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Socio-ecological resilience in water systems: a literature review

Resiliência socioecológica em recursos hídricos: uma revisão da literatura

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ABSTRACT

The world faces challenges with regard to water resources, including pollution and governance related to access and use. In this perspective, the study of socio-ecological resilience contributes to minimizing the problems inherent to water resources, as it offers an adaptive, participatory, and innovative approach. The aim of this article was to analyze current topics related to socio-ecological resilience in water resources (SERWR) in order to better understand the approaches used, investigate the potentialities of the topic, and identify the challenges of SERWR evaluation methods. The study is a systematic review of literature carried out by means of searches in the databases ScienceDirect and Scopus, comprising research between the years 2010 and 2022. The 30 scientific papers analyzed were classified into four topics and the results were divided into quantitative and qualitative analyses. The quantitative outcomes describe bibliometric computer analysis, and the qualitative outcomes show that involving the community and managers (stakeholders) is crucial for improving the capacity of the SERWR. Most studies reveal the multiplicity of methods and method combinations used in SERWR evaluation. Future research should focus on the creation of a comprehensive evaluation methodology capable of assessing SERWR in degradation and vulnerability scenarios, as well as preventing subsequent damage.

Keywords: socio-ecological systems; natural resources; governance; multidisciplinarity; methods.

RESUMO

O mundo enfrenta desafios no que diz respeito aos recursos hídricos, incluindo a poluição e a governança relacionadas com os acessos e utilização. Nessa perspectiva, o estudo da resiliência socioecológica é contributivo para a minimização dos problemas inerentes aos recursos hídricos, pois oferece uma abordagem adaptativa, participativa e inovadora. O objetivo deste artigo foi analisar temas atuais relacionados à resiliência socioecológica em recursos hídricos (RSERH) a fim de melhor compreender as abordagens utilizadas, investigar as potencialidades do tema e identificar os desafios dos métodos de avaliação da RSERH. O estudo é uma revisão sistemática de literatura realizada por meio de buscas nas bases de dados ScienceDirect e Scopus, compreendendo pesquisas entre os anos de 2010 e 2022. Os 30 artigos científicos analisados foram classificados em quatro temas e os resultados foram divididos em análises quantitativas e qualitativas. Os resultados quantitativos descrevem a análise informétrica bibliométrica. e os qualitativos mostram que envolver a comunidade e gestores (*stakeholders*) é fundamental para a melhoria da capacidade da RSERH. A maioria dos estudos revela a multiplicidade de métodos e combinações de métodos utilizados em avaliação de RSERH. Pesquisas futuras devem centrar-se na criação de uma metodologia avaliativa abrangente capaz de avaliar a RSERH em cenários de degradação e vulnerabilidade, assim como prevenir danos subsequentes.

Palavras-chave: sistemas socioecológicos; recursos naturais; governança; multidisciplinaridade; métodos.

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Introduction

The growing population worldwide highlights recurring environmental problems, such as irregular occupation of areas at risk from environmental hazards, lack of adequate housing, problems with sanitation infrastructure, transportation, energy, and mobility, which are precepts for sustainability. The phenomenon of urban growth also characterizes aggravating occurrences in climate change due to the unsustainable use of natural resources, especially water resources.

Maintaining water systems security in the current context of climate change can help avoid serious floods or extreme droughts, as well as impacts on water quality. In this sense, we must seek to preserve global social and ecological security, corroborating Sustainable Development Goal 11 — "make cities and human settlements inclusive, safe, resilient and sustainable", designed to understand that cities are fundamental units for overcoming global challenges.

The concept of resilience has evolved over time and has been explored and used in multiple ways, arising in the materials sciences and permeating various areas of knowledge (Bianchi and Zacarias, 2016; Herrera-Enríquez et al., 2021; Kapucu et al., 2021; Yi and Jackson, 2021). Although the concept of resilience seems recent in the literature, several classic authors have studied and described it since 1973. It began with the work by Holling, who analyzed the limits of the ecosystem after suffering a "disturbance", evaluating resilience as the possibility of returning to equilibrium. However, systems are in a state of transition, not stable and not linear, so this resilience can be intrinsic to the system but can also be planned on an ongoing basis, after or even before the interference or "disturbance". The concept and approach proposed by the authors have been widely used for multiple purposes in specific contexts.

From these considerations, it can be inferred that the concept of resilience needs to be explored from a multidisciplinary perspective, considering its complexity and the diversities in the multiple forms of empirical applications. In this regard, Nassour et al. (2020) define resilience as "a multifaceted concept that describes the ability to deal with changes or interruptions". The authors address the main themes found on resilience, which are generally of environmental, socio-ecological, organizational, and operational origin. In a minority, they are related to infrastructure, resource management, and health issues.

