Ecological Questions 36(2025)1 http://dx.doi.org/10.12775/EQ.2025.013

The ecohydrology framework. Bibliometric network analysis and literature review

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Received: 7 June 2024/ Accepted: 21 February 2025

Abstract In the context of increasing environmental stressors, Ecohydrology represents an interdisciplinary and comprehensive framework useful to ensure the sustainable management of water resources, mitigating risks to both anthropic and ecological systems. This research examines the milestones of Ecohydrology through a Bibliometric Network Analysis and literature review, emphasizing its possible integration with Ecosystem and Environmental accounting. In particular, it explores how the Ecohydrological perspective can support researchers, local managers, policy-makers and other stakeholders in building climate-resilient cities. A total number of 3335 articles were analysed using the VOSviewer software to perform a bibliometric network analysis. Three thousand one hundred articles were screened for the literature review. Then, 719 were selected through cross-reference and their abstracts were reviewed. Finally, 290 full text articles were reviewed and data were extracted from 36 articles. Key findings highlight the urgent need to study the interplay between hydrological processes and water-related ecosystem services for addressing the mounting challenges posed by human activities and the resulting climate change. The main objective of this field of science is to comprehend and mitigate the effects of land use changes on water and to forecast the impact of climate change on ecosystems and water supply. Bibliometric network maps reveal limited research on the convergence of Ecohydrology, Ecosystem accounting, and Environmental accounting, indicating the need for further research and collaborative efforts to overcome this knowledge gap. Lastly, ecological and socioeconomic considerations are crucial in water-related management, as economic growth and human well-being are intricately linked to water resources and healthy ecosystems. Addressing these challenges and ensuring sustainable water management require cooperation among ecohydrologists, other scientists, stakeholders, and decision-makers. Integrating the ecohydrological perspective into ecosystem accounting is essential to facilitate dialogue among different disciplines and better adapt to climate change.

Keywords: ecohydrology, ecosystem accounting, ecohydrological modelling, bibliometric network analysis.

1. Introduction

As emphasised by the 2023 IPCC Report, climate change increasingly affects hydrological dynamics, with profound implications for societies and ecosystems worldwide (IPCC, 2023a). Despite water being a cornerstone of sustainable development and intersecting directly with several Sustainable Development Goals (SDGs), holistic studies of aquatic systems remain limited, fostering effective management approaches such as Integrated Urban Water Management and Green-Blue Infrastructures. Addressing these challenges necessitates a broader interdisciplinary perspective, such as the one provided by Ecohydrology.

Ecohydrology is an emerging discipline that integrates hydrological processes with ecological dynamics, evaluating the reciprocal role of water and biotic processes in regulating each other (Rodriguez-Iturbe, 1999; Rockström & Gordon, 2001; Zalewski et al., 2016a; Laio et al., 2009; Rodriguez-Iturbe et al., 2001). By combining hydrology with ecosystem science, Ecohydrology enables more comprehensive water management strategies that support ecological sustainability while considering societal needs (Porporato & Rodriguez-iturbe, 2002). Although still in need of further development, a significant component of Ecohydrology concerns the accounting of ecosystem services, which quantifies the socioeconomic benefits of natural ecosystems, such as water purification and flood regulation, facilitating informed decision-making to prioritise long-term resilience.

Historically, the integration of ecological processes in regulating hydrology has been acknowledged, yet the development of Ecohydrology as a distinct field began in the late 20th century, particularly after its adoption by UNESCO in 1992 as a priority topic. Since then, Ecohydrology has evolved significantly, allowing a better understanding of river systems, wetlands, and hydrological cycles across diverse climatic and geographical regions. The work of Ignacio Rodriguez-Iturbe and Maciej Zalewski has been key in shaping the field. Rodriguez-Iturbe focused on hydrological modelling at the watershed level to understand the interaction between hydrological processes and ecological dynamics (Rodriguez-Iturbe, 2000), while Zalewski promoted an integrated approach that emphasises socio-cultural influences in water resource management (Zalewski, 1997, 2002).

In this complexity, ecohydrological models provide an important means of simplifying, analysing and understanding the interactions between water, soil and vegetation on different spatial and temporal scales. Such models are crucial for the planning and implementation of blue-green infrastructure to support evidence-based strategies for conservation and ecological resilience. In this context, the river basin emerges as a fundamental unit for ecohydrological analysis, offering insights into the interconnections of ecosystems within drainage networks (Rodriguez-Iturbe, 2001; Rinaldo, 2020).

Indeed, the integration of Ecohydrology, supported by models and ecosystem service accounting, into broader water management practices, such as the use of blue-green infrastructure, offers a promising pathway for improving environmental resilience, promoting ecosystem health and supporting sustainable development.

This study aims to explore the development of Ecohydrology, focusing on its role in sustainable water management, its integration with ecosystem services, and the use of ecohydrological modelling to enhance socio-ecological resilience. By examining the interplay between ecological processes, hydrological dynamics, and human activities, we aim to show how Ecohydrology can contribute to the adaptive management of water resources, ensuring sustainability for both ecosystems and human communities in an increasingly uncertain climate.

1.1 Research Questions, Goal, and Novelty of the Study

The present study aims to address the following research questions:

Q1: What are the main research gaps and emerging trends in the global scientific literature on Ecohydrology?

Q2: What is the current status of the global research concerning the interplay between Ecohydrology and Ecosystem Accounting?
The goal of this study is to examine the global scientific literature on Ecohydrology, with a specific focus on its relationship with Ecosystem Accounting. We conducted a review of the scientific literature on the topic, performing a bibliometric network analysis to generate maps based on network data showing the connections among keywords, authors, and countries associated with Ecohydrology research.
The novelty of this study lies in its extensive investigation of the Ecohydrology field in connection to the timely topic of "Ecosystem Accounting". Therefore, the study aims to provide a comprehensive overview on Ecohydrology, exploring the complexity of the subject and its connections with both hydrological and ecological perspectives.

2. Materials and Methods

2.1 Bibliometric Network Analysis

We employed a systematic methodology comprising three steps in conducting Bibliometric Network Analysis using the VOSviewer software. Firstly, we retrieved a comprehensive dataset of scholarly publications from the Scopus database. Secondly, we processed and standardised the retrieved data to ensure uniformity and accuracy. Lastly, we utilised VOSviewer's advanced visualisation capabilities to map and analyse the bibliographic network, enabling to identify key themes, influential authors, and emerging research trends.
This analysis generated knowledge domain maps pertaining to country co-authorship, organisation co-authorship, author co-authorship, journal co-citation, and keyword co-occurrence.
A bibliometric network analysis was conducted to investigate the global scientific literature and research trends concerning Ecohydrology and its relationship with ecosystem accounting. This approach has been proven effective in examining worldwide scientific trends on a specific topic. Using the VOSviewer software (version 1.6.16), network maps were generated based on bibliometric data to explore connections among authors, keywords, countries, journals, and organisations.
The bibliometric data for this analysis were obtained from the Scopus database in July 2023, using the keywords "Ecohydrology" and "Ecosystem Accounting". All relevant documents associated with the selected keywords were included in the analysis without imposing any specific time constraints.
Several analyses were performed, including tracking the temporal evolution of the topic based on document output, examining keyword co-occurrence, investigating co-authorship patterns among authors, and exploring co-authorship patterns among countries. The VOSviewer software facilitated the construction of network maps, with different items (e.g., keywords, countries, authors) organised into clusters based on their relationships, such as shared keywords, document counts per source or author, and co-citations. These network maps visually represented the connections between items, with thicker lines indicating stronger links. The resolution parameter, set at 1.00 and 1.25 in this study, determined the level of detail and number of clusters displayed in the maps. Adjusting the resolution value allowed for an appropriate balance between detail and clarity.

