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A review of watershed-scale water quality monitoring: Integrating real-time systems and spatial modeling for sustainable water resource management

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Abstract: Maintaining water quality is essential for numerous fields, but pollution challenges have become more pronounced with population growth and industrial expansion. Although monitoring technologies have advanced, comprehensive watershed analyses remain limited, especially in developing countries. This study conducts a bibliometric review of watershed-scale water quality monitoring research, applying the PRISMA 2020 method alongside tools such as Scopus, VOSviewer, Orange Data Mining, and qualitative content analysis to identify trends, research gaps, and future directions across 107 studies. From 2005 to 2024, there has been a significant rise in research on real-time monitoring systems and spatial modeling in water quality, with notable peaks. The United States leads in publication volume, while 'Watershed Flow Modeling' remains underexplored and underrepresented. Studies show that implementing real-time monitoring systems and spatial modeling in developing countries faces challenges related to infrastructure and funding. However, recent advancements in IoT-based tools and satellite remote sensing are progressively enhancing water resource management.

Introduction

Water is a fundamental resource for life and economic advancement, impacting sectors such as drinking, agriculture, industry, and recreation (Adeyeye et al. 2020). However, increasing population growth and industrial expansion are compromising water quality and availability (Dawood et al. 2021), leading to severe issues like eutrophication caused by excessive nutrient loading (Damanik et al. 2024). Urbanization and inadequate waste management, particularly in developing countries, exacerbate pollution, affecting aquatic ecosystems and leading to sedimentation problems (Vane et al. 2022). Contaminants, including organic and inorganic pollutants, further degrade water quality and disrupt ecosystems (Huang et al. 2021). For example, River Gudenå in Denmark has experienced a significant water quality decline and fish stock reduction due to nutrient enrichment exacerbated by aquatic weed proliferation (Paraskevi et al. 2022). These challenges highlight the need for balanced development and environmental protection to effectively manage water resources (Muhirwa et al. 2022). Continual monitoring and accurate modelling of water quality are essential for managing pollution and ensuring sustainable water resource management (Syeed et al. 2023, Tanjung et al. 2024).

Monitoring water dynamics in aquatic environments is challenging due to various environmental factors such as internal loads, hydrodynamic mixing, and nutrient recycling (Sun et al. 2024). This complexity often makes it difficult to interpret limited data accurately (Yuan et al. 2020). Key issues that need to be addressed for effective monitoring include optimizing sampling frequencies (Jiang et al. 2020, Li et al. 2021), selecting relevant variables and indicators (Acuña-Alonso et al. 2021), and adapting to environmental changes and unexpected events (Zhang et al. 2022). Special emphasis should be placed on anthropogenic impacts, such as soil leaching and wastewater discharge, as shown in studies from various locations (Czatzkowska et al. 2022). Real-time monitoring systems (RMS), including those using advanced sensor algorithms and geographic distribution methods, are crucial for accurate data collection and anomaly detection (Khan et al. 2021). The development of integrated monitoring systems (Ighalo et al. 2021) along with the use of technologies like Unmanned Aerial Systems (UAS) (Vélez-Nicolás et al. 2021) and spatial modeling (SM) (Zabłocki et al. 2022) has shown promise in improving environmental monitoring. Nonetheless, challenges remain, including system maintenance, sensor reliability, and the need for extensive monitoring points to accurately assess nutrient concentrations (Łaszczyca et al. 2023).

Recent studies on watershed-scale water quality monitoring highlight diverse approaches to tackling pollution and improving assessment methods. Yuan et al. (2020) reviewed nonpoint source pollution models, analyzing their suitability for watershed applications, while Chow et al. (2020) emphasized the need for extensive pesticide monitoring to account for variable application rates and hydrological influences on water quality. Matos et al. (2024) explored turbidity and sediment monitoring techniques, including advancements in optical and satellite imaging technologies. Anyango et al. (2024) addressed agricultural water quality management, proposing key assessment metrics and policy measures. Locke (2024) reviewed statistical methods for analyzing land use impacts on water quality, highlighting geographic and methodological gaps. Aloui et al. (2023) assessed the effectiveness of the Soil and Water Assessment Tool (SWAT) model in Mediterranean watersheds, calling for improved data inputs. Razguliaev et al. (2024) examined continuous stormwater monitoring, stressing the importance of adaptive sensor and data management techniques for accurate assessments.

