Human Dimensions of Water Vulnerability under Climate Change: A Systematic Review

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Abstract

Water crises are a global risk, but the concept of water vulnerability remains fragmented. This systematic review identifies and compares the conceptual framings underpinning different research approaches, with attention to how human dimensions are represented under climate change. We reviewed 62 peer-reviewed articles published between 2005 and 2024. Our findings show that water vulnerability scholarship remains strongly rooted in hydrological and environmental sciences. System-centred, top-down, and expert-led approaches dominate the field. Social science contributions, qualitative methods, and participatory or stakeholder-driven designs remain peripheral. Low-income and highly exposed regions, notably Sub-Saharan Africa, remain underrepresented. We synthesize the definitions of water vulnerability into four overlapping framings: water systems, water users, socio-ecological systems, and water infrastructure. We also argue that these framings can be understood as linked components of a natural-social system through which water resources, infrastructure, governance, and users jointly determine whether human water needs can be met. Across these approaches, five recurrent challenges limit the robustness and policy relevance of assessments: data shortages, scale mismatches, methodological oversimplification, subjective indicator choices, and unresolved uncertainty. The paper contributes by clarifying conceptual framings, showing the limited uptake of bottom-up approaches, and proposing a research agenda that connects long-range modelling with locally grounded assessment.

Keywords: water vulnerability, vulnerability assessment, climate change, water system, human dimension, social science

1. Introduction

The escalating crisis in global water resources has become one of the defining challenges of the twenty-first century. Up to three billion people experience water shortages for at least one month per year, and 2.2 billion still lack safely managed drinking water (UN-Water, 2023) . Climate change intensifies these risks through prolonged droughts, floods, and shifts in water availability and quality.

To support decision making about these challenges, numerous efforts have been made to assess water vulnerability. Early efforts predated the present climate emergency (Jiménez-Cisneros, 1996), while major international assessments in the early 2000s, such as the UNESCO World Water Assessment Programme (2003) and Millenium Ecosystem Assessment (2005), explicitly considered global climate change. These assessments were completed in the same decade when the IPCC Third Assessment Report (TAR) provided a highly cited definition of vulnerability (McCarthy et al., 2001), and when influential scholarly contributions on climate change vulnerability were published (Adger, 2006; Ford et al., 2006; O'Brien et al., 2007) . However, there is still no consensus on what water vulnerability means or how it should be investigated.

For over two decades, water vulnerability has been defined and assessed in different ways, due to its multifaceted properties and the varying contexts and scales in which the concept is understood (Aslam et al., 2018; Plummer et al., 2012). A 1994 guidebook, for example, defined vulnerability in terms of the hydrogeological property of a water system and its susceptibility to human or natural impacts (Vrba and Zaporozec, 1994). Such approaches, focusing on physical and hydrological dimensions, have been widely adopted for policy-making purposes and used to map vulnerability across large areas (Carey et al., 2017; National Research Council, 1993) .

However, such approaches are described by development scholars and practitioners as technocratic (Morchain et al., 2019). They indicate a methodological preference for measuring and demonstrating biophysical vulnerabilities (Dessai and Hulme, 2004). As an alternative, the social vulnerability approach, such as the one advanced by the United Nations World Water Development Report, defines vulnerability as "a function of human actions and behaviour that describes the degree to which a socio-economic system is susceptible to the impacts of hazards" (UNESCO World Water Assessment Programme, 2003, p.279), putting a stronger emphasis on human systems and people's livelihoods.

Despite these differences, Plummer et al. (2012) contend that progress had been made in the mid/late 2000s to incorporate socio-economic factors into water vulnerability assessments. Examples include the Arctic Water Resource Vulnerability Index developed by Alessa et al. (2008), which includes physical and social indicators of change, and the Water Vulnerability Index (WVI) developed by Sullivan (2011), which measures the vulnerability of both water systems and water users. Climate change impacts exacerbate pre-existing vulnerabilities that are contextualized in social, economic, and political structures (Eriksen et al., 2021; O'Brien et al., 2007), raising the importance of integrated perspectives encompassing institutions, society, and governance. Plummer et al. (2012, p.4340) have noted that 'the vulnerability literature beyond the context of water' often stresses these features, and various tools have been developed to capture the biophysical and social aspects of climate change vulnerability and adaptive capacity. This leaves us some important questions concerning the vulnerability literature *within* the context of water.

Fifteen years have passed since Plummer et al.'s (2012) review was published. Has the recent literature on water vulnerability strongly reflected a broad range of human dimensions? Is there a tendency for encompassing both supply (e.g., water resources and systems) and demand (e.g., water use and users) in water vulnerability studies, aligned with the broader literature on climate change vulnerability? Has the 'bottom-up' approach described Dessai and Hulme (2004) for understanding water vulnerability been more commonly adopted?

There are no clear answers from recent reviews with climate change considerations. Most of them put a strong emphasis on assessment techniques, field methods, and modelling strategies. Our review examines the representation of human dimensions in water vulnerability research. It focuses on the capacity of human systems for adapting to climate change, the use of alternative research methods, and the framings of water vulnerability. The review is guided by two main research questions:

1. What are the trends in the study of water vulnerability in human systems under climate change?
2. How is water vulnerability understood, defined, operationalized, and assessed in research?

This review contributes by unpacking the differing framings of water vulnerability underlying recent studies. Its novelty lies in examining who or what is considered vulnerable, how vulnerability is defined, and which research practices these definitions legitimize. It also proposes a natural-social framing that connects water resources, infrastructure, governance, and users in relation to human water needs.

2. Conceptual background

2.1 Climate change vulnerability

In the IPCC TAR, vulnerability is defined as:

> The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity. (McCarthy et al., 2001, p. 995)

Although what the system refers to is subject to context, there has been a shift towards broader system thinking encompassing natural and human systems. Adger (2006) considers the IPCC's recognition of exposure, sensitivity, and adaptive capacity as fundamental for understanding social and community resilience to climate change. In social sciences, such as political ecology and development studies, vulnerability is often analyzed in terms of people's access to resources, livelihoods, and the wider social, economic, and political conditions that make them susceptible to environmental stressors (Adger 2006).

This approach characterizes what Dessai and Hulme (2004) call the 'social vulnerability approach'. This perspective is skewed towards the analysis of social exposure units, such as households, communities, and, to a lesser extent, nations. It centers on the social and economic well-being of society, rather than physical exposure and natural processes. The social dimensions are often manifested in the assessment of adaptive capacity.

Adaptive capacity is not unique to human systems, but the concept implies agency: the ability to address, cope with, or mitigate the effects of stimuli. It is articulated in the IPCC TAR (Smit and Pilifosova, 2001) and by Adger (2006) in terms of a community's characteristics and its potential or ability to respond. The more recent IPCC definition of vulnerability is broader: "The propensity or predisposition to be adversely affected" (Möller et al., 2022, p. 2927). This definitional flexibility allows vulnerability to be understood in relation to communities, individuals, ecosystems, and inequalities associated with race, gender, wealth, and other attributes (Ara Begum et al., 2022).

The emphasis on human systems returns us to Dessai and Hulme's (2004) bottom-up approach of vulnerability research. This approach is more concerned with social exposure units than physical or natural exposure units, and more with past and present conditions of climate and livelihood than the mid/long-term future. In contrast, the top-down, biophysical approach breaks down the problem into discernible component parts and processes, usually removing the human element that is hard to predict (Dessai and Hulme 2004). However, bottom-up approaches are not limited to social science methods. Local hydrogeological monitoring, household water-quality testing, citizen science, participatory GIS, and locally calibrated models can also be bottom-up when they begin from situated water problems rather than externally imposed scenarios or indicators.

These two approaches are not mutually exclusive, but they indicate a conceptual divide. O'Brien et al. (2007) distinguish between outcome vulnerability, which focuses on projected negative impacts after factoring in adaptation, and contextual vulnerability, which addresses the social, political, and ecological conditions that currently make a system susceptible to harm. The latter is consistent with the idea that climate change adaptation should address the pre-existing social challenges people are struggling with (Schipper, 2007).