2.2 Literature Review

The research made use of the Scopus and Web of Science databases and was conducted in several sequential phases. In the first phase, the keywords "Ecohydrology" OR "Eco-hydrology" were used to retrieve relevant articles. The study period was not restricted, and no filters were applied to analyse Ecohydrology's interdisciplinary nature and diffusion. The results were sorted by relevance and yielded 3961 articles on Scopus (search made in Article title, Abstract, Keywords) and 2343 articles on Web of Science (search made in Topic).
In the second phase, only peer-reviewed articles were selected from the initial results. This filtering reduced the number of articles to 3335 on Scopus and 2022 on Web of Science.

In the third stage, a refined search was conducted to select articles from 2018 to 2022 and focus on the most relevant subject areas. The results from Scopus yielded 1260 articles while the results from Web of Science yielded 943 articles.
In the final stage of the bibliographic search, the research was conducted using the keywords "Ecohydrology" OR "Eco-hydrology" AND "Ecosystem accounting", and then "Water" AND "Ecosystem accounting", with only 8 results in Scopus. This search aimed to ascertain the state of the art and the extent to which these topics have been investigated at global level.

3. Results and Discussion

3.1 Annual Quantitative Distribution of the Literature

Changes in its literature output can measure a research field's development status, knowledge accumulation, and maturity. The time-series output distribution of Ecohydrology-related literature is shown in Figure 1.

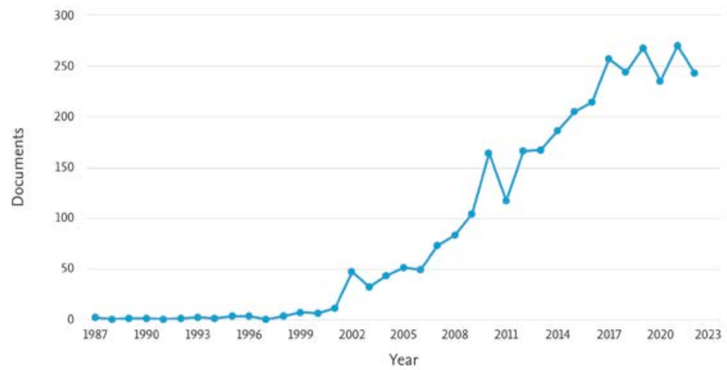

Figure 1. Ecohydrology-related literature: number of documents by year.

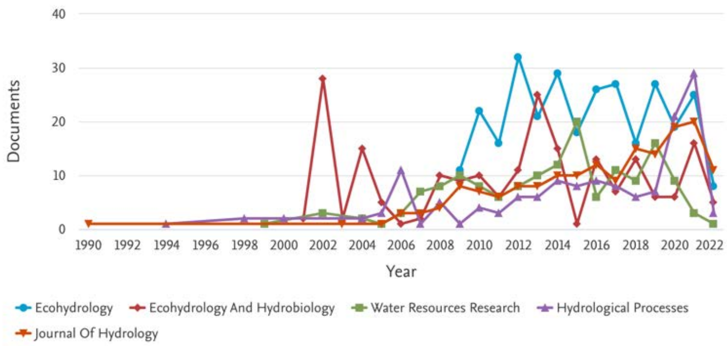

Figure 1. Documents per year by source.

In Figure 2, it is noteworthy that the journal "Ecohydrology", which is currently among the most active journals publishing about ecology and hydrology, commenced its activity in 2009 under the publisher Wiley-Blackwell. Among the publications on Ecohydrology, the "Ecohydrology" journal currently has published 9% of them, followed closely by "Ecohydrology and Hydrobiology" with

6.5%. Yet, it is worth noting the equitable distribution of publications across various hydrologic and biological domains of this journal.

3.2 Quantitative Distribution of the Literature among countries, authors, and keywords.

After sharpening the search by selecting only articles, we proceeded to explore the literature from 1987 to the present, analysing its geographical spread, the scenario of authors and affiliations. The analysis of subjects and keywords is furthermore essential to understand in which context the study of Ecohydrology has developed and what elements it consists of.

Concerning the geographic dispersion of research on Ecohydrology, as depicted in Figures 3 and 4, it is unsurprising that the United States tops the list of countries, with 1533 documents, and with the main sponsor, the National Science Foundation. The People's Republic of China is closely following, with 783 documents, with main sponsors the National Natural Science Foundation of China, the Chinese Academy of Sciences, and the National Key Research and Development Program of China. The European Commission ranks ninth in sponsorship, and it is worth noting that the United Kingdom (with 404 documents), Germany (with 369 documents), Italy (with 203 documents), the Netherlands (with 152 documents), Poland (with 161 documents), and Switzerland (with 157 documents) all feature in the top ten list of countries active in this field. Australia, which has consistently shown sensitivity to topics related to water and ecology, has also made significant and innovative contributions since 1993, with 371 documents, while Canada has contributed 285 documents.

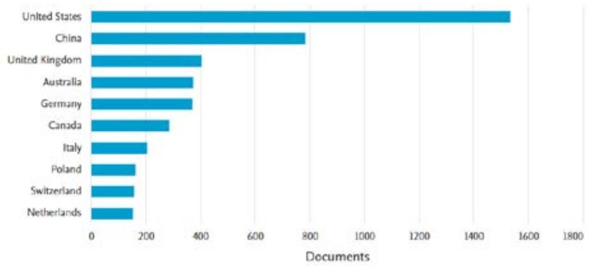

Figure 2. Documents on Ecohydrology by country.

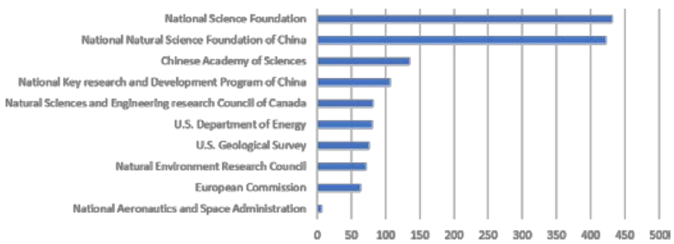

Figure 3. Documents on Ecohydrology by funding sponsor.

In Figure 6, the countries depicted on the maps are represented by nodes, with their relative sizes corresponding to their frequency of appearance in the academic literature, which can be compared with the map in Figure 5. Notably, in recent years, a generational transition has occurred among these countries, with notable increases in prominence for Finland, Mexico, Singapore, India, and, above all, China.

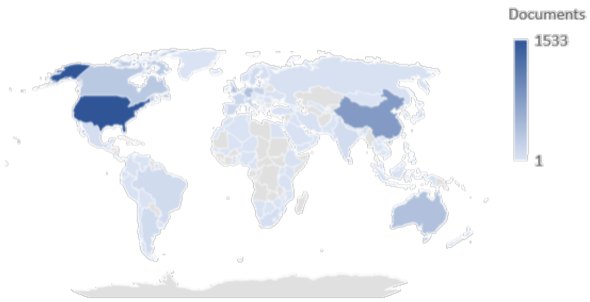

Figure 4. Geographical distribution of Ecohydrology' research.

