water protection in transboundary river basins in Nepal. Everard et al. (2018) combined literature reviews, field visits, and semi-structured interviews to evaluate ecosystem-based approaches to water security in the Banas River basin, India. Van de Sand et al. (2014) relied on participatory rural appraisal, focus groups, and farmer workshops to assess whether payments for ecosystem services could support climate change adaptation. Vollmer et al. (2016) used a qualitative systematic review to examine water-related indices through normative, procedural, and systemic perspectives.

In general, the scarcity of qualitative studies suggests that a mixed, multidimensional approach best captures vulnerability. Integrating biophysical modeling with social, institutional, socioeconomic, and perceptual information can therefore provide a better representation of how socio-ecological vulnerability is distributed across the watershed and how ecosystems and beneficiaries experience and respond to changes in the WES.

## **Integrated socio-ecological vulnerability assessment framework**

Based on the dimensions and indicators identified in the literature review, we developed an integrated conceptual framework to assess socio-ecological vulnerability associated with water-related ecosystem services in watersheds (Fig. 3). The framework conceptualizes vulnerability as a dynamic property of socio-ecological systems, resulting from the interaction between external drivers of change, exposure, and sensitivity, and adaptive capacity. It therefore recognizes that vulnerability is shaped not only by biophysical and hydrological conditions, but also by social dependence on water resources, governance arrangements, institutional responses, and local knowledge and perceptions.

Climate variability and change (D1) and changes in land-use and land cover (D2) represent the main external pressures influencing the conditions to which watershed systems are exposed. These pressures can intensify hydroclimatic stressors and the degradation of water quality and quantity (E1–E2), which, in turn, interact with social demand and dependence on water resources (S1–S2) to amplify vulnerability. However, vulnerability is not determined solely by these pressures. Governance and public policies, substitution capacity, and local perceptions and knowledge (A1–A3) can reduce exposure and sensitivity and strengthen the system's capacity to respond to and recover from changes. Thus, adaptive capacity functions as a mechanism through which institutional, technological, and social resources can mitigate vulnerability and increase resilience.

These dimensions are integrated by combining biophysical, hydrological, and quantitative climate models with quantitative information derived from beneficiaries' perceptions of vulnerability and their ability to substitute water sources, as well as information and data on watershed governance, thereby providing a more comprehensive representation of vulnerability than approaches based exclusively on biophysical indicators. The resulting assessment guides adaptive watershed governance and decision-making, supporting targeted interventions, conservation strategies, planning, and sustainable watershed management.

Governance decisions can modify the conditions that generate vulnerability. Effective interventions can strengthen institutional and social adaptive capacity while influencing the dynamics of land use and land cover, thereby reducing future pressures and risks. This feedback establishes a continuous and adaptive cycle in which vulnerability assessment guides governance, governance reshapes system conditions and adaptive capacity, and these changes, in turn, influence future vulnerability. Thus, the framework offers a diagnosing socio-ecological vulnerability, and a mechanism for proactive risk reduction and adaptive watershed management.

## **Research gaps, suggestions, and conclusions**

Based in this review, we indicate that vulnerability associated with water-related ecosystem services (WES) in watersheds is multidimensional and dynamic, emerging from interactions between hydrological, ecological and social components and processes.

This systematic review was conducted with the aim of categorizing the indicators and methodological approaches used to assess socio-ecological vulnerability to changes in the WES in watersheds. Although the number of studies analyzed was relatively limited, the literature reveals substantial differences in how vulnerability components and indicators are operationalized.

Based on the main gaps identified, approaches to address these issues are proposed and summarized in Table 3.

Table 3

Methodological approaches and proposed contributions for addressing gaps in the assessment of socio-ecological vulnerability in watersheds