A vulnerability assessment designed to reflect these social aspects should have participatory elements. Researchers may define the system as the community and employ in-community methods, including semi-structured interviews, participant observation, and focus groups (Smit and Wandel, 2006). The methodologies used and the narratives reproduced by researchers therefore show that vulnerability can be conceptualized in different ways, each legitimizing different forms of policy, technical, or social intervention.

2.2 Water vulnerability

The study of water vulnerability is influenced by both traditions of scientific inquiry. However, the impact of the top-down approach and the outcome vulnerability framing was more evident in the early years than their alternatives. In a comprehensive review, Plummer et al. (2012) conclude that water vulnerability assessments from pre-1990s to the early 2010s had not considered biophysical and human elements adequately. Less than half of the documents they reviewed encompassed both elements to some degree, and there was limited emphasis on institutional and social dimensions.

Nonetheless, Plummer et al.'s (2012) note that analyses at lower spatial scales more commonly adopted integrative or comprehensive perspectives. Such a 'holistic' approach to water resource management recognizes a diverse range of values associated with water, aspects of uncertainty and complexity, and connections between biophysical aspects of water and its governance. Water resource vulnerability is defined accordingly as "the susceptibility of a system (individual, community, place) to damage as a function of exposure to external forces (shocks, stress, disturbances), sensitivity of the system, and the ability of the system to respond (cope, recover, adapt)" (Plummer et al., 2012, p.4328).

One of the prominent attempts aligned with the holistic approach is Sullivan's (2011) WVI, building on her previous work on Water Poverty Index in early 2000s (Sullivan, 2002; Sullivan et al., 2006; Sullivan et al., 2003). Sullivan's (2011) methodology is designed to represent water vulnerability in the context of human development, targeting developing countries. It includes indicators of demand-driven socio-economic vulnerability, such as percentage of economically vulnerable households and employment in water-dependent sectors, as well as supply-driven indicators, such as percentage cover of irrigated land. Sullivan (2011) considers her WVI an applied innovation that can provide a means for practitioners to address vulnerability, putting into practice the theoretical insights advanced by O'Brien et al. (2004), Adger et al. (2007), and others.

Many of these interventions explicitly addressed the Millennium Development Goals, which were superseded by the Sustainable Development Goals in 2015. Securing human development and sustainability has since become a major global mission. The evolving global priorities leave us a question: have water vulnerability studies embraced both biophysical and human elements adequately?

Answers are not immediately clear. Recent reviews have focused on assessment techniques, field methods, and modelling strategies, rather than concepts and framings. For example, Cantelon et al. (2022) and Davamani et al. (2024) concentrate on hydrological processes and models, while Bordbar et al. (2023) emphasize statistical analysis, multicriteria decision-making, machine learning, and model improvement. Aslam et al. (2018) cover human dimensions but focus mainly on assessment methodology and indicator choice. The scope of Sohns et al. (2019) review is confined to Arctic communities and, inevitably, geographically unrepresentative. Recent studies show continuing interest in vulnerability assessment under climate change (Cao and Ying, 2025). Our systematic review adds to these works by examining how water vulnerability is conceptualized, framed, and assessed in recent research.

3. Review methods

A systematic review uses a transparent and structured method to identify, screen, appraise, and synthesize evidence on a clearly formulated question (Tawfik et al., 2019). It is long established in health sciences but has gained traction in social sciences and environmental studies (Petticrew and Roberts, 2006; Pickering et al., 2021). Our review was informed by the PRISMA checklist and by systematic review guidance for environmental and social research, but adopted a less prescriptive approach because the focus is on peer-reviewed publications and conceptual framing rather than clinical or experimental interventions.

Our primary review question is: how is water vulnerability defined, framed, and assessed in the context of climate change? Relevant publications were identified through a keyword search in Clarivate's Web of Science (WoS). To capture different phrasings, we used topic terms closely related to climate change, including global warming, extreme weather, and climate variability, and those representing different forms of water vulnerability, including freshwater, groundwater, surface water, water system, and water resource vulnerability. The search string used is:

ALL=("climat* change*") OR ALL=("global warming") OR ALL=("extreme weather") OR ALL=("climat* variability")) AND (ALL=("water vulnerability") OR ALL=("freshwater vulnerability") OR ALL=("ground*water vulnerability") OR ALL=("surface water vulnerability") OR ALL=("water resource vulnerability") + OR ALL=("water system vulnerability")

We focused on the literature published in the past two decades, i.e. from 2005 to 2024. The search was completed in March 2025, returning a total of 282 documents.

We distinguish between human and natural systems. The scope of analysis is limited to human systems, as our specific interest lies in how human and social elements are represented in research. Our search and screening strategies are operationalized by the inclusion and exclusion criteria in Table 1. We excluded three non-English documents and thirty non-article documents, including reviews, editorials, and proceeding papers, leaving 249 research articles for full-text review (Figure 1).

The remaining documents were subject to further selection. Four criteria were applied. First, the document must be primarily about water systems, not only damage related to water or lack of water (e.g., flooding or drought), and not exclusively about other systems (e.g., agriculture or ecosystems). Second, it must explicitly focus on vulnerability, and not primarily on climate change adaptation. Third, climate change must be included as a parameter of analysis or clearly articulated as an analytical context. Lastly, the research must account for human exposure and/or sensitivity, and not only natural systems, including the physical, chemical, and hydrological aspects of water systems.

Based on these criteria, 190 documents were excluded. Further manual search was then conducted on Google Scholar, using the same criteria. The document titles and abstracts were reviewed, covering the first 20 pages of records returned. Three additional documents were identified. The final set consists of 62 research articles. A full list is available in Appendix 1.

Three categories of data were extracted from these articles: 1) publication information (e.g., year, author affiliation, source title, WoS index, field-weighted citation impact), 2) methodology (e.g., focus country/region, type of water system, human subject involvement, choice of quantitative/qualitative methods, inclusion of adaptive capacity indicators), and 3) the subject matter (e.g., definition of water vulnerability, challenges to vulnerability assessment). The first two categories were coded using a structured scheme, while the third was summarized as short narratives and thematically analyzed using Nvivo.

4. Results

4.1 Science vs. social science journals

To assess disciplinary focus, we compared our pre-screening database with two other user-generated WoS databases on heat/drought vulnerability and flood vulnerability. These comparison databases were generated using the same search string structure, substituting water vulnerability terms with heat, drought, and flood vulnerability terms. This supporting analysis used the raw, unscreened databases and focused on whether source journals were indexed in the Social Science Citation Index (SSCI). Only 22% of articles identified using water vulnerability terms were published in SSCI-indexed journals, which is lower than heat/drought and flood vulnerability articles (Table 2). This confirms that science journals remain the preferred publication outlets for water vulnerability research.

The majority of the 62 articles reviewed were published after 2015, whereas only two were published between 2005 and 2010 (Figure 2). Over 67% (n = 42) were published in a journal exclusively indexed in the Science Citation Index Expanded (SCIE). Four articles were published in three SSCI-indexed journals, namely, *Applied Geography, Land,* and *the International Journal of Climate Change Strategies and Management*. Twelve articles found themselves in a journal included in both SCIE and SSCI. Four journals in the Emerging Sources Citation Index (ESCI) are represented in our review sample, including *Environmental and Sustainability Indicators, Modelling Earth Systems and Environment, Sustainable Water Resource Management,* and *International Journal of Geomate*.

A Chi-square test indicates that the choice of publication outlets does not vary with time (Table 3). Recent research therefore shows no increasing tendency for reporting in SSCI-indexed journals. However, the choice of publication outlets is related to the type of water systems studied. Groundwater studies are concentrated in SCIE-indexed journals, whereas few of them are reported in SSCI-indexed journals.

4.2 Focus of analysis

Figure 3 shows the regional distribution of the 62 articles included in our review. A larger number of articles reported research conducted in East Asia and Pacific (n = 13), and North America (n = 12)[1], led by China, Canada, and USA. There are fewer studies about Latin American and the Caribbean, Africa, and Middle East. Only four Sub-Sahara African countries are represented in the sample, and only two of them, i.e., Democratic Republic of Congo and Burkina Faso, are classified as Low-Income Countries. Global and multi-

[1] Countries are assigned to a region in accordance with the World Bank's classification system. In this classification system, Southeast Asia is included in East Asia and the Pacific. In our review, Southeast Asia is extracted as a separate group.

regional studies are reported in only four articles, but they have created larger citation impacts, measured by average Field-Weighted Citation Impact[2].