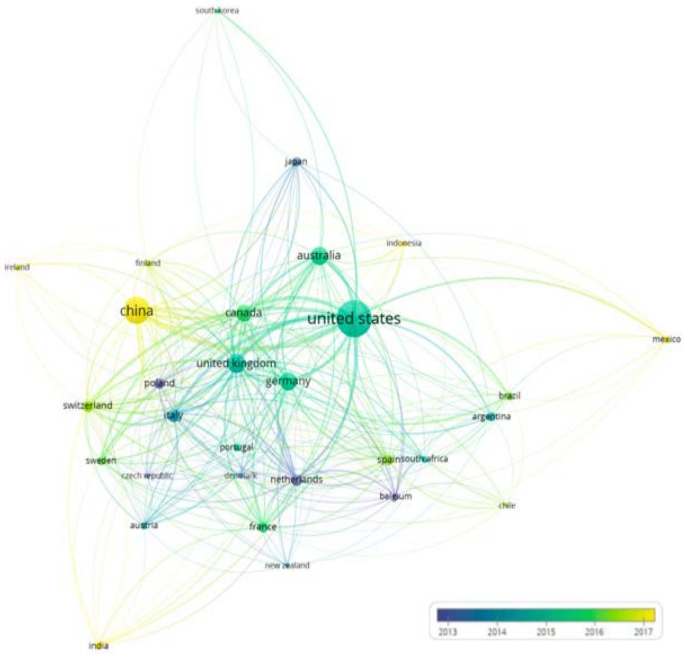

Figure 6. Overlay visualization of the Country co-authorship.

The visualisation of co-authorship relations reveals a more pronounced level of collaboration among certain countries, while others remain relatively isolated in their partnerships for academic publications.

In Figures 7 and 8, information regarding the most active authors in the field is depicted. The foundational work of Zalewski and his colleagues unearthed the necessity of a transition from a mechanistic paradigm to an evolutionary and ecosystem-based approach, taking a significant step forward from earlier philosophies during the industrial era. Thanks to Xianli Xu, with 41 publications, the Ecohydrology perspective was applied to karst landscapes as well, building a bridge between Soil science and Ecology. Among the authors from the United States, Vivoni, Rodriguez-Iturbe, Wang, and Porporato are noteworthy for their interdisciplinary contributions.

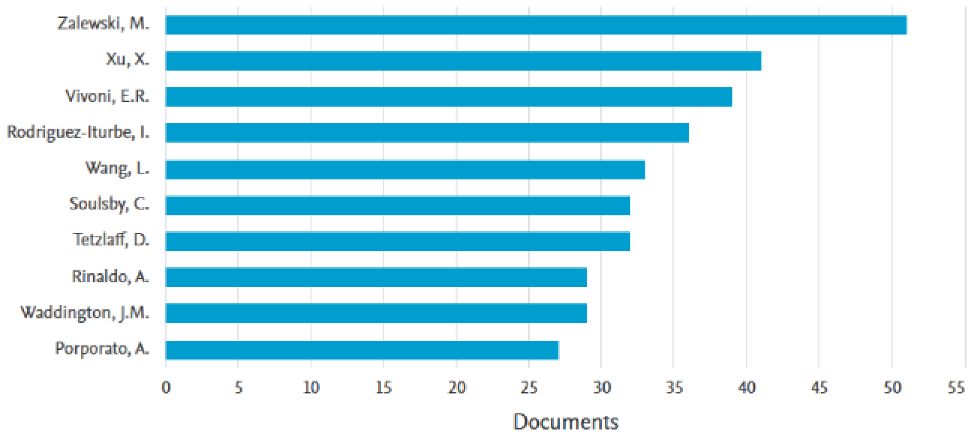

Figure 7. Documents by author.

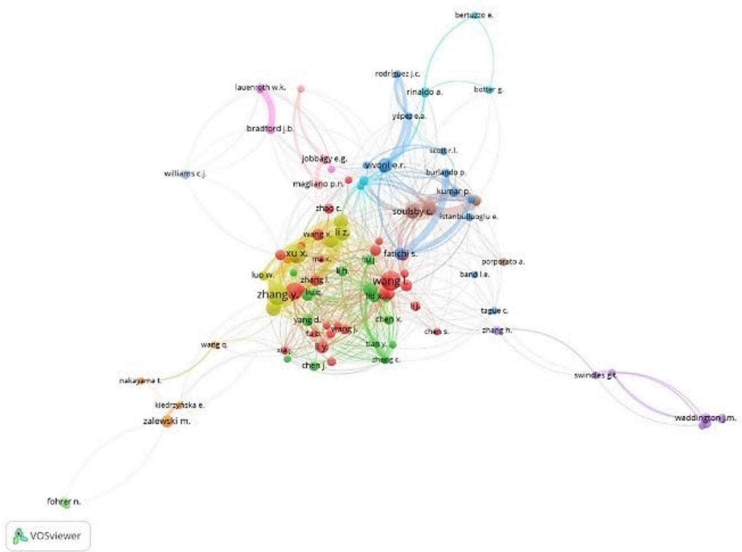

Figure 5. Knowledge domain map for the citation.

In Figure 8, it can be observed that some authors collaborate more closely than others, and their publications exhibit thematic clustering. For instance, Bradford J.B. and Lauenroth W.K. have primarily focused their research on semiarid steppes and drylands. Bertuzzo E. and Rinaldo A. have published extensively on the topic of waterborne diseases, mainly focusing on cholera. Waddington J.M and Swindles G.T., located on the map's right side, have researched peatlands. In Figure 9, the knowledge domain map for the citation is represented with overlay visualisation in order to distinguish which are the most recently active authors.

