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Advancing Water Security in the Tropical and Subtropical Regions: An Integrative Topic Modeling Approach

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ABSTRACT

Water security in tropical regions faces escalating pressures from climate change, land-use shifts, and population growth. We conducted a bibliometric review of 1146 peer-reviewed articles (1964–2023) on tropical water security. Latent Dirichlet Allocation identified 13 thematic topics and their evolution. Publications rose sharply after 2012, peaking post-2018, mirroring mounting concern over climate-related risks. Research has centered on climate-water interactions, water quality and treatment, and hydrological modeling, whereas interest in soil-moisture remote sensing declined. A new focus on land-cover-water linkages signals increasing interdisciplinary integration. Gap analysis revealed methodological compartmentalization: SWAT-based modeling studies rarely intersect with empirical water-quality work, creating a persistent evidence divide. Conversely, topics on vegetation, land use, and water balance show strong semantic coherence. Our reproducible topic-modeling framework clarifies evolving research foci and highlights underexplored areas, offering a roadmap to bridge disciplinary divides and inform science-based water-governance strategies across the Global South.

1 | Introduction

Water security has emerged as one of the defining global challenges of the 21st century (Mishra et al. 2021), encompassing not only the sustained provision of water in sufficient quantity and quality for human consumption, agriculture, and industry (Witter and Whiteford 1999), but also the safeguarding of aquatic ecosystem integrity (GWP 2000) and adaptive capacity to environmental and socioeconomic perturbations (Cheng et al. 2004). Initially framed through the lens of supply reliability and physical access, the concept evolved into a multidimensional governance framework (Cook and Bakker 2012), integrating the sustainability of water resources, ecosystem protection, and institutional coordination across sectors and scales (Bakker 2012; Institute for Water, Environment and Health 2013; WaterAid 2012). The intensification of water-related crises in diverse geographies has further illuminated the embedded interdependencies between water, food, and energy systems, reinforcing water security as a structural pillar of sustainable development and societal resilience (De Girolamo et al. 2017; de Melo et al. 2023; Pophare et al. 2014; Rosa et al. 2018; Teixeira et al. 2024). Climate change acts as a threat multiplier in this context, amplifying hydrological extremes and accelerating the onset of scarcity, particularly across tropical and subtropical belts (Raut and Ganguli 2024; World Economic Forum 2024). Consequently, there is an intensifying convergence of scientific and policy efforts aimed at elucidating the proximate and systemic drivers of water insecurity and designing actionable strategies for mitigation and adaptation (Kim et al. 2024; Lebu et al. 2024; Shao and Xu 2023). These strategies are increasingly anchored in global policy frameworks, most notably the United Nations

Key Points

- Water-security studies in tropical regions have grown after 2012, reflecting rising global alarm over climate-driven water risks.
- Methodological gaps between hydrological models and field data hinder integrated, multiscale solutions for sustainable water governance.
- New research links land use, vegetation cover, and hydrologic balance, offering key guidance for more resilient water-management strategies.

Sustainable Development Goals, with SDG 6 articulating a collective mandate for the equitable and sustainable management of water and sanitation by 2030 (UN General Assembly 2015; Vörösmarty et al. 2018).

Water security challenges are particularly pronounced across tropical and subtropical regions, where the convergence of climatic volatility, hydrological instability, and socioeconomic disparities amplifies systemic vulnerability (Barbosa 2024; Intergovernmental Panel on Climate Change 2022; Marengo et al. 2020; Nauditt et al. 2022; Raut and Ganguli 2024). Elevated rainfall variability, characterized by alternating regimes of protracted drought and high-intensity precipitation, undermines the reliability of water storage and distribution infrastructure and weakens the buffering capacity of both natural and engineered systems (Barbosa 2024; Méllo Júnior et al. 2022; Nauditt et al. 2022). The increasing frequency of hydroclimatic extremes, including flash floods and severe water deficits, imposes cascading constraints on food production, urban water supply, and hydropower reliability (Raut and Ganguli 2024; Schillerberg and Tian 2024). Concurrently, land degradation, deforestation, and diffuse pollution have impaired ecosystem-based hydrological regulation, reinforcing both quantitative and qualitative declines in water resources (D'Acunha et al. 2024; Farooqi et al. 2024). Demographic expansion, agro-industrial intensification, and spatial proliferation of unregulated urban settlements continue to escalate anthropogenic pressures, aggravating intersectoral water competition and inequities in access (Leijnse et al. 2024; N. Liu, Dobbs, et al. 2022). These dynamics are further compounded by governance deficits, including fragmented institutional mandates, limited cross-sectoral coordination, and chronic underinvestment in resilient infrastructure systems (Green et al. 2024; Nie et al. 2024). Against this backdrop, identifying research frontiers and knowledge gaps in water security across tropical and subtropical landscapes is critical to inform context-sensitive strategies for climate adaptation, risk mitigation, and integrated water governance.

Over the past several decades, water security has been explored through multiple disciplinary lenses (Cook and Bakker 2012; Gerlak et al. 2018; Rafaai and Lee 2024), reflecting intensifying concerns over the long-term viability of water resource management amid accelerating environmental and societal transformations (Zhao and Boll 2022). Among the field's most salient advances is the growing recognition of climate change as a primary determinant of hydrological stability, particularly in tropical systems where feedbacks between warming, precipitation variability, and land-use pressures increasingly manifest themselves (Bamal et al. 2024; Ciampittiello et al. 2024). In response, integrated water resource management (IWRM) has gained traction as a strategic governance model that emphasizes cross-sectoral coordination and participatory mechanisms to reconcile competing demands from domestic, agricultural, and ecological water users (Ganoulis 2023; Otamendi et al. 2024). Simultaneously, nature-based solutions (NbS), such as riparian restoration (Fonseca et al. 2024), wetland rehabilitation (Vicarelli et al. 2024), and the deployment of green infrastructure, have demonstrated efficacy in buffering climate-induced hydrological extremes and enhancing water quality regulation (Rodrigues et al. 2024). Despite these conceptual and operational strides, the scholarly landscape has remained fragmented. Methodological heterogeneity, variation in spatial and temporal scales, and disciplinary compartmentalization continue to inhibit meta-synthetic analysis and the emergence of unified theoretical frameworks (Cosgrove and Loucks 2015; Vörösmarty et al. 2013). Addressing these constraints necessitates the application of advanced analytical tools such as topic modeling and bibliometric synthesis to systematically extract latent patterns (Blei 2012; Calistus et al. 2024), diagnose critical knowledge gaps (Luiz et al. 2019; J. D. Rezende and Moretti 2023) and inform the strategic orientation of future research agendas and public policy design (Graciani 2025).

Topic modeling has emerged as an innovative approach for analyzing large volumes of scientific literature (Calistus et al. 2024), enabling the identification of dominant research themes, emergent frontiers, and underexplored domains within a given field (Blei 2012; Luiz et al. 2019; Westgate et al. 2015). Among the available algorithms, Latent Dirichlet Allocation (LDA) has gained prominence because of its capacity to infer probabilistic topic distributions across documents, effectively clustering publications based on shared semantic and syntactic features (Blei et al. 2003; Calistus et al. 2024; Griffiths and Steyvers 2004; Westgate et al. 2015). Within the domain of tropical water security, the application of LDA has proven instrumental in disentangling mature research areas from nascent lines of inquiry and delineating thematic blind spots that warrant further investigation (Calistus et al. 2024; McCallen et al. 2019; Westgate et al. 2015). By offering a scalable and reproducible approach to knowledge synthesis, topic modeling contributes not only to the refinement of theoretical constructs but also to the operationalization of interdisciplinary frameworks in support of integrated water resource governance (Calistus et al. 2024; Luiz et al. 2019; Mo et al. 2024).

