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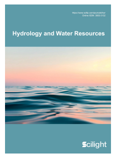

Expert Review

Global Water Resources Management Under Climate and Land Use Changes: Emerging Trends and Future Perspectives

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How To Cite: Yang, Z.; Li, C.; Zhou, X.; et al. Global Water Resources Management Under Climate and Land Use Changes: Emerging Trends and Future Perspectives. *Hydrology and Water Resources* **2026**, *1*(2), 8. https://doi.org/10.53941/hwr.2026.100008

Received: 31 August 2025
Revised: 20 December 2025
Accepted: 23 January 2026
Published: 27 February 2026

Abstract: This study offers a comprehensive overview of global water resource research under climate and land use changes from 1990 to 2025. Using bibliometric analysis and traditional systematic literature review, we analyzed trends, hotspots, and challenges in this field. The results reveal a substantial growth in research output, with an average annual growth rate of 32.07% over the full period, peaking significantly in the post-2020 era due to the proliferation of digital technologies. Early studies (1990–2000) concentrated on hydrological and ecological modeling at the basin scale, while the intermediate period (2001–2015) emphasized climate scenario downscaling and integrated water resources management. Recent research (2016–2025) represents a paradigm shift toward systemic complexity, integrating socio-economic aspects such as the water-energy-food nexus, carbon emissions, and environmental justice. Key advancements between 2020 and 2025 include the operational transition of AI and digital twins for monitoring and decision support; transformative observational advances from satellite missions such as SWOT (launched in 2022) and the continuing GRACE-FO; and a growing, evidence-based focus on the trade-offs inherent in implementing sponge city and broader nature-based solutions under climate and land-use change. Furthermore, the study highlights the necessity for interdisciplinary and multi-scale methodologies to tackle the intricate interactions between climate, land use, and water resources. Major challenges involve bridging the "digital divide" in data-scarce regions, overcoming the "black box" interpretability limitations of machine learning models, and translating scientific consensus into actionable policy for global water resilience. This research provides insights and guidance for future research studies and policy-making, aiming to promote effective and sustainable water resource management in response to global environmental changes.

Keywords: water resources; climate and land use changes; research foci and hotspots; research trends and challenges; bibliometric analysis

1. Introduction

1.1. Global Water Resources Status

Water resources are essential for the survival of human beings and for supporting ecosystem services, functions, and socio-economic systems [1,2]. Throughout history, water resources have supported agriculture, industrial production, domestic use, energy generation, and sanitation, among other sectors [3–5]. However, in recent decades, surface and groundwater systems have faced unprecedented quantitative and qualitative pressures [6–8]. Driven by climate change (CC) and land use change (LUC), global water consumption and pollution levels are predicted to escalate further [9,10]. The demand for freshwater has surged exponentially to meet the needs of the increasing global population, especially during the COVID-19 pandemic, when there was a high demand for clean water and sanitation. This has led to a critical imbalance between water supply and demand. Notably, global water use has increased six-fold over the past century and continues to rise by approximately 1% annually, while terrestrial water storage has declined at a rate of 1 cm per year [11,12]. Recent data from the Food and Agriculture Organization revealed that rapid population growth has driven a decline in per capita freshwater availability of over 20% in the last two decades, pushing many nations toward the water stress threshold. Specifically, approximately 57% of the global population will face clean water scarcity by 2050, as reported by the United Nations World Water Development Report [12]. This crisis is compounded by widespread pollution affecting over 100 countries, severely hindering progress toward the United Nations Sustainable Development Goals (SDGs) [2,13]. Such scarcity precipitates cascading failures, including aquifer depletion, land subsidence, salt intrusion, crop destruction, fish stock depletion, delta disappearance, energy crisis, and food security. On the other side, water distribution is spatially and temporally heterogeneous worldwide. World Bank statistics indicate that the top ten resource-rich countries possessed over 60% of the world's total renewable water in 2022. The increasing interannual and interdecadal variability and uneven distribution exacerbate disaster risks and economic losses. Therefore, the strategic protection and adaptive management of water resources have become urgent priorities for ensuring long-term economic and societal sustainability.

1.2. Water Resources in a Changing Environment

As a global scientific issue, water resources remain a thriving research domain that has experienced numerous developments over the past three and a half decades. Water resources are highly affected by climate and land-use changes, which have attracted tremendous attention among researchers and managers [14–16]. Over the past several decades, global warming has driven widespread glacier retreat, snowmelt, permafrost degradation, sea-level rise, and seawater intrusion, posing severe threats to water stability and security [17–19]. A comprehensive 2024 assessment by the UN Environment Programme (UNEP) revealed that freshwater ecosystems are now degraded in half of the world's countries, with river flow significantly decreased and pollution levels rising globally [20]. According to the World Meteorological Organization (WMO) report released in 2025, the global mean surface temperature in 2024 was 1.55 °C higher than the 1850–1900 baseline, making it the hottest year on record and surpassing previous IPCC AR6 decadal averages [21]. Furthermore, the UNEP indicates that global greenhouse gas (GHG) emissions set a new record of 57.1 $GtCO_2e$ in 2023, increasing by 1.3% from 2022 levels—exceeding the average growth rate of the previous decade [22]. This warming significantly enhances the ability of the atmospheric boundary layer to accommodate water vapor, thereby increasing the intensity and frequency of hydroclimatic extremes [23]. Consequently, this has accelerated the water cycle rate and altered runoff formation processes, leading to increasingly erratic "drought-to-deluge" transitions in many regions worldwide [24].

The climate mitigation targets set by the Paris Agreement have catalyzed a transformative research agenda aimed at limiting global warming to below 2 °C, with aspirations to stay within the 1.5 °C threshold [19]. Despite these ambitions, there remains a critical gap in synthesizing innovations and addressing challenges to achieve net-zero GHG emissions in line with these goals [25]. Zhang [26] suggested that if global temperatures rise by 1 °C, the 5–day average of consecutive heavy precipitation in China will intensify by approximately 6.5%. The increasing frequency and intensity of extreme hydrometeorological events—including unpredictable precipitation events, persistent or sudden droughts, floods, typhoons, and heatwaves—introduce new challenges to achieving SDGs [27,28]. While global observations indicate that regions experiencing intensified heavy precipitation now outnumber those seeing a decrease [29], higher total precipitation in arid regions may be offset, or even overcompensated, by increased evaporation in a warming atmosphere, potentially leading to a net deficit in water availability. Furthermore, large-scale teleconnections and oceanic-atmospheric oscillations—such as the Gulf Stream, the North Atlantic Oscillation, the El Niño-Southern Oscillation, the Pacific Decadal Oscillation, and the Atlantic Multidecadal Oscillation—modulate the global hydrological cycle by redistributing energy, heat, and moisture [14,17,30]. CC is likely to exacerbate the vulnerability of water resources, making water management increasingly complex and challenging. A poignant example occurred in 2022, when a record-breaking compound heatwave and extreme drought—driven by the synergy of high temperatures and precipitation deficits—caused water levels in China's largest freshwater lake to plummet to unprecedented lows, underscoring the urgent need for adaptive management.