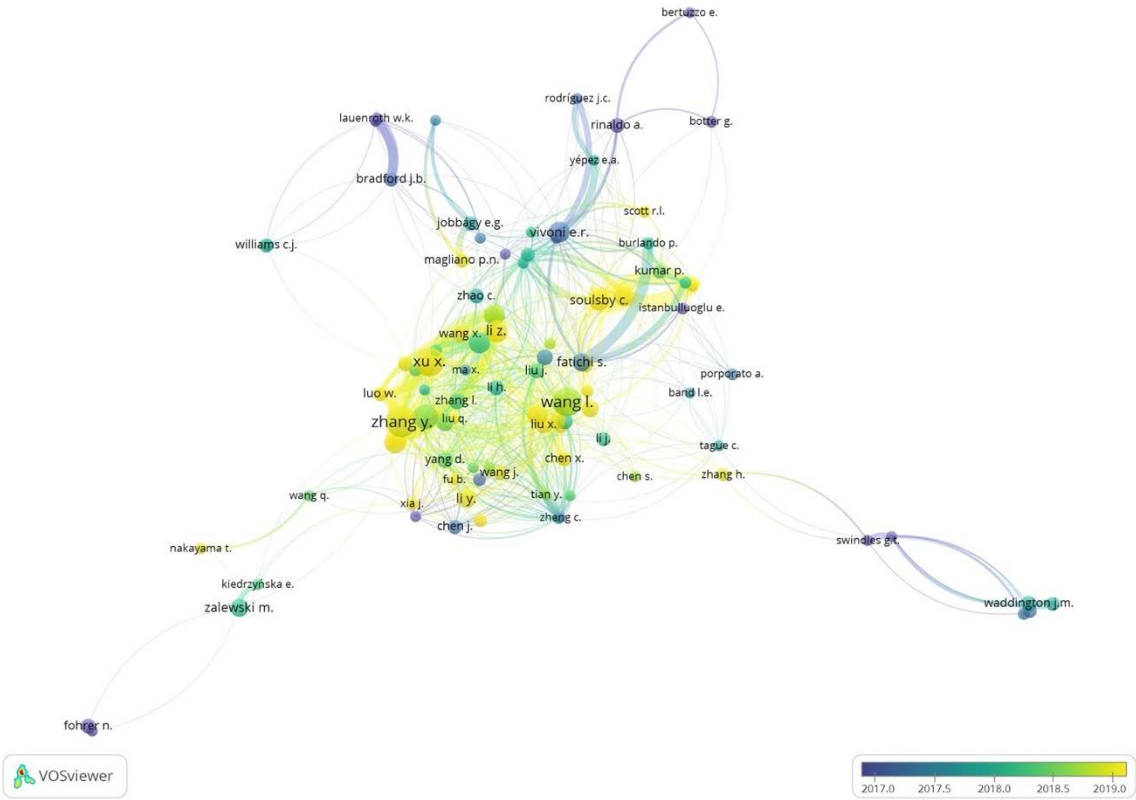

Figure 6. Knowledge domain map for the citation with overlay visualisation.

Regarding the subject areas in which Ecohydrology has been analysed, the main one is undoubtedly Environmental Science (41.3%). Agricultural and Biological Sciences are following with Earth and Planetary Sciences right after. The results show how Ecohydrology is also addressed by subjects such as Social Sciences, Biochemistry, Genetics and Molecular Biology, Engineering, Decision Sciences, Immunology and Microbiology, Economics and others, demonstrating the interdisciplinary distribution of the subject.

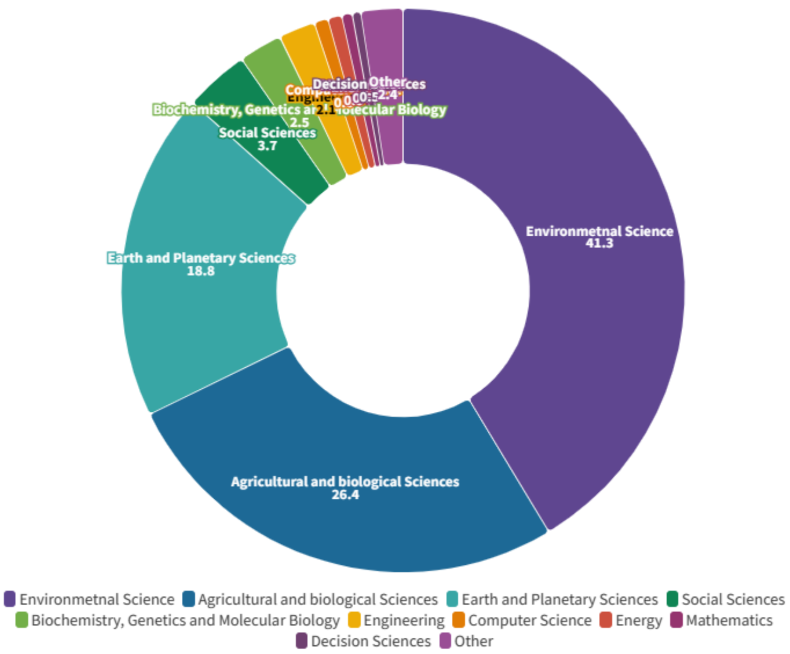

Figure 7. Documents by subject area.

To describe the core content and structure of Ecohydrology and reveal the subject's research frontier, The keywords co-occurrence analysis was employed. It involves identifying and analysing patterns of simultaneous occurrence of keywords in a set of documents. The study helps reveal relationships between keywords, their frequencies, and how often they appear together. It provides insights into the thematic structure of a field, highlighting important concepts, connections, and potential research trends based on the co-occurrence patterns of keywords within the analysed literature.

The top ten keywords related to Ecohydrology are Hydrology, Climate change, Soil moisture, Vegetation, Ecosystems, Evapotranspiration, Runoff, Groundwater, Ecology and Forestry. As previously stated, the items depicted in the maps are illustrated as nodes; the greater their size, the higher their frequency in the related literature.

As shown in Figure 11, the keyword co-occurrence analysis highlights different clusters, each representing different research directions. The first green cluster encompasses elements within the sphere of Ecohydrology, including ecosystem services, water characteristics, and ecosystem status. The second cluster, in red, is formed by a constellation of keywords in the spectrum of evapotranspiration, including rainfall, vegetation, soil, and their interrelationships. In the third cluster, in blue, we find elements related to modelling, closely linked to climate change, land use, and components associated with water flows (runoff, catchment, streamflow).

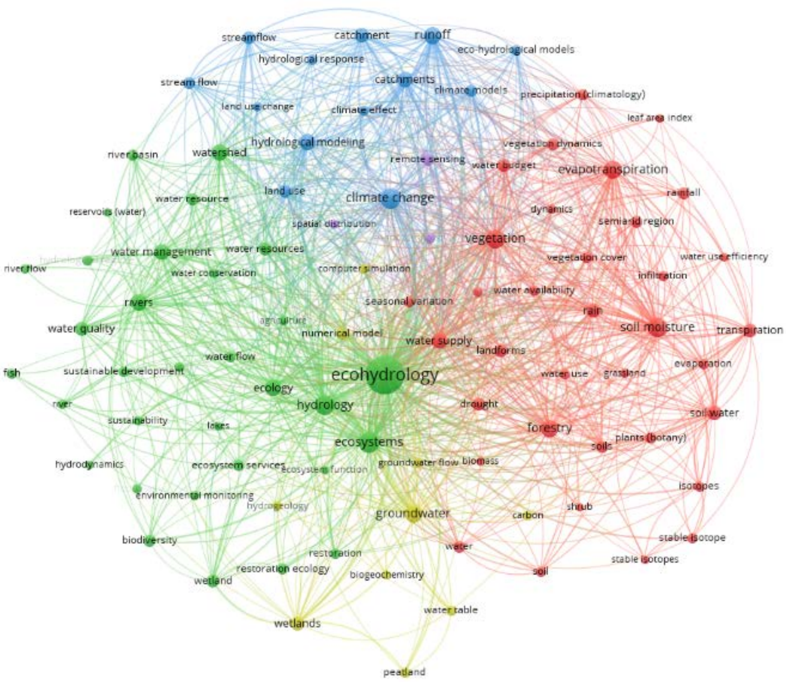

Figure 8. Keyword Co-Occurrence Analysis on Ecohydrology.