Resilience should be studied from a systemic, holistic perspective that complements the social and ecological dimensions. Resilience is not just a static concept; it involves an emergent and latent property. Therefore, understanding these properties is important for the studies of the concept (Chontasi Morales et al., 2021; Urquiza et al., 2021). A systemic perspective is the understanding of how the elements that make up resilience interact. In general, perspectives involve a view of the system as a whole, including all forms of perception of the subject, and its multiple forms of interrelationships, and long-term changes.

In various areas of knowledge, the different existing concepts have left the term "resilience" open to some conceptual deviations, making it necessary to specify which type of "resilience" will be studied. Correlated to this understanding, over the last two decades or so the term "socio-ecological resilience" has emerged, conceptualized by several classic authors, such as Adger (2000), Folke et al. (2002), and Walker et al. (2004), to describe the relationship between social and ecological systems. By assessing socio-ecological resilience, procedures such as measuring the degree of the shock's ability to regenerate and analyzing the reorganization of these systems also become necessary.

In order to reorganize these systems, it is necessary to understand that there is interdependence between the social and the ecological environments, and this is strategic for promoting resilience. From this point of view, resilience theory brings a new understanding of socio-ecological systems because it recognizes that human society is part of these systems "with strong connections between anthropogenic processes (social, economic and political) and biophysical processes (climate, forests and rivers)" (Buschbacher et al., 2016, p. 38).

Salas-Zapata et al. (2011) counter attempts to conceptualize socio-ecological resilience. These authors contrast with others, arguing that the socio-ecological subsystem can readjust and adapt under intervention, while still maintaining some essential characteristics, through a "process, a behavior and a system dynamic". This approach recognizes the dynamic and evolutionary nature of resilience. Resilient socio-ecological systems can withstand impacts, especially in the most vulnerable areas, and allow cities and communities to develop through sustainable processes. In the case of sustainable subsystems, the main focus is on seeking balance and equity between the various dimensions and indicators used. In resilient subsystems, the focus is on the capacity for change, transformation, and adaptation. In this sense, it can be inferred that these subsystems are complementary.

It is also necessary to understand that a resilient subsystem is not always positive, as it is often a domain of stability that is considered undesirable (Buschbacher, 2014; Lindoso, 2017), which can disturb resilience between systems. Schlüter and Herrfahrdt-Pähle (2011), in their work on the socio-economic and environmental crisis, support the thesis that high resilience in the social system is not positive and also interferes with the resilience of other systems, such as the water system.

SERWR refers to the ability of rivers, lakes, aquifers, and aquatic ecosystems, as well as the human communities that depend on them to adapt, recover, and continue to function sustainably in the face of environmental changes and disturbances. In this sense, Buschbacher (2014) points out that SERWR is related to the general strategies of integrated water resources management, including risk planning, monitoring, conservation practices, participation of the community involved, multiple resource uses, policies, investments, and education.

It is necessary to emphasize the importance of associating the most recent studies and research on socio-ecological resilience with water resources, considering the assessment of socio-ecological resilience. This will ensure a minimal guarantee of ecosystem services and the integrity of these resources, as global environmental changes

continue apace, with high rates of deforestation, pollution, and loss of biodiversity, among other degradations. These attacks on the natural environment are the result of various factors such as climate change, the sometimes-disorderly growth of cities, and many other anthropogenic activities.

This study arises from the need to address the global challenges associated with water resources, especially due to climate change and the growing human pressure on them. By reviewing the international literature on SERWR over the last 12 years, we aimed to establish a basis for future research, highlighting the importance of developing a robust evaluation methodology to measure SERWR in contexts of degradation and vulnerability. Classic studies such as those by Holling (1973), Adger (2000), Folke et al. (2002), Walker et al. (2004), Salas-Zapata et al. (2011), and Buschbacher et al. (2016) emphasized conceptual approaches to the subject, which over time has left a gap in studies focusing on evaluation methodologies. This research fills the gap by focusing on the analysis of evaluation methodologies, highlighting the importance of the contribution of practical knowledge in this field since the application of these methodologies can assist in decision-making and contribute to adjustments and adaptations in the improvement of sustainable management practices.

Based on these considerations, this systematic review article aimed at analyzing current issues related to SERWR to better understand the approaches used, investigate the potential of the topic, and identify the challenges of SERWR assessment methods.

Methodological Procedures

This article consists of a literature review conducted in four phases: planning, conducting, screening, and analysis adapted from Kitchenham and Charters (2007). All phases are detailed below.

Planning

During the planning phase, the research question, search strategies, and databases were defined. Keywords and related terms or words were identified in the literature, described in English, and presented as "social ecological"; "resilience"; "water resources"; "water"; "rivers"; "water systems"; and "hydrographic basin". A combination of these keywords was tested in some databases available on the Coordination for Higher Education Personnel Improvement (CAPES) journal portal, and the two databases that identified the most articles were ScienceDirect and Scopus, which were chosen for the final analysis.