Parallel to climatic drivers, LUC exerts a crucial influence on the global hydrological cycle and climate system, which is essential for forecasting future freshwater availability. A previous study quantified that LUC increased global runoff by 0.08 mm/year^2, contributing nearly 50% of the reconstructed global runoff trend over the last century [30]. In the past few decades, land use types have changed significantly worldwide due to continuous population growth, expansion of agricultural areas, energy-intensive activities, and the acceleration of industrialization and urbanization [31,32]. The rapid expansion of impervious surface area has drastically attenuated soil infiltration and natural water storage capacities. Consequently, the heightened frequency of urban pluvial flooding between 2020 and 2025 has catalyzed a shift toward integrated management that synchronizes regional climate resilience with sponge city concepts and nature-based solutions [33]. Furthermore, recent research has highlighted the complexity of land-water feedbacks; for instance, Humphrey [34] noted that terrestrial greening over the last two decades has offset approximately 15% of the reduction in surface water availability. Beyond simple coverage shifts, modifications in terrestrial biogeophysical properties—including surface albedo, roughness, soil moisture, and latent heat fluxes—directly modulate the exchange of energy and GHGs. These alterations perturb key hydrological fluxes such as convective precipitation, infiltration, evapotranspiration, and large-scale water vapor transport [35].

Beyond the hydro-physical dimensions of precipitation, evapotranspiration, and sea level rise, the socio-hydrological complexities of water resources under the dual pressures of climate and land use change have become increasingly prominent. During the 2020–2025 period, the global population surpassed the 8 billion milestone (late 2022), coupled with accelerated urbanization and post-pandemic industrial recovery. These dynamics have profoundly reshaped water demand and utilization patterns, intensifying competition for water rights among agricultural, domestic, and industrial sectors [2,18]. The expansion of impervious surfaces has compromised infiltration capacities and heightened the risk of urban waterlogging, requiring integrated planning that considers both climatic conditions and land-use status. Moreover, energy-intensive activities and irrigation practices have emerged as primary drivers of water consumption, altering regional water balances and exacerbating scarcity in vulnerable areas [1]. These socio-economic pressures highlight the importance of water resource development, allocation, and management strategies that incorporate sustainability principles and address trade-offs between economic growth, environmental protection, and social equity [5,9]. Consequently, integrating human dimensions into hydrological research is imperative for fostering resilience and effective governance.

The synergistic interplay of CC and LUC exerts far-reaching implications for aquatic ecology, environmental integrity, and water security, fundamentally reshaping the paradigms of water resource planning and management [36]. Beyond environmental repercussions, targeted interventions to mitigate CC and LUC have been shown to yield significant socio-economic co-benefits, ranging from job creation and poverty alleviation to improvements in public health and social equity [37]. Consequently, the dynamics of water resources within these evolving environments have become a focus of international research efforts in both the natural and social sciences, which have captured the attention of local and global decision-makers and stakeholders [38–40]. While a wealth of high-quality research has addressed domains such as hydro-climatic coupling, the water–energy–food–carbon nexus, and satellite-based groundwater monitoring [32,41,42], much of the existing literature remains compartmentalized. These fragmented investigations often provide localized insights that lack scalability across broader spatiotemporal scales. Hence, a systematic synthesis of the status, foci, trends, and hotspots of water resources at the global scale is imperative to provide a long-term, holistic perspective on water resource resilience.

1.3. Analysis of Research Progress

Over the past three decades, research on global water resources under the dual pressures of climate and land-use changes has exhibited a clear trajectory of methodological and thematic evolution. The 1990s were characterized by a focus on hydrological and ecological modeling at basin scales, emphasizing vegetation dynamics, precipitation variability, evapotranspiration, and runoff processes, and reflecting the centrality of land–atmosphere–hydrology couplings in diverse climatic and land-use contexts [14]. Entering the 2000s, the scientific scope expanded to flux measurements and large-river sediment diagnostics, including systematic assessments of water and sediment fluxes in major basins worldwide. This era was marked by the identification of a distinct 'anthropogenic signal' where deforestation, dam construction, irrigation, and land clearance fundamentally altered hydrological regimes [30]. From 2006 to 2015, the field pivoted toward the integration of coupled human-natural systems, elevating resilience, adaptive capacity, and socio-economic drivers to the forefront of the research agenda; concurrently, comparative evaluations of global hydrological and land-surface models provided new insights into large-scale water resource dynamics and underscored model limitations and data needs [34]. Since 2016, progress has accelerated around interdisciplinary frameworks—most notably the water–energy–food nexus and carbon–water linkages—alongside the deployment of advanced monitoring technologies and flux assessments. These efforts have increasingly aligned empirical observation and modeling with sustainability and climate mitigation agendas [8]. Entering the post-2020 era, the field underwent a further transformative shift. The COVID-19 pandemic served as a pivotal systemic stress test, exposing vulnerabilities in water infrastructure while simultaneously catalyzing a transition toward remote sensing and big-data-driven hydrology. Furthermore, the 2020–2025 interval has been defined by the integration of generative AI and large language models into disaster risk communication and the maturation of multi-source data fusion. Collectively, this evolution marks a shift from localized, process-based studies to global, socio-ecological perspectives, aiming to balance economic recovery with climate resilience and environmental justice under the framework of the United Nations 2030 SDGs.

1.4. Main Work and Meaning

The study provides a bibliometric analysis by synthesizing research on global water resources under CC and LUC from 1990 to 2025, with a focus on evolving interdisciplinary approaches such as the water-energy-food nexus and emerging technologies like GRACE for groundwater monitoring. Specifically, this study offers: (i) a comprehensive overview of how research trends have shifted from natural and ecological drivers of water systems toward the integration of societal and economic factors; (ii) systematical identification of under-researched areas where further work is necessitated, including inter- and multi-disciplinary prospects that couple hydrology, socioeconomics, and sustainability [13,37]; and (iii) scientific insights that can inform policymakers on current research gaps and potential focus areas for decision-makers and early-career researchers [10].

To achieve these goals, the study aims to (i) visualize the global research landscape—including outputs, countries, research foci, hotspots, trends, and challenges—over the past 35 years; and (ii) elucidate high-frequency keywords, burst detection, and co-network analysis by combining bibliometric analysis and traditional literature review method. This study provides a quick reference for water science research in a changing environment and guide practices for the effective management of water resources, particularly addressing gaps in socio-economic integration with water management models, thereby paving the way for future inter- and multi-disciplinary studies.

2. Bibliometric Analysis

Bibliometric analysis was conducted to quantitatively examine publications, evolutionary trends, and future prospects of the research field by performing illustrative data representation and preparing figures [10,43]. Figure 1 shows the research methodology framework. To achieve this, CiteSpace and R-based tools were combined, enabling rapid identification of research area distributions and the comprehensiveness of research content [13]. The SCIE database within the Web of Science Core Collection was selected as the primary source, given its reliability, rigorous peer-review standards, and provision of updated and systematic information for scientists and researchers [44].