| Identified gap                                                            | Proposed approach to address the gap                                                                                                                                                                                                   | Potential contribution to future socio-ecological vulnerability assessments                                                                                                                                     | References                                                                                          |
|---------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|
| Over-reliance on biophysical supply as a proxy for human well-being       | Integrating quantitative biophysical supply models with participatory, demand-side assessments and spatial flow mapping of ecosystem services.                                                                                         | Could strengthen the understanding of actual resource access, social demand, and distributional equity (who benefits and who loses) across a watershed.                                                         | Wang et al. (2017); Chen et al. (2021); Ma et al. (2019)                                            |
| Static and linear modeling of dynamic socio-ecological systems            | Coupling biophysical and hydrological models with dynamic scenario planning, multi-temporal trend analysis, and feedback regulation frameworks.                                                                                        | It could enable the detection of nonlinear ecological thresholds, inflection points, and long-term feedback loops between human-induced land-use changes and hydrological responses.                            | Niu et al. (2024); Hazbavi et al. (2018); Vollmer et al. (2016)                                     |
| Scale mismatch and artifacts in cross-scale spatial data integration      | Apply spatial harmonization and cross-scale mapping procedures to reconcile remote-sensing grids, environmental units, and administrative boundaries, including grid-based normalization and spatial disaggregation where appropriate. | It could reduce spatial boundary and aggregation artifacts, improve the spatial consistency of vulnerability estimates, and enable a more accurate identification of localized vulnerability patterns.          | Ma et al. (2019); Macharia et al. (2020); Norman et al. (2012)                                      |
| Data viability asymmetry and proxy saturation                             | Deploying mixed-method workflows that integrate participatory appraisals and household surveys directly into spatial modeling pipelines co-developed hybrid qualitative-quantitative indicators.                                       | It can enable vulnerability assessments that give equal weight to social adaptive capacity and local qualitative data as they do to quantitative hydrological and biophysical data obtained via remote sensing. | Macharia et al. (2020); Berrouet et al. (2020); Bolaños-Valencia et al. (2019); Veira et al. (2023) |
| Exclusion of subjective perceptions, cultural values, and local knowledge | Combining biophysical modeling with participatory appraisals, focus groups, and mixed-methods frameworks like the Social Perception of Risk (SPR).                                                                                     | May improve the integration of local/indigenous ecological knowledge and subjective well-being metrics, revealing sociocultural dependencies.                                                                   | Bolaños-Valencia et al. (2019); Berrouet et al. (2020); Wang et al. (2017); Zakari et al. (2025)    |
| Science-policy disconnect due to top-down index design                    | Co-developing vulnerability assessments and indicators through action research, stakeholder co-production, and iterative participatory validation.                                                                                     | Could strengthen the salience, legitimacy, and policy relevance of indices, ensuring they align with local institutional capacities and direct management responses.                                            | Vollmer et al. (2016); Chen et al. (2021); Macharia et al. (2020)                                   |
| Fragmented sector policies                                                | Establishing collaborative, nested multi-scale governance networks (such as Water Funds/MRSE) that integrate upstream-downstream stakeholders.                                                                                         | May enable coordinated, polycentric decision-making across administrative boundaries, reducing sector silos and mitigating regional power asymmetries.                                                          | Khan et al. (2019); Bhattarai et al. (2020); Tostes et al. (2020); Everard et al. (2018)            |

| Identified gap                                                                                       | Proposed approach to address the gap                                                                                                                                                                                                                                                                                                                                                               | Potential contribution to future socio-ecological vulnerability assessments                                                                                                                                       | References                                                                                     |
|------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| Weak translation of socio-ecological vulnerability assessments into management and policy priorities | Integrate socio-ecological vulnerability information with the design and targeting of ecosystem-service management and incentive mechanisms, combining biophysical priority areas with information on beneficiaries, dependence, coping, and substitution capacity. In PES contexts, this may support allocation criteria that consider both ecosystem-service provision and social vulnerability. | It could transform vulnerability assessments into tools for management interventions aimed at identifying where socio-ecological vulnerability exists as a result of changes in water-related ecosystem services. | Van de Sand et al. (2014); Berrouet et al. (2020); Osuna et al. (2014); Pissarra et al. (2021) |

The first gap is that most studies focus on one or two dimensions, particularly biophysical mapping and ecosystem service modeling, while underrepresenting social, institutional, and cultural dimensions, well-being, social demand, and beneficiaries' perceptions. A high ecosystem-service supply does not necessarily imply high human well-being, as access, dependence, cultural values, and perceived risks vary among social groups. Therefore, assessing WES direct beneficiaries' perceptions on a case-by-case basis is also necessary to truly understand their dynamics and vulnerability.

A further gap concerns limited incorporation of governance and institutional indicators. Without these dimensions, vulnerability assessments may identify problems without providing information that can support policy responses, conservation strategies, or trade-off management. From a methodological perspective, mixed-methods approaches remain underutilized despite their potential to combine biophysical modeling of exposure and sensitivity with qualitative information on social sensitivity and adaptive capacity. No study identified in this review simultaneously integrated all indicators proposed in the consolidated framework, reinforcing the need for more comprehensive approaches.