Previous studies have extensively covered water quality monitoring at the watershed level across various regions globally (Behmel et al. 2016, Giri, 2021). Many review articles have examined advanced methods for addressing water quality challenges (Topp et al. 2020, Uddin et al. 2021, Uddin et al. 2022). However, no review has focused on how watershed-scale water quality monitoring contributes to sustainable water resource management, particularly in developing countries. Additionally, earlier reviews in this field often rely on a single application perspective for analyzing bibliometric trends. This study aims to fill this gap by conducting a bibliometric review of research trends in watershed-scale water quality monitoring using RMS and SM. It employs tools such as VOSviewer and Orange Data Mining to map and analyze bibliometric trends, identify potential research gaps, and suggest future research directions. Furthermore, this study will also explore previous research on RMS and SM monitoring in developing countries, an area that has not been covered in earlier reviews.

Materials and methods

This review utilizes the Systematic Literature Network Analysis (SLNA) method, integrating systematic literature review and bibliometric analysis to examine research trends in RMS and SM for watershed-scale water quality management (Ikhlas and Ramadan, 2024). A four-phase framework was developed, following PRISMA 2020 guidelines (Page et al. 2021), to address the study's research questions. A series of research questions that emerge in this study are as follows: (Q1) What are the research interests over the past 20 years regarding using RMS and SM for managing water resources at the watershed scale? (Q2) What research gaps exist in the monitoring of water quality at the watershed level using RMS and SM? (Q3) To what extent have studies on RMS and SM been conducted in developing countries? The review process consists of four distinct phases: phase 1: literature examination and database selection, phase 2: application of screening criteria, phase 3: bibliometric and content analyses, and phase 4: discussion of findings, with an emphasis on identifying research gaps and drawing conclusions. The search utilized Boolean operators to connect keywords and expand the scope, selecting documents published between 2005 and 2024 (Pranckutė, 2021, Zheng et al. 2020). Various document types, publication statuses, and access levels were included (Table 1), while irrelevant documents were excluded after thorough manual reviews. The applied keywords are listed below.

Table 1. Specifics of retrieval configuration

Exclusion criteria	Filters employed
Open access	All Open Access, Gold, Hybrid Gold, Bronze, Green
Time span	2005 – 2024
Document type	Article, Conference Paper, Conference Review, Review, Book Chapter, Note, Book
Publication stage	Final
Source type	Journal, Conference Proceeding, Book Series, Book, Trade Journal
Language	English
Retrieval time	Tuesday, July 9, 2024

Keywords 1: TITLE-ABS-KEY (spatial AND modeling OR real AND time AND monitoring AND system OR modeling)
Keywords 2: TITLE-ABS-KEY (river OR stream OR creek OR channel OR waterway OR watershed)
Keywords 3: TITLE-ABS-KEY (water AND quality)

For bibliometric analysis, VOSviewer was employed to visualize keyword co-occurrence trends, providing insights into global research collaboration on RMS and SM topics (Ejaz et al. 2022). The co-occurrence of keywords was analyzed to identify frequently discussed topics, employing two visualization types—cluster display and overlay display—to show topic clustering and temporal trends (Chen et al. 2016, Gao et al. 2021). Additional visualizations, created using Origin and Quantum GIS software, showcased annual publication counts and the geographic distribution of citations. These analyses provided a comprehensive overview of the global evolution of RMS and SM research over the last two decades. The study also evaluated citation metrics across the top 20 countries, visualizing the number of citations per document to highlight impactful contributions in the field.