The search strategy utilized a combination of specific keywords including “water resources”, “climate change” and “land use change”. The search terms were combined using the “AND” logical operator to ensure comprehensive coverage. In total, 10324 studies published between 1990 and 2025 were extracted and analyzed. These records included theses, conference proceedings, and peer-reviewed journal articles, and were exported with metadata such as titles, authors, abstracts, keywords, and references to organize the local database.

CiteSpace, developed by Chaomei Chen’s team at Drexel University, was applied to explore the intellectual bases, trends, and frontiers of the literature [45,46]. This software generates diverse visualizations to reveal evolutionary characteristics and critical developmental points within a domain [47]. In this study, to clearly review the water resources in a changing environment, article outputs, citation frequencies, high-frequency keywords, burst keywords, innovative literature, keywords co-occurrence, and references co-citation networks were analyzed. Article outputs were considered as indicators of research productivity, reflecting the development trajectory of the field, while citation counts served as proxies for research quality [48,49]. Keywords, as condensed descriptors of research content, were analyzed to highlight research foci [50]. Furthermore, burst detection was applied to identify the emerging directions through burst intensity index [37]. For keyword co-occurrence analysis, the Pathfinder algorithm was applied with data selection criteria set to the top 50% and a time-slice interval of 5 years [13,45].

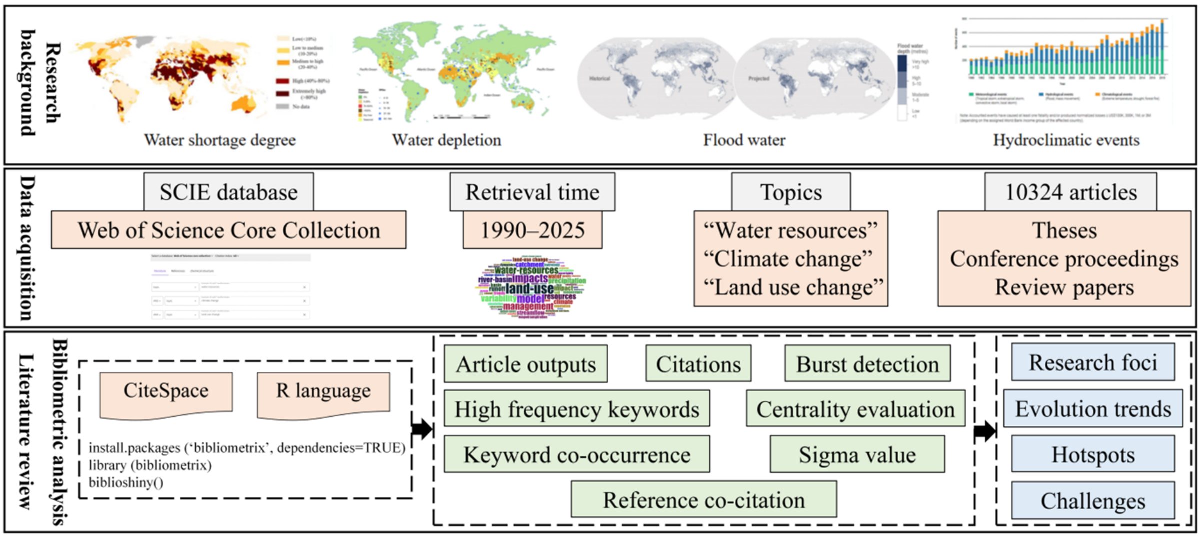

Figure 1. Research methodology framework.

Complementing CiteSpace, the bibliometrix package (version 3.0) in R was used to facilitate data collection, analysis, and visualization, providing a comprehensive representation of research evolution and academic impact [51]. Geographic distribution of outputs was also mapped to reveal global research patterns and disparities. Meanwhile, a traditional systematic literature review method was conducted alongside bibliometric analysis to provide a systematic and in-depth analysis.

3. Results

Research on water resources under climate and land use change has progressed through distinct phases, reflecting shifts in focus and methodology. The 1990s emphasized natural hydrological processes such as precipitation, evaporation, runoff, and groundwater recharge, relying mainly on field observations and regional case analyses [3,8,41]. From the 2000s onward, attention expanded to global drivers including greenhouse gas emissions, ocean circulation, and land-use transitions, with remote sensing, GIS, and statistical modeling increasingly applied to capture spatial and temporal dynamics [14,17,30]. The early 21st century advanced toward integrating high-resolution climate models, satellite monitoring, and machine learning to examine the water–energy–food–carbon nexus, resilience under extreme events, and governance frameworks [5,9,39]. The 2020–2025 period has redefined the field through a 'digital and resilience' revolution. This era is characterized by the synergy of high-resolution satellite monitoring, AI-driven interpretability, and the implementation of nature-based solutions under extreme climate pressures. This evolution demonstrates a clear shift from localized, single-document studies to broader, multi-scale syntheses that combine physical, ecological, and social dimensions, providing a more comprehensive understanding of water resources in dynamic environments [2,25,42].

3.1. Research Outputs Trends

The annual number of global research outputs showed an exponential increase from 3 in 1991 to 1180 in 2025, with an average annual growth rate of 32.07% (Figure 2a). The fitted trend line was $y = 8.93e^{0.22x}$, with an R^2 of close to 1 (0.99), indicating an excellent fit. While the pre-2000 era was characterized by a slow growth phase with total outputs below 100, a significant acceleration occurred in the 21st century, with over 93.65% of the outputs published after 2010. Geospatial analysis (Figure 2b) further identifies China and the United States as the primary contributors, which together accounted for 52.35% of the total outputs (Figure 2c).

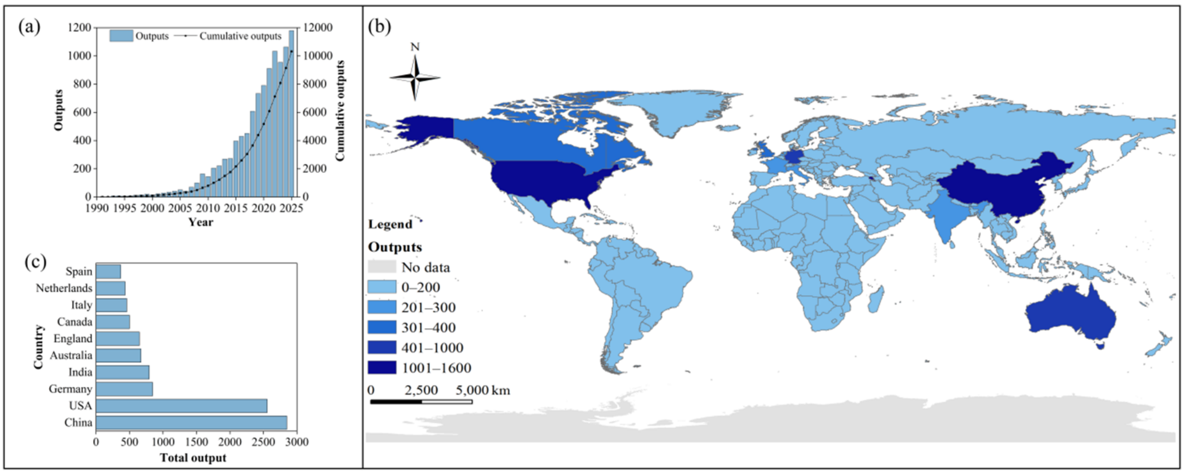

Figure 2. Geographic distribution and temporal evolution of global research outputs in water resources research. Outputs refers to the number of published papers.