This study undertakes a systematic, data-driven synthesis of the scientific literature on water security in tropical regions through the application of topic modeling to elucidate prevailing thematic patterns and diagnose critical gaps in current knowledge. Specifically, it aims to: (i) identify dominant research trajectories in the field of tropical water security and (ii) map underrepresented areas of inquiry with the potential to inform future research agendas and improve the conceptualization of water-related challenges and opportunities in these regions. By embedding automated quantitative techniques into the literature review process, the analysis offers

a transparent and replicable framework that enhances the objectivity and granularity of scholarly assessments (Calistus et al. 2024; Mo et al. 2024). The resulting insights are positioned to inform evidence-based decision making by researchers, policymakers, and water resource managers, while also contributing to the design of more adaptive and context-sensitive governance strategies. Ultimately, this work seeks to advance sustainable water management practices in tropical settings and reinforce the scientific foundations that support integrated policy and planning initiatives.

2 | Material and Methods

2.1 | Bibliographic Search

The literature retrieval process was structured into two sequential phases, employing targeted keyword strategies to optimize coverage and thematic relevance. An initial exploratory search, hereafter referred to as the "naive" query, was conducted using a broad array of general terms to map the conceptual landscape and refine search taxonomy (Grames et al. 2019). This was followed by a focused and systematically constructed query, using a finalized set of keywords. The comprehensive search was implemented across two major bibliographic databases, Scopus and Web of Science, using the following keyword combinations: (["water security" OR "water security index" OR "Water resilien*" OR "Water sustain*" OR "Water manage*" OR "Water suppl*" OR "Water resource*" OR "Water availability*" OR "Water sufficienc*" OR "Water ris*" OR "Water stability*" OR "Water protect*"] AND ["watershed" OR "catchment" OR "River basin" OR "Drainage basin" OR "watershed" OR "River catchment" OR "Hydrological basin" OR "River system" OR "River network" OR "Riverine system"] AND ["equatorial" OR "subtropical" OR "intertropical" OR "megathermal" OR "tropics" OR "neotropical"OR "pantropical" OR "warm-temperate" OR "torrid" OR "Tropical zone" OR "Tropical region"]).

This approach facilitated the construction of a curated dataset comprising essential bibliographic metadata for each record, including the full title, abstract, author-defined keywords, year of publication, and source journal. Data extraction and preprocessing were performed using the R package *litsearchr*, which supports reproducible workflows for systematic literature reviews (Grames et al. 2019). All titles and abstracts were screened to retain only manuscripts that directly addressed water security in tropical and subtropical contexts. Duplicate entries and records lacking abstracts were excluded from analysis. The temporal scope of the review encompassed publications from 1964 to May 2024, yielding a final dataset of 1146 documents (Figure 1).

2.2 | Text Mining

Subsequent text mining and topic modeling procedures were implemented following established protocols for ecological bibliometric analysis (Luiz et al. 2019; Ponweiser et al. 2014; Westgate et al. 2015). The thematic content of each manuscript was characterized using text extracted from the titles, abstracts, and author-provided keywords. Unigram tokenization was applied to isolate individual terms. Non-informative elements, including common stopwords (e.g., "the", "and", "or"), numerical digits, and punctuation, were removed. The remaining tokens were stemmed to their root forms to normalize the lexical variation.

To identify meaningful multiword expressions, an automated *n*-gram detection algorithm was employed to detect word pairs and phrases exhibiting co-occurrence frequencies significantly higher than random expectations ($p < 0.05$). The terms were then manually screened for contextual relevance, and semantically redundant expressions were consolidated. Extremely rare ($n < 3$) and overly frequent ($n > 50$) terms were excluded to reduce noise and enhance the thematic resolution (Westgate et al. 2015). The final corpus comprised 3718 unique terms, which served as the analytical foundation for downstream topic modeling. To facilitate visual exploration, a word cloud was generated using the *wordcloud* package in R, depicting the 40 most probable terms in tropical water security literature over the study period (Figure 2).

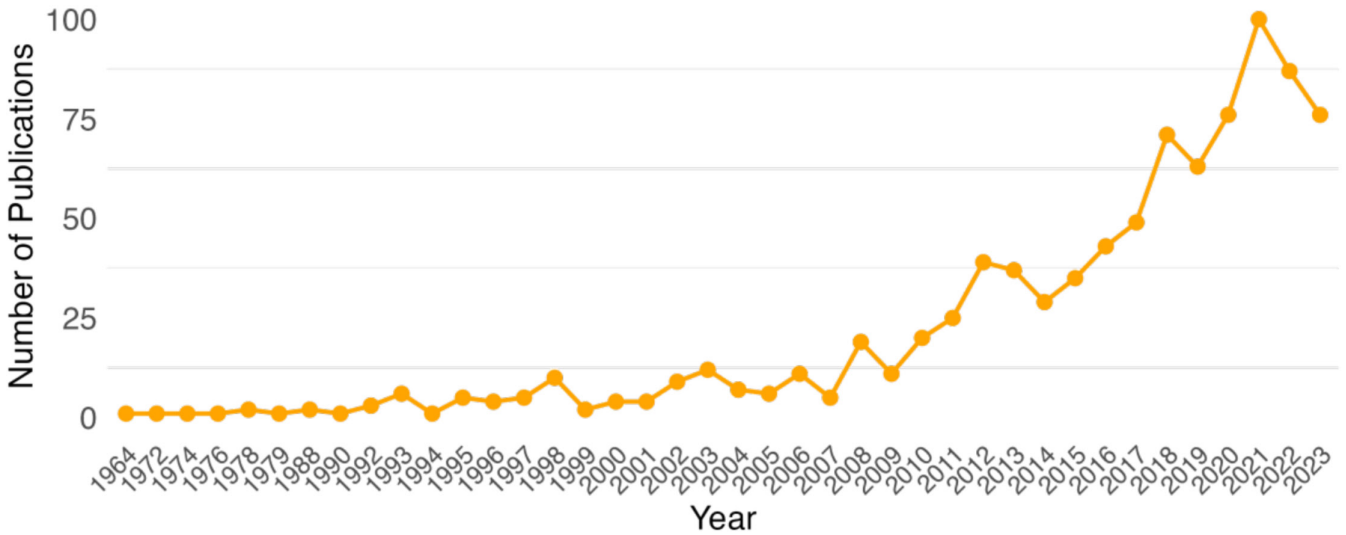

FIGURE 1 | Number of research manuscripts about water security published per year.

2.3 | Topic Modeling

Topic modeling was conducted following established methodological frameworks designed to extract latent thematic structures from large textual corpora (Luiz et al. 2019; Ponweiser 2012; Ponweiser et al. 2014; Westgate et al. 2015). In this context, the "topic" is operationally defined as a probabilistic cluster of terms that exhibits significant co-occurrence patterns, collectively expressing semantic cohesion and conceptual alignment across documents (Ponweiser 2012). To infer these hidden structures, we applied LDA, a generative probabilistic model that identifies sets of terms that co-appear more frequently than expected by chance within a shared linguistic context. LDA assumes that individual documents are mixtures of multiple topics, each represented in varying proportions, thereby accommodating the interdisciplinary nature and heterogeneity of the literature corpus (Ponweiser 2012).

Because LDA requires a pre-specification of the number of topics (K), we implemented a model-tuning procedure using the *ldatuning* R package, fitting 50 models with K ranging from 1 to 50, as recommended by prior studies (Luiz et al. 2019; Ponweiser 2012). Model selection was guided by the information-theoretic optimization criterion proposed by Deveaud et al. (2014), which balances model fit and topic distinctiveness. The optimal model, inferred using the *topic models* package in R, identified 13 distinct topics. Because LDA does not intrinsically assign semantic labels, a post hoc interpretative analysis was conducted wherein the top-ranking terms for each topic were examined and triangulated with representative documents in which those topics were dominant. This interpretative process enabled the assignment of meaningful thematic labels to each of the 13 topics.