Many assessments treat watersheds as relatively closed systems and overlook ecosystem-service spatial flows and interregional linkages. Populations inside and outside watershed boundaries may consume services generated within them, creating uncertainty in vulnerability mapping and potentially underestimating socio-ecological risks. Fourth, limited data availability favors easily quantifiable provisioning services, such as water supply and agricultural production, while cultural services, biodiversity maintenance, and regulatory services such as water purification receive less attention.

Another gap, or methodological challenge, is the incompatibility of scale and approach between biophysical modeling and social assessments. Tools such as SWAT and InVEST generate continuous spatial results at sub-basin or raster scales, while indicators such as risk perception, local knowledge, and substitution capacity are localized and generally derived from household surveys or community-based methods. Aggregating fine-scale social information to the watershed scale can obscure localized vulnerabilities, while downscaling hydrological metrics from the watershed level to household-level decisions can introduce analytical uncertainty. Future assessments should therefore develop multiscale integration protocols that explicitly link spatial modeling units to socio-institutional boundaries, moving beyond simple data overlay toward qualitative-quantitative integration.

From a policy perspective, the proposed indicator set provides a basis for integrating scientific assessment with watershed governance. Current Payment for Ecosystem Services (PES) programs and watershed management plans may prioritize biophysical targets, such as sediment reduction or water yield, without adequately considering social equity and local land managers' adaptive capacity. Integrating governance, perception, and substitution indicators with biophysical information could support more targeted and equitable PES schemes and identify areas where high exposure coincides with low adaptation or substitution capacity.

We recommend that future research develop methodological frameworks capable of integrating, within a unified structure, quantitative data from hydrological, biophysical, and socioeconomic models with qualitative indicators derived from social

perceptions, institutional dynamics, and cultural processes. Standardizing protocols for operationalizing these indicators is also necessary to enable comparisons between watersheds at different scales and contexts.

This review's main contribution, therefore, lies in critically and systematically organizing the literature's available indicators into a framework that categorizes exposure, sensitivity, and adaptive capacity indicators, thereby guiding future vulnerability assessments in river basins' socio-ecological systems. It highlights both existing research and literature gaps. This framework provides an analytical basis for researchers and managers seeking to assess watershed vulnerability more comprehensively and can serve as a potential methodological tool for building knowledge that will guide future strategies for sustainable watershed management, climate adaptation, and the conservation of ecosystems and their water-related ecosystem services.

## Declarations

## Competing Interests

The authors have no relevant financial or non-financial interests to disclose that are directly or indirectly related to the work submitted for publication.

## Funding

The authors would like to thank the National Council for Scientific and Technological Development (CNPq) and the Coordination for the Improvement of Higher Education Personnel (CAPES) for granting a scholarship to the authors.

## Author Contribution

P.A. and L.R.V. contributed to the conceptualization and overall structuring of the study. P.A. conducted the literature search, selection, and systematic review of the selected articles, performed the analysis of the results, developed the figures and tables, and wrote the initial manuscript, including the results, discussion, and conclusions. L.R.V. contributed to the methodological development and refinement of the analytical framework, interpretation and critical analysis of the results, and development of the results and discussion. P.A. and L.R.V. critically reviewed and refined the manuscript and approved the final version.

## Data Availability

No primary data were generated in this study. The data analyzed were derived from published literature identified through the Scopus database. The search strategy and study selection process are described in the manuscript.