3.2. Keyword Analysis

High-frequency keywords. Beyond the primary retrieval keywords ("water resources", "climate change" and "land use change"), the main high-frequency keywords included "hydroclimatic modeling", "ecosystem services", "water governance", "groundwater geochemistry", "vegetation mapping", and "climate change adaptation". Overall, developing hydrologic, climatic, and/or land surface models to investigate the impacts of various global change factors (CC and LUC) on water resource availability, and/or developing integrated watershed management policies, were important research foci in the field of water resource research under a changing environment [52].

Keywords burst detection. Burst detection revealed the rapidly rising research topics and emerging directions in specific years. The topic "CO_2" exhibited the highest burst intensity (23.54) with the longest active duration of 24 years, coinciding with a major surge in climate-water-related research. The term "climate" emerged as early as "CO_2" in 1990, with a burst intensity of 13.59. **Not strangely, Climate Change remains a long-debated and inevitable topic in water resources research. "Simulation" was also a strong emergent term, with a burst intensity of 13.92.**

3.3. Co-Network Analysis

3.3.1. Co-Occurrence Analysis of Keywords

Co-occurrence analysis of keywords can contribute to the identification of main research topics and trends. This paper visualized the keyword co-occurrence network from a time zone perspective, and the thirty-five years were divided into five distinct phases (Figure 3). From 1990 to 2000, the terms "vegetation", "evapotranspiration", "precipitation", "carbon dioxide", "forest" and "response" were the main keywords. From 2001 to 2005, keywords such as "global warming", "flux", "streamflow", "catchment" and "crop" appeared more frequently. The IPCC reported in 2001 that global warming in the 20th century was unprecedented compared to the past millennium [53], which attracted widespread interest from researchers in the water resources field. Notably, the keyword "fluxes" showed a rapid increase in occurrence during this stage. From 2006 to 2015, the keywords "adaptive capacity", "risk", "use efficiency", "resilience", "water budget" and "assessment tool" received significant attention, marking a shift toward adaptation strategies and quantitative assessment [54]. In the fourth phase (2016–2020), "groundwater quality", "carbon", "synergy" and "world" emerged as important research topics, indicating growing concern for subsurface water security and global-scale connections [55]. In the most recent phase (2021–2025), a paradigm shift towards intelligent and systemic management is evident. Emerging keywords such as "artificial intelligence", "machine learning", "digital twins", "nature-based solutions", and "water-energy-food-health nexus" have surged in frequency. This trend highlights the rapid integration of advanced digital technologies (e.g., AI-driven forecasting and the SWOT satellite mission) with holistic ecological strategies to address complex hydro-climatic challenges in the post-pandemic era [56].

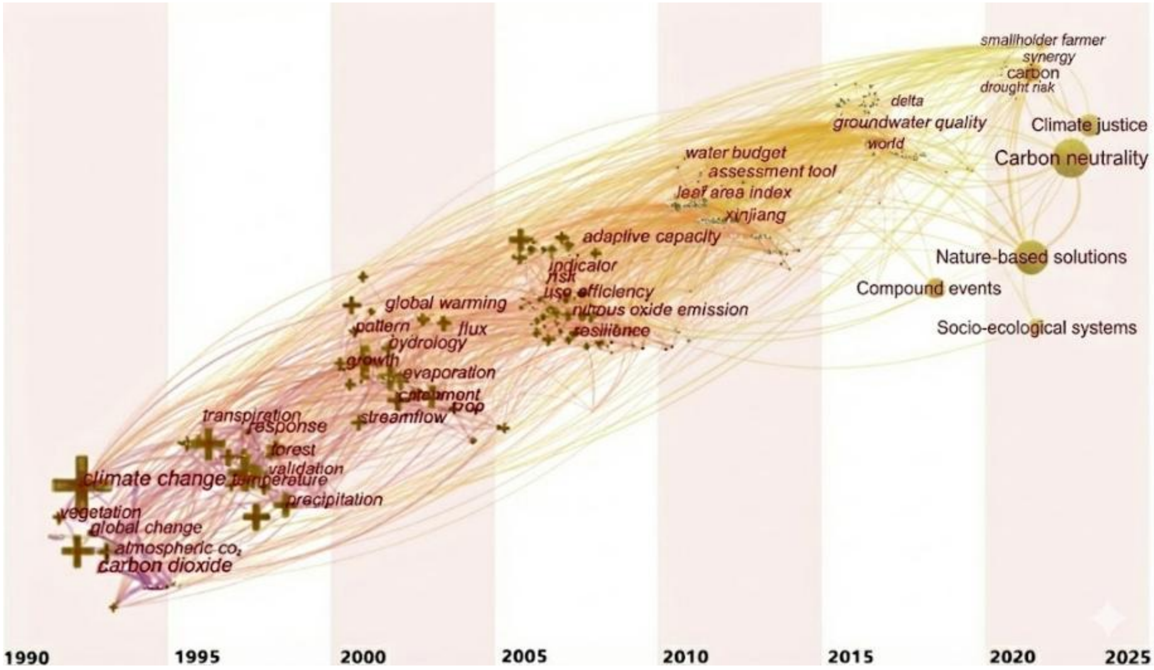

Figure 3. Relationships among keywords in the targeted field. The horizontal axis represents the year, each node represents a popular keyword, and the size of each node is proportional to its frequency of occurrence. The line between each node represents the temporal evolution of the keyword; these lines reflect the connections between keywords, indicating how certain terms have been transferred or adopted in newer studies while others have been inherited from previous research.

1990–2000. The primary focus of the global water resources research was ecological-hydrological-geomorphological processes. Specifically, vegetation, as a key indicator of global change, was recognized as crucial for ecohydrological regulation through evapotranspiration [38,57]. During this period, the mechanisms of atmosphere–hydrology–vegetation interactions under different climatic and land-use conditions were extensively explored. Furthermore, many countries began to implement low-impact development strategies in the 1990s, and various measures were implemented to control stormwater runoff and pollution. Additionally, the parameterization of second-generation land surface atmospheric models incorporated the effects of the hydrologic cycle and vegetation on energy and water fluxes by the mid-1980s. The structure of vegetation can regulate water fluxes across the biosphere–atmosphere interface with great effects on water resources [58]. As an important land-use type and one of the identified co-occurrence keywords in this period, forests could provide important climate forcing and feedback by exchanging energy, water, carbon dioxide, and other chemical species with the atmosphere [59]. Moreover, increasingly frequent droughts or floods significantly affected the composition, structure, and functions of global forest ecosystems [60,61]. Conversely, forests can sequester large amounts of carbon annually to mitigate CC [62]. The most studied region was Amazonia, where large-scale conversion of forest to pasture created a warmer and drier climate. The loss of natural forests worldwide in the tropics during the 1990s was as high as 152,000 km^2 per year, with Amazonian forests cleared at a rate of approximately 25,000 km^2 per year [63].