In the topic analysis, Orange Data Mining tools were used to extract key topics from titles, abstracts, and author keywords (**Fig. 1**), employing Latent Dirichlet Allocation (LDA) to model

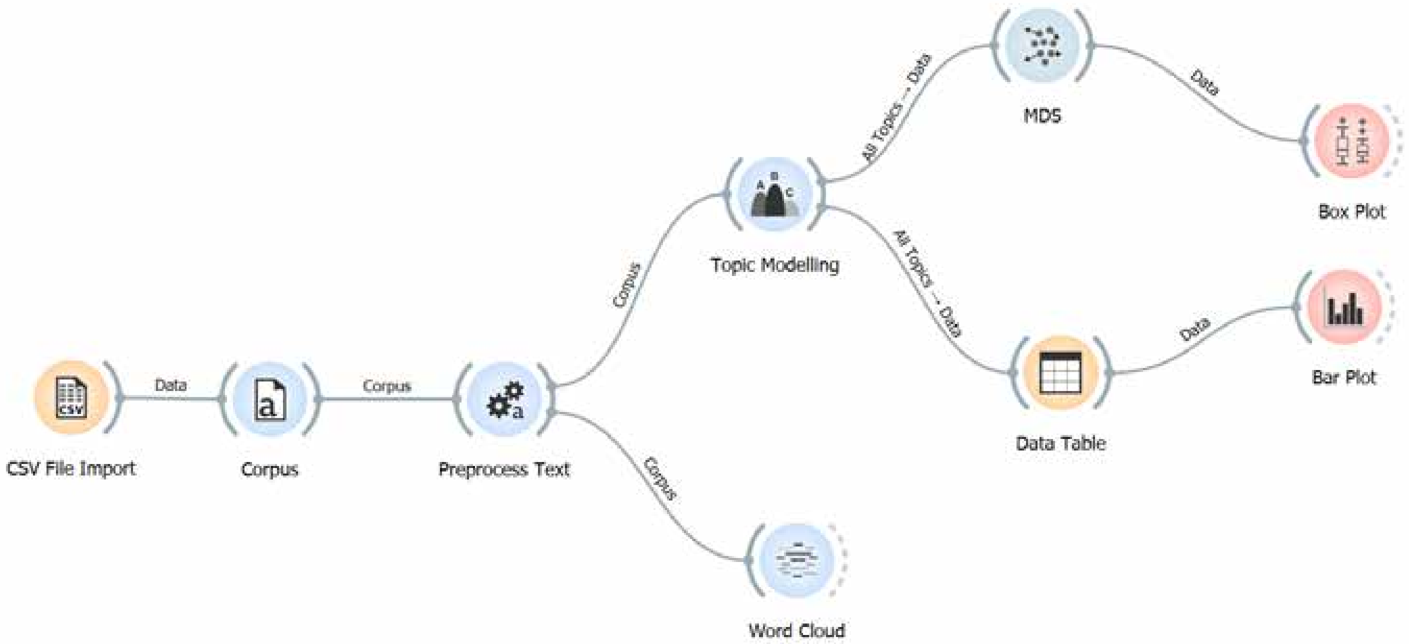

Fig. 1. Topic analysis using Orange Data Mining.

thematic structures (Han, 2020). LDA helped uncover hidden topics, facilitating a better understanding of recurring themes and improving document classification and trend analysis (Madzík and Falát, 2022, Tomojiri et al. 2022, Wibowo et al. 2024). Qualitative content analysis was conducted following Lindgren et al. (2020) to interpret core content within the selected literature. This approach involved decontextualizing and recontextualizing meaning units to identify patterns and themes within the text. The process of condensing and coding meaning units ensured a balance between abstraction and interpretation, ensuring an in-depth analysis. By integrating these methodologies, the study offers a thorough exploration of RMS and SM research, highlighting knowledge gaps and emerging trends in water quality monitoring at the watershed scale.