As shown in Figure 1, results of the article search suggest that many water vulnerability studies focus on natural systems (n = 122, excluded). These include a significant number of vulnerability assessments using the DRASTIC model, which stands for Depth to Groundwater, Net Recharge, Aquifer Media, Soil Media, Topography, Impact of the Vadose Zone, and Hydraulic Conductivity. Few of these modelling studies include a reasonable number of human system parameters or investigate the exposure and/or sensitivity of human systems to climate change impacts (e.g., Chen et al., 2021; Haidu and Nistor, 2020; Mehta et al., 2024).

The exposure and/or sensitivity of certain aspects of human systems are represented or accounted for in the final set of articles reviewed (n = 62). These vulnerability-related human dimensions range from human development indicators, such as family dependency and livelihood strategies (Pandey et al., 2015) and water supply stability and water conflicts (Nath et al., 2021), to common modelling inputs, such as land use data (Nistor, 2020), and a direct focus on agricultural water resources (Papadopoulou et al., 2020).

In terms of the water system studied, the sample is dominated by freshwater studies. We created a separate category for the 25 articles that specifically focus on groundwater, despite it being a form of freshwater. This grouping strategy aids in explaining certain methodological choices detailed later. Furthermore, three articles focus on agricultural water availability, emphasizing rainfall/precipitation impacts (Kim et al., 2016; Marselina et al., 2022; Safi et al., 2012). The final seven articles cover multiple water systems.

4.3 Methodology

Our review shows a wide spectrum of methodological traditions. Despite differences in scale, data, and conceptual framing, these studies can be grouped into four interrelated, non-exclusive categories: (1) indicator- and index-based quantitative methods, (2) modelling-based analytical methods, (3) spatial and integrative assessment methods,

[2] Field-Weighted Citation Impact (FWCI) in Elsevier's SciVal (scival.com) indicates how the number of citations received by an entity's publications compares with the average number of citations received by all other similar publications in the data universe. Similar publications are those publications in the Scopus database that have the same publication year, publication type, and discipline, as represented by the Scopus journal classification system.

and (4) participatory and stakeholder-driven approaches. Table 4 summarizes these categories.

4.3.1 Four groups of research methods

1. Indicator- and Index-Based Quantitative Methods

The most prevalent approach across the literature involves the construction of composite indices that quantify water vulnerability through measurable physical, environmental, and socio-economic indicators. Such methods provide standardized metrics for comparing regions and identifying vulnerability gradients.

Commonly used frameworks include the WVI, Water Poverty Index, and the DRASTIC model, which operationalize vulnerability through combinations of exposure, sensitivity, and adaptive capacity indicators (e.g., Huang et al., 2017; Sresto et al., 2022; Sullivan, 2011; Yang et al., 2016). Indicators are often weighted using multi-criteria decision-making tools such as the Analytic Hierarchy Process, entropy weighting, or fuzzy logic techniques (e.g., Wu et al., 2023). Some studies therefore do not rely only on preset expert weights. They use entropy weighting, data-driven feature selection, fuzzy algorithms, or sensitivity comparison to reduce arbitrariness, although these methods do not fully remove judgment from indicator selection. Outputs are usually composite scores or vulnerability maps for regional ranking and policy prioritization.

2. Modeling-Based Analytical Methods

A second major category encompasses model-based approaches, which simulate the dynamic processes that shape water vulnerability. These include hydrological, climatic, and socio-hydrological models that quantify interactions among precipitation, runoff, groundwater recharge, and human water demand. Many studies apply scenario-based modelling, including IPCC Representative Concentration Pathways or Special Report on Emissions Scenarios, to project future vulnerability under changing climatic and socio-economic conditions (e.g., Benini et al., 2016; Chang et al., 2007; Hayward et al., 2021; Papadopoulou et al., 2020). More recent contributions integrate machine learning and data-driven models to capture non-linear feedbacks, uncertainty, and human-environment interactions (Li et al. 2023).

3. Spatial and Integrative Assessment Methods

Spatial analysis has become an essential component of water vulnerability assessment. GIS and remote sensing tools allow researchers to integrate environmental, climatic, hydrological, and socio-economic data into spatially explicit frameworks. In many studies, spatial integration is coupled with index-based analysis, resulting in multi-dimensional vulnerability mapping that connects physical scarcity with socio-economic and infrastructural conditions (e.g., Alizadeh and Moshfeghi, 2023; Chhetri et al., 2020; Nistor, 2020; Seeboonruang, 2015).

4. Participatory and stakeholder-driven approaches

While quantitative and spatial methods dominate, a subset of studies employs participatory and stakeholder-driven approaches to address social, institutional, and governance dimensions. Sohns et al. (2021), for example, used causal loop diagrams and Qualitative Comparative Analysis to model household water vulnerability with stakeholders. Questionnaires and Delphi techniques have also been used in index development (Alessa et al., 2008; Alizadeh and Moshfeghi, 2023). Such approaches enhance relevance by incorporating local knowledge and governance insights (e.g., Plummer et al., 2013; Van Schmidt et al., 2023).

In summary, the literature shows an enduring preference for indicator-based, index-based, and modelling-based methods. There are signs of movement from static indicator assessments toward dynamic and spatially explicit frameworks, including machine learning. However, evidence for a strong shift toward holistic and bottom-up approaches involving stakeholders and knowledge end users (e.g., policy makers, water users) remains limited.

4.3.2 Qualitative methods, adaptive capacity, and human subject

As discussed in Section 2, the social dimensions of vulnerability are often represented in the assessment of adaptive capacity. Bottom-up approaches can capture these dimensions and the processes that reproduce vulnerabilities, rather than only predictions, probabilities, and scenarios (Dessai and Hulme, 2004). These approaches often use qualitative and participatory methods (Licuanan et al., 2015; Morchain et al., 2019; Thanh Thi Pham et al., 2020), but they may also use natural science methods when the research begins from local water problems, such as local monitoring, well testing, and community-based hydrological observation. To examine methodological shifts, we identified studies that included adaptive capacity, used qualitative methods, and involved human subjects.

Table 5 shows that qualitative research methods are reported in only ten articles. These include Delphi and snowballing techniques for eliciting expert opinions on water infrastructure vulnerability in Iran (Alizadeh and Moshfeghi 2023), stakeholder interviews for mapping agricultural water vulnerabilities in Burkina Faso (Gahi et al., 2017), and focus group discussions in Nepal for developing vulnerability indicators (Babel et al., 2011). Adaptive capacity is assessed or examined in 33 studies, most commonly using predefined indicators in index- and indicator-based assessments (Chauhan et al., 2021; Koutroulis et al., 2019; Pandey et al., 2015; Powlen et al., 2023). Human subjects are reported in 17 articles, most commonly involving experts, stakeholders, community members, or households.

Table 5 also shows the results of Chi-square tests across the four five-year periods in which the 62 articles were published. These results suggest that, although more of the three methodological features discussed above have been identified in recent years, this increase follows the changes in the total number of articles published in each five-year period. Therefore, we do not detect a clear tendency for adopting qualitative research methods, representing adaptive capacity in vulnerability assessment, and involving human subject in research over time.

Nevertheless, we found a tendency for adopting qualitative research methods and representing adaptive capacity in vulnerability assessment across the type of water systems examined. Table 6 indicates that qualitative research methods are more likely to be used in freshwater studies, and less so in groundwater studies, despite these two water system types are almost equally represented in our review sample. The same is true for the inclusion of adaptive capacity, but not human subject.

4.4 Definitions and conceptual framings

Methodological choices are influenced by researchers' understanding and definition of the subject matter. We extracted the definition of water vulnerability from each article and conducted a thematic analysis, focusing on two questions: whose vulnerability and what constitutes vulnerability? Informed by Sullivan (2011) and Boruff et al. (2018), who distinguish between the vulnerabilities of water users, water supplies, water supply infrastructure, and water stress, we group nuanced definitions into four interrelated, non-exclusive categories concerning systems, people, and infrastructure. These categories are summarized in Table 7. Figure 4 presents these framings as linked components of a natural-social system. Hydrological availability and quality form the resource base. Infrastructure mediates storage, treatment, and distribution. Water users experience vulnerability through unmet needs, limited coping capacity, and livelihood impacts, which are mediated by institutional arrangements determining resource allocation and access.