2001–2005. The measurement of water, heat, and carbon fluxes become an important research avenue in this period. For example, AsiaFlux, ChinaFlux and KoFlux were established in 1998, 2002, and 2000, respectively, to promote the development of long-term flux observations in water resource research [62]. Long-term water-sediment and GHGs fluxes emerged as critical research areas. The global water and sediment fluxes in 4307 large rivers (basin area ≥ 1000 km^2) worldwide were systematically evaluated [64]. As a whole, water flux variation in most of the world's large rivers was closely related to precipitation changes, while sediment flux variation was greatly correlated with LUC caused by human activities such as deforestation, dam construction, mining, land clearance, irrigation, and water–soil conservation projects [14,64]. The observation of CO_2 fluxes in terrestrial and river ecosystems, together with water, energy, nutrient cycles, and ecosystem dynamics, was recognized as essential for predicting and managing water resources in a changing environment [22].

2006–2015. From 2006 to 2015, a more comprehensive understanding of the inherent consistency among water resources, climate, and land-use changes was developed, further expanding research on the interaction between water and human social systems. Therefore, enhancing the resilience of water systems and reducing/preventing water risks in a changing environment became important issues in this period [61,65]. The World Bank emphasized promoting water security worldwide by sustaining water resources, delivering services, and building resilience. Climate-resilient development pathways also emerged as a new paradigm for sustainable water security [66]. Environmental change aggravated water scarcity risks from a supply-based perspective in most regions [2,67]. Meanwhile, the normal metabolism of water consumers and mitigation options against CC and LUC directly and indirectly affected water usage from a demand-based perspective [9]. Considering the adaptive capacity and behavioral characteristics of water consumers was highlighted as a way to improve water-use efficiency. For instance, coupled human–natural systems were increasingly applied to review the progress of urban water demand modeling methods, while urban water adaptive landscapes were proposed to improve the carrying capacity of water resources and human settlements.

2016–2020. During this period, rising temperatures accelerated evapotranspiration, altered precipitation regimes, and increased the frequency of extreme events such as droughts and floods, thereby reducing the reliability of surface water supplies. At the same time, urbanization, deforestation, and agricultural expansion intensified runoff variability, reduced infiltration, and increased pollution loads, further destabilizing surface water quality and quantity. This inherent instability of surface water—driven by the synergistic impacts of climate-induced hydrological polarization and human-induced land degradation—pushed researchers to seek more reliable alternatives. As a result, research focus shifted to groundwater, which represents the largest freshwater storage on Earth, provides a more stable supply during droughts, and supports over 43% of global irrigation and 20% of total water use [8]. Notably, this period marked a critical transition from localized, site-specific aquifer characterization to quantifying global-scale groundwater depletion and its socio-ecological consequences. Advances in satellite monitoring (e.g., GRACE), integrated hydrological models, and machine learning enabled more precise analysis of groundwater systems, reinforcing this shift in emphasis. “Groundwater quality” emerged as an important burst keyword in co-occurrence analysis, consistent with the “GRACE” clustering theme, which highlighted the role of satellite monitoring in groundwater system measurement. The thematic focus during this stage significantly deepened from basic chemical monitoring to assessing the intricate nexus between geogenic contamination (e.g., arsenic and fluoride) and human health risks under the combined pressures of intensive overexploitation and climate variability. Accurate measurement and monitoring of groundwater storage and fluxes are critical for water, food, and energy security.

The magnitude and timing of groundwater recharge and discharge and fluctuations in groundwater levels were profoundly influenced by CC (e.g., rainfall, snowmelt) [7]. Consequently, a prominent research trend emerged during this stage centered on evaluating the sensitivity and resilience of groundwater-dependent ecosystems to hydro-climatic shifts. Increasing evapotranspiration and decreasing precipitation aggravated groundwater withdrawals and overexploitation, posing threats to groundwater quality and security. LUC could either suppress or amplify groundwater responses to CC. Although groundwater quality deterioration was less visually apparent than surface water changes [44], it attracted significant attention worldwide. Furthermore, research themes in this phase began to move beyond isolated hydrological assessments, increasingly integrating groundwater into broader global water governance frameworks and examining its strategic role as a buffer within the water-energy-food nexus. To avoid health risks from exposure to contaminated groundwater, efficient technologies to ensure clean water supply are urgently needed [68]. At the same time, “carbon” was another crucial keyword in this stage. The United States, the European Union, and China were the three largest contributors to CO_2 emissions, with the goal of achieving carbon neutrality by 2050 or 2060. Approximately 33% of anthropogenic carbon is emitted from LUC and fossil fuels [57]. Studies also suggested that land-to-ocean carbon transport through inland waters, estuaries, tidal wetlands, and continental shelves was often ignored [69]. Changes in water chemistry associated with extreme climate events could increase carbon emissions in rivers. Recently, the determination and generation mechanisms of GHG sources and sinks in water conservancy projects have become a hot research topic worldwide [16,70]. Seasonal or annual variations in water-related GHGs based on long-term observations or simulations remain to be developed.

2021–2025. In the post-2020 era, the convergence of digital innovation and ecological sustainability defined the research frontier. The exponential growth of publications featuring “artificial intelligence” and “deep learning” indicates a methodological transition from traditional physically-based models to data-driven or hybrid paradigms. These technologies are increasingly deployed to forecast extreme hydro-climatic events and optimize reservoir operations under deep uncertainty. Concurrently, the concept of “digital twins” has transcended manufacturing to become a cornerstone of smart water management, enabling real-time simulation and dynamic control of urban water systems and river basins. On the observational front, the launch of the SWOT satellite mission in 2022 marked a revolution in global monitoring, addressing critical data gaps in river discharge and lake storage with unprecedented high-resolution measurements. Furthermore, the focus on urban resilience has solidified “nature-based solutions” and "sponge cities" as dominant adaptation strategies against urban flooding and heat islands, moving beyond the "grey infrastructure" dominance of previous decades. Finally, the COVID-19 pandemic catalyzed the expansion of the nexus approach to include public health, giving rise to the "water-energy-food-health nexus", which emphasizes the critical role of water security in maintaining public health and systemic stability in a volatile world.

3.3.2. Co-Citation Analysis of References

To explore the research trends across different periods, a co-citation analysis of references was applied. The temporal evolution of clustering themes could be divided into four phases. In the first phase (1990–2000), "public infrastructure" and "general circulation models" (GCMs) were identified as two major clustering themes. During the second stage (2001–2010), the breadth and depth of research significantly improved, the theoretical system was gradually enhanced, and the application value received extensive attention. The main clustering topics—including "temperature", "carbon dioxide", "planning", "food prices", "conservation tillage" and "water resources assessment"—flourished. From 2011 to 2020, the "water–energy–food nexus" and "GRACE" were the leading research topics. In the most recent phase (2021–2025), themes such as "compound extremes", "wastewater-based epidemiology", "circular economy" and "net-zero water" rose to prominence, reflecting a shift towards systemic risk management and sustainability limits.