Conducting

In the conduction phase, two Boolean operators were included after attempts to relate the keywords to the databases. The search terms used were "resilience" AND "social-ecological systems" AND "water" OR "water resources" OR "watersheds", limiting the search to the title, abstract, and keywords, indicating publications from 2010 to 2022, in order to obtain the most recent literature. Three filters were also applied, as follows: Filter 1 – Open access; Filter 2 – Environmental sciences; and Filter 3 – Type of document ("*revista*"; magazine in English).

Screening

A total of 103 documents from Scopus and 957 from ScienceDirect were registered at the screening phase. After removing duplicates, 1,055 articles were screened by reading titles and abstracts. At this stage, 856 articles were excluded using the criteria described in Figure 1. The remaining articles (168) were analyzed using quality criteria and the texts were read in full. Articles with unclear objectives and approaches to SERWR were excluded. For the final analysis, 30 articles were chosen. The files were organized and stored using Mendeley reference. Figure 1 shows the steps described in a flowchart.

Analysis

The analysis stage was conducted using quantitative and qualitative methods. The quantitative analysis of the articles was carried out by employing a bibliometric characterization, which included graphs showing the number of publications per year and the countries of these publications. The aim was to understand the growth of research in the area over time and the geographical distribution in order to gain an overview of the countries involved in the research. The qualitative analysis of the articles involved evaluating and associating them by types of studies, approaches, methodologies, conclusions, and recommendations to determine their relevance to the theme and objectives of the article.

Presentation and analysis of results

By using bibliometric analysis and numerical data, it is possible to obtain a proper understanding of the objectives of the articles analyzed, their concepts, and theoretical and methodological approaches used. This is quantifiable data for a statistical analysis of the topic. For a more subjective perception, it was necessary to carry out a qualitative analysis of the articles, looking at common themes between the studies.

Quantitative informetric analysis

The final analysis results, as shown in Figure 2, indicate that there has been an increase in the number of publications on the Scopus and ScienceDirect platforms each year. Between 2010 and 2016, only eight articles were published, while between 2017 and 2022, there were 22 articles. This represents a 60% increase in the number of articles released in the last three years of the survey. The years 2021 and 2022 saw the highest number of publications on the topic analyzed.

Publications in the field of SERWR are distributed across 17 countries (Figure 3). The United States leads in the number of articles published, followed by China. Most of the research was carried out on the water resources of the countries mentioned in Figure 3; however, in the case of theoretical research, the country of the first author's university was considered.