Bibliometric analysis

Ongoing studies trends

The research trends for RMS and SM were analyzed by screening 277 documents, narrowing the focus to 107 directly relevant studies (**Fig. 2**). Bibliometric analysis of RMS and SM research from 2005 to 2024 reveals a steady growth in publications, with notable peaks in 2013 and between 2020-2023, reflecting increasing global interest in these technologies. The early growth was moderate, with a sharp rise in 2013 coincided with advancements in monitoring and modelling tools (Hojjati-Najafabadi et al. 2022). After some fluctuations from 2014 to 2019, the field experienced a surge in research activity driven by the adoption of Internet of Things (IoT)

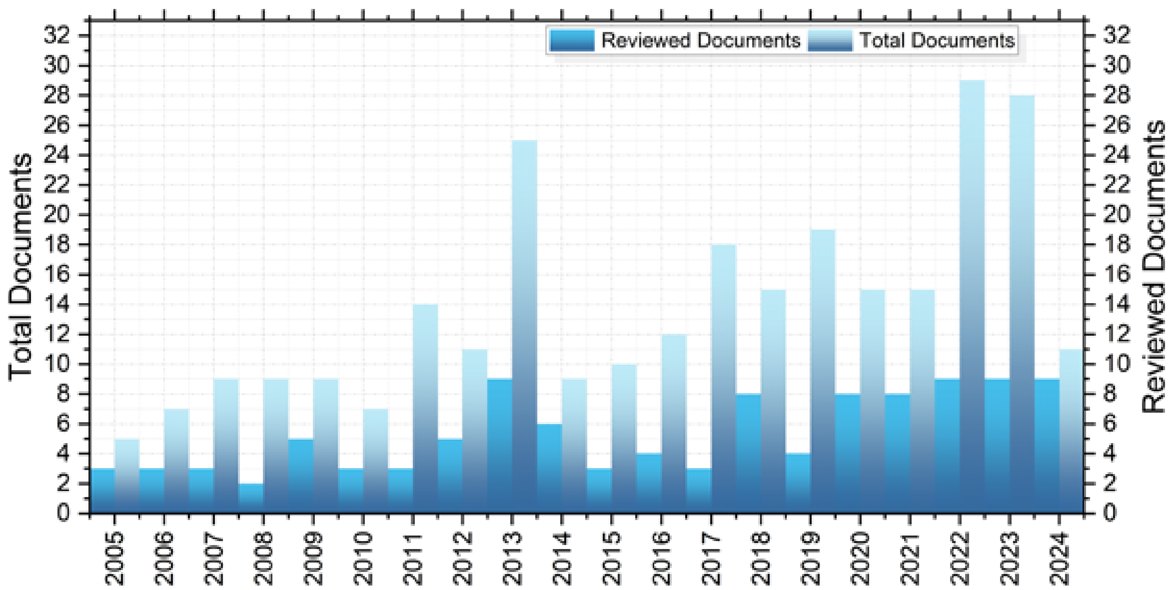

Fig. 2. Publication frequency per year.