1990–2000. During this period, the increasing population placed severe stress on public water infrastructure. Besides, there was a drive to construct, operate, and refurbish water infrastructure in response to the SDGs to address the water crisis and keep pace with water demand [25]. Many studies explored atmospheric circulation models with future CC and LUC scenarios to analyze water resources. However, accurately predicting how the climate would change was still challenging. GCMs and their outputs remained crude and were often inappropriate for watershed-scale hydrological analyses due to their relatively coarse grid resolution, computationally expensive downscaling, and simplified physical processes.

2001–2010. More dramatic LUC and CC exacerbated water vulnerability, posing threats to food security and even human health during this period. The global grain crisis erupted, attributed to water shortages, more frequent natural disasters, land degradation, urban expansion, cropland reduction, outdated agricultural infrastructure, increasing crop demand from population growth, and improved living standards, among other factors.. An imbalanced supply and demand for food, feed, fiber, and fuel caused commodity prices to rise, increasing the livelihood burden for people living in poverty worldwide. Compared to early 2006, the global prices of rice, wheat, corn, soybean, and biofuels rose by 217%, 136%, 125%, 107%, and 75% on average, respectively. Driven by these global challenges, water resource research during this stage underwent a critical shift from traditional irrigation engineering toward a more systemic evaluation of "water productivity". Scholars intensified the development of crop-water production functions and water-use efficiency models to optimize limited resources.

Furthermore, this period marked the academic maturation of the "Virtual Water" and "Water Footprint" theories, which allowed researchers to quantify the hidden water flows in global grain trade and analyze how international markets could either alleviate or exacerbate regional water scarcity. Some studies also demonstrated that food security and prices were linked to ozone levels. A recent study showed that the yields of wheat, rice, and maize in China were reduced by 33%, 23%, and 9%, respectively, due to the increased ozone concentrations [63]. Consequently, a key research hotspot emerged around the synergistic impacts of multiple environmental stressors, specifically focusing on how water scarcity interacted with atmospheric changes (e.g., ozone pollution) and LUC to affect agricultural resilience. The development of irrigation systems and water-saving technologies was emphasized as essential and sustainable solutions to stabilize crop yields and mitigate high food prices. At the same time, land restoration and soil–water conservation practices—including vegetation rehabilitation, soil and water conservation measures, and desertification control—were widely implemented to enhance water availability and agricultural resilience [71]. Conservation tillage and sustainable farming systems, such as minimum tillage, no-tillage, and reasonable planting, were promoted to reduce soil loss, improve water retention, and increase crop productivity. In addition, scholars examined how water resource vulnerability interacted with atmospheric changes, showing that water scarcity combined with ozone pollution and climate variability could further affect food production.

2011–2020. Water, energy, and food, as key international resources and environmental issues, are the material bases for human survival and social development. The coupling, collaboration, and linkages of water-energy-food, especially in virtual water trade or transboundary water resources issues, received unprecedented attention during this period. The trinity of water, energy, and food security was a fundamental transformation pathway for sustainable development, which was first proposed at the Bonn Climate Change Conference in 2011 and was re-emphasized in the United Nations 2030 Agenda for Sustainable Development. Models and tools for the "water-energy-food" nexus required further development to support decision-making [72]. Essentially, the trade-offs and synergies of water-energy-food became central to SDGs [73]. Specifically, energy utilization was critical for a range of water treatment processes, including water distribution, wastewater treatment, and desalination. Water resources were essential for biobased or renewable energy production, including the extraction, transportation, and processing of fossil fuels and the irrigation of biofuel feedstocks, as well as crop irrigation and production. Biomass from crops played an important role in energy systems for heat, power, fuel, pharmaceuticals, and green chemical feedstocks. Water conservation measures could reduce energy consumption and mitigate GHG emissions; similarly, improving energy efficiency would help reduce water usage and carbon emissions [74]. Yue [75] proposed a novel water-food-energy-climate-land nexus to provide a reference for social-economic development and low-carbon targets. GRACE, as another important clustering theme, provided new insights into variations in water storage in many regions of the world [68]. For example, using GRACE products, a recovery in terrestrial water storage was observed in central North America and northern Europe following an extreme drought in the Canadian Prairies [52]. Through precise GRACE measurements, global-scale changes in water storage, the depth of groundwater layers, and actual changes in sea level under the impact of CC and LUC were determined. A global study conducted by Liu [68] applied GRACE products to calibrate hydrologic model parameters in 59 large basins worldwide. Other advanced remote sensing techniques, such as airborne electromagnetic systems, global navigational satellite systems, and interferometric synthetic aperture radar, were also used to obtain groundwater information [8].

2021–2025. The release of the IPCC Sixth Assessment Report (AR6) marked a turning point in this period, shifting the research focus from isolated climate impacts to compound and cascading risks. Co-cited literature increasingly addressed how concurrent stressors—such as heatwaves overlapping with hydrological droughts—amplify vulnerabilities in water systems, challenging traditional stationarity-based infrastructure design. Simultaneously, the global response to the COVID-19 pandemic catalyzed a new domain of high-impact research: wastewater-based epidemiology. Citations in this cluster highlighted the repurposing of urban drainage infrastructure as a critical public health observatory for pathogen tracking, establishing a novel link between sanitary engineering and disease surveillance. Furthermore, the circular water economy evolved into a dominant thematic cluster. Distinct from the earlier nexus research, this stream emphasizes the technological and policy pathways for achieving "net-zero water" cycles, focusing on energy recovery from sludge and the decarbonization of water utilities. Finally, recent highly cited works reassessed the "dry gets drier, wet gets wetter" paradigm, incorporating terrestrial water storage data to reveal more complex, non-linear hydrological responses to planetary warming.

4. Discussion

4.1. Research Foci and Hotspots

The selection of research foci for this review was based on a comprehensive analysis of the literature, emphasizing areas that have shown significant growth in research activity and relevance to the interactions between water resources, climate change, and land-use change. The following key research foci were identified:

Next-generation hydrologic modeling and intelligence. The impacts of CC and LUC on water resources have traditionally been simulated using hydrologic models under multiple scenarios. Hydrological models (HMs), ranging from simple conceptual models to complex distributed models developed together with modern information technology, remain the primary tools for sustainable water resource research [74]. Over 20% of the reviewed papers applied HMs to describe the interactions between CC/LUC and regional water resources. Over the past decades, many hydrological models (Xin'anjiang model, Tank model, SWMM, PRMS, HSPF, HBV, TOPMODEL, SHE, SWAT, VIC, TOPKAPL, PDTank, etc) and hydrodynamic models (MIKE, Delft3D, AQUATOX, etc) have been developed and used. Among them, the open-source SWAT is an integrated model widely applied in water resource research across many regions of the world [76]. Hydrologic modeling under CC/LUC requires robust scenario simulation and prediction results as constraining inputs. In this regard, outputs from climate models, land-surface models, nonstationary time-series statistical models, and social-economic models can be used as inputs for HMs to assess the response of water resources to CC/LUC. These results can also be co-shared and applied by stakeholders and policymakers to enable their widespread use in water management [77,78]. However, the 2020–2025 period has witnessed a fundamental methodological evolution: the rise of Physics-Informed Machine Learning (PIML) and Differentiable Hydrology. Unlike traditional "black-box" data-driven models, PIML embeds physical laws (e.g., conservation of mass and energy) directly into deep learning architectures. This hybrid approach addresses the long-standing limitations of physically-based models—such as parameter uncertainty and computational cost—while ensuring that AI predictions remain physically consistent, even under unseen future climate conditions. Furthermore, the integration of new-generation earth observation data, particularly from the SWOT mission, is allowing models to move from point-based calibration to spatial pattern matching, significantly reducing equifinality in ungauged basins.