2.4 | Topic Similarity

To elucidate the semantic architecture underlying the set of topics identified by the LDA model, we first assessed the degree of thematic similarity between them (Westgate et al. 2015). LDA outputs a term-topic matrix in which each word is assigned a weight representing its probability of occurrence within a given topic. This probabilistic distribution can be operationalized as a multivariate dataset to be explored using ecological dissimilarity metrics (Luiz et al. 2019; Rezende and Moretti 2023). Conceptually, this approach parallels traditional community ecology frameworks, wherein words are treated like species, and topics are treated like sampling sites. To quantify pairwise thematic dissimilarity, we computed Bray–Curtis distances across topics based on their respective word-weight vectors ("word distance matrix"). The resulting dissimilarity matrix was then subjected to nonmetric multidimensional scaling (NMDS) to facilitate visual exploration of the semantic proximity and clustering structure among the topics.

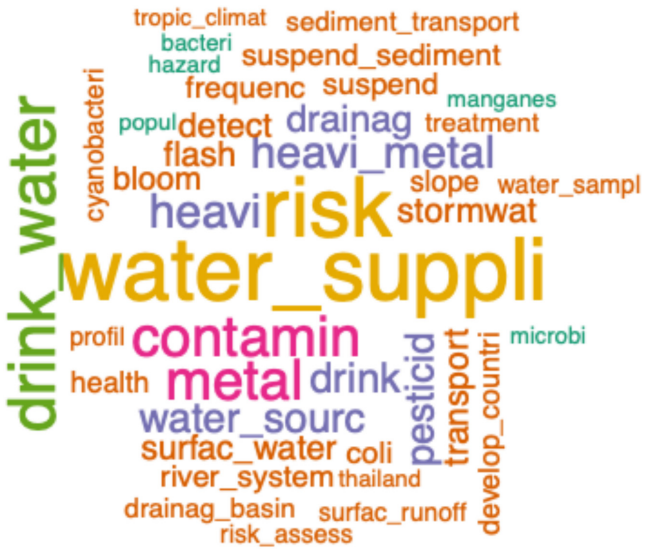

FIGURE 2 | Word cloud from research manuscripts about water security published.

2.5 | Research Gap Analysis

To identify research gaps in the water security literature, we examined pairs of topics that were both thematically dissimilar and infrequently co-occurring across the document corpus (Westgate et al. 2015). In addition to the term-topic matrix used for semantic similarity analysis (see Topic Similarity), the LDA model also outputs a document-topic matrix that quantifies the proportional representation of each topic within individual documents. This matrix was transposed such that topics were treated as rows and document weights as columns, thus yielding a topic-by-document matrix. Bray–Curtis dissimilarities were then calculated across topic pairs using this structure, generating what we refer to as the article distance matrix. To integrate both the lexical and contextual dimensions of topic divergence, we computed the element-wise product of the word distance matrix and the article distance matrix, resulting in a composite gap distance matrix (Westgate et al. 2015). This matrix captures the magnitude of the disconnect between topics, based on both vocabulary and document-level co-occurrence. Higher dissimilarity values indicate research gaps, i.e., topic pairs that exhibit distinct semantic profiles, and minimal overlap in their distribution across literature (Luiz et al. 2019; Rezende and Moretti 2023). These gaps were visualized by plotting the corresponding dissimilarity scores, which facilitated the identification of conceptual discontinuities and underexplored intersections within the field.

2.6 | Topic Popularity

To assess thematic proximity among topics, we clustered semantically related groups based on the topic probability matrix generated by the LDA model in accordance with the procedures outlined by Luiz et al. (2019); Ponweiser (2012). Topic weights, reflecting the proportional representation of each topic across the corpus, were used to calculate the Bray–Curtis dissimilarities between all topic pairs, enabling quantitative evaluation of topic similarity. To characterize topic dynamics over time, we computed the annual mean topic proportions, which served as proxies for the relative prevalence of each theme across the study period (Luiz et al. 2019; Ponweiser 2012). Temporal trajectories were examined by analyzing the interannual changes in these mean values. Following the framework proposed by Griffiths and Steyvers (2004), and further developed by McCallen

et al. (2019), topics exhibiting a mean annual increase in prevalence exceeding 0.1 were classified as "hot," indicating growing research attention. Conversely, topics with a mean annual decline below −0.1 were designated as "cold", reflecting a downward trend in scholarly interest.

3 | Results

A marked acceleration in publication output was observed beginning in 2012, with a pronounced surge in article volume after 2018 (Figure 1). Among the identified topics, those most frequently represented across the corpus included water supply, risk assessment, and drinking water provision, indicating a persistent research emphasis on the fundamental aspects of water access and safety (Figure 2).

The model selection procedure identified a 13-topic solution as optimal for capturing the latent thematic structure of the corpus. The most representative terms for each topic, along with the assigned thematic labels, are summarized in Table 1, with extended term lists available in Supplementary Tables SM1 and SM2. Notably, several high-frequency terms were shared across multiple topics, reflecting partial thematic overlap and reinforcing the integrative nature of water security research (see SM2). The identified topics spanned a broad range of hydrological and ecological subfields. Traditional domains such as hydrological modeling, water quality assessment, and potable water supply were well represented, alongside more contemporary and interdisciplinary themes, including stable isotope applications, climate change impacts, and IWRM. The ecological dimensions ranged from fine-scale bioindicator studies to macrosystem analyses of ecosystem services across both managed and natural landscapes, underscoring the field's multiscalar complexity.

Over the full temporal extent of the dataset, the most frequently represented topics were "climate change and water resources", appearing in 97 publications, followed by "water quality and treatment" ($n = 90$), "soil and water assessment tools" ($n = 84$), "hydrological modeling" ($n = 76$), and "groundwater recharge and human activities" ($n = 70$). In contrast, the topics "water balance and vegetation cover" and "land cover and water resources" were the least prevalent, with 52 and 53 publications, respectively. Ordination analysis revealed that the topics concerning land cover, water balance and vegetation, water resource management, stable isotope monitoring, soil moisture, remote sensing, and climate change were spatially clustered, reflecting a higher degree of thematic similarity (Figure 3). Notably, the topic "soil and water assessment tools" exhibited the greatest dissimilarity from all other topics, suggesting a distinct conceptual niche within the corpus. Figure 3 shows a composite visualization of topic groupings, their proportional representation, and their distribution across individual publications.

Overall, the research gap analysis indicated a relatively high degree of thematic congruence and internal consistency across the corpus (Figure 4). The most substantial conceptual discontinuities, defined by low co-occurrence and divergent lexical structures, were observed between the topics "water quality and treatment" and "soil and water assessment tools", as well as between "groundwater recharge and human activities" and "water quality and treatment", and between "hydrological modeling" and "water quality and treatment" (Figure 4). In contrast, minimal research gaps were identified between "water balance and vegetation cover" and "land cover and water resources", as well as between "water resource management" and "land cover and water resources", reflecting stronger thematic alignment and more frequent co-occurrence within the literature (Figure 4).

Temporal analysis of topic prevalence, quantified as the proportional representation of each topic across the document corpus, revealed relatively stable patterns over time, with limited fluctuations in overall thematic dominance (Figure 5). During the 1960s and the 1970s, the leading topics included "soil moisture and remote sensing", "water resource management", and "water quality and treatment" (Figure SM3). A shift in focus occurred in the 1980s and 1990s, with an increased emphasis on "soil and water assessment tools using the SWAT model", "water balance and vegetation cover", and "groundwater recharge and human activities". In the 2000s and 2010s, "ecosystem services in landscapes" maintained prominence, while "water quality and treatment" and "aquatic bioindicators" also featured strongly (Figure 6 and SM3). In the current decade (2020s), thematic priorities have increasingly centered on "water resource management" and "climate change and water resources", reflecting an alignment with global sustainability and adaptation agendas.

Longitudinal trends revealed a decline in the proportional representation of certain topics, most notably "soil moisture and remote sensing", which has undergone sustained decreases in prevalence and is thus classified as a "cold topic" in the current literature (Figure 5). In contrast, "land cover and water resources" demonstrated a marked rise in prominence after 2020, warranting classification as a "hot topic" (Figure 5). It is important to emphasize that the designation of a topic as "cold" does not imply a low absolute prevalence but rather reflects a downward trajectory in temporal popularity. For instance, while "water quality and treatment" and "hydrological modeling" exhibited notable declines in relative frequency, they continued to occupy a substantial share of recent publications. Conversely, the topic "climate change and water resources" experienced a pronounced increase in prevalence, reinforcing its emergent status as a central focus in contemporary water security research.