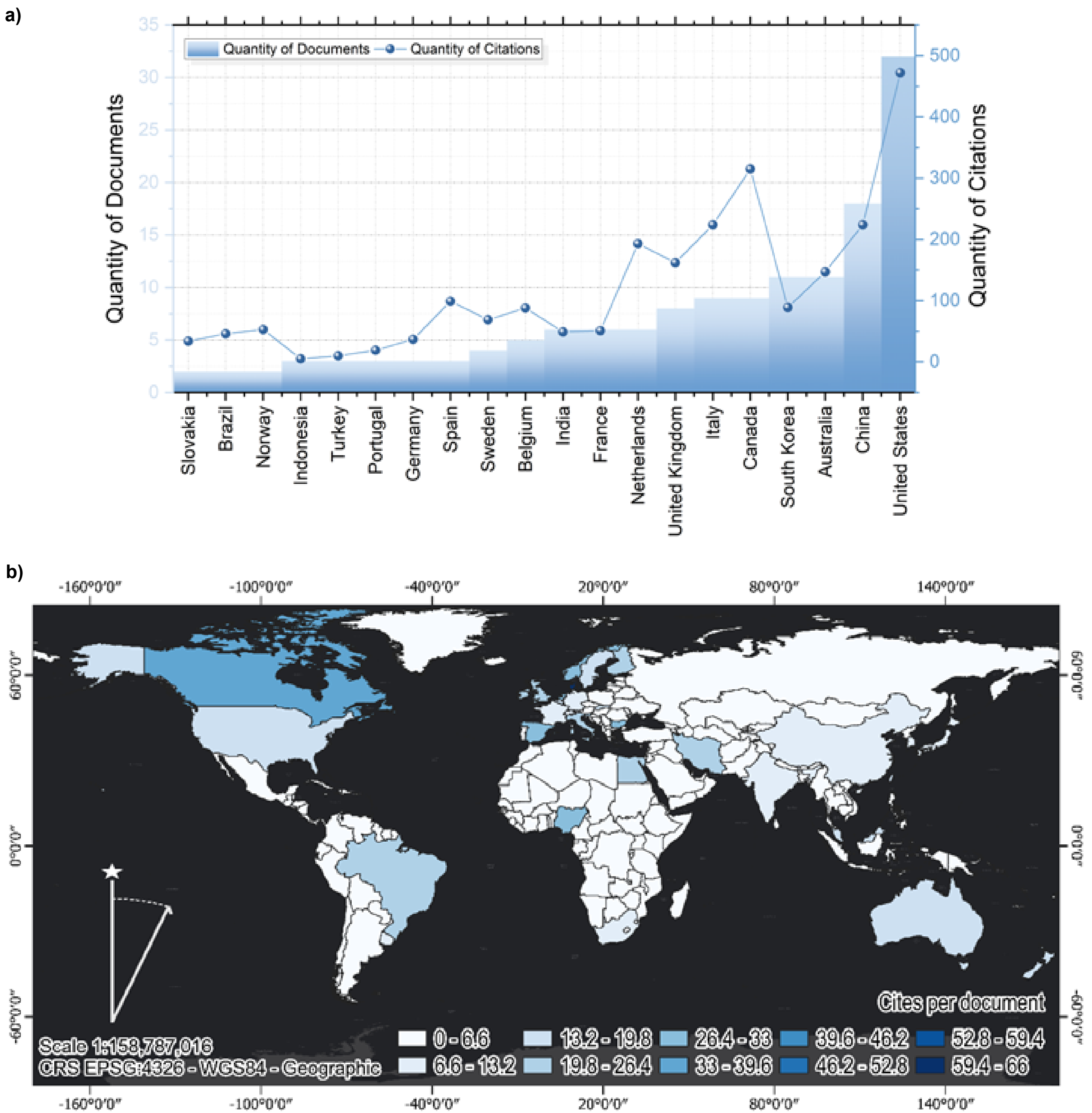

Fig. 3. Cumulative publications across countries: (a) Quantity of documents associated with citation counts per top 20th country and (b) Citations per document for each country.

and satellite technologies (Sagan et al. 2020). This growth culminated in a peak of 29 publications in 2022 and 28 in 2023. Although 2024 shows a slight decline, the overall trend denotes a sustained and evolving focus on RMS and SM applications for environmental monitoring and resource management.

The analysis of contributions in real-time monitoring systems and spatial modeling highlights significant disparities between research quantity and impact across countries. The United States leads with 32 publications, followed by China with 18 and Australia with 11, reflecting their dominance in research output (**Fig. 3a**). Indonesia, notably, is the only Southeast Asian country among the top 20 contributors, reflecting its growing interest in the field. Canada stands out with 315 citations across just 9 documents, indicating its high research relevance and an average of 35 citations per record. Similarly, the Netherlands and Italy demonstrate strong influence, with 32.2 and 24.9 citations per document, respectively. Denmark, with only a single document, achieves the highest citation impact at 66 citations (**Fig. 3b**). Spain and Norway also show notable influence despite producing fewer publications, with Spain averaging 33 citations per record. In contrast, research from some developing countries