However, existing GCMs remain relatively crude in simulating several key physical processes, particularly those involving cloud formation, atmospheric convection, and soil moisture dynamics [79,80]. These processes are highly complex and involve multiple interactions at micro and macro scales, which are challenging to model robustness. For example, the representation of cloud cover and its associated effects on radiative forcing remains a source of significant uncertainty in the modeled temperature and precipitation changes. Advanced parameterization techniques and the integration of high-resolution observational data are required to better capture nonlinear interactions in the climate system for improving these simulations.

Smart watershed governance and digital twins. A watershed is a complex adaptive system consisting of water, atmosphere, soil, ecosystem and humans [81]. With the intensification of CC and LUC, integrated watershed management has evolved into smart water management [1], which is an inevitable subject for sustainably coordinating upstream and downstream, left and right river banks, sectors, industries and regions. The frontier of this domain is the operationalization of digital twins for river basins. Far beyond static 3D models, modern watershed digital twins integrate real-time sensor streams, meteorological forecasts, and socio-economic agents to simulate "what-if" scenarios dynamically. This enables managers to visualize cascading impacts of dam releases or sudden pollution events in real-time, facilitating agile decision-making that coordinates upstream–downstream and cross-sectoral trade-offs. In transboundary basins, where geopolitical friction often hinders data sharing, these digital replicas offer a neutral platform for joint fact-finding and cooperative scenario planning [15,82].

Beyond institutional and managerial challenges, watershed governance must also address the evolving spectrum of environmental threats. Traditional pressures such as nutrient enrichment and heavy metals are now accompanied by emerging contaminants including microplastics, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), bisphenol A (BPA), and radionuclides. These substances are persistent, prone to bioaccumulation, and present complex ecological and health risks, particularly when combined with climate and land use dynamics. Addressing this evolution of threats requires ongoing research and systematic reviews to integrate current findings, reveal critical gaps, and provide guidance for adaptive watershed management under global environmental change.

Carbon emissions. As an important driver for global warming, carbon emissions in hydrological systems has raised much concern among the scientific community, government, and the public [83]. During water resource development and utilization, activities such as hydropower generation, reservoir construction, irrigation, and water treatment inevitably produce greenhouse gases (CO_2, CH_4, N_2O), creating environmental externalities [84]. Carbon dioxide contributes approximately 66% of the global warming effect by trapping heat in the atmosphere, increasing temperatures, and driving more extreme weather, ice melt, sea-level rise, and ocean acidification [85]. Starting in 1992, the IPCC developed several CO_2 emissions scenarios and used them to elaborate GCMs and climate scenarios. According to Global Carbon Project data, global CO_2 emissions declined by 5.4% in 2020 due to confinement measures implemented during the COVID-19 pandemic [86]. However, the slowdown of industry did not curb record levels of global mean atmospheric CO_2 in 2020, as this reduction was smaller than or comparable to the natural year-to-year variability of CO_2 [85]. Carbon emissions were mainly derived from electricity and heat producers worldwide, which increased by 6% in 2021 and almost returned to pre-epidemic levels [87]. The energy sector accounted for more than 80% of global CO_2 sources, followed by LUC (11%). On the sink side, the atmosphere accounted for more than 40% of emissions, followed by the continent (29%) [86].

Beyond these trends, recent studies have emphasized the mechanisms of interaction between carbon emissions and water systems. Reservoirs and wetlands act as both sources and sinks of carbon, with water temperature, nutrient cycling, and microbial activity influencing emission rates [39,60]. Irrigation and agricultural water use alter soil moisture and carbon fluxes, while water treatment and desalination processes consume large amounts of energy, directly linking water management to carbon footprints [59,62]. These mechanisms highlight the coupling of water and carbon cycles under environmental change.

Research priorities in this field have expanded accordingly. Scholars have focused on quantifying carbon fluxes in rivers, lakes, reservoirs, and wetlands; assessing how land-use change and water management reshape carbon sources and sinks; evaluating the carbon footprints of water-intensive sectors such as agriculture, energy, and industry; and exploring mitigation strategies including carbon capture, utilization and storage (CCUS), low-carbon water treatment technologies, and integrated basin-scale planning [63,88]. By the end of 2020, there were 65 large-scale integrated projects worldwide on CCUS [89]. A shift to low-carbon and zero-carbon electricity (wind, solar, geothermal, hydro, nuclear, CCUS, etc.) represents an important future tendency, particularly for supporting advanced water treatment. In addition, the application of low-carbon materials and decentralized technologies for water treatment and recovery has potential for decarbonization [25].

The relationship between carbon emissions and hydrological systems underlines the need for an integrated water resource planning approach that emphasizes carbon neutrality while ensuring sustainable water availability [90]. To mitigate these effects, future research should focus on quantifying net emissions associated with different water management strategies and minimizing the carbon footprints of water-intensive sectors, such as agriculture and energy production.

4.2. Research Challenges

Based on a critical evaluation of the bibliometric results, three primary challenges need to be addressed to advance water resource research and management in the mid-21st century.

Model uncertainty in hydrological simulations. When using models, insufficient data may be encountered. The uncertainty, calibration, verification, and sensitivity analyses of these models should be considered [91]. Dynamic precipitation–runoff relationships caused by CC and LUC create limitations and challenges in model application, making established models less skillful and accurate in new environments [74]. In addition, the limitations of current GCMs and HMs, particularly in representing complex processes such as cloud dynamics, soil moisture, and vegetation–water interactions, remain a key challenge. Recent studies show that improved parameterization and real-time integration of remote sensing data can help address this issue. Therefore, future research should focus on improving parameterization and developing models that combine high-resolution climate and hydrological data with socio-economic datasets to reduce uncertainties and improve predictive capabilities [92]. The combination of models requires in-depth research; and modifications and improvements in accuracy and innovation are still needed for practical application [93,94]. Researchers are encouraged to employ machine learning and AI-based modeling approaches, which have shown potential in addressing nonlinearity and data limitations in traditional models [95].

Risks in a changing environment. The water-energy-food nexus indicates significant trade-offs among different sectors, particularly in regions with scarce water resources. Managing trade-offs between immediate human demands and the sustainable development of water resources, while ensuring the long-term provision of ecosystem goods and services under changing environmental conditions, constitutes a critical challenge in contemporary water governance [96]. Therefore, future studies should focus on developing practical solutions with integrative frameworks that use optimization algorithms to balance resource use among water, energy, and agriculture [97]. This includes promoting policies that encourage sustainable practices, such as water-efficient technologies in agriculture and renewable energy adoption, and assessing the effectiveness of these interventions through long-term monitoring.