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## Figures

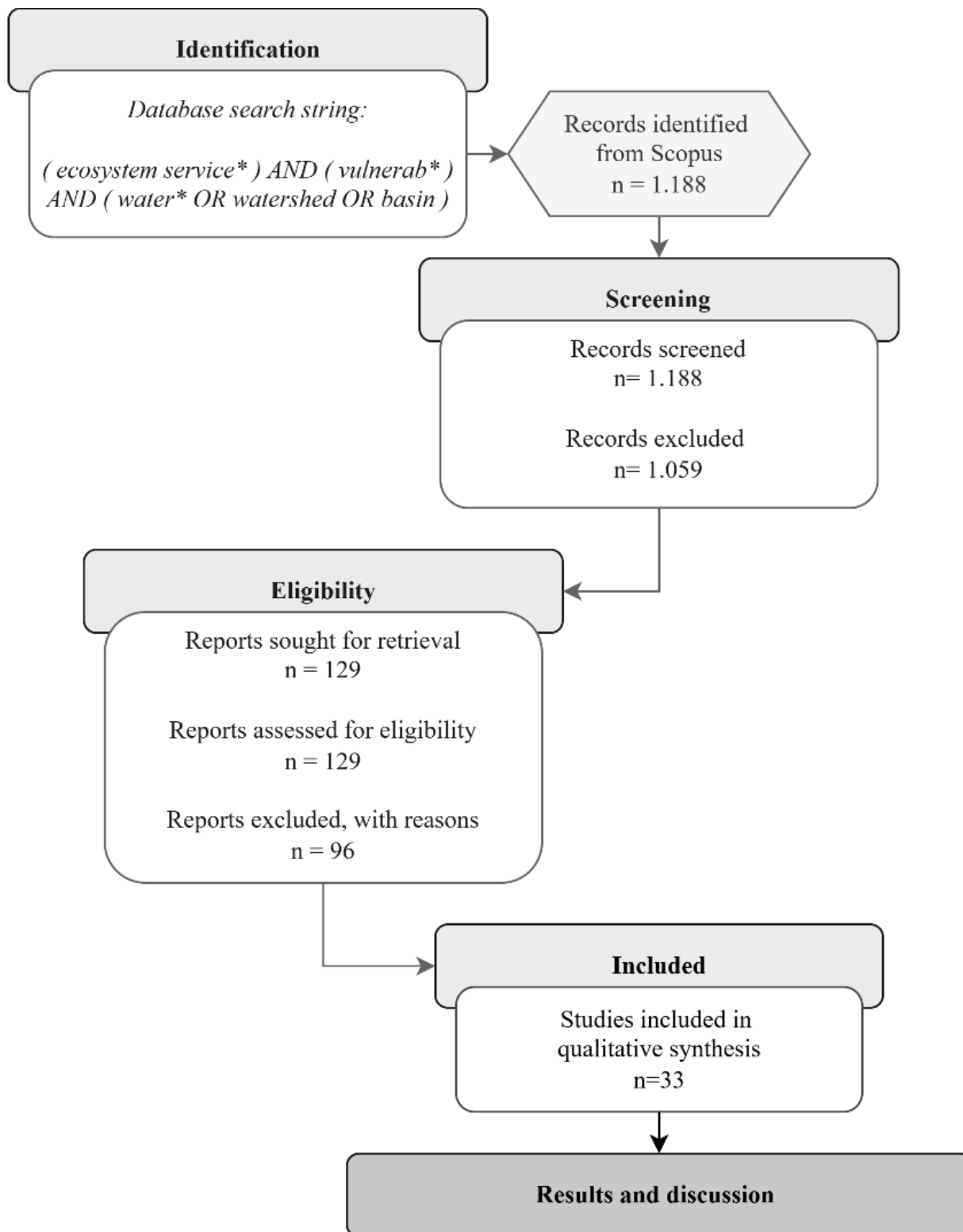


**Figure 1**

Methodological flowchart of the review

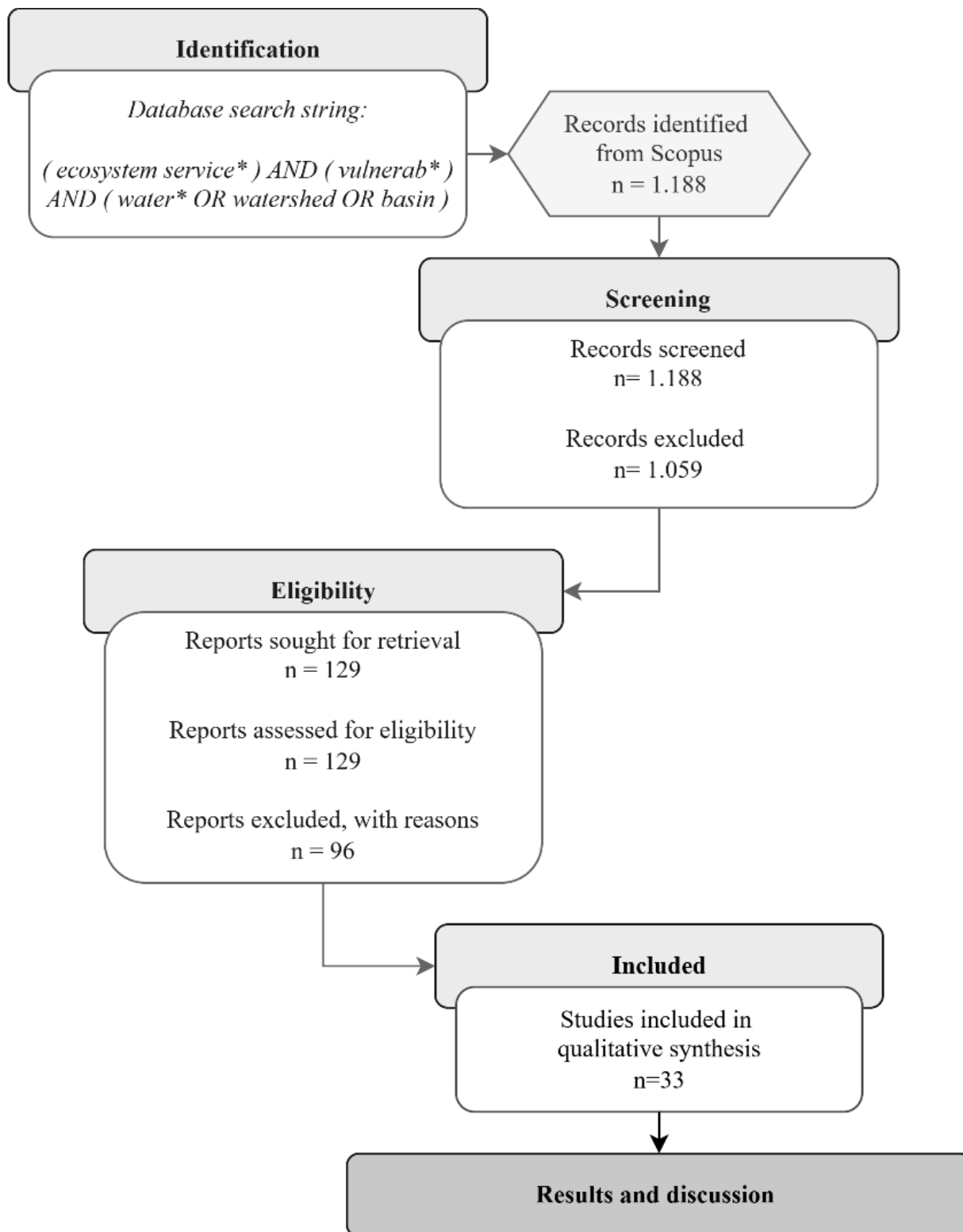