4 | Discussion

4.1 | Research Topics Diversification

The marked increase in water security research across tropical regions, particularly after 2012 and even more sharply from 2018 onward, reflects a system-level response to rising hydroclimatic pressures and growing human water demand (Aguirre and Paredes Cuervo 2023; Ballarin et al. 2023; Volmar et al. 2023). This trend aligns with a deeper understanding of how climate change alters hydrological regimes and intensifies the frequency and severity of extreme events, including protracted droughts and abrupt flooding (AghaKouchak et al. 2020; He et al. 2021). Concurrently, demographic expansion and proliferation of agro-industrial

TABLE 1 | Uncovered topics from 1146 research articles about water security published during the period 1964–2023 were identified from latent Dirichlet allocation Modeling (LDA). Each topic displayed 15 words with the highest probability of occurrence. The topics were assigned names that best described the semantics of the top words. An extended version of this table with the top 70 words for each topic is provided in the supplemental material (Table S2).

Topic number and name	Top topic terms (stemmed)
1. Hydrological modeling	Hydrolog_model, remot_sens, satellit, rainfal_runoff, gaug, spatial_distribut, tropic_catchment, tropic_region, river_discharg, rainfal_data, model_perform, yangtz_river, extrem_precipit, error, yangtz
2. Water resource management	River_basin, water_resourc, resourc_manag, water_resourc_manag, climat_variabl, tropic_river, india, human_activ, springer_natur, sediment_load, station, increas_trend, flash, mann_kendal, river_flow
3. Water quality and treatment	Water_qualiti, load, organ, carbon, dissolv, flux, nitrogen, treatment, phosphoru, trophic, eutroph, organ_carbon, dissolv_organ, organ_matter, oxygen
4. Water balance and vegetation cover	Tree, water_resourc, water_avail, plant, water_balanc, plantat, surfac_runoff, karst, record, estuari, regress, raini_season, ring, shallow, water_manag
5. Stable isotope monitoring and forecast	Isotop, forecast, stabl_isotop, month, mountain, riparian, export, stabl, composit, climat_zone, agricultur_land, solut, stream_water, tempor_variabl, weather
6. Soil and Water Assessment Tool	Swat, enso, swat_model, assess_tool, eastern, summer, water_assess, atmospher, southern_oscil, water_assess_tool, tool_swat, assess_tool_swat, stream_flow, ocean, atlant
7. Groundwater recharge and human activities	Recharg, groundwat_recharg, glacier, storm, time_seri, aquif, regim, resolut, drainag, decad, seri, coastal, peak, flow_regim, coeffici.
8. Aquatic bioindicators	Commun, speci, freshwat, fish, aquat, phytoplankton, australia, protect, biomass, macroinvertebr, diatom, divers, disturb, structur, metric.
9. Soil moisture and remote sensing	Soil_moistur, soil_water, water_storag, baseflow, hydrolog_process, forest_cover, hydrolog_respons, tropic_forest, infiltr, root, rainfal_event, water_content, depth, headwat, overland_flow.
10. Land cover and water resources	And_cover, water_resourc, irrig, water_balanc, water_yield, lulc, humid_tropic, vulner, surfac_runoff, tropic_region, tropic_watersh, natur_resourc, cultiv, humid_subtrop, cover_chang.
11. Climate change and water resources	Climat_chang, lake, wetland, water_resourc, climat_model, water_level, floodplain, connect, adapt, region_climat, chang_impact, climat_chang_impact, inund, channel, upstream.
12. Ecosystem services in the landscape	Landscap, eros, ecosystem_servic, water_manag, crop, semi_arid, sediment_yield, soil_eros, sensit, demand, arid, loss, intervent, water_demand, water_conserv.
13. Water supply and contaminants	Water_suppli, surfac_water, risk, drink_water, contamin, metal, heavi, heavi_metal, drink, water_sampl, pesticid, transport, water_sourc, stormwat, health.

systems have substantially heightened freshwater withdrawals while accelerating water quality degradation, particularly within densely populated and ecologically sensitive tropical landscapes (Abraão et al. 2024; Rockström et al. 2009). Recent bibliometric syntheses further underscore the institutionalization of water security as a transdisciplinary research frontier, distinguished by the global diffusion of integrative assessment tools, such as the Water Security Index, and a normative emphasis on sustainable governance frameworks in socio-ecologically vulnerable regions (Volmar et al. 2023).

Empirical investigations of tropical and subtropical catchments have elucidated the tangible ecological consequences of riparian deforestation (Dala-Corte et al. 2020; Inhamuns et al. 2021), dam-induced longitudinal discontinuities (Couto et al. 2023; Rezende et al. 2023), and diffuse anthropogenic pollution on the structural and functional attributes of freshwater biota (Borges et al. 2024; Burdon et al. 2023). Notably, disruptions to longitudinal connectivity have been linked to shifts in fish assemblage composition, even within upstream reaches highly isolated from direct impoundment effects,