1. Water Systems

This category defines vulnerability as a property of the hydrological system itself, i.e. the natural processes regulating water availability, quality, and variability. Definitions in this group examine how water systems respond to climate variability, extreme events, contamination, environmental change, and human activity. They emphasize hydrological processes, physical exposure to hazards, system sensitivity to climatic or anthropogenic stressors, and the stability or resilience of hydrological cycles.

The subject of inquiry is the vulnerability of water resources (Chai et al., 2024; Wu et al., 2023). For example, Leveque et al. (2021, p.3) suggest that "Vulnerability of water resources under climate change depends mainly on temperature, precipitation, evapotranspiration (ET) and solar radiation". Vulnerability is often described as the susceptibility of water resources to degradation, depletion, or disruption, affecting quantity, quality, ecosystem flows, and reliability. Vulnerability assessment is framed as a means to address an adverse change to the water system: "Water resource vulnerability exists when there is a potential for damage to a groundwater system" (Ojeda Olivares et al., 2020, p.1-2).

Water contamination, in particular, is a common theme. For instance, Sresto et al. (2022, p.3144) use a DRASTIC model to assess groundwater vulnerability, which "refers to the risk of an underlying aquifer being polluted as a result of natural man-made occurrences of both events [sic]". González-Herrera et al. (2020, p.2) adopt the U.S National Research Council's (1993) approach, defining the concept as "the tendency or likelihood that contaminants will reach a specific position in the hydrogeologic system after their introduction somewhere above the upper aquifer". Vulnerability assessment is used for "evaluating sensitivity of groundwater to contamination" and seen as a tool for "preventing or reducing groundwater contamination" (Huang et al., 2017, p.1).

Consistent with Klima et al. (2020), these interventions seek to reflect risk by articulating and assessing vulnerability in terms of physical exposure and sensitivity. Water vulnerability has also been defined in terms of quantity or availability, such as available liquid reservoir water (Medeiros et al., 2023, p.6). Water systems-based definitions therefore demonstrate the notion of 'specific vulnerability', which is concerned with particular land uses, management solutions, and the chemical characteristics of the compounds in question (Bordbar et al. 2023).

This is the dominant conceptual framing. It is consistent with long-standing practice of hydrological sciences that treats hydrological systems as independent vulnerable entities (National Research Council, 1993; Vrba and Zaporozec, 1994). The articles we reviewed, however, have considered human factors.

2. Water Users

Studies in this category articulate vulnerability in terms of how individuals, households, communities, or economic sectors experience water-related risks. This includes drinking water access, agricultural water demand, water affordability, and exposure to water insecurity. There is an emphasis on human well-being, livelihoods, water security, and individual and community response. This category corresponds to widely used concepts in development studies, human security research, and social vulnerability/ resilience research (Grasham et al., 2019; O'Brien et al., 2007; United Nations Environment Programme, 2008).

The subject of inquiry is the needs and coping capacity of water users. People, not hydrological systems, are the primary unit of vulnerability, which is treated as the degree to which water-related stresses affect people or social groups. Water demand, relative to its supply, is the key issue of concern. For instance, Sohns et al. (2021, p.26) define water vulnerability "as a lack of water availability and water access in the time and place that households require it".

This perspective captures lack of access, social sensitivity to change, limited coping resources, inequities in water distribution, and risks to health, food security, and household resilience. Some studies include indicators such as water conflicts and travel time to water source (Nath et al. 2021), per capita income and farm population (Zhu et al. 2022), socio-economic disadvantage (Boruff et al. 2018), and traditional knowledge and land tenure (Alessa et al. 2008).

The strong focus on human beings and their activity is manifested as the assessment of people's capacity to response to change. Many studies have adopted the IPCC definition, which consists of exposure, sensitivity, and adaptive capacity. Plummer et al. (2012) have adopted this definition, highlighting the idea that vulnerability represents the interface between physical exposure to threats and the capacity of people and communities to cope with those threats. This stands in contrast to the first category, which prioritizes assessment of physical exposure and sensitivity.

Despite these differences from water system-based definitions, user-based elements are often treated as part of a broader concept of water vulnerability, encompassing water supply, water access, and socio-economic conditions. Sullivan (2011), for example, created a composite index with an equal emphasis on water resource supply and water resource users. Chishugi et al.'s (2021) assessment combines stream water quality parameters with whether the population can adapt to climate-related change. The need to account for adaptive capacity therefore links system- and user-based perspectives.

3. Socio-Ecological Systems

This category integrates both human and biophysical components, defining vulnerability as a property of coupled systems where water, ecosystems, and society interact. It acknowledges complex feedbacks between ecological processes, governance systems, and social dynamics. The scope of this perspective goes beyond the water or human systems, emphasizing systemic vulnerability that spans ecological and societal domains.

The vulnerability definitions in this category do not substantially depart from those based on water systems or users. They typically encompass both and address a larger system connected to sources of water supply and demand. Kim et al. (2016), for example, assess the vulnerability of paddy rice to which precipitation is an important input. Babel et al. (2011) include the adaptive capacity of a socio-ecological system, represented by natural, physical, human, and economic capacities. El Garouani et al. (2024) assess the vulnerability of an agricultural area in Morocco using indicators of resources, environment, infrastructure, and socio-demography, while Chung et al. (2014) identify the water resource vulnerability characteristics of administrative districts in South Korea. There are, however, only a handful of examples contextualized in a socio-ecological system.

The subject of inquiry is often a resource-dependent system, typically agriculture-related. These analyses emphasize interdependence between ecosystems and human communities, ecological integrity, ecosystem services, resource use, and adaptive capacity at multiple scales. Vulnerability is seen as emerging from interactions between environmental change, societal structures, institutional capacity, and human-ecosystem feedback loops. This category is aligned with socio-ecological resilience literature, where vulnerability is co-produced by social and ecological processes (Adger, 1999; McCarthy et al., 2001).

4. Water Infrastructure

The final category addresses the material linkage between water systems and water users. Water vulnerability is conceptualized in terms of physical systems designed to store, transport, or treat water (Boruff et al. 2018), including dams, reservoirs, pipelines, treatment facilities, and urban supply networks. This perspective recognizes the susceptibility of infrastructure to damage or performance decline, and the consequences for water supply, public health, and economic stability.

Alizadeh and Moshfeghi (2023), for example, define and assess the vulnerability of urban water infrastructure assets in terms of their ability to withstand and deal with negative effects. Their assessment includes indicators of distribution and adaptation. Zhu et al. (2022) assess the vulnerability of water supply systems and include indicators of infrastructural capacity, such as piped schemes and irrigation infrastructure. These studies address neither a natural system nor people per se, but the physical intermediaries through which water reaches users (Noi and Nitivattananon, 2015).

The infrastructure-based perspective is established in engineering and urban management (Fletcher et al., 2019; Zio, 2016), but remains underrepresented in vulnerability research. It differs from other perspectives by emphasizing structural sensitivity to hazards, system failures, service interruptions, operational capacity, redundancy, and reliability under stress.

4.5 Challenges to assessing water vulnerability

Assessing water vulnerability remains complex and contested. Across diverse geographic and disciplinary contexts, we found five recurrent challenges that constrain the reliability, comparability, and practical utility of vulnerability assessments. A summary is provided in Table 8.

1. Data availability, quality, and monitoring limitations

Data limitations are the most widespread challenge across studies. Many regions, especially rural areas, small islands, mountainous terrains, and developing countries, lack basic hydrological and socio-economic datasets or long-term indicators (e.g., Boojhawon and Surroop, 2021; Chai et al., 2024; Holding et al., 2016; Zhu and Fang, 2022). Key groundwater and pollution variables are poorly monitored, requiring proxies (Seeboonruang, 2016; Cantelon et al., 2022). Remote socio-economic data are limited (Sohns et al., 2019), reducing model fidelity and validation potential (Nistor, 2020).