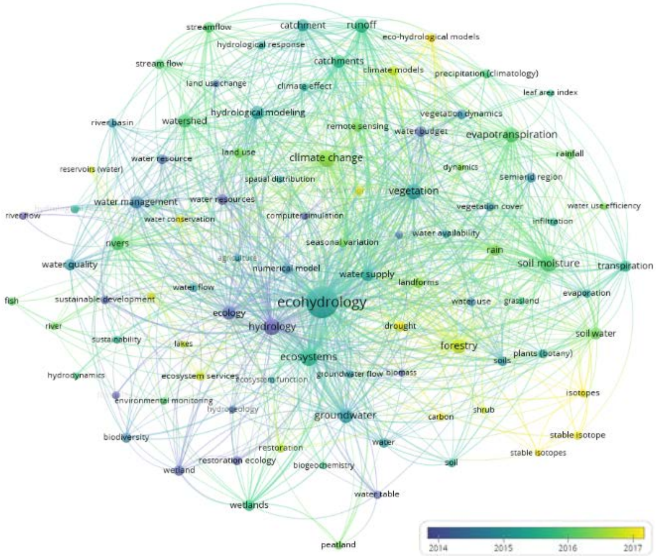

Figure 9. Keyword Co-Occurrence Analysis on Ecohydrology: overlay visualization.

The interconnection among elements from different clusters, which are hard to define as non-leaky, highlights the close relationship between Ecohydrology and the fields of ecology, biodiversity, and environmental flows, as these components are all critical for understanding the interactions between terrestrial and aquatic ecosystems. Ecohydrology seeks to understand how water flows, and availability impact ecological processes and biodiversity and how these processes, in turn, impact water quality and quantity. Environmental flows, or the amount, timing, and quality of water necessary to sustain freshwater and estuarine ecosystems, are fundamental to ecohydrological research and management. By integrating these fields, ecohydrologists can develop a holistic understanding of the complex feedback between water resources, biological communities, and human activities and develop sustainable management strategies to maintain healthy ecosystems and water resources.

To analyse the temporal distribution of the keywords and the development in the years of the topics discussed along with Ecohydrology, we report the Keyword Co-Occurrence Analysis with overlay visualisation (Figure 12). The words that have been recurring for most years, in blue, are Ecology, Water Resources, Biodiversity, Plant, Moisture. In more recent years, in yellow, new themes are gaining popularity and becoming associated with Ecohydrology, such as Cyber, Carbon sequestration, and Isotopes.

The term "Cyber" is crucial in Ecohydrology due to its association with information technologies, data analysis, and computational modelling. Cyber technologies facilitate advanced data collection, analysis, and modelling techniques, enabling a comprehensive understanding of hydrological processes and ecosystems using robotics, smart sensors, and artificial intelligence. The Carbon sequestration process is pivotal for assessing the function of ecosystems in mitigating climate change and maintaining ecological balance. Isotope analysis provides a precise means to trace and understand water movement, biological processes, and ecosystem dynamics.

The fact that there are no social, cultural, or political references among these keywords is symptomatic. It prompts reflection on the need to raise awareness in this direction since Ecohydrology should also engage with fields that study human dynamics, as humans are the primary modifying agent of Ecohydrology's cycles.

The concepts of restoration, nature conservation, environmental monitoring, and water and soil quality, represented in green, have become more stable and persistent over the years. We also note that the most recent sensitization on groundwater and recharging aquifers, visible in yellow, perfectly aligns with the mission and goals of the UNESCO Water Division. Indeed, in 2022, as an answer to the water scarcity and the decrease in surface water availability, UNESCO with the International Groundwater Resources Assessment Centre (IGRAC) has led the World Water Day 2022 campaign on “Groundwater: Making the invisible visible”.

The results underline the significance of Ecosystem services and Ecohydrological modelling, which stand out as recent and widely employed keywords as well. These two disciplines are making a significant contribution to water resource management and ecosystem protection and will also increasingly serve as crucial tools in devising solutions for adapting to climate change.

3.3 Ecohydrology and Ecosystem accounting

The connection between Ecohydrology and Ecosystem Accounting lies in their complementary roles in holistic environmental management. Ecohydrology provides a scientific understanding of how ecosystems and hydrology interact, while Ecosystem Accounting quantifies the value of the services these ecosystems provide. When integrated, these two fields offer a powerful approach to inform decision-making, particularly in water-related management. For instance, Ecohydrology and Ecosystem Accounting enable a comprehensive approach to environmental management, ensuring that both ecological and economic factors are considered when making decisions about the sustainable use and conservation of natural resources.

Ecosystem accounting involves the systematic assessment of ecosystems contribution to economy, human well-being and environmental sustainability. It furnishes a framework for measuring and assessing ecosystem services, such as water supply, carbon sequestration, and habitat maintenance, which are essential to sustain human life and economic activities.

We conducted a bibliometric analysis of the relationship between Ecohydrology and Ecosystem Accounting to provide an objective overview of the field, revealing research gaps and opportunities and guiding decisions and policies aimed at sustainable water management and conservation efforts to ensure the continued provision of valuable ecosystem services to current and future generations.

By combining ecohydrology and ecosystem accounting research, we obtained 53 documents, setting the minimum number of occurrences of keywords at 4. Figures 13 and 14 show the Keyword Co-Occurrence Analysis.

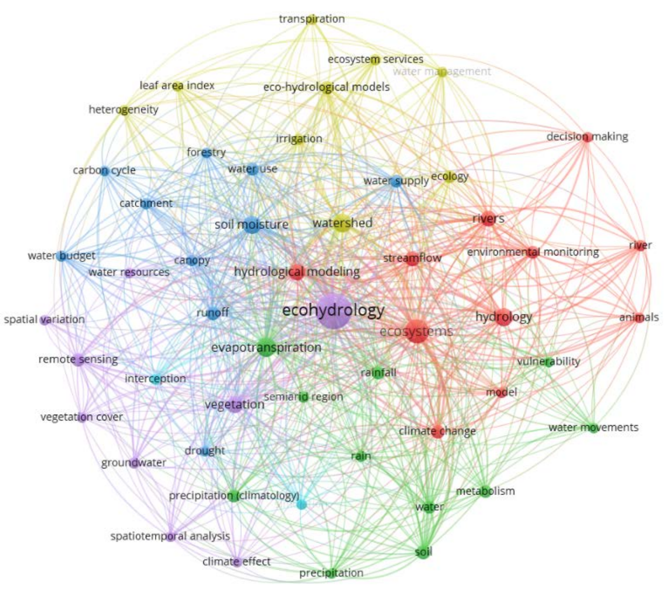

Figure 10. Keyword Co-Occurrence Analysis on Ecohydrology and Ecosystem Accounting.

In Figure 14, a comprehensive examination of the interplay between Ecohydrology and ecosystem service underscores their direct relevance to decision-making processes. These two disciplines engage in dynamic interactions encompassing a range of factors, including vegetation and forestry dynamics, canopy characteristics, and elements related to hydrological cycles, such as precipitation patterns, water utilisation, irrigation practices, soil moisture dynamics, and watershed delineation. Notably, ecohydrological models assume a pivotal role in unravelling these intricate relationships. They enable the assimilation of hydrological and ecological data, empowering informed decision-making concerning sustainable water resource management and strategies for ecosystem preservation.