The increase in water consumption and the decrease in freshwater availability, both in per capita and absolute terms, pose mitigation challenges to impending water risks [25]. Over 70% of European waterbodies encounter ecological risks in a changing environment [98]. The global warming trend is mainly caused by anthropogenic activities and cannot be controlled by natural processes alone, posing severe risks to human survival and development [99]. Increasingly dramatic CC and LUC complicate the generation mechanisms of water-related risks, thus requiring close attention to potential emerging risks to the human settlements, including compound risks, key risks, emergent risks, and systemic risks [100]. Recently, local, regional, and watershed natural disasters have occurred more frequently and surpassed historical observation records [32,94]. Various natural disasters and public safety events related to water resources pose serious risks and challenges to the sustainable development of society [73,93]. Water infrastructure worldwide is facing major challenges in resisting water-related disasters. Risk mitigation is essential through the combination of technological innovations, policy measures, and conservation efforts [101].

Integration of socio-economic factors in water resources management. While most research on water resources has focused on natural and ecological factors, the integration of socio-economic elements has been insufficient. Climate change and land-use change not only affect the natural availability of water resources but also influence human water demand, economic activities, and social structures [73,96]. Population growth, urbanization, and industrial expansion are among the socio-economic drivers that intensify water demand. Future studies must focus on integrating socio-economic factors into water resource management models. Understanding the interdependencies between water availability, human behavior, and economic development is crucial for designing sustainable water management strategies that are equitable and resilient.

Multiprocess and multiscale interactions. Elastic models that incorporate multiple processes—such as hydrological, ecological, biogeochemical, geomorphological, biophysical and social processes—are encouraged for integrated basin management at different temporal and spatial scales [44,102]. Substantial challenges that must be explored include the mutual coupling of multiple processes and scales for an integrated "atmosphere–land–

hydrological" system in water resource research under a changing environment [39,69]. In addition, to optimize the allocation of water resources among various human uses, the adaptation mechanisms and complex interactions of surface water and groundwater, and their response to CC and LUC, need to be further explored [103]. Moreover, long-term water monitoring and observation are imperative to understand the mechanism of critical water-related issues in a changing environment.

Impact of extreme climatic events on water resources. As global temperatures rise, extreme climatic events such as droughts, floods, and heatwaves are becoming more frequent and intense, significantly impacting water resources. These events can lead to abrupt changes in water availability and quality, with long-term consequences for ecosystems and human societies. Research should focus on improving the modeling and prediction of extreme climatic events and their impacts on water resources. There is a need for more accurate climate models that can predict the spatial distribution and intensity of extreme weather events. Furthermore, adaptation strategies, including infrastructure improvement and community-based adaptation, should be developed to mitigate the impacts of these events on water resources.

In addition to summarizing current research trends, it is crucial to consider the next steps for advancing this field. Our analysis shows a growing trend of water resources management towards inter- and multi-disciplinary research that couples ecological, hydrological, and socio-economic systems. Therefore, researchers should adopt multi-dimensional and cross-disciplinary approaches to address the intensified complexity of water-related issues. Moreover, advancing models to include nature-base solutions (e.g., wetland restoration) real-time human behavior, and socio-economic policies will help bridge the gap between theoretical research and practical applications. For example, recent advances—such as using GRACE satellite data for groundwater monitoring and developing climate-resilient water infrastructure—are encouraging; however, more work is required to transform these advances into actionable strategies at the local level. These strategies should prioritize community-based adaptation measures that consider local socio-economic conditions and involve stakeholders in both planning and implementation phases.

5. Summary and Conclusions

An overview of water resource research in a changing environment during 1990–2025 was obtained through bibliometric analysis based on article outputs and citations, high frequency keywords, burst detection, and co-network analyses. The responses of water resources to CC and LUC, and their mechanisms, have attracted much attention, requiring multidisciplinary and international collaboration. Research outputs showed significant growth over the past three and a half decades. There was a trend from a focus on the natural water system to a coupled natural-social water system, with a shift in co-occurrence keywords from natural factors in 1990–2005 to human social elements in 2006–2020. Academically, the term "carbon dioxide"and "energy" evolved from isolated variables to central components of the water–energy–food–health nexus.

Key emerging themes and trends, identified through the combination of bibliometric analysis and traditional literature review, reveal the evolving focus of research from natural and ecological aspects of water systems towards the integration of socio-economic and digital systems. This reflects a broader understanding of the importance of human–water interactions, policy, and sustainability practices under climate and land use changes. The key findings include: (i) the emergence of the water–energy–food nexus as a significant focal area of research, emphasizing the need for comprehensive and integrated approaches in future research to address the challenges associated with sustainable water management; (ii) growing trends in understanding the impact of carbon emissions on hydrological systems, including implications for climate mitigation strategies; and (iii) the provision of a roadmap for identifying research gaps and opportunities for collaboration across multisource synthesis, multidata composition, multimodel coupling, multiscale integration, and multidisciplinary cooperation, which can support the development of effective strategies for mitigating the impacts of climate change and land-use change on water resources. Our findings provide important implications for future research and policy-making: (i) themes such as the water–energy–food nexus, carbon emission effects, and integrated management approaches underscore the importance of inter- and multi-disciplinary collaboration, which encourages researchers to adopt cross-sectoral approaches to address the complexities of water resource management in a changing environment; (ii) the evolution in research focus suggests that policymakers must prioritize the integration of water management strategies that account for societal needs, including equity, sustainability, and resilience to climate change; (iii) the identified gaps highlight that synergistic effects of climate, land use, and socio-economic systems on water resources management require further investigation to advance this field; and (iv) the challenges reveal that advanced models should be developed to incorporate real-time data from remote sensing, in-situ observations, climate simulations, and socio-economic systems to fully understand the long-term impacts of climate change and land use-change on water systems. This review aims to highlight the challenges of global water resources in a changing environment and to draw the attention of the scientific community, policymakers, and the public to these pressing issues.

Author Contributions

Z.Y.: conceptualization, methodology, data curation, formal analysis, visualization, writing—original draft; C.L.: resources, methodology, validation, writing—review & editing; X.Z.: methodology, formal analysis, writing—review and editing; L.L. (Lirong Liu): formal analysis, validation, writing—review and editing; L.L. (Lyuliu Liu): conceptualization, formal analysis, writing—review and editing; J.C: visualization; X.W.: writing—review and editing, supervision; Y.Y. and Q.L.: validation, supervision. All authors have read and agreed to the published version of the manuscript.

Funding

This work was supported by the Joint Funds of the National Natural Science Foundation of China (U2243236), the National Key Research and Development Program of China (2022YFC3202001 and 2022YFC3202002), the National Science Fund for Distinguished Young Scholars (52025092), and the Qinghai Haidong Urban-rural Eco-development projection (L3443-PRC-HD-CB-CS4).

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Publicly available datasets were analyzed in this study. This data can be found here: http://doi.org/10.6084/m9.figshare.28293146.

Acknowledgments

We would like to thank the editors and anonymous reviewers for all their detailed comments and valuable suggestions in greatly improving the quality of this paper.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used AI to assist in language polishing.

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