2. Scale and Resolution Mismatches

Persistent mismatches between data scale and the scale needed for meaningful assessments compound data limitations. Global climate models with coarse grids fail to represent local hydrological processes (Seeboonruang, 2016), hindering applications such as DRASTIC (Nistor, 2020). Even with downscaling, integrating datasets of varying resolutions and balancing national versus local variability remains difficult. Macro-level methods often do not translate to micro-level household analysis (Chauhan et al., 2021), leading to assessments that are overly coarse or poorly aligned with local realities (Keshavarz, 2016).

3. Methodological Oversimplification

A third challenge is the methodological oversimplification common in many frameworks. Assumptions such as fixed fractions of runoff, uniform infrastructure, equal importance of extraction and pollution, and simplified groundwater–climate linkages overlook system complexity (Garrote et al., 2015; Boojhawon and Surroop, 2021; Ojeda Olivares et al., 2020; Zhu et al., 2022). Linear assumptions and constant aquifer properties further oversimplify groundwater dynamics (Aslam et al., 2018). Balancing complexity with usability is difficult, and limited, uncertain social data constrain human-water modeling (Li et al., 2023).

5 Weighting, Indicator Selection, and Subjectivity

A related challenge is the high subjectivity in selecting and weighting indicators. Many studies rely on expert judgment to choose variables and assign importance (Noi and Nitivattananon 2015; Chung et al. 2014; Alizadeh and Moshfeghi 2023), introducing potential biases (Bordbar et al. 2023). Equal and differential weighting are both criticized when they lack empirical support (Plummer et al. 2013; Hoque et al. 2016; Chhetri et al. 2020). Data-driven and non-preset approaches, such as entropy weighting, fuzzy algorithms, machine learning feature importance, and sensitivity testing, can reduce but not eliminate this problem because indicator selection itself remains theoretically and politically consequential.

6 Uncertainty in Models and Validation Difficulties

Substantial uncertainty in modeling and validation further complicates assessments (McDonald et al., 2015; Nistor, 2020). Uncertainty originates from climate and hydrological models, downscaling, and incomplete data, and is amplified by poorly understood interactions between social conditions and quantitative variables (Ojeda Olivares et al., 2020). Many regions also lack monitoring networks needed for validation, and limited reference data make verification difficult. Because vulnerability is intangible and contested (El Garouani et al., 2024), resulting assessments are often approximations rather than definitive representations.

5. Discussion

5.1 Methodology and analytic focus

Water vulnerability research is rooted in hydrological and environmental sciences. According to Bordbar et al. (2023, p.47), (ground)water vulnerability was first defined in the 1960s by Margat (1968) as "the possibility of penetration and spread of pollution in groundwater systems under natural conditions". The following three decades saw clearer recognition of human factors and human-water dynamics, which were codified in assessment frameworks such as Vrba and Zaporozec (1994) and the National Research Council (1993). However, the hydrogeological properties of water systems remain the main analytic focus.

In the early 2010s, Sullivan (2011), Plummer et al. (2012), and others called for engaging socio-economic factors and adopting an integrated, holistic perspective. Their call was aligned an earlier tendency in the study of climate change vulnerability for incorporating the social drivers and indicators of vulnerability into research and practice (Adger, 2006; O'Brien et al., 2007; Schipper, 2007). Our review was designed to examine the extent to which water vulnerability to climate change is understood, defined, and assessed in these terms.

Our review suggests that this field of research remains dominated by perspectives and methodologies derived from hydrological and environmental sciences. Predominantly social science contributions are rare. Only a handful of studies reviewed were published in social science journals that are indexed in SSCI only. This practice differs from cognate fields of research, such as drought/heat vulnerability and flood vulnerability, where SSCI-indexed journals are more adequately represented. The number of SSCI articles did not increase substantially during the past two decades. The water vulnerability scholarship continues to engage primarily in hydrological and environmental sciences.

Regional representation remains uneven. Sub-Sahara Africa has received limited research attention, despite its large populations, severity of water crises, and high exposure to climate change impact. We also found that global and multi-regional studies have shown larger citation impacts. Local or nationally focused research tends to receive fewer citations (weighted by field of research), partly due to limited visibility and relevance to other geographical areas. As citation metrics are often used to assess research impact and allocate resources, this can discourage funding agencies and researchers from investing in local-scale studies from smaller or less-resourced countries (Confraria et al., 2017; Tijssen and Winnink, 2022).

Groundwater vulnerability studies account for 40% of the articles reviewed. This can explain some of the methodological choices identified. While indicator- and index-based approaches have been used across the two main types of water systems, modelling approaches, notably DRASTIC, are commonly used to examine groundwater vulnerability to pollution (Huang et al., 2017; Musálem et al., 2015). As groundwater studies are a significant subset of our review sample, modelling naturally becomes a dominant assessment method reported. Furthermore, groundwater studies primarily investigate aquifer properties, contamination pathways, pumping impacts, and modeling future groundwater availability. These questions can be answered through physical measurements, laboratory tests, and numerical modeling, without collecting personal information or interacting with human participants. Science journals are generally regarded as a better place to report research involving these techniques and approaches.

Social science methods, especially qualitative techniques, are less suitable for assessing the hydrogeological and physical properties of groundwater. Adaptive capacity is also not usually treated as a key component when groundwater vulnerability is system-centred rather than people-centred. In contrast, more freshwater studies address people's access and direct use of domestic or agricultural water resources (Alessa et al. 2008; Pandey et al. 2015; Kim et al. 2016; Sohns et al. 2019; Leveque et al. 2021; Chishugi et al. 2021). However, bottom-up approaches can still include natural science work, such as local water-quality monitoring or locally calibrated groundwater modelling, when these are guided by users' situated problems.

This is not suggesting that fewer studies have used these alternative research techniques and approaches. The number of studies involving qualitative research techniques, adaptive capacity and human subject has increased (Table 5), but it is offset by a proportionate increase in the number of studies not reporting those. Although recent research has shown a stronger focus on human dimensions, their elevated representation runs parallel to the more widespread use of the traditional 'technocratic' approach (Morchain et al. 2019).

5.2 Concepts and research directions

The review shows a fragmented conceptual landscape of water vulnerability. Water vulnerability can be understood in terms of volumetric scarcity, quality, access, and security. While most researchers have engaged more than one of these dimensions, their primary research framing is often reflected in their unit of analysis. In our typology, each category employs different units of analysis (resources, people, ecosystems, infrastructure) and prioritizes different epistemologies (hydrological science, development studies, socio-ecological resilience, engineering). This diversity enriches the field but also creates inconsistency when studies claim to assess water vulnerability broadly while operationalizing it narrowly. Figure 4 responds to this by treating the four framings not as orthogonal dimensions only, but as a linked natural-social system organized around the ability of societies to meet human water needs.

The review confirms the dominance of hydrological, system-based definitions. Studies adhering to the traditional research approaches treat vulnerability as a technical property of water resources, sometimes reducing complex socio-ecological realities to biophysical metrics. This methodological reductionism reinforces the critique by O'Brien et al. (2007) and Morchain et al. (2019) that such framings and approaches overlook social and institutional dimensions. Vulnerability is reduced to a physical characteristic, rather than a socially produced and negotiated condition related to livelihoods, institutions, and agency, as described in the literature of climate change vulnerability (Adger 2006; Ford et al. 2006; Smit and Wandel 2006; Setiadi et al 2026; Lo et al 2026).

Consequently, a top-down approach is commonly adopted. Slightly departing from Dessai and Hulme's (2004) description, a top-down approach in water vulnerability does not always begin with global climate scenarios and then move down to local impacts. It typically begins with researchers' pre-existing understanding of what water vulnerability means. Researchers then select a framework, indicators, and analytic techniques for measuring the vulnerability of a water system. This approach can provide long prediction lead time, especially when linked to climate and hydrological modelling, but it often has lower local accuracy because social priorities and coping practices are assumed rather than investigated.

This contrasts with a bottom-up approach, which is concerned with the capacity of individuals or social groups to respond to external stress placed on their livelihoods and well-being (Dessai and Hulme 2004). Methodologically, research typically begins with inputs from people affected by environmental stressors. Plummer et al. (2013), for example, built a shared understanding of water vulnerability through interactions with community and First Nations representatives, public events, meetings, and personal conversations. This approach can produce more accurate assessments of present vulnerability and adaptive capacity, but usually has a shorter prediction horizon.