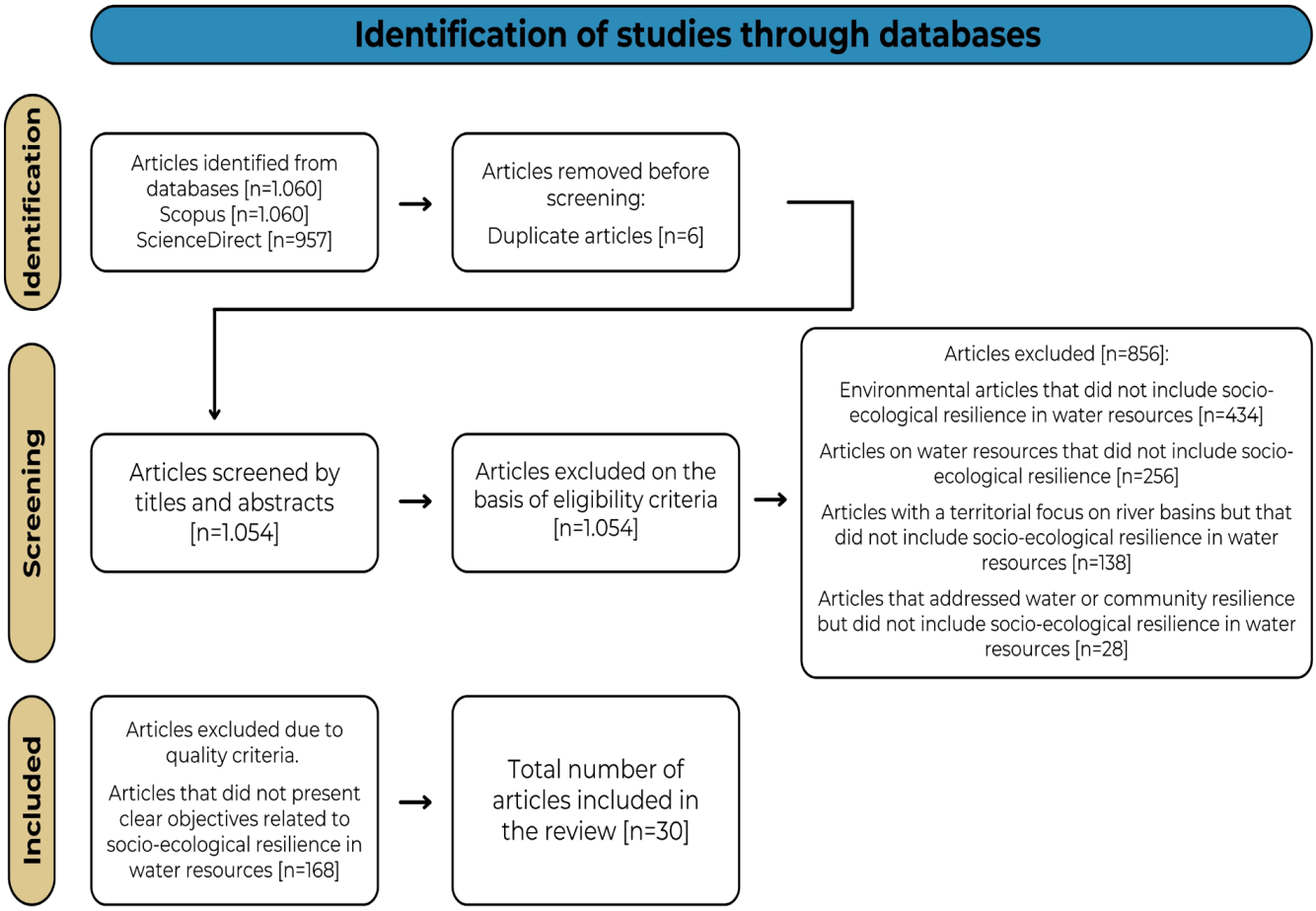

Figure 1 – Criteria for article selection.
Source: adapted from Iocca and Fidélis (2022).

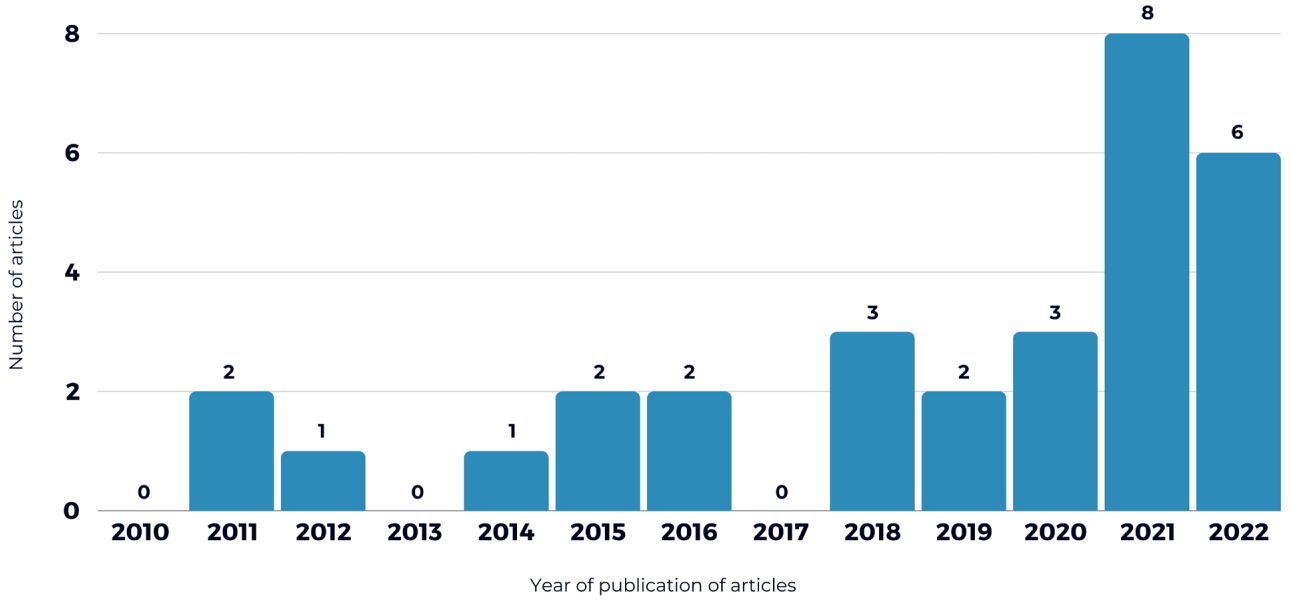

Figure 2 – Number of articles published by year.