**Figure 1**

Methodological flowchart of the review

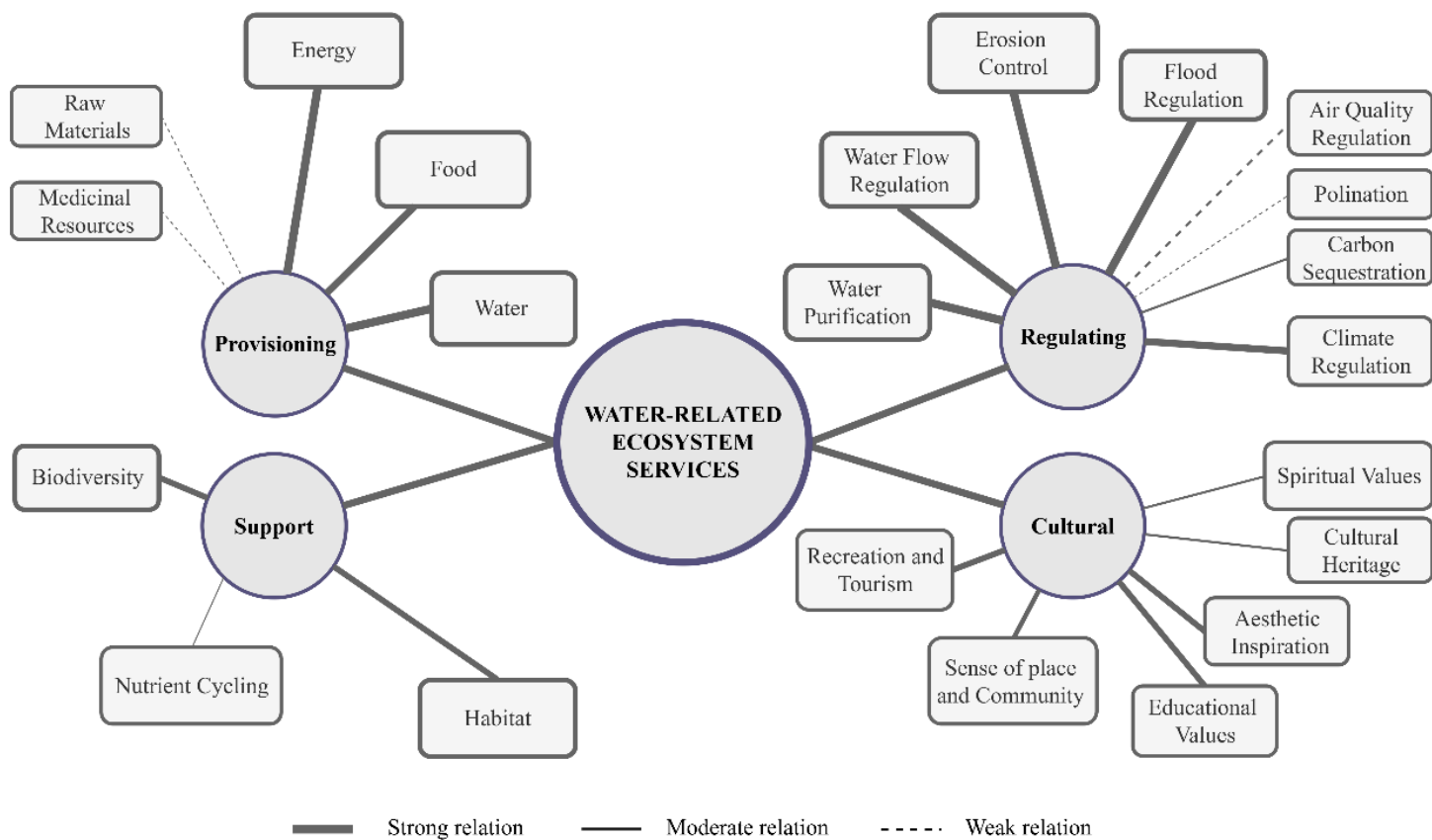


**Figure 2**

Most ecosystem services identified, mapped, and/or evaluated in the reviewed literature