Such a fundamentally bottom-up, emergent approach is reflected in a handful of studies that examine the water vulnerability of social exposure units, such as people and communities. A more common strategy involves researchers pre-selecting indicators to examine water users' vulnerability and adaptive capacity (e.g., Nath et al. 2021; Pandey et al. 2015; Sullivan 2011). It can be described as operating from the top-down while advancing integrated, holistic perspectives. Socio-ecological systems are not commonly treated as a unit of analysis. Where they are, research tends to adhere to a top-down approach (e.g., Chung et al. 2014; El Garouani et al. 2024).

Plummer et al. (2012) have suggested that the social dimensions of water vulnerability have received limited attention. In the past two decades, there are gradual shifts in the field of research, such as increasing attention to water users and the social dimensions, as well as social-ecological systems and water infrastructure. This suggests a closer alignment with development-oriented framings, manifested in official vulnerability definitions such as ‘a function of human actions and behaviour that describes the degree to which a socio-economic system is susceptible to the impacts of hazards’ (UNESCO, 2003, p.279), and a combination of physical water scarcity risks and the water service level (UNICEF, 2021, p.9).

However, these tendencies have met with a growing body of published research that is skewed towards the system-centred definitions and top-down approaches. Taking all reviewed articles into account, water vulnerability in the context of climate change is primarily conceptualized in terms of water systems and assessed through expert-led methods, predominantly using quantitative indexes and modelling.

The five challenges identified in our review reveal a field that is advancing but still constrained by structural data gaps, methodological fragmentation, and conceptual inconsistencies. Overcoming these limitations requires better monitoring networks, standardized yet flexible frameworks, stronger uncertainty analysis, and models capable of capturing multi-scalar interactions. It also requires countermeasures for social and integrated research: transparent stakeholder sampling, attention to local power relations, triangulation between qualitative and quantitative data, sensitivity tests for indicator weights, and clear reporting of the limits of locally specific findings.

Our review raises three important prospects for research:

1. First, there is a need for integrative frameworks that bridge top-down, model-driven assessments with bottom-up, context-rich approaches. This means combining hydrological and climate modelling with locally grounded insights into livelihoods, governance, and social inequities. Such work can balance prediction lead time and assessment accuracy by using models to anticipate future stress while using local evidence to calibrate assumptions, indicators, and weights.

2. Second, bottom-up, human-centred research is particularly needed in domains and regions that remain dominated by system-focused analyses, notably groundwater for domestic use and underrepresented areas such as Sub-Saharan Africa, small islands, and low-income countries. Concrete research areas include household water diaries, participatory mapping of access and reliability, well-user interviews combined with water-quality testing, and community-based monitoring of seasonal water stress.

3. Third, future work should more fully integrate water infrastructure and governance into socio-ecological vulnerability frameworks. Operationally, this may involve combining network failure analysis with utility-manager interviews, mapping service interruptions by neighbourhood, and examining how water rights, emergency

response, maintenance decisions, and accountability mechanisms shape the distribution of vulnerability across social groups.

6. Conclusion

This review paper clarifies how water vulnerability is conceptualized and assessed in the context of climate change, with particular attention to human dimensions, adaptive capacity, and bottom-up approaches. Drawing on a systematic review of 62 peer-reviewed articles published between 2005 and 2024, we show that the field remains largely rooted in hydrological and environmental sciences, with a strong emphasis on biophysical exposure and system properties and a marked preference for publication in science rather than social science journals. Research is unevenly distributed across world regions, with limited coverage of low-income and highly exposed contexts, especially in Sub-Saharan Africa.

Methodologically, water vulnerability assessments are dominated by indicator- and model-based, expert-led approaches that are frequently applied to groundwater and other physical systems, while qualitative, participatory, and stakeholder-driven methods remain marginal. Conceptually, we identify four main framings of water vulnerability that are centred on water systems, water users, socio-ecological systems, and water infrastructure, respectively. Although these perspectives occasionally overlap, system-centred, top-down understandings prevail, and vulnerability is often treated as a technical attribute of hydrological systems rather than a socially produced and negotiated condition. This pattern is reinforced by persistent challenges around data scarcity, scale mismatches, methodological oversimplification, subjective indicator choices, and difficulties in handling uncertainty and validation.

Addressing these limitations is essential if water vulnerability research is to inform climate adaptation and development policy in ways that are effective and equitable. Our review points to three directions: connecting top-down modelling with bottom-up inquiry; expanding human-centred and participatory research in system-dominated domains and underrepresented regions; and embedding infrastructure and governance into socio-ecological analyses. These shifts would move the field beyond technocratic diagnosis towards a more holistic and practice-relevant understanding of how water vulnerability is created, distributed, and reduced under climate change.