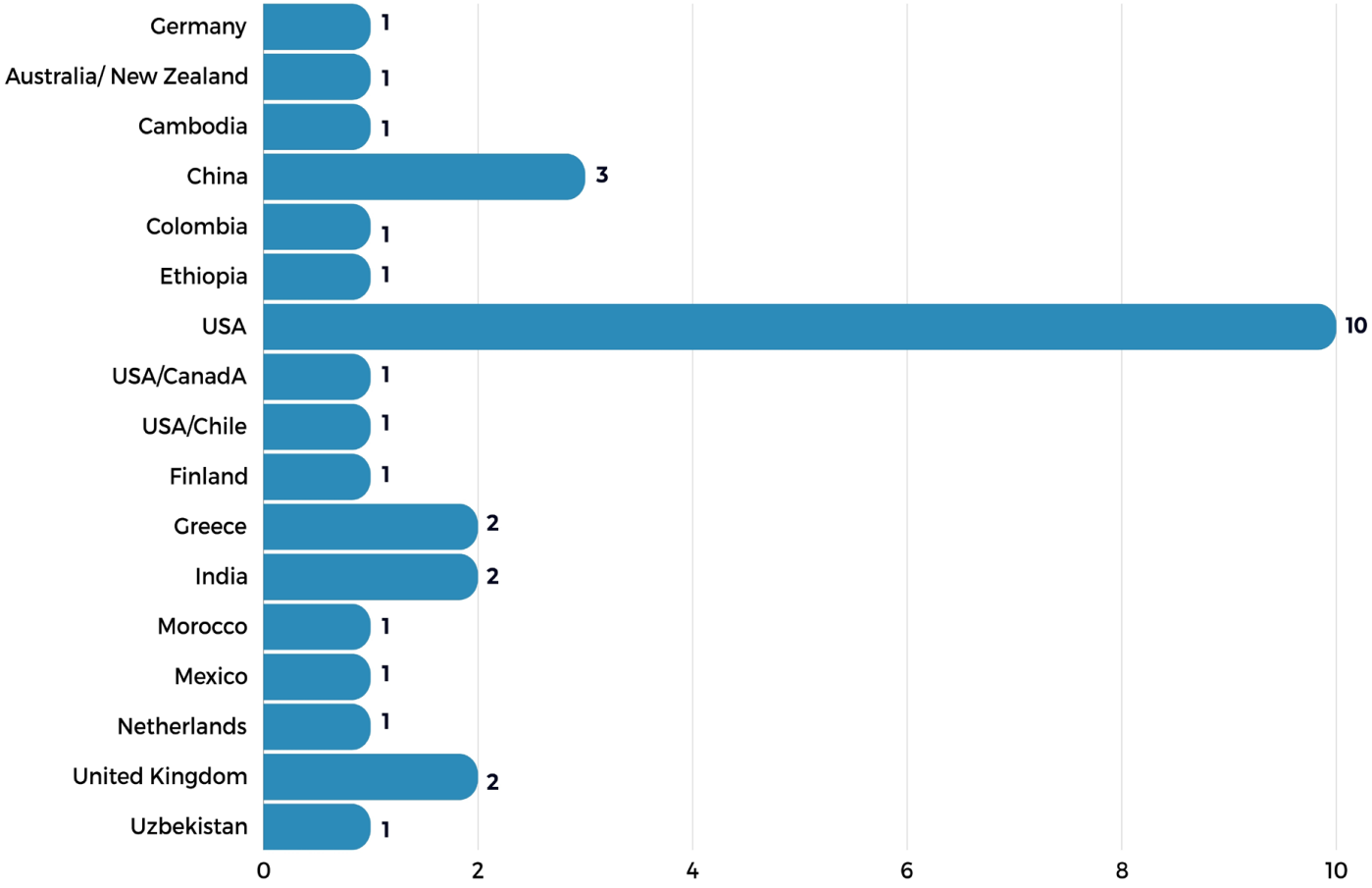

Figure 3 – Countries where the research was developed.

In general, the research was interdisciplinary, published in high-impact, peer-reviewed journals, and well classified according to Qualis. As for the qualitative analysis, the articles were divided into four categories (themes) for better analysis. Most of them are empirical studies and present very diverse methods for evaluating the water resources studied in the countries cited.

Qualitative analysis

The qualitative research indicates that the SERWR uses multidisciplinary approaches, considering social and ecological dimensions at local, regional, and global levels, including as subjects: communities, system workers, governments, policymakers, and water resource managers, among others.

The analysis of the articles reveal four major themes in SERWR: 1. SERWR through participatory management, emphasizing the importance of the participation of communities as the main subjects in the process; 2. SERWR through resilient infrastructures, exploring experiences in water resources infrastructure, such as distribution networks, water treatment plants, and water squares; 3. SERWR with evaluative methodological approaches, unpublished or adapted; and 4. Indicator, index, and modeling in SERWR, through articles that describe quantitative and qualitative technical methods, unpublished or adapted. The qualitative aspects of the articles have been grouped into the corresponding themes and will be discussed in the following paragraphs, focusing on the approach of each article. Theme 4, although an evaluative methodological approach, was considered separately due to its specific nature.

Socio-ecological resilience in water resources through participatory management

Baehler and Biddle (2018), Bunney et al. (2021), and Golladay et al. (2021) analyzed the participatory management of drinking water systems and water sectors in the United States (USA), England, and Wales, revealing the perceptions of the managers of these systems. They corroborate expert opinions and studies of system deficits related to acute or chronic threats, through multi-sector regional resilience plans, as well as considering users' perceptions of inclusive and participatory management. The authors emphasize the need for integrated education on the value of water and building trust, and the importance of investing in infrastructure and innovative technologies, developing contingency plans to deal with extreme events such as droughts and floods.