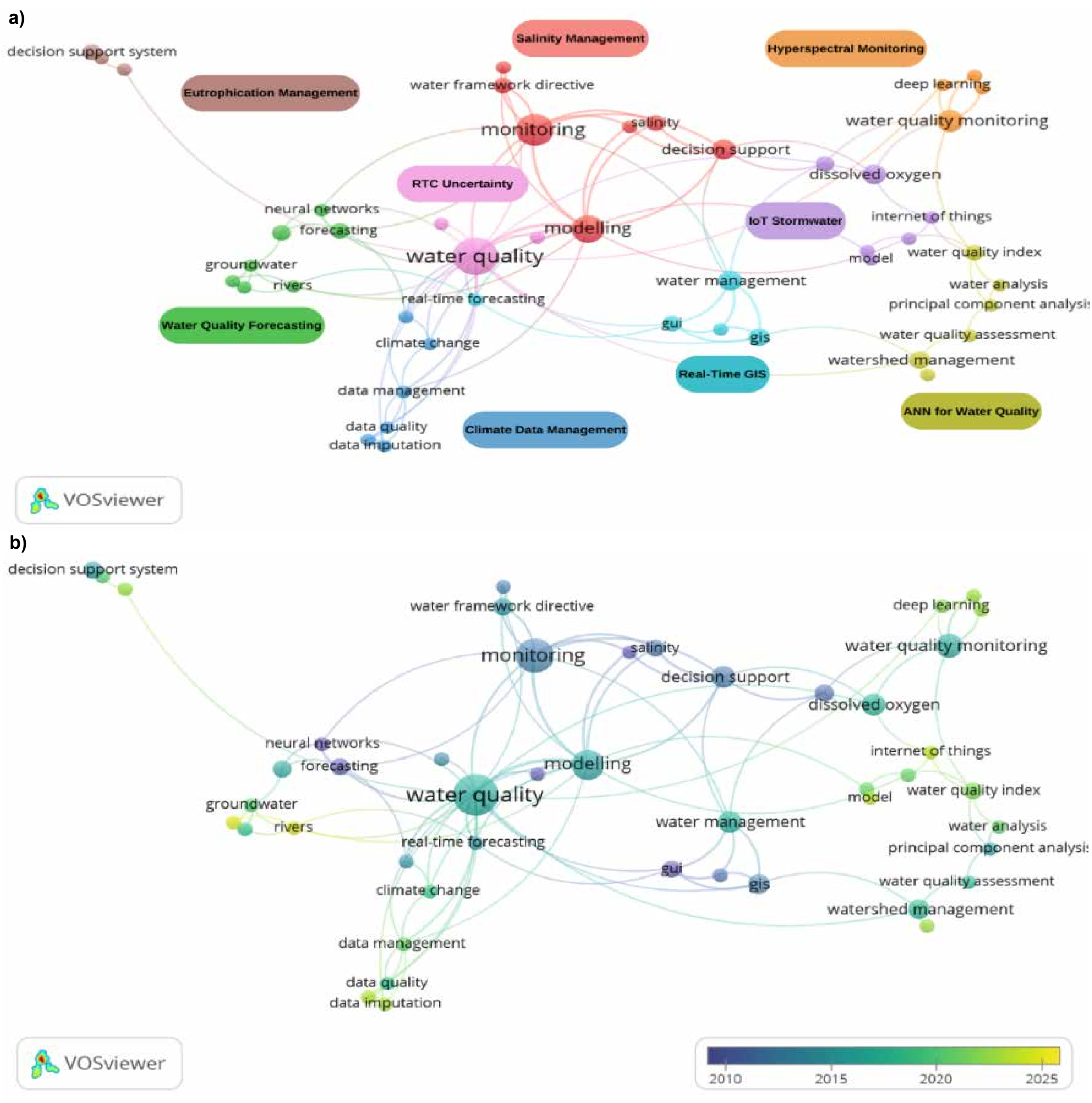

Fig. 4. Co-occurrence keywords depiction: (a) Cluster display and (b) Overlay display.

exhibits lower impact, underscoring the need to improve their research. These findings suggest that while some nations excel in research volume, others achieve substantial impact through highly cited, influential work. Ultimately, the balance between research quantity and citation impact varies, with countries like Canada and Denmark outperforming in terms of relevance and influence.