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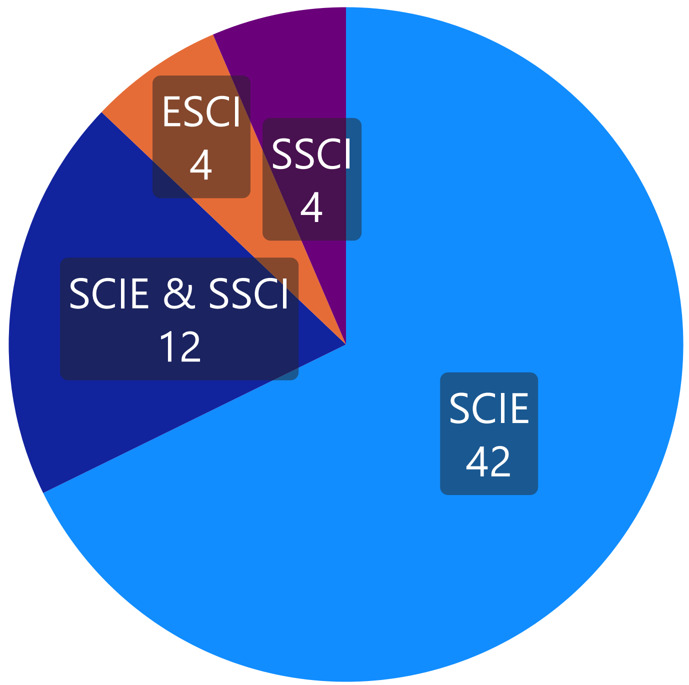
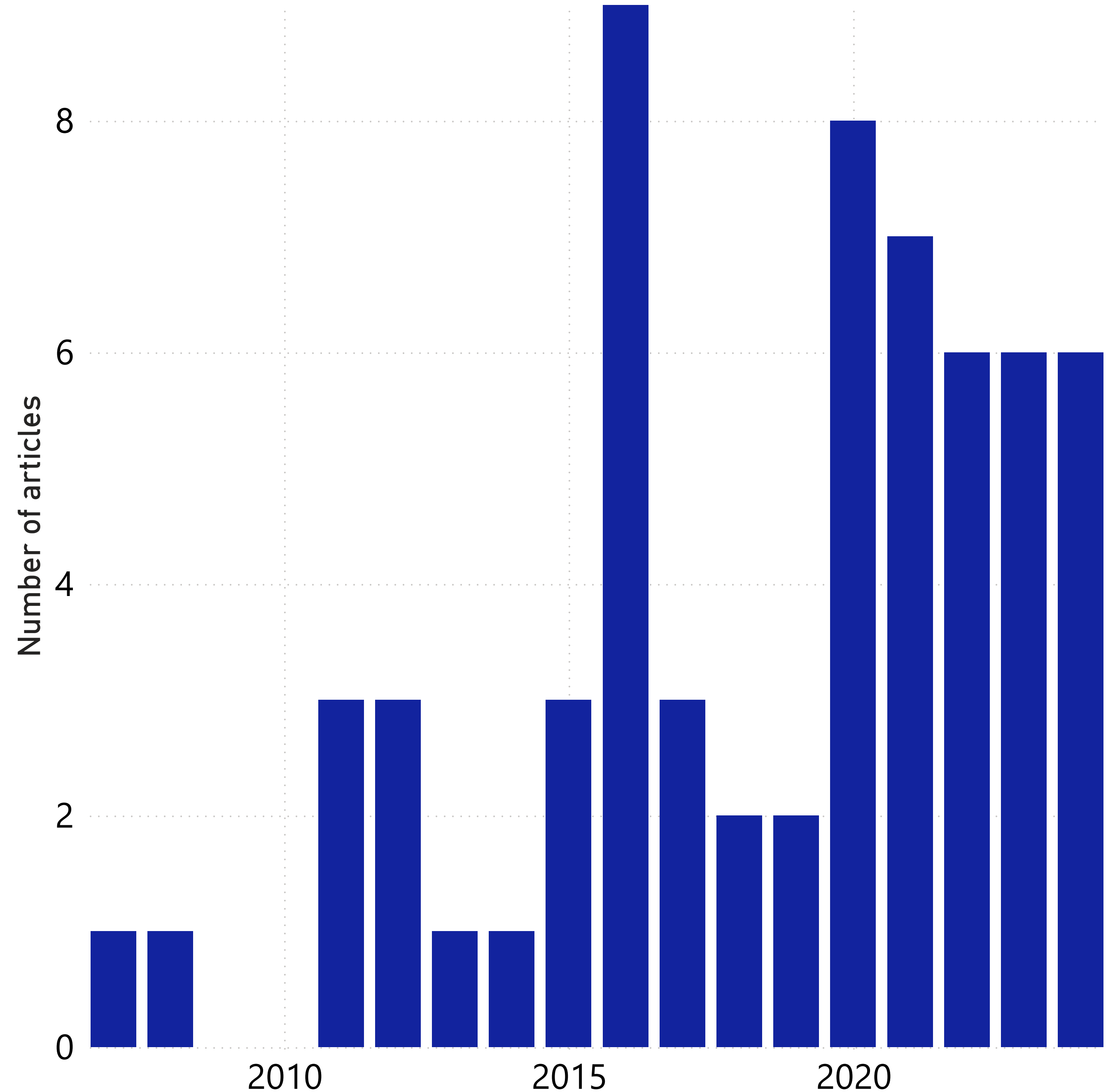
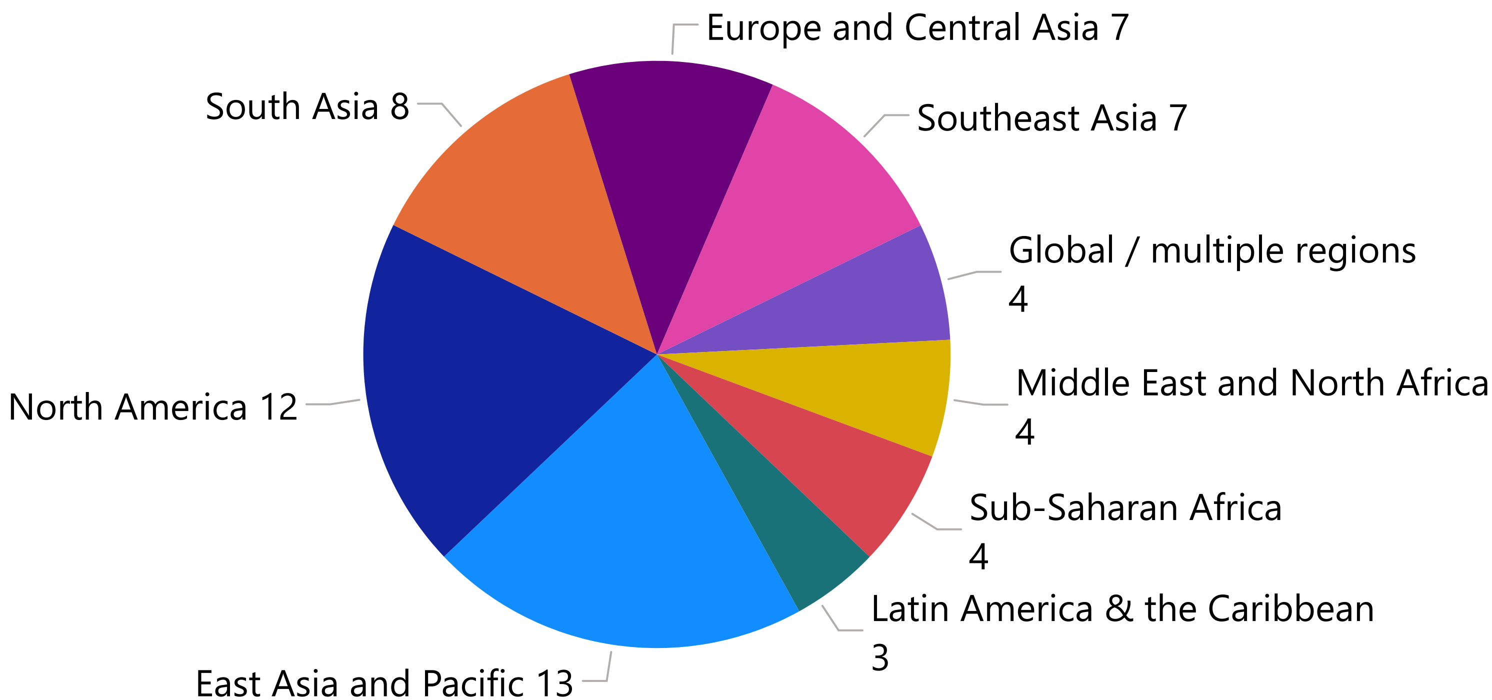
Number of articles by WoS journal index



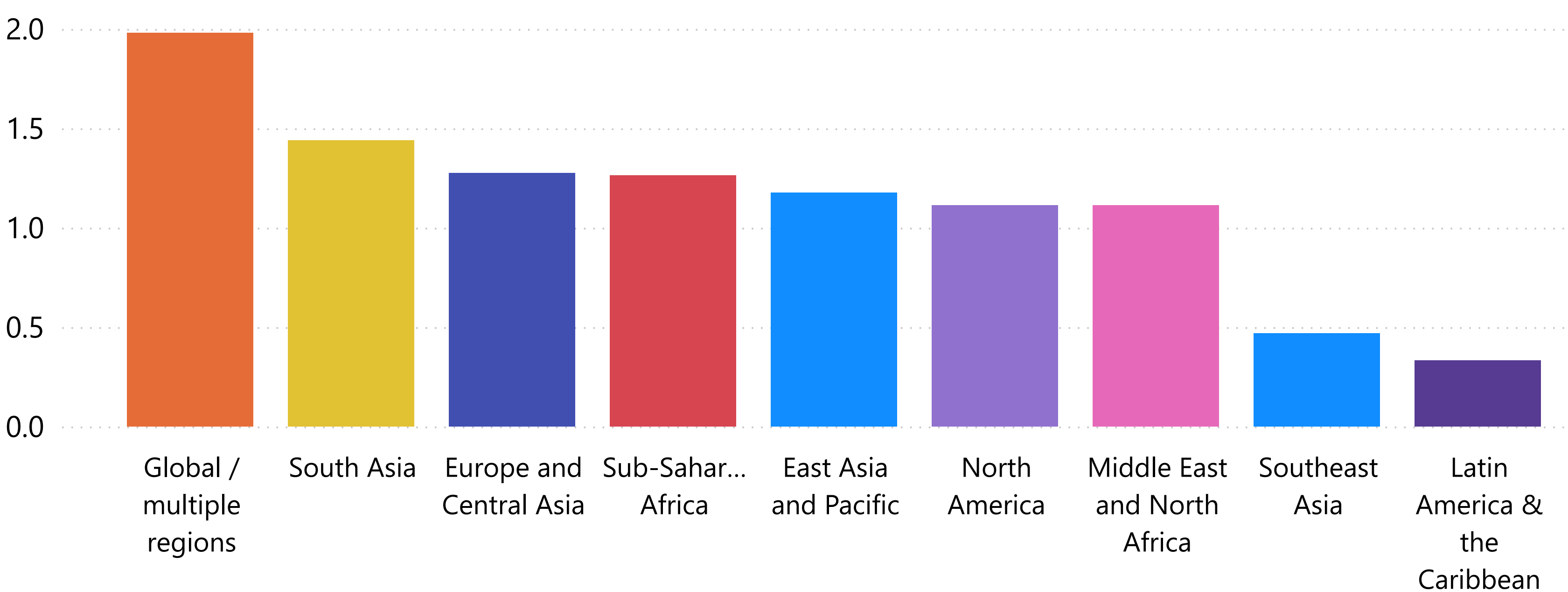
Number of articles by year of publication