Noble et al. (2016) and Camp et al. (2020) analyzed socio-ecological fishing systems, with participatory management of work related to the inclusive political process, contributing to the generation of political initiatives and resilience plans, including potential actions to be implemented for each stage of the resilience of socio-ecological systems.

Changes in the attitudes of the parties, management decisions, and the lack of accurate data and information on the state of socio-ecological systems can make it difficult to implement effective strategies for building resilience (Camp et al., 2020). Noble et al. (2016), based on a literature review and secondary data research, describe sustainable fisheries as ecosystems to be recovered and protected through participatory governance in the management of freshwater socio-ecological systems, as they are part of the survival of the indigenous community.

The articles by Adger et al. (2021) and Mahjoubi et al. (2022) describe the fundamental role of communities, including users and traditional institutions, in the participatory management of river basins, aimed at the resilience of socio-ecological systems. This participation includes learning about social, political, economic, and cultural processes, and identifying ecosystem services. By including the community in the process of building the resilience of systems, it is possible to make more sustainable use of resources and minimize negative consequences.

Rajarethinam and Devadas (2021) discuss the importance of managing the water crisis in India due to overpopulation, citing the lack of integrated strategic planning and policies that cover all water-related disruptions. The authors state that this corroborates that high community resilience may not be positive, since a community may be resilient in terms of polluted water or water scarcity. Therefore, although there is an interrelationship between the two systems, this is not always direct with ecological resilience.

Rodina and Chan (2019) and Yager et al. (2021), in turn, emphasize that improving ecosystem health is linked to water resource resilience through adaptability. Infrastructure, for example, through livelihood diversification such as rainwater reuse, use of treated wastewater, access to water, and irrigation are some adaptive strategies in water resource management to increase resilience along with ecosystem health and access. Using infrastructure and planning, it is necessary to prioritize flood mitigation, as climate change driven by unsustainable attitudes contributes to a decrease in resilience. Adaptability in infrastructure also intensifies the idea of interdisciplinary and integration between the water, housing, planning, and environmental sectors to propose effective resilience strategies.

The article by Fallon et al. (2022) explores how socio-ecological theories of resilience and interactive governance, drawing on diverse theories and epistemologies, allow resilience to be seen not only as a goal but also as a non-normative property of government. This implies that resilience can be understood as an intrinsic and adaptive process of government systems, essential to their ability to respond to challenges and changes effectively and sustainably.

The authors Noble et al. (2016), Baehler e Biddle (2018), Rodina and Chan (2019), Camp et al. (2020), Adger et al. (2021), Bunney et al. (2021), Golladay et al. (2021), Rajarethinam and Devadas (2021), Yager et al. (2021), Fallon et al. (2022), and Mahjoubi et al. (2022), in various countries, at various stages of development, through various research techniques, address the importance of social participation for decision-making in integrated water resources management. These studies correlate political, social, ecological, environmental, economic, and administrative functions in order to achieve the expected resilience results.

Socio-ecological resilience in water resources through resilient infrastructures

Better infrastructure in water resource systems can contribute to increasing SERWR, as described by this group of studies. The topic of storm drainage systems is described by Ilgen et al. (2019), Prager and Pfeifer (2015), and Schlüter and Herrfahrdt-Pähle (2011) as resilient infrastructure, linked to the irrigation of agro-systems. These works point out and analyze the learning orientation, also considering listening to the population involved, consultants, architects, and academics, through interviews, meetings, or observations in networks, paying attention to the social contexts and associated experiences.

The article by Ilgen et al. (2019) analyzes how policy-relevant knowledge about water plazas (storm drains) is exchanged between Rotterdam and Mexico City (USA), contributing to building infrastructure resilience. Tajuddin and Dabrawsk (2021) in Chennai (India), describe the challenge of resilient urban communities, transferring knowledge from one city to another, implementing resilient solutions and creating a global stimulus network. They examine how to operationalize socio-ecological resilience in the face of a conflict between rapid urbanization and natural water resources.

Schlüter and Herrfahrdt-Pähle (2011) evaluated a water resource in Uzbekistan, which is exploited through excessive use of water in agriculture and inadequate drainage, causing waterlogging, soil salinization, and desertification of wetlands. The study challenges the theory of resilience as positive, questioning the fact that very high social resilience does not contribute to increased SERWR.

According to Lorenz and Pelz (2020), the use of infrastructure can improve the resilience of water distribution systems, taking into account physical feasibility and cost-benefit analysis. The aim is to increase the resilience of the existing water distribution system by adding pipes to optimize the cost-benefit without losses in the water system, and contributing to the pursuit of SERWR.