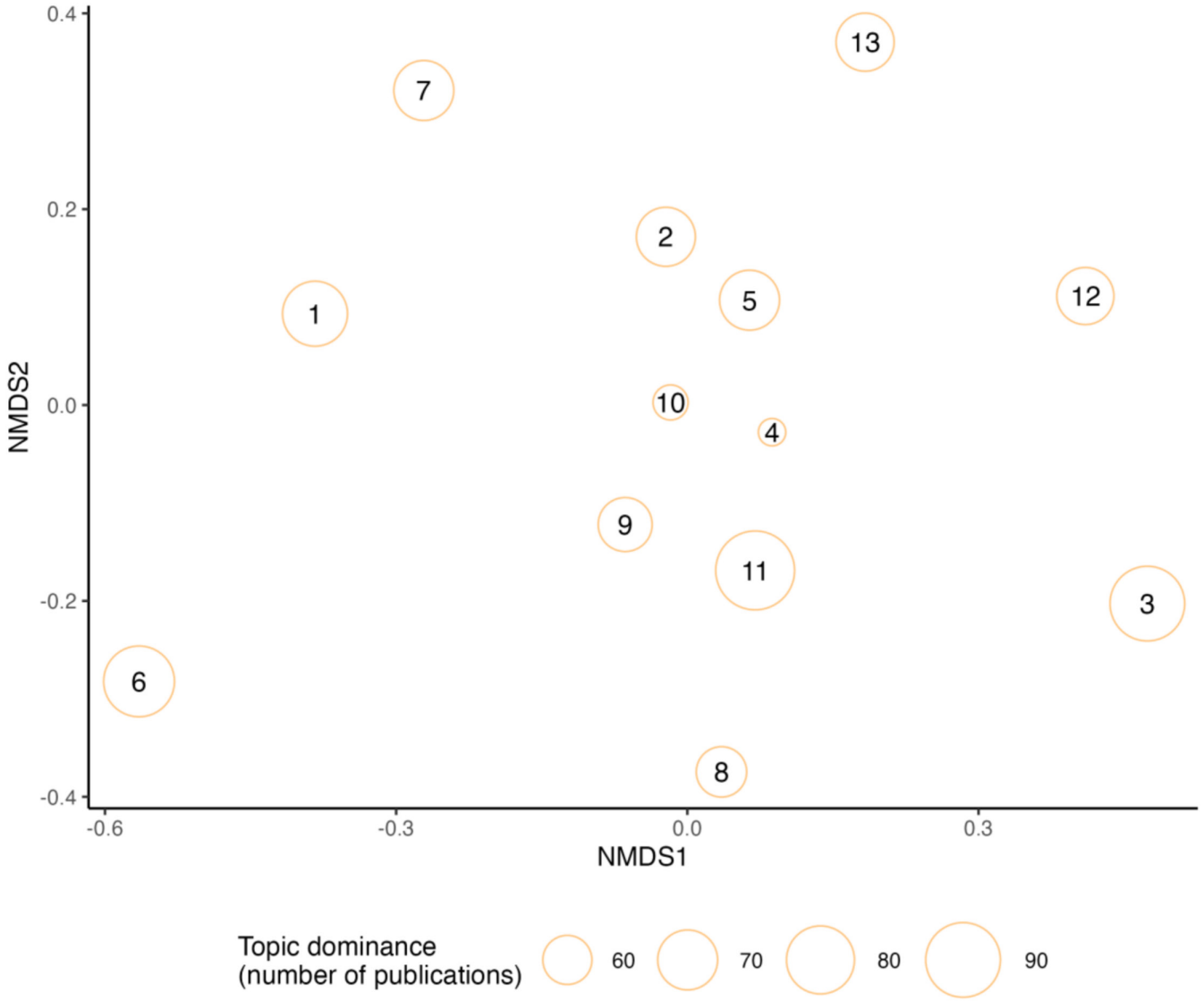

FIGURE 3 | Two-dimensional representation (via nonmetric multidimensional scaling) of topic distances is based on term distribution similarity. The size of bubbles indicates the number of papers in which a topic dominates. Topic numbers correspond to those listed in Table 1.

underscoring the foundational role of hydrologic continuity in sustaining aquatic ecosystem integrity (Couto et al. 2023; Rezende et al. 2023). Complementarily, bioassessment tools, including EPT richness, BMWP indices, and trait-based metrics, have demonstrated diagnostic value in capturing land-use-mediated gradients of ecological degradation, offering operational frameworks for monitoring and restoration efforts (Feio et al. 2021; Sánchez Herrera et al. 2024; Vadas et al. 2022). However, the spatially limited implementation of standardized biomonitoring in tropical regions, which is frequently constrained by institutional fragility and chronic underfunding, continues to impede the translation of ecological diagnostics into actionable water governance (Feio et al. 2021). Advancing the alignment between ecological science, spatial planning, and adaptive institutional architecture has emerged as a critical pathway for supporting the socioecological resilience of tropical freshwater networks. Recently, Campos et al. (2024) proposed a Tropical Water Health Index that employs a pressure-condition-response approach that could help in the integration of hydrographic basin management through the application of the developed model. This index integrates the pressures on aquatic ecosystems caused by anthropogenic activities, assesses their hydrology, water quality, and biological factors, and evaluates social and governmental responses (including the CONAMA Resolution 357 for the classification and management of freshwater resources in Brazil, Brazilian federal law).

Within this broader context, topic similarity analysis revealed strong semantic affinities among themes related to water resource management, hydrological monitoring, and climate-driven alterations to water systems. Land cover and vegetation have emerged as central integrators of these dynamics, given their pivotal roles in modulating hydrological processes such as infiltration, surface runoff, and evapotranspiration (Chen et al. 2023). These mechanisms are fundamental drivers of the watershed-scale water balance (Wang et al. 2022) and aquifer recharge (Yan et al. 2024), which underpin long-term freshwater availability and system resilience. Soil moisture, an essential variable in hydrological modeling, serves as a critical proxy for soil–plant–atmosphere interactions (Vereecken et al. 2022) and is frequently monitored via remote sensing platforms to capture

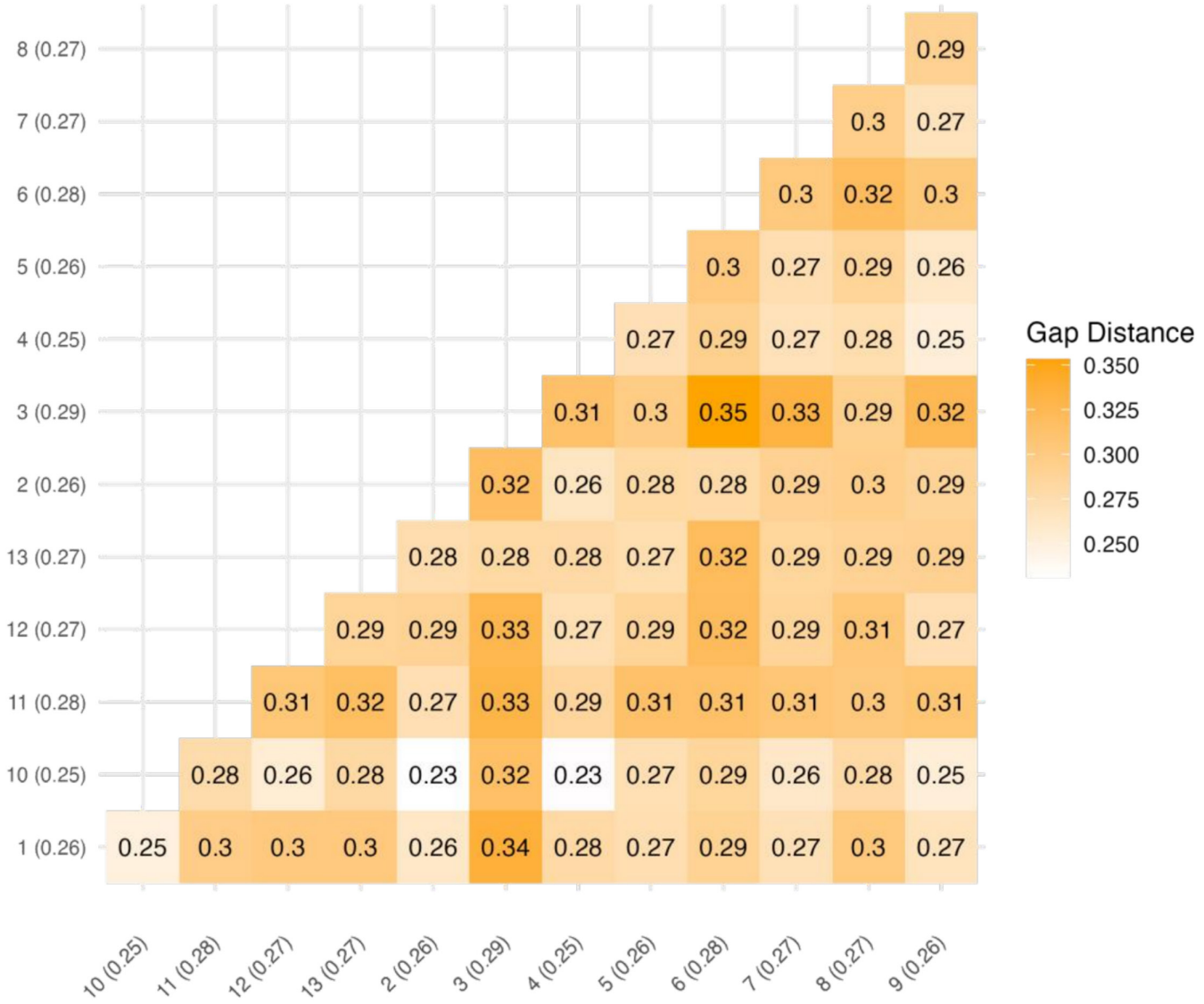

FIGURE 4 | Research gap distance matrix heat-map (dark = high gap, clear = low gap) on water security literature. The research gap distance is the product of the "word" and "article" distance matrices. The greater the metric, the higher the gap between topics (topics that both contain different sets of words and topics that rarely co-occur in the same article), indicating topic pairs that were poorly integrated in the fish-trait-based literature. The numbers in brackets indicate the average gap distance of a topic across all topics. Topic numbers correspond to those listed in Table 1.

spatiotemporal variations in land use and vegetation structure (Mishra et al. 2021). These interconnected topics coalesce with an integrated understanding of the water resource dynamics in tropical environments. In contrast, the topic "soil and water assessment tools" displayed marked dissimilarity relative to the other clusters. This divergence stems from its methodological orientation, focusing primarily on the application of process-based models, such as the SWAT, which is widely employed to simulate land use and management scenarios at the watershed scale (Aloui et al. 2023). While vital for predictive assessments, the technical specificity and model-centric nature of this topic distinguish it from broader ecological or climate-integrated frameworks, potentially explaining its thematic separation in the ordination space.