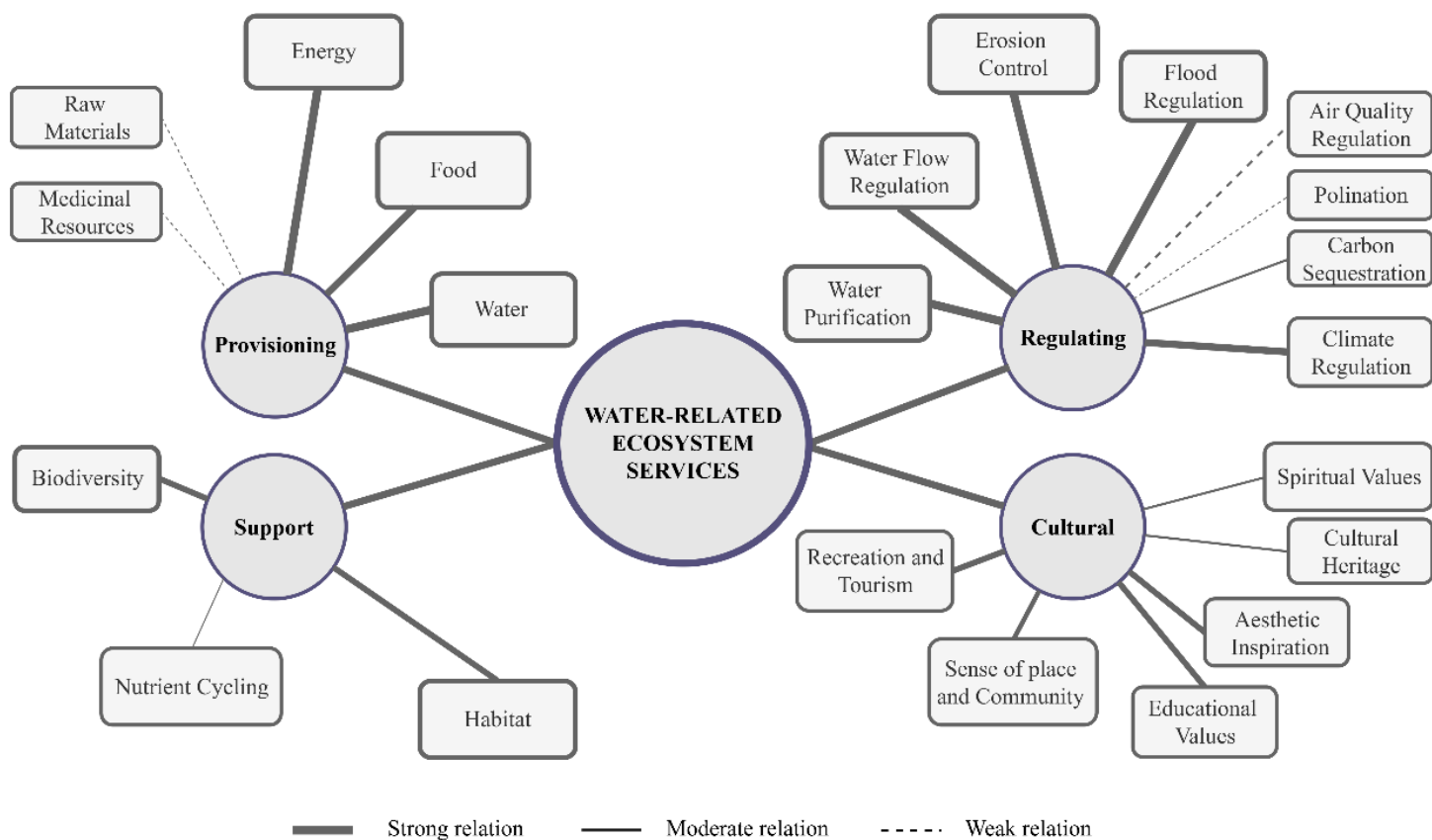


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