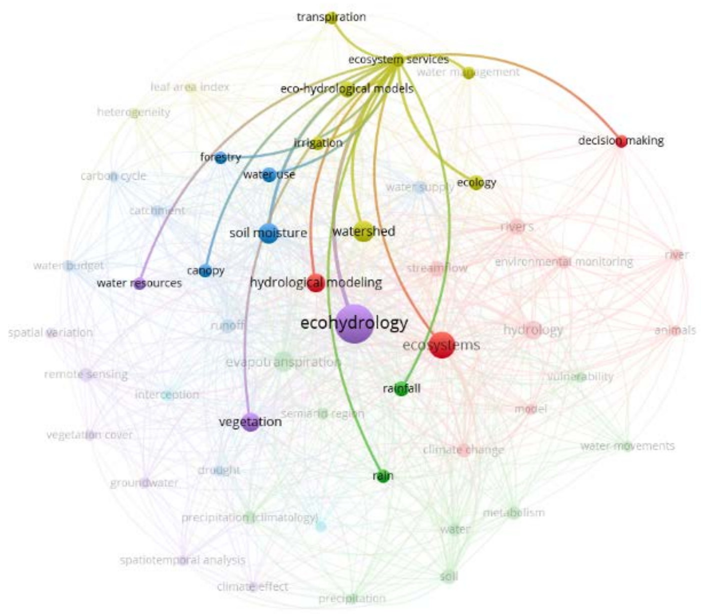

Figure 11. Keyword Co-Occurrence Analysis on Ecohydrology, highlighting the connections with Ecosystem services.

The amalgamation of insights from ecohydrology and ecosystem accounting enhances our comprehension of the ecological worth of water-related services and their ramifications for socioeconomic well-being. This, in turn, equips stakeholders and policymakers with the knowledge required to make prudent decisions aimed at preserving the delicate equilibrium between human activities and natural ecosystems. Hydrological ecosystem services manifest considerable diversity and can be broadly categorised into five primary groups (Zalewski, 2010): enhancement of extractive water supply, augmentation of in-stream water supply, water damage mitigation, provision of cultural services linked to water, and support services with water-related functions.

Following the previous research, it was deemed interesting to replace the keyword "Ecohydrology" with “Water” (Figure 15). The result was a greater number of articles found in Scopus, but we reduced the minimum number of keyword co-occurrences on VOSviewer to sharpen the analysis. The search aimed to investigate the dissemination of ecosystem accounting in the water domain, noting terms that had not appeared in the previous analysis, such as Natural Capital Accounting as well as SEEA-EA and SWAT.

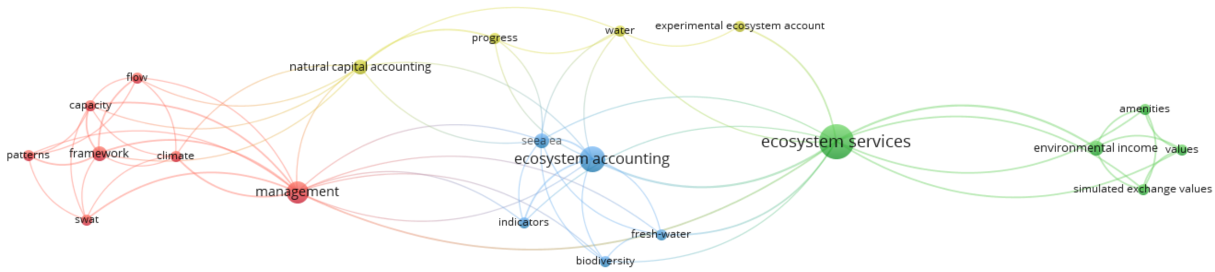

Figure 12. Keyword Co-Occurrence Analysis on "Water" and "Ecosystem Accounting".

In the context of the analysis between Ecohydrology and Ecosystem services, Natural Capital Accounting (NCA) has experienced a rapid development in recent years, driven by international organisations and the scientific community. It involves quantifying and valuing the stocks and flows of natural resources and ecosystem services within a specific region or country. SEEA-EA is a framework designed to integrate environmental and economic information, specifically focusing on ecosystem accounting, while SWAT is a hydrological model used to handle the impact of land use practices on water resources.

Even though the map has been limited to a straight number of keywords co-occurrence, it is emblematic of the fact that the ecohydrological approach is still relatively unfamiliar in research on ecosystem services. Despite being one of the disciplines that effectively describes and gathers data essential for assessing such services due to its multidisciplinary nature, it remains somewhat overlooked. Moreover, many ecohydrological models have the potential to significantly contribute to refining and making Ecosystem accounting more accurate.

3.4 Ecohydrology and Modelling

To complete the Bibliometric Network Analysis, it is important to address the relationship between Ecohydrology and modelling, as emerged from the literature review. The intersection between Ecohydrology and hydrological modelling is crucial for understanding water cycle dynamics across different ecosystems, particularly in the context of climate change. Bibliometric analysis confirms a strong research connection between these two fields, encompassing various ecohydrological and instrumental dynamics. As highlighted by the network map (Figure 16), research clusters focus on soil moisture dynamics, evapotranspiration processes, and runoff generation, utilising numerical and mathematical models to simulate these phenomena within catchments.

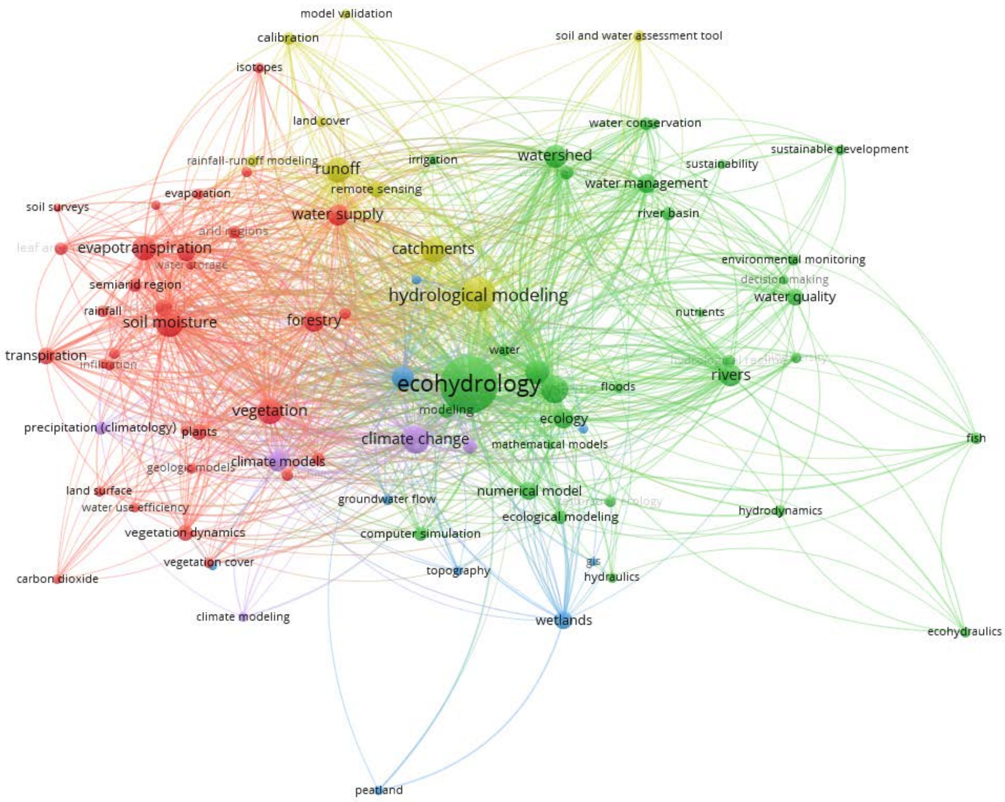

Figure 16. Keyword Co-Occurrence Analysis on "Ecohydrology" and "Modelling".