The findings also revealed a notable diversification of research themes over time, reflecting the maturation and conceptual broadening of the water security field. While early studies primarily emphasized traditional concerns such as water supply, risk mitigation, and drinking water quality, recent contributions have increasingly incorporated topics such as ecosystem services, integrated watershed governance, and nature-based solutions. This thematic expansion suggests a paradigm shift toward more holistic frameworks that account for the complex feedback between hydrological, ecological, and social systems in water management (Mishra et al. 2021). The intensification of water security research in tropical contexts appears particularly responsive to the biogeophysical and socioeconomic distinctiveness of these regions, which are characterized by high climatic variability, elevated biodiversity, and pervasive development challenges (Muller et al. 2024). Tropical settings often amplify the adverse effects of climate change, such as reductions in streamflow and increased frequency of hydrological extremes, resulting in elevated vulnerability and heightened demand for context-sensitive scientific interventions (AghaKouchak et al. 2020; Ballarin et al. 2023). In this light, the literature increasingly advocates for

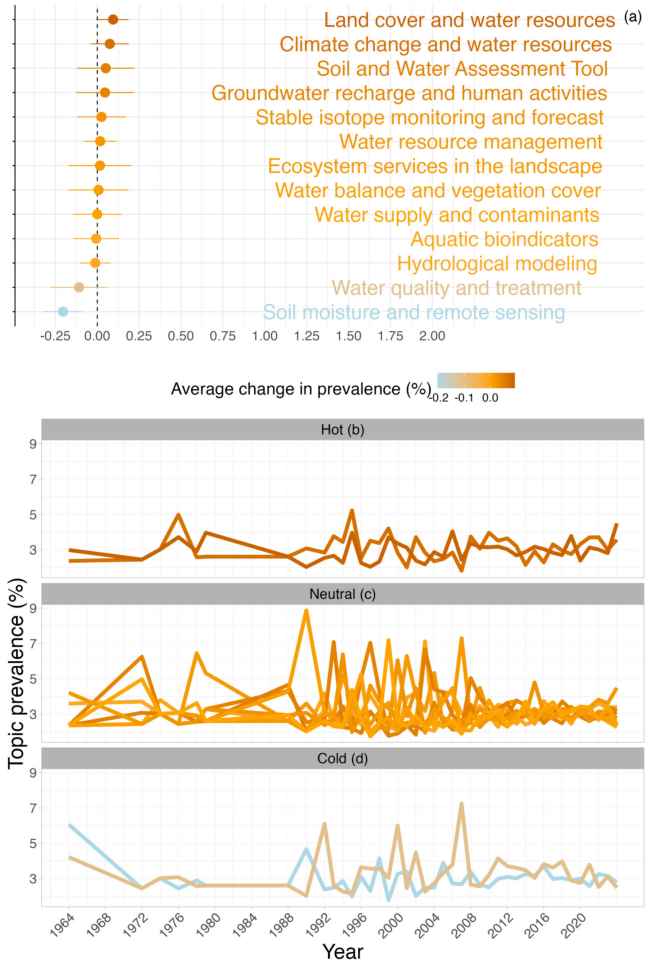

FIGURE 5 | Change in prevalence in the literature over the study period for each of the 13 topics. (a) Each dot represents the average change in prevalence among consecutive year groups (shown in d); bars represent standard errors. The plots on the right side of the panel track the temporal changes in topic prevalence of (b) hot, (c) neutral, and (d) cold topics.

integrative responses that combine ecosystem restoration, efficient resource use, and community-based adaptation as foundational strategies for building water resilience (Lebu et al. 2024; Ren and Coffman 2023). The expanding volume and thematic breadth of the literature underscore not only the scientific urgency of water security, but also the critical imperative to translate research into actionable frameworks capable of sustaining water systems under accelerating environmental and anthropogenic pressures (Mishra et al. 2021).

In addition to advancing conceptual frameworks, several applied initiatives across the Global South illustrate how integrated water security strategies have been operationalized in practice. In Latin America, the implementation of the Freshwater Health Index in Colombia and Peru has provided actionable tools to reconcile competing water demands while strengthening basin-level governance (Bezerra et al. 2022). In Brazil, the adoption of ecological bioassessment protocols and the development of the Tropical Water Health Index have supported policy instruments such as CONAMA Resolution 357, promoting the integration of ecological indicators into water classification and management (Campos et al. 2024). In Africa, ecological flow assessments in the Ethiopian highlands have enabled the alignment of hydrological restoration with local community water needs (Abebe et al. 2021). Similarly, in Southeast Asia, the restoration of riparian and wetland systems has been applied as a nature-based solution to buffer climate-induced hydrological extremes, with positive outcomes for both ecosystem integrity and water supply reliability (Fonseca et al. 2024; Vicarelli et al. 2024). These examples demonstrate the translation of research into practice and underscore the potential of context-sensitive, interdisciplinary approaches to bridge science and governance in tropical water security.

4.2 | Hot Topics in Tropical Aquatic Systems

The predominance of the topics "climate change and water resources" and "water quality and treatment" within the tropical water security literature underscores the central scientific concern regarding how climatic variability reshapes the hydrological cycle and affects water quality. The intensification of the hydrological cycle driven by global temperature increases amplifies processes such as evaporation and precipitation (Ehtasham et al. 2024), contributing to more frequent and severe extreme events, including prolonged droughts and flash floods (Wang et al. 2023). These dynamics reduce water availability and degrade water quality. Extreme hydrological events promote eutrophication and toxic algal blooms, which are exacerbated by high temperatures and irregular rainfall regimes (Wang et al. 2022; Xia et al. 2021). These outcomes jeopardize the integrity of aquatic ecosystems and compromise drinking water safety, emphasizing the intrinsic ecological and operational link between water quality and availability. Water quality is critical not only for human needs, such as consumption and sanitation, but is also essential for sustaining ecological functionality and enabling efficient water resource governance (Sun et al. 2023).

Moreover, deteriorating water quality restricts water usability, thereby exacerbating water insecurity, particularly in regions already facing climatic stress (Chen et al. 2021; Gunda et al. 2019). Under such conditions, water management becomes increasingly complex, particularly when scarcity or contamination is acute. Thus, ensuring water quality is fundamental to achieving Sustainable Development Goals (SDGs), particularly those related to access to clean water and universal sanitation (Li 2022). This highlights the urgency of integrating climate change mitigation, freshwater conservation, and investment in treatment technologies into a unified water security strategy. Ongoing research and monitoring are essential for informing evidence-based policies and adaptive management frameworks that foster global water resilience.