The authors Schlüter and Herrfahrdt-Pähle (2011), Prager and Pfeifer (2015), Ilgen et al. (2019), Lorenz and Pelz (2020), and Tajuddin and Dabrawsk (2021) discuss the importance of integrated management for the SERWR process, emphasizing the importance of the social axis based on integration with the community. This integrated management involves the execution of water infrastructures, including engineering projects, computerization of physical structures in various water resources around the world, but supports the contribution of users to raise this SERWR.

Socio-ecological resilience in water resources using evaluative methodological approaches

This theme encompasses various approaches with diverse end goals, such as analyzing urban watershed changes, community tourism associated with community water crises, installing a municipal well, building a large dam, cyber-attacking the water system, and mediating the impact of a historically severe drought on a network of wetlands. The diversification of approaches and methods demonstrates the multiplicity of methodologies for evaluating SERWR. The articles make use of widely applied evaluation models, such as the analysis of scientific material or interviews and questionnaires (Carpenter et al., 2015; Allen et al., 2018; McGuire and Ehlinger, 2018; van Schmidt et al., 2021; Reyes-Santiago et al., 2022).

Allen et al. (2018) tested the approach in four river basins in North America, asking the interested parties (governments, researchers, end-users, and non-governmental organizations) 26 questions, sent by email, designed to probe different aspects of water resources. The results of the study indicate that the comparative approach has the potential to assess the relative resilience of socio-ecological systems in relation to resilience properties.

Carpenter et al. (2015) assessed the Yahara watershed in the USA, intended to determine multiple drivers of change over a 60-year period. Through an integrative methodology with stakeholders, quantitative time series were developed for climate and land use/cover in addition to quantitative ecosystem models, regional governance studies, and new biophysical field observations.

Reyes-Santiago et al. (2022) deepened their knowledge of tourism as an adaptive response of the population to the water crisis, through interviews with 12 community leaders and the application of a questionnaire to 88 community participants, as well as partial least squares structural equation modeling.

McGuire and Ehlinger (2018) used the installation of a high-capacity municipal well in southeastern Wisconsin (USA), document analysis, and open interviews, from which they extracted 16 control variables. These variables were placed in a boundary matrix consisting of a 3X3 grid where each cell represented a domain (biophysical, economic, and social) at a scale (watershed and regional/state); the control variables were placed with possible alternative states separated by a boundary. The relationships between control variables across scales and domains of a system are described in order to understand the multi-scalar socio-ecological aspects of the conflict. Among the dynamics described, identity-based resilience and cross-spectrum conflict dynamics were important for evaluations of the benefit of SERWR based on people's identity.

van Schmidt et al. (2021) investigated a region of California (USA) affected by a historic drought; the multiple evaluative method consisted of factor analysis, remote sensing, field research, and questions to landowners. This method was able to quantify social diversity, describing that, in order to increase the resilience of water availability, it is necessary to assess not only historical ecological diversity but also new types of socially induced diversity.

Nemec et al. (2014) produced an article using scientific, social, and historical literature review methodology to evaluate the effects of the construction of a large dam and the implementation of ecosystem restoration on the resilience of a river in Nebraska (USA). This study shows there is a direct relationship between social and ecological systems. However, socio-ecological resilience does not always behave in a direct analysis. It was assessed separately that social resilience increased over the period while ecological resilience decreased, corroborating the results found by Rajarethinam and Devadas (2021), which point out that high social resilience is not necessarily positive for the ecological approach.

Nikolopoulos et al. (2021) researched cyber-attacks on water network sensors, assessing the resilience and vulnerability of the water monitoring system under such cyber-attacks, using TEVA-SPOT software. This methodology can be useful for risk assessment. Although the study does not describe risk mitigation, water quality sensor placement decisions impact social resilience. In this context, sensor designs for water quality assessment can contribute to socio-ecological resilience.

Even though the evaluation methodologies are not similar, the common objective of this group of articles was to evaluate SERWR through various research techniques, including literary analysis, historical analysis, interviews, questionnaires, and integrative methodologies, not just using a single approach. These are articles that, besides more explicitly describing evaluation methodologies, also emphasize the effective contribution of the subjects involved in contributing to integrated management public policies, thus corroborating the same approaches as the first and second themes.

Indicator, index, and modeling in water resources socio-ecological resilience

Although this topic is also an evaluation methodology, it was considered separately due to its specificity, which lies in its ability to quantify and represent complex phenomena in a systematic and measurable way. The articles explored mathematical descriptions and explanatory models for the development of indicators, indexes, and models. The papers analyzed are aimed at modeling simulation processes, forecasting, and understanding the behavior of complex systems under different conditions.

The article by Liu et al. (2021) evaluated climatic and human variations to examine changes in the resilience of seasonal runoff from the Yangtze Basin, a culturally and economically important river in China, from 1961 to 2014. The methodology consisted of a resilience indicator—the primary energy use (PEU)—and the MIKE 11HD model. The natural resilience of the watershed was reconstructed using a regression model. The resilience indicator PEU quantified the contributions of climatic factors (droughts and floods) and anthropogenic factors, identifying the main reasons for the decline and increase in the

watershed's resilience over time. These changes have been driven by a combination of factors, such as population growth, economic development, increased frequency, and intensity of extreme weather events, and changes in the operation of dams, which are recurrent in areas with increasing occupation.