The integration of GIS tools further enhances spatial analysis, while model validation and calibration are essential for ensuring the accuracy and reliability of ecohydrological predictions. These modelling approaches are crucial for assessing the effects of climate variability and supporting adaptive water resource management strategies across different spatial scales. Within the complexity of the interactions that Ecohydrology addresses, models play a pivotal role in simplifying, describing, and forecasting intricate processes. When these models are supported by thorough validation using empirical data, they become powerful instruments for guiding sustainable development that respects the complex ecosystems in which we coexist. This ability to navigate and operationalise ecological complexity is fundamental to fostering resilience and ensuring ecosystem sustainability.

4. In-Depth Literature Review

The importance of implementing sustainable water management in the face of escalating climate change is underscored by the 2023 IPCC Report, which emphasises the growing impact of climatic changes across all global regions and the resulting threat to societies and ecosystems. Water, as a critical element of sustainable development, directly intersects with several Sustainable Development Goals (SDGs), yet holistic studies of aquatic systems are still insufficient, limiting the advancement of effective management strategies, such as Integrated Urban Water Management and Green-Blue Infrastructures (IPCC, 2023b). This gap calls for a broader, interdisciplinary approach such as the one addressed by Ecohydrology. Ecohydrology, as defined by several leading researchers, is a paradigm that integrates the understanding of hydrological processes with ecological dynamics. It focuses not only on how water influences ecosystem processes but also on the reciprocal role that biotic processes play in regulating hydrological variables (Rockström & Gordon, 2001; Jenerette et al., 2012; Zalewski et al., 2016b; Xia et al., 2021). This definition hints at the vast scale that the subject covers, both from a spatial and governmental perspective.

Indeed, its range of actions on various scales is also evidenced by the presence of several international initiatives that promote sustainability in water management with ecohydrological awareness, such as the International Geosphere-Biosphere Programme (IGBP/BAHC) and the Intergovernmental Hydrological Programme, hosted by UNESCO (IHP-UNESCO) (Xia et al., 2021).

Ecohydrology focuses on issues connected with sustainable development, particularly concerning the management of water resources and ecosystem conservation, and closely links it to socio-political, energetic, and health-related themes (Zalewski, 2010).

Regarding its practical application, Ecohydrology provides a scientific foundation for developing comprehensive and integrated strategies that address the complex interactions between hydrology and ecosystem science (Wilcox, 2010; Asbjornsen et al., 2011a; Muneepeerakul, 2008, 2019; Rodriguez-Iturbe et al., 2009a).

A key example of this is the implementation of Blue-Green Infrastructures (BGI). Ecohydrology provides BGI with a comprehensive theoretical framework to examine how the structure and function of ecosystems interact with the dynamics of freshwater flow and quality (Beier et al., 2022; Ghofrani et al., 2017; Lamond & Everett, 2019).

BGI result from a land management and planning approach that utilises environmental dynamics to address anthropic necessities and providing ecological, social, and economic benefits (Nesshöver et al., 2017). This holds particular significance when considering that traditional and hard-engineering-based approaches relying on watershed management, conservation, or technological solutions to tackle water-related challenges have not met their intended objectives (Anderies et al., 2006; Asbjornsen et al., 2011a).

The understanding of flows between water and ecosystems is conveyed through tools such as ecohydrological modelling, ecosystem and environmental accounting, hydrological monitoring and remote sensing techniques (Izydorczyk et al., 2019; Jarlan et al., 2015; Nedkov et al., 2022). These tools provide insights into the interactions between water cycles and ecological processes, enabling more effective management of water resources and ecosystems in changing environmental conditions. For instance, to mitigate air and water pollution, the filtration capacity of specific types of vegetation and soils is employed to remove pollutants (Dutta et al., 2021; Nguyen et al., 2022). To address flood risks, floodplains or stormwater ponds, they can be utilised to retain excess water, reduce peak flows, and facilitate groundwater recharge. These nature-based strategies harness ecological processes to enhance environmental resilience, demonstrating the multifunctionality of BGI in urban and rural settings (Alvarado et al., 2019; Tache et al., 2023).

The fundamental significance of ecosystems in regulating numerous hydrological processes, and vice versa, has been acknowledged for a considerable period, garnering recognition from ecologists and hydrologists. This awareness enhanced and broadened comprehension of water fluxes, circulation, and conveyance within their respective fields. Nevertheless, the cooperation of these disciplines has traditionally encountered restrictions or fragmentation. In the early 20th century, the first scientific studies explained the connections between vegetation-water interactions and watershed-scale reactions (Asbjornsen et al., 2011b; D'Odorico, 2019; Eagleson, 2000; Engler, 1919; Rodriguez-Iturbe , 2004).

The term Ecohydrology first appeared in literature in 1987 with Ingram in peat wetland research in Scotland (Ingram, 1987; X. Li et al., 2017) and in the same year with De Molenaar regarding the floral and vegetational patterns in arctic landscape ecology (De Molenaar, 1987).

The role of Ecohydrology in ensuring the sustainability of global waterways has seen a rapid increase in investigation since UNESCO introduced the concept as a priority topic in 1992 at the United Nations Conference on Water and Environment. For instance, UNESCO/IHP-V initiated the project "Hydrology and Water Resources Development in a Vulnerable Environment" to promote the sustainable utilisation of landscape resources and ecohydrological processes. With the evolution of the concept and the utilisation of ecohydrological tools, our understanding of interactions and dynamics within river systems, floodplains, wetlands, and the hydrological cycle across various ecosystems, climatic and geographical regions has significantly advanced. This enhanced understanding has played a central role in evaluating waterway conditions and vulnerabilities globally (Janauer, 2000).