This methodological process has also emerged as a key feature of recent contributions to the field. Techniques such as stable isotope monitoring (Saghravani et al. 2024; Watson et al. 2024) and the use of aquatic bioindicators (Abebe et al. 2021; Hampel et al. 2023) have extended the analytical frontier beyond conventional hydrology. Stable isotope applications, for instance, enable the tracing of water fluxes and identification of water source origins within hydrological systems, thereby improving

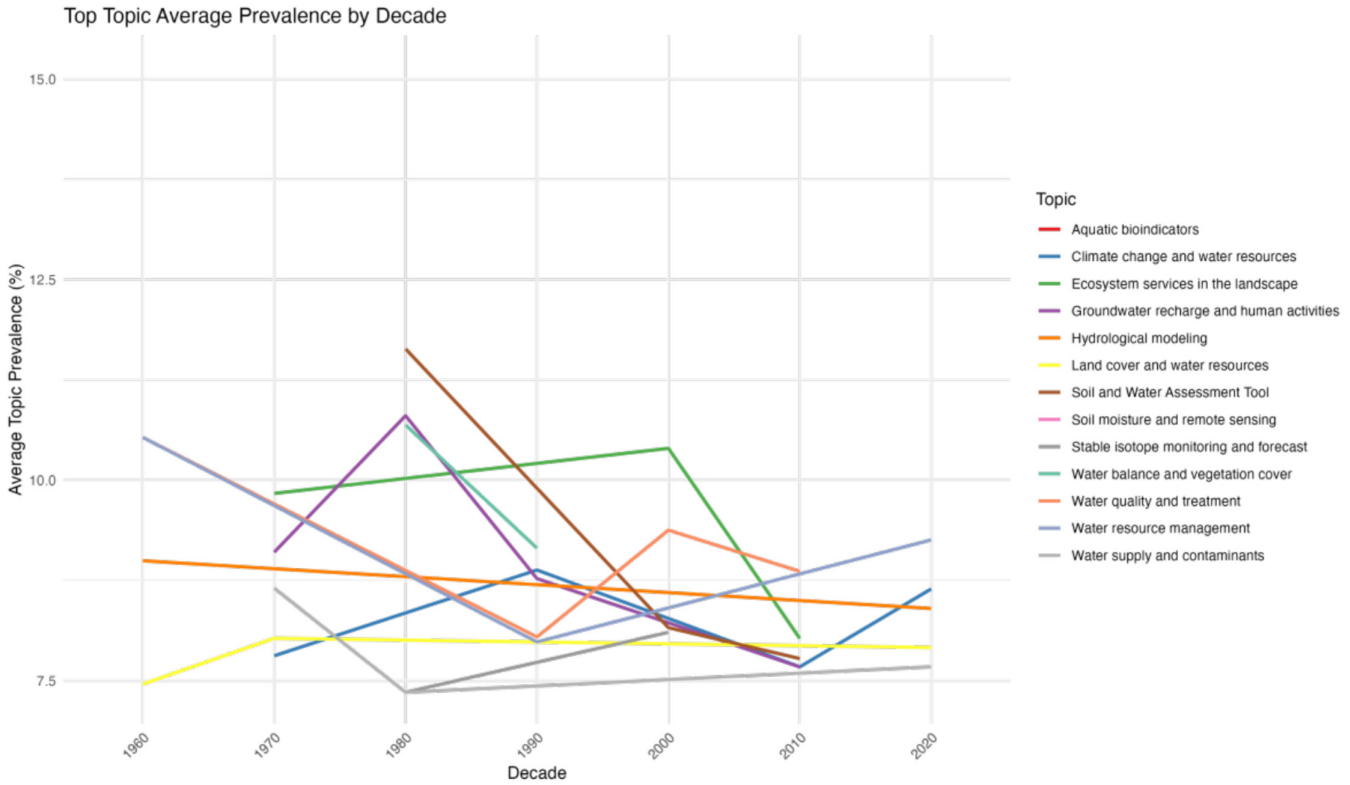

FIGURE 6 | Change in prevalence of top topics (by average values) in the literature over the study period for decade of the 13 topics.

diagnostic precision in hydrological assessments (Stadnyk and Holmes 2023). These advanced tools allow the characterization of ecological dynamics and hydrological processes with enhanced resolution, particularly in environmentally sensitive systems. Furthermore, the increasing emphasis on local-scale dynamics, such as ecosystem service provisioning, reflects a broader shift toward aligning water resource management with sustainability objectives (Falasca and Marucci 2024). These findings underscore the need for convergence of innovation, interdisciplinarity, and established practices in water security research (Mdee et al. 2022). Such an integrated approach is essential for addressing complex and emerging challenges and securing hydrological resilience, environmental integrity, and human well-being on a global scale (Rafaai and Lee 2024).

4.3 | Research Gaps and Opportunities

The identification of research gaps among the analyzed topics in tropical regions highlights strategic areas for scientific advancement and demonstrates the utility of LDA modeling as a diagnostic tool for mapping and prioritizing research needs (Dillan and Fudholi 2023). Our analysis revealed that the most pronounced gaps occur between the topics "SWAT (Soil and Water Assessment Tool)", "groundwater recharge and human activities", and "hydrological modeling" in relation to "water quality and treatment". These discontinuities stem primarily from methodological limitations (Das et al. 2024) and insufficient integration across disciplinary fragmentation often hinders integrated analysis of these themes within individual manuscripts (Luiz et al. 2019).

Conversely, topics characterized by minimal gaps, such as "water balance and vegetation cover", "water resource management", and "land cover and water resources", demonstrated strong conceptual alignment, largely due to the inherent interdependence of their components. The interactions between vegetation cover and hydrological balance are well documented in the literature (Benegas et al. 2021; Ebodé et al. 2024; Joyal et al. 2023; Li et al. 2021; Ouyang et al. 2021; Reddy et al. 2022; Sadhwani and Eldho 2023; Sharma et al. 2024; Zhang et al. 2021). Numerous studies have shown that vegetation directly influences infiltration (Houteta et al. 2023; W. Jiang et al. 2020; Peng et al. 2023; Shi et al. 2022), evapotranspiration (Chen et al. 2022; Feng et al. 2024; Jin et al. 2023; Li et al. 2023) and surface runoff (Hu et al. 2023; Liu, Sheng, et al. 2022; Wiwoho et al. 2023). These established relationships support analysis and application in water resource management, thereby providing a robust foundation for understanding the interface between ecological and hydrological processes.

4.4 | Topic Trends Across Decades

The temporal analysis of topic prevalence revealed both thematic continuity and the gradual incorporation of emerging issues in tropical water security research. During the 1960s and 1970s, prominent topics included "soil moisture and remote sensing", "water quality and treatment", and "water resource management". These trends reflect the socio-environmental priorities and technological advancements at this time (Panke 2020). The development of remote sensing technologies has facilitated large-scale environmental monitoring and revolutionized water management at the watershed scale (Abdulraheem et al. 2023;

Cracknell 2018). In particular, satellite imagery enables the mapping of soil moisture and land use, supporting more integrated and data-informed planning approaches (Bauer 2020; Cracknell 2018; Sheffield et al. 2018). At the same time, rapid urbanization and increasing pollution have underscored the urgency of ensuring potable water quality and catalyzing research in water treatment technologies (Pizzi 2023; Ray 2008). Water resource management also gained traction during this period as a strategic response to the growing awareness of water scarcity, promoting basin-level planning to balance supply and demand, and mitigating water crises (Jiang et al. 2024). These developments were shaped by demographic pressures, technological progress, and nascent global environmental consciousness, further reinforced by early environmental policies aimed at sustainable water governance (Costanza et al. 2017).

Moving into the 1980s and the 1990s, the focus began to shift toward topics such as "SWAT modeling", "groundwater recharge and human activities", and "water balance and vegetation cover" reflected both the increased stress on water systems and advancements in hydrological modeling. The development of the SWAT modeling during the 1990s was a milestone in watershed-scale simulations, enabling researchers and decision makers to assess land-use impacts and develop mitigation and adaptation strategies in response to climate change (Dubey et al. 2023; Janjić and Tadić 2023). The intensive exploitation of aquifers during this period highlights the urgent need to understand and manage groundwater recharge processes (Letuka and Oke 2024; Sufyan et al. 2024). As demand continues to rise, developing strategies to ensure the sustainability of this vital resource has become imperative (Letuka and Oke 2024). These efforts have increasingly integrated anthropogenic pressures and land-use dynamics to inform sustainable groundwater management. Simultaneously, the expansion of agricultural frontiers and urban areas has emphasized the role of vegetation cover in mediating climate regulation, and water balance components, such as infiltration, runoff, and evapotranspiration (Huang and Xu 2022; Pereira et al. 2023). This shift toward ecosystem-based understanding has laid the foundation for more varied assessments of water availability and quality under changing land-use regimes (Larned and Snelder 2024).