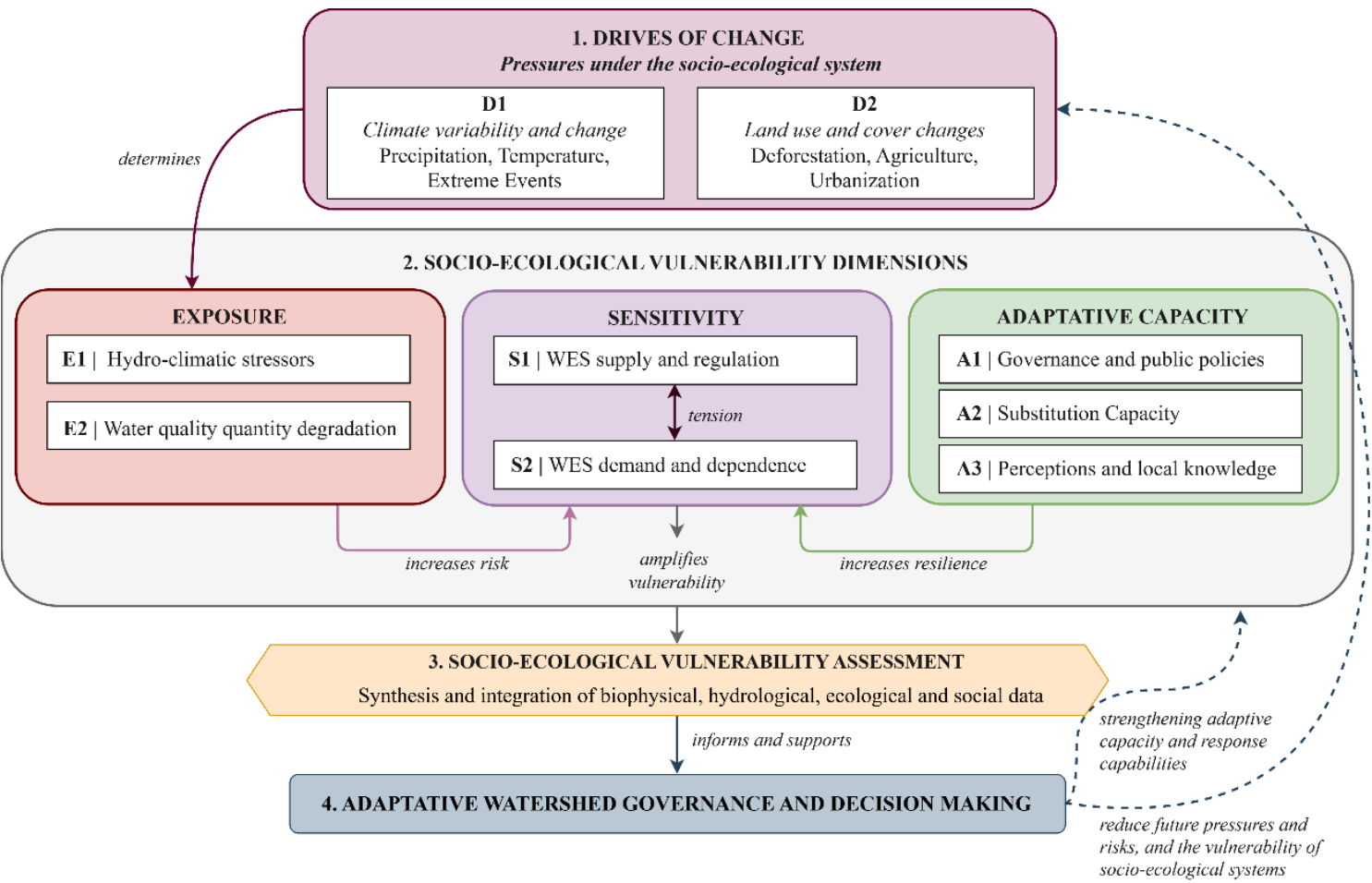