Number of articles by Region



Average Field-Weighted Citation Impact by Region



Study country	No. of articles
Multiple	9
China	8
Canada	6
USA	6
South Korea	4
India	3
Nepal	3
Bangladesh	2
Iran	2
Mexico	2
Thailand	2
Vietnam	2
Australia	1
Burkina Faso	1
Cyprus	1
DRC (Congo)	1
Indonesia	1
Italy	1
Mauritius	1
Morocco	1
Paraguay	1
Philippines	1
Romania	1
South Africa	1
UK	1
Total	**62**

Table 1 Inclusion and exclusion criteria for the systematic review

Inclusion	Exclusion
Phase 1: Keyword search	
1 January 2005 - 31 December 2024	Pre-2005 or after 2024
English	Non-English
Articles	All other document types (e.g. reviews, proceeding papers, editorials)
Phase 2: Full text review	
Water systems	Water damage (e.g., flooding), drought only. Focus on other systems (e.g., agriculture, ecosystem) exclusively.
Vulnerability focus	Adaptation only. (Discussing implications for vulnerability without taking it as a primary analytical focus)
Climate change focus	Climate change neither as a parameter nor context of research
Human exposure and sensitivity	Natural system exposure and sensitivity only. (Primarily concerning about the spatial, biophysical, hydrogeological, or hydrochemical aspects of water)

Table 2 Number of articles published in Social Science Citation Index (SSCI) journals by search term

Search term	Number of articles published in Social Science Citation Index (SSCI) journals*	Total number of articles returned	Percentage (%)
Water vulnerability	62	282	22.0
Heat / drought vulnerability	169	490	34.5
Flood / flooding vulnerability	149	407	36.6

* Including journals that are indexed in both SSCI and Science Citation Index Expanded (SCI-EXPANDED).

Table 3 Number of articles reviewed by journal index, year of publication, and type of water system

Description	Journal index			Total number of articles	Pearson Chi-square	p value
	ESCI	SCIE	SSCI^			
Year of publication						
2005 - 2009	0	2	0	2	6.901	> 0.05
2010 - 2014	0	4	4	8		
2015 - 2019	0	14	5	19		
2020 - 2024	4	22	7	33		
Total	4	42	16	62		
Water system						
Freshwater	1	14	12	27	10.083	< 0.05
Groundwater	2	20	3	25		
Rainwater	1	1	1	3		
Total	4	35	16	55*		

^Including journals that are indexed in both SSCI and Science Citation Index Expanded (SCI-EXPANDED). * seven articles reporting on multiple water systems were excluded.

Table 4 Summary of four categories of water vulnerability research methods

Category	**Core Purpose**	**Typical Methods / Tools**	**Main Outputs**
1. Indicator- & Index-Based Quantitative Methods	Quantify vulnerability through weighted composite indicators integrating physical, social, and climatic factors	WVI, WPI, DRASTIC, GOD models; AHP, TOPSIS, VIKOR, fuzzy logic, entropy weighting	Composite indices, regional rankings, vulnerability scores
2. Modeling-Based Analytical Methods	Simulate hydrological, climatic, and socio-hydrological dynamics to assess and forecast vulnerability	Hydrological and climate models, water balance, RCP/SRES scenarios, socio-hydrological and ML models	Scenario projections, trend analysis, dynamic simulations
3. Spatial & Integrative Assessment Methods	Map spatial and temporal variability and integrate diverse datasets into unified analytical frameworks	GIS, remote sensing, spatial overlay, multi-dimensional indices	Vulnerability maps, hotspot analysis, cross-scale comparisons
4. Participatory & Conceptual Framework Approaches	Incorporate human, institutional, and stakeholder perspectives and link causes, impacts, and responses	DPSIR, exposure–sensitivity–adaptive capacity, CLD, FLAP, QCA	Conceptual frameworks, participatory scenarios, governance insights

WVI: Water Vulnerability Index, WPI: Water Poverty Index, DRASTIC: Depth to Water, Recharge, Aquifer Media, Soil Media, Topography, Impact of the Vadose Zone, Hydraulic Conductivity, GOD: Groundwater occurrence (G), Overall lithology of the aquifer (O), Depth to groundwater (D), AHP: Analytic Hierarchy Process, TOPSIS: Technique for Order of Preference by Similarity to Ideal Solution, VIKOR: VlseKriterijumska Optimizacija I Kompromisno Resenje (Multi-Criteria Optimization and Compromise Solution), RCP: Representative Concentration Pathway, SRES: Special Report on Emissions Scenarios, ML: Machine Learning, GIS: Geographic Information System, DPSIR: Drivers–Pressures–State–Impact–Response framework, CLD: Causal Loop Diagram, FLAP: Framework for Local Adaptation Planning, QCA: Qualitative Comparative Analysis

Table 5 Number of articles reviewed by year of publication and selected methodological features

Description	Year of publication 2005 – 19	2010 – 14	2015 – 19	2020 – 24	Total number of articles	Pearson Chi-square	p value
Qualitative research methods used							
No / Not reported	1	6	17	28	52	2.626	> 0.05
Yes	1	2	2	5	10		
Total	2	8	19	33	62		
Adaptive capacity explicitly addressed or included in assessment							
No / Not reported	0	2	9	18	29	4.084	> 0.05
Yes	2	6	10	15	33		
Total	2	8	19	33	62		
Human subject involved in research							
No / Not reported	1	4	14	26	45	3.213	> 0.05
Yes	1	4	5	7	17		
Total	2	8	19	33	62		

N = 62

Table 6 Number of articles reviewed by type of water system and selected methodological features

Description	Water system			Total number of articles	Pearson Chi-square	p value
	Freshwater	Groundwater	Rainwater			
Qualitative research methods used					6.851	< 0.05
No / Not reported	19	24	3	46		
Yes	8	1	0	9		
Total	27	25	3	55*		
Adaptive capacity explicitly addressed or included in assessment						
No / Not reported	7	18	0	29	13.758	< 0.05
Yes	20	7	3	32		
Total	27	25	3	55*		
Human subject involved in research						
No / Not reported	18	22	2	42	3.438	> 0.05
Yes	9	3	1	13		
Total	27	25	3	55*		

*seven articles reporting on multiple water systems were excluded.

Table 7 A typology of water vulnerability to climate change

Category	Core Focus	What These Definitions Emphasize	Representative definition	Examples (non-exclusive)
Water Systems (dominant)	Hydrological and biophysical vulnerability of water resources	Water scarcity, contamination, drought, climate impact, recharge, aquifer conditions	'the risk of an underlying aquifer being polluted' (Sresto et al., 2021). 'Water resource vulnerability exists when there is a potential for damage to a groundwater system' (Olivares et al., 2020)	Chang et al. (2007), Musálem et al. (2015), Hua et al. (2020), Olivares et al. (2020), Sresto et al. (2021), Medeiros et al. (2023), Wu et al. (2023), Chai et al. (2024)
Water Users	Human access, needs, and coping capacity	Household access, community resilience, water conflict, reliability of supply	'lack of water availability and water access in the time and place that households require it' (Sohns et al. 2021)	Sohns et al. (2019, 2021), Sullivan (2011), Plummer et al. (2013), Boruff et al. (2018), Nath et al. (2021)
Socio-Ecological Systems	Interacting climate, ecological, and social systems	Climate change, land-use change, governance, institutions, societal adaptation	'the ability of water resources system, consisting of environmental or physical and socio-economic components, to function in the face of socio-economic and environmental changes' (Babel et al. 2011)	Babel et al. (2011), Chung et al. (2014), Kim et al. (2016), Garouani et al (2024)

Category	Core Focus	What These Definitions Emphasize	Representative definition	Examples (non-exclusive)
Water Infrastructure	Resilience and functioning of built water systems	Distribution networks, structural vulnerability, emergency management, engineering capacity	'incapability (of urban water infrastructure) to withstand and deal with the negative effects of instantaneous accidental or malicious events (Alizadeh and Moshfeghi, 2023)	Noi and Nitivattananon (2015), Alizadeh and Moshfeghi (2023)