In particular, the work of two figures who have made parallel yet distinct contributions to the current methodological framework, Ignacio Rodriguez-Iturbe and Maciej Zalewski, gave an essential structure to the research.
Rodriguez-Iturbe focused on analysing the emergent properties of hydrological systems, mainly modelling hydrological processes at the watershed level. His approach aimed to understand how basin-level hydrologic processes influence the ecology and how these processes can be managed sustainably (Rodriguez-Iturbe, 2000). He focused on the interactions between vegetation, soil, and water in semi-arid and arid environments (Porporato et al., 2002; Rodriguez-Iturbe & Porporato, 2005; Cammeraat et al., 2010; Cleverly et al., 2016) and the connection between hydrologic and human mobility networks (Rodriguez-Iturbe et al., 2009b).
He developed innovative mathematical models to understand the role of vegetation in the water cycle and to analyse how human activities influence water resources (Jun & Yongyong, 2008; Li et al., 2016). In particular, he emphasised the importance of conserving water resources in arid and semi-arid regions, where the consequences of climate change are notably intense. Thanks to his research, Rodriguez-Iturbe opened new ways to sustain water resources and conserve water ecosystems (Rinaldo & Rodriguez-Iturbe, 2022).
On the other hand, Zalewski focused on the integrated management of water resources and cultural influences. His approach is based on the idea that understanding local culture and traditional practices is essential to developing sustainable water resources management strategies. He is responsible for the methodological framework of the ecohydrological approach, which has been, and still is, adopted in numerous subsequent research and projects.
Furthermore, awareness was raised regarding over-engineering and its side effects. As Zalewski claimed, the mechanistic approach has led to the overengineering of the environment, seriously diminishing the consideration of the role of ecological processes in regulating the water cycle (Zalewski, 2002).
Indeed, there is clear evidence that an approach based on hard engineering alone cannot be compatible with the sustainable transition and the conservation of water systems and their biodiversity (Revenga et al., 2000). The restoration of aquatic ecosystem capacity has an undeniable positive impact on water retention and self-purification, coping with the simplification of habitats and consequent ecological degradation.
Zalewski, therefore, promoted an integrated approach to sustainable water resource management that considers the ecology of river systems. With the WBSR approach (Water, Biodiversity, Ecosystem Services, and Resilience), he emphasised the importance of incorporating sociological and cultural perspectives in achieving sustainable development (Wagner & Breil, 2013). It also highlighted how hydrological dynamics play a complex role in determining ecosystem changes and that people are crucially involved in causing, managing and mediating such changes.
“Ecological Foundations for River Management”, published in 1997 by Zalewski, introduces the concept of “ecological integration” in river management (Zalewski, 1997). This approach proposes to consider river ecosystems as a whole, taking into account the relationships between the biological, physical, and chemical components of the river for a more sustainable management of water resources (Eagleson, 2000; Heimsath, 1997; Mari et al., 2014; Maritan, 2002; Montgomery, 1988, 1992; Porporato, 2022; Rodriguez-Iturbe, 2004; Rodriguez-Iturbe, 2001).
In “Integrated Watershed Management: Ecohydrology & Phytotechnology” he considered the ecology of river systems in water resource management at the watershed scale (Zalewski, 2008). He proposed an integrated approach that combines ecological conservation, ecosystem service assessment, and innovative technologies such as phytotechnology for sustainable water resource management.
In “Ecological Modelling for Resource Management”, Zalewski tackled the importance of ecological modelling for sustainable water resource management (Zalewski, 2012). He used integrated models to consider the fluxes between river systems' biological, physical, and chemical components for management of water resources and long-term planning.

Regarding the cultural and social perspective, he emphasised their fundamental role in influencing the management of hydrological and ecological systems. In particular, he highlighted how cultural practices influence decisions made by local communities on water resource management and biodiversity conservation. Culture can also affect people's perceptions of nature and its processes and, thus, their attitudes toward sustainable environmental management.
Hiwasaki and Aricò (2007) went further and defined conceptual and methodological approaches to analyse the linkages between water and people at international and intergovernmental levels (Hiwasaki & Arico, 2007). In this regard, UNESCO-IHP, through its 9 phases, has played an important role in researching, developing, and proposing Ecohydrology as the best practice for environmental management, fostering cooperation, and sharing achievements. They also introduce the WBSR+CE to illustrate that all actions and investments in catchment area water management should enhance four key aspects: "Water, Biodiversity, Services for society, and Resilience to climate change and anthropogenic impacts". The successful implementation of these aspects should be widely supported by culture and education related to water sustainability, fostering society's informed and prudent engagement. Additionally, WBSR links NESC-IHP and the Sustainable Development Goals (Bridgewater, 2021).

Table 1. SGDs targets and Ecohydrology's potential, and actual, contribution area (Bridgewater, 2021).

Target	Action
6.1	By 2030, achieve universal and equitable access to safe and affordable drinking water for all (link to 6.4, 6.5, 6.6, 13.1, 15.1,15.3)
6.4	By 2030, substantially increase water-use efficiency across all sectors (link to 6.1, 6.5 6.6, 15.3)
6.5	By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate (link to 13.1,14.2,15.1,15.3)
6.6	By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes. (link to 6.1, 13.1, 14.2, 15.1, 15.3)
13.1	Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries (link to 6.5, 6.6, 14.2,14.5, 15.1,15.3)
14.2	By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, (link to 6.5, 6.6, 13.1, 14.5, 15.1)
14.5	By 2020, conserve at least 10 per cent of coastal and marine areas, consistent with national and international law and based on the best available scientific information (link to 6.5, 6.6, 13.1, 14.2, 15.1)
15.1	By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services (link to 6.1,6.5,6.6, 13.1, 15.3)
15.3	By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought, and floods, and strive to achieve a land degradation-neutral world (link to 6.1, 6.4, 6.5, 6.6, 13.1)

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Ecohydrology can, and constantly does, make a valuable contribution to the achievement of the SDGs in various ways, regarding the actions listed in Table 1. For instance, ecohydrological models provide fundamental data for ecosystem services and environmental services accounting, which, in turn, are essential tools for the decision-making process. For instance, the contribution that Ecohydrology can provide may concern the managing and conservation of water resources and water-related ecosystems, improving water quality (SDG 6 Clean Water and Sanitation). Regarding SDG 13

Climate Action, studying water and carbon cycles, Ecohydrological models and approaches can help in understanding climate change effects and Climate Action by studying water and carbon cycles. Indeed, Ecohydrological models and approaches can help in understanding climate change effects while developing adaptation and mitigation strategies. Analysing and taking action on the interactions between ecosystem fluxes, Ecohydrology has among its priorities ensuring Life Below Water (SDG 14). The promotion of biodiversity and the sustainable water resource management that Ecohydrologists carry out, through BGI and sustainable planning, play an important role with regard to Life on Land (SDG 15). These are some of the contributions Ecohydrology can provide, and already provides, to the achievement of the SDGs (Bridgewater, 2021).

5. Conclusions

In light of the findings gained from analysing the literature, both in terms of contents and for the bibliometric network analysis, we can draw the following conclusions.

Water resources' quantity, quality, and timeliness can be significantly altered as human activities change the environment. Ecohydrologists need to create and implement innovative methods to evaluate how climate change may affect ecosystems and water supplies as well as generate adaptation plans to minimise these effects. The substantial amount of literature on Ecohydrology testifies that this approach's importance is well understood. However, the discrete richness observed in the Bibliometric Network Analysis can be seen as a significant indicator of the limited scope of research conducted at the intersection of Ecohydrology and Ecosystem accounting.

The scarcity of comprehensive studies and surveys embracing these fields is reflected in the shortage of information and connections represented in the network maps. The limited examination of the intersection between Ecohydrological processes and Ecosystem accounting practices indicates a potential knowledge gap, emphasising the need for additional research and collaborative endeavours in this domain. By addressing this gap, researchers and policymakers can gain valuable insights into the interplay between ecological and hydrological dynamics and their contributions to ecosystem services and environmental sustainability. Such investigations could foster a more holistic understanding of the intricate relationship between ecological systems and their broader environmental implications, thereby facilitating the development of more effective and integrated strategies for sustainable resource management and conservation efforts. Indeed, Ecohydrological modelling can simulate even the most complex dynamics, predict how the systems will respond to changes, and thus create the fundamental data necessary to develop strategies and foster climate change adaptation.

Including socioeconomic issues in ecohydrological studies and management is another crucial theme for Ecohydrology in the upcoming years. Economic growth and human well-being are closely related to water resources and ecosystems, and socioeconomic issues like land use, water demand, and governance can affect both.

As retraced through the bibliometric network analysis and the literature review, Ecohydrology will have to deal with several important issues and problems in the upcoming years, including managing and restoring ecosystems and managing land use and climate change. Addressing these challenges and ensuring sustainable management of water resources and ecosystem management require collaboration among ecohydrologists, other scientists, stakeholders, and decision-makers.

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