Figure 3

Framework for assessing the socio-ecological vulnerability of water-related ecosystem services in watersheds

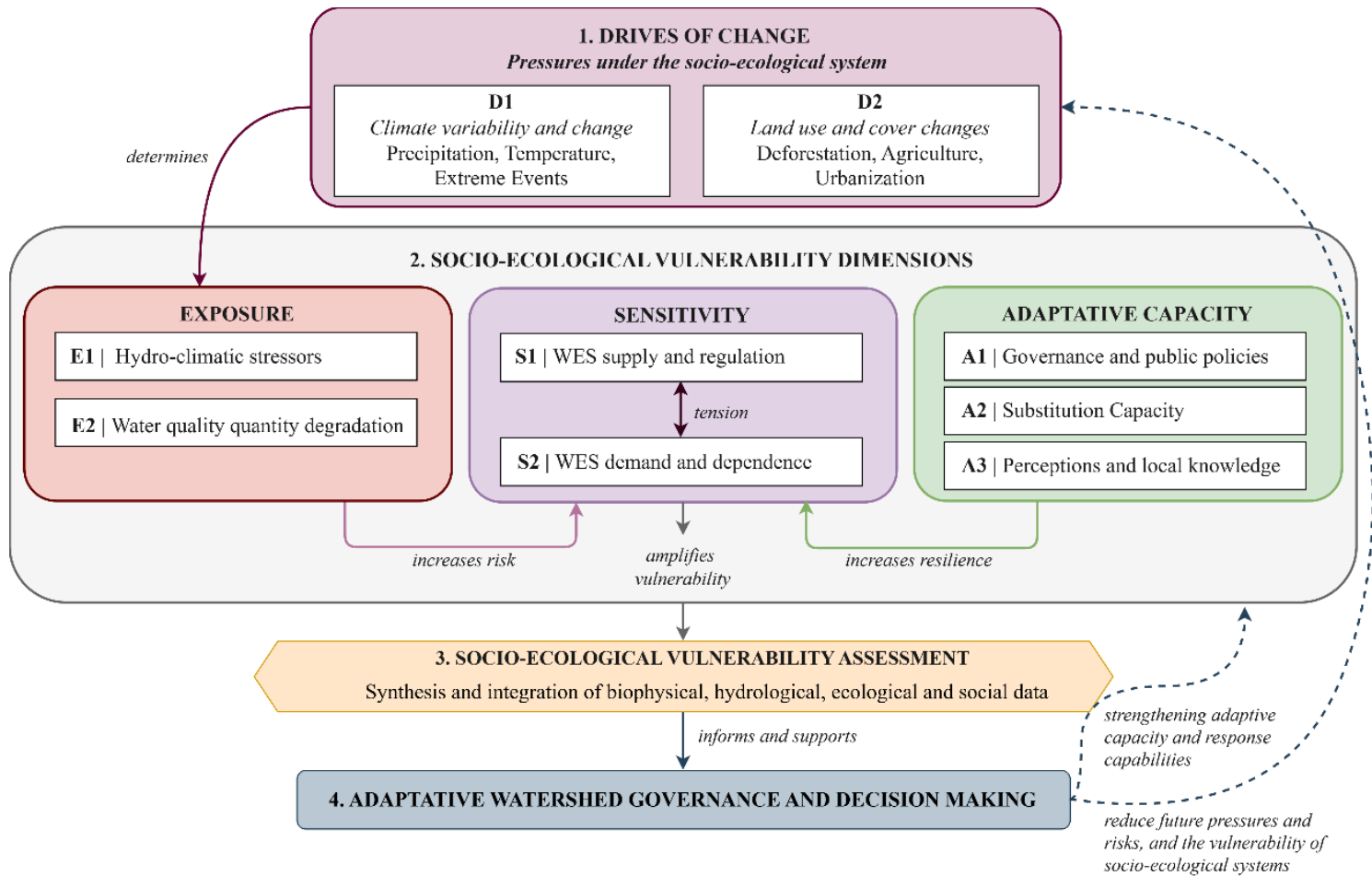


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