While SWAT, was identified as methodologically distinctive, its widespread adoption raises an important debate regarding standardization versus homogenization in tropical water security research. On the one hand, the dominance of SWAT has provided clear benefits: it has established a reproducible, widely validated framework for simulating hydrological responses to land-use and climate scenarios, thereby enabling cross-basin comparisons and supporting policy-oriented applications at multiple scales (Aloui et al. 2023; Janjić and Tadić 2023). On the other hand, this methodological centrality entails risks of homogenization. Overreliance on a single model may constrain the diversity of analytical perspectives, neglect site-specific hydrological processes poorly represented in SWAT, and reinforce a separation from empirical water quality and ecological assessments (Das et al. 2024; Luiz et al. 2019). Such limitations underscore the need for methodological pluralism, combining SWAT-based scenario modeling with empirical monitoring, ecohydrological indicators, and participatory approaches to ensure that model outputs remain context-sensitive and decision-relevant. Rather than advocating for the abandonment of SWAT, our findings suggest that its role should evolve from being the dominant standard toward serving as one component in a diversified methodological toolkit for water security research in the Global South.

During the 2000s and 2010s, attention shifted toward "ecosystem services in landscapes", "water quality and treatment", and "aquatic bioindicators", reflecting a growing emphasis on sustainability and integrated management. The popularization of the ecosystem services framework by the Millennium Ecosystem Assessment (2005) reframed water security as a nexus issue linking biodiversity, human well-being, and environmental governance (Braat and De Groot 2012; Costanza et al. 2017; Valencia Torres et al. 2021). This conceptual evolution supports the integration of ecological and social values in landscape planning and conservation strategies (Zolyomi et al. 2023). Simultaneously, the increasing demand for high-quality water in urban and industrial contexts has driven innovation in treatment technologies to address emerging contaminants, such as microplastics and pharmaceuticals. Advances in circular economy strategies have also promoted wastewater reuse, underscoring the transition toward more sustainable water use models (Garrick et al. 2019; Krueger, Borchardt, et al. 2019; Krueger, Rao, and Borchardt 2019; Zhou et al. 2024). Aquatic bioindicators have gained prominence as cost-effective tools for ecological monitoring, supported by policy instruments such as the European Water Framework Directive (WFD 2000/60/EC) and the Marine Strategy Framework Directive (MSFD 2008/56/EC), which mandate standardized water quality assessments (El-SiKaily and Shabaka 2024; Poikane et al. 2020).

After 2020, the compounded effects of climate change placed topics such as "climate change and water resources", "water resource management", and "hydrological modeling" at the forefront of tropical water security research. The increasing frequency and intensity of extreme events, particularly droughts and floods, have driven the demand for adaptive strategies to safeguard water availability under uncertain climatic conditions (Ciampittiello et al. 2024; Jiang et al. 2024). Integrated management approaches have become essential for mediating competing demands across sectors and regions under hydrological stress (Kalogiannidis et al. 2023). Coupled with technological advances, these frameworks enable dynamic assessments and promote resilience through ecosystem-based and participatory planning (Bezerra et al. 2022; Grison et al. 2023; Ingold and Tosun 2020; Otamendi et al. 2024). Hydrological modeling has similarly advanced as a cornerstone of climate adaptation, with tools such as SWAT enabling scenario-based planning to evaluate the impacts of land use, climate trends, and anthropogenic pressures on water systems (Lou et al. 2024; Paul et al. 2024). These predictive capabilities are critical for long-term planning and development of robust policy instruments. As climate pressure intensifies, the role of the scientific community in producing actionable knowledge through adaptive management, model integration, and evidence-based governance has become increasingly pivotal in sustaining water resources under global change (Ciampittiello et al. 2024; Kotamäki et al. 2024).

The rise and decline of specific topics in tropical water security research may be closely tied to the interplay between shifting socio-environmental pressures, methodological innovation, and policy

priorities. For example, the increasing prominence of land cover and water resources after 2020 may be attributed to advances in remote sensing and GIS platforms, which have enabled high-resolution monitoring of vegetation-hydrology interactions and their influence on infiltration, evapotranspiration, and aquifer recharge (Chen et al. 2023; Wang et al. 2022). Likewise, the growing attention to climate change and water resources parallels the development of coupled climate-hydrological models and reflects the urgency emphasized in successive IPCC reports, which consistently frame hydroclimatic extremes as priority challenges for the Global South (IPCC, 2022; Ciampittiello et al. 2024).

In contrast, the decline of soil moisture and remote sensing as a dominant research focus appears to reflect the maturation of this field. Early enthusiasm during the 1970s–1990s, when satellite-based soil moisture retrieval was novel, has progressively shifted toward integrative applications in which soil moisture functions as a key variable embedded within broader land-climate-water frameworks (Abdulraheem et al. 2023; Cracknell 2018). A comparable trajectory characterizes SWAT-based hydrological modeling: once central to scenario analyses of land-use change, its relative decline can be traced to the diversification of modeling platforms and to increasing critiques regarding the overreliance on process-based simulations without sufficient empirical validation (Das et al. 2024; Janjić and Tadić 2023). These thematic trajectories indicate that research dynamics are not stochastic but shaped by cycles of technical advancement, policy relevance, and empirical applicability. Emerging topics typically occupy the intersection of pressing environmental challenges and new analytical tools, whereas declining topics often reflect conceptual consolidation and subsequent incorporation into broader interdisciplinary agendas.

5 | Conclusion

This study provides a comprehensive synthesis of the scientific literature on water security in tropical regions by employing LDA to uncover thematic structures, temporal dynamics, and research gaps within a corpus of 1108 peer-reviewed articles spanning six decades. The results revealed a pronounced increase in publication volume beginning in 2012, with a steep surge after 2018, reflecting heightened global concern over hydrological vulnerabilities driven by climate change, land-use transitions, and escalating anthropogenic demand. Topic modeling identified 13 distinct thematic clusters, with "climate change and water resources", "water quality and treatment", and "hydrological modeling" emerging as dominant areas of research. These findings underscore the prioritization of systemic responses to hydroclimatic extremes and water quality degradation, particularly in ecologically and socially sensitive tropical contexts. In contrast, topics such as "soil moisture and remote sensing" exhibited a declining trajectory, whereas "land cover and water resources" were identified as a rising research frontier.

Semantic similarity and gap analyses further revealed substantial conceptual disjunctions between model-based approaches (e.g., SWAT applications) and empirical water quality research, pointing to persistent methodological silos that hinder integrative frameworks. Conversely, strong thematic coherence was observed among topics addressing vegetation cover, land use, and water balance domains with well-established hydrological linkages. Collectively, these findings highlight the increasing complexity and interdisciplinarity of water security research in tropical regions and underscore the importance of bridging epistemological and methodological boundaries.

Beyond summarizing these patterns, our findings may highlight priorities for future research. First, integrating SWAT-based hydrological modeling with field-based monitoring and ecological assessments would reduce methodological compartmentalization and enhance the policy relevance of model outputs. Second, coupling land cover change analyses with ecosystem service frameworks can yield more direct insights into the ways hydrological processes underpin human well-being, biodiversity, and ecosystem resilience. Third, the apparent decline of soil moisture and remote sensing as a research focus warrants re-examination in view of recent advances in high-resolution satellite technologies, which may reinstate soil moisture as a central variable in understanding soil–plant–atmosphere interactions. Finally, promoting methodological pluralism, combining modeling approaches, empirical data, and participatory governance perspectives, should be considered a central pathway for advancing water security research across the Global South. By embedding automated bibliometric analyses within the synthesis process and outlining concrete avenues for future work, this study may provide not only a replicable, evidence-based framework but also a practical roadmap for guiding the next generation of interdisciplinary research and for strengthening the scientific foundations of sustainable, multiscale water governance.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table SM1.** Uncovered topics from 1146 research articles about water security published during the period 1964–2023 identified from Latent Dirichlet Allocation Modeling (LDA). Each topic displays the 9 words with highest probability of occurrence. **Table SM2:** Uncovered topics from 1146 research articles about water security published during the period 1964–2023 identified from Latent Dirichlet Allocation Modeling (LDA). **Figure SM3:** Change in prevalence in the literature over the study period for decade of the 13 topics.