Zhang et al. (2020) conducted a quantitative analysis of the spatial and temporal differences in the resilience of the socio-ecological production landscape subsystem (SELPs). The system used geographic information system (GIS), field research, ENVI 5.1 processing, geographic data cloud, ArcGIS 10.2, three-dimensional magic cube method, and obstacle model. The evolutionary characteristics and trade-offs in developing of socio-ecological production landscapes on the Loess Plateau are discussed, with a case study in Mizhi County (China), to understand the importance of socio-ecological landscape resilience and its influence on regional progress.

The authors agree that socio-ecological resilience indicators and indices are effective tools for assessing the capacity of a socio-ecological system to protect ecosystems, biodiversity, and other systems integrated with water resources.

The five modeling papers discuss different methods. The articles by Santelmann et al. (2012) and Ioannou and Laspidou (2022) discuss modeling for climate change, a general trend in resilience studies. Ioannou and Laspidou (2022) addressed a case study in Greece on the resilience analysis framework for a water-energy-food nexus system under climate change. The authors used a parametric sensitivity analysis research technique—a system dynamics model that maps sector data from large databases. Santelmann et al. (2012) examined the modeling of river basins as complex socio-ecological systems, proposing hypotheses about the system's resilience to water scarcity and climate change in the Willamette River Basin (Oregon, USA). The model is based on Invision and integrates various landscape change models, emerging scarcity feedbacks and multi-agent representations of human decision-making in the hydrological, ecological, social, and economic dimensions.

Zhao et al. (2022) produced an article that provides an assessment of the resilience of systems on 12 Hongxinglong farms in Heilongjiang Province (China), using Principal Component Analysis (PCA) research techniques, and the Projection Pursuit Classification (PPC) model optimized by the Cat Swarm Optimization algorithm (CSO-PPC). For their part, Vazquez and Muneepeerakul (2022) describe a simulation of environmental variability linked to social and ecohydrological dynamics in systems prone to floods and droughts.

Cai et al. (2016) addressed the identification of relationships between a set of socio-environmental indicators and community resilience in the lower Mississippi River Basin (Louisiana, USA). The authors employed the Resilience Inference Measurement (RIM) model, addressing the empirical basis, which aims to measure community resilience with fine-scale validation, and can be used as a tool to extract indicators and promote community resilience.

The application of SERWR assessment models faces numerous challenges due to the inherent complexity of water systems, which varies significantly according to the characteristics of the territory, class, and uses of water resources. The absence of secondary data is a considerable barrier, hampering the information essential for integrating diverse perspectives and limiting both the effectiveness of models and the implementation of strategies. These challenges are recognized as important gaps in the articles reviewed. When applying the evaluative models of SERWR, it is also necessary to find solutions to overcome and anticipate problems such as extreme droughts, floods, flash floods, and other natural or human-influenced disasters. Replicating these methods for different realities, based on their ecological and social adaptations, is a challenge.

Conclusions

The analysis of the articles revealed four current SERWR research themes: the importance of participatory management; the inclusion of resilient infrastructures; studies on evaluation methods; and indicators, indices and modeling. The majority of studies are classified under the theme of evaluation methods, highlighting the variety and combinations used in SERWR.

In general, the articles address questions about water resources as socio-ecological environments, whether they are represented by rivers, lakes, oceans, rainwater, water treatment systems, agropastoral systems, or water for irrigation. They present SERWR as a way of minimizing issues such as water and soil pollution, water scarcity, flooding, climate change, excessive multiple uses of water resources, and conflicts of use, impacting on the governance of these resources. The studies generally adopt approaches that highlight the importance of community and stakeholder integration, resulting in significant contributions to SERWR improvement.

The SERWR study has potential for growth, since this research identified publications on six continents, making the topic relevant on the world stage. Of the themes identified, the one with the greatest potential for growth over time is evaluation methodologies.

In this sense, this study found it challenging to use evaluative methodologies to measure socio-ecological resilience, given that the methods used are diverse, multiple, integrated, and complex, and cannot be used solely on the basis of formal techniques.

Considering the results, future research should focus on developing a method capable of assessing the SERWR in degradation processes and anticipating possible damage resulting from vulnerability situations to be used in various research scenarios. It is imperative that strategies are adaptable and robust, incorporating dynamic data and multidisciplinary approaches to ensure SERWR in the face of variable and unpredictable environmental and social conditions. Practical knowledge of measuring SERWR aids decision-making and the improvement of sustainable management practices, taking into account this study's conclusions about more democratic and participatory approaches.

Author's Contributions

Souza, F.C.: conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization, writing – original draft, writing – review & editing. **Cândido,** G.A.: conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization, writing – original draft, writing – review & editing.

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