Bibliometric network analysis using VOSviewer

Co-occurrence analysis of author keywords reveals emerging research trends by identifying frequently paired topics in scholarly publications, thereby highlighting key areas of focus and interest (Kasavan et al. 2021, Wibowo et al. 2024). This interconnected approach provides insights into the evolution of knowledge within the field, illustrating how new ideas build on existing concepts and how research themes develop over time (Leong, 2021, Nobanee et al. 2021). By identifying common themes, co-occurrence analysis enables researchers to connect with peers in related fields, thereby strengthening research networks and fostering collaborations that can lead to innovative outcomes (Budihardjo et al. 2021, Ikhlas and Ramadan, 2024). It also supports strategic planning by revealing gaps in the current research landscape, allowing targeted efforts to address underexplored or emerging topics, thereby ensuring the efficient allocation of research resources (Ejaz et al. 2022, Wahyuningrum et al. 2023). Moreover, optimizing keyword selection based on co-occurrence patterns enhances the visibility and searchability of publications, making it easier for relevant audiences to discover and engage with the research (Fioramonte et al. 2022, Gao et al. 2021).

Fig. 4 depicts the frequency of keywords across a dataset of 423 distinct keywords, focusing on those that appear at least twice. The most prominent keywords - ‘water quality’, ‘monitoring’, and ‘modelling’ - occur 18, 12, and 9 times, respectively, highlighting their central role in the research topic. Fig. 4a, color-coded for clarity, reveals at least nine distinct clusters. Among these, ‘Salinity Management’ and ‘Water Quality Forecasting’ emerge as the largest cluster, each containing 7 keywords, indicating significant areas of research focus. In contrast, the smallest cluster, ‘RTC Uncertainty,’ includes only 3 keywords, indicating a narrower scope and highlighting a potential research gap.

The ‘Hyperspectral Monitoring’ cluster emphasizes the use of advanced imaging and deep learning techniques to enhance pollution detection accuracy (Mashala et al. 2023). The ‘IoT Stormwater’ cluster showcases the integration of real-time sensor networks for managing stormwater runoff and monitoring critical water quality parameters such as dissolved oxygen (Webber et al. 2022). Similarly, the ‘ANN for Water Quality’ cluster demonstrates the increasing reliance on artificial intelligence for modeling complex water quality systems (Rajaee et al. 2020), while the ‘Real-Time GIS’ cluster emphasizes the use of GIS technology for spatial-temporal water quality analysis and forecasting (Singh et al. 2020). Collectively, these clusters indicate a shift toward more sophisticated, real-time, and interdisciplinary approaches to water quality management. This evolution is driven by the increasing need for better prediction capabilities, faster response times, and more precise monitoring to address challenges such as urbanization and climate change.

Keyword frequency trends over time, depicted in Fig. 4b, indicate emerging topics such as ‘rivers’ and ‘recreational water quality,’ which have gained relevance from 2020 to 2024. Conversely, keywords like ‘forecasting,’ ‘salinity,’ and ‘wetlands’ exhibit older average frequencies, showcasing their sustained importance in research. Co-occurrence analysis reveals that while certain topics are gaining prominence, others maintain their long-standing significance over time. The clustering and frequency trends provide insight into current research concentrations and emerging themes that may influence future studies (Okafor et al. 2023).

Topic analysis utilizing Orange Data Mining

The topic analysis performed using Orange Data Mining employs techniques such as LDA (Latent Dirichlet Allocation), MDS (Multidimensional Scaling), and MTP (Marginal Topic Probability) to explore variables including author keywords, titles, and abstracts within the dataset (Ikhlas and Ramadan, 2024). The word cloud analysis underscores the importance of data in RMS and SM, with terms like ‘data’, ‘monitoring’, and ‘model’ reflecting a strong focus on data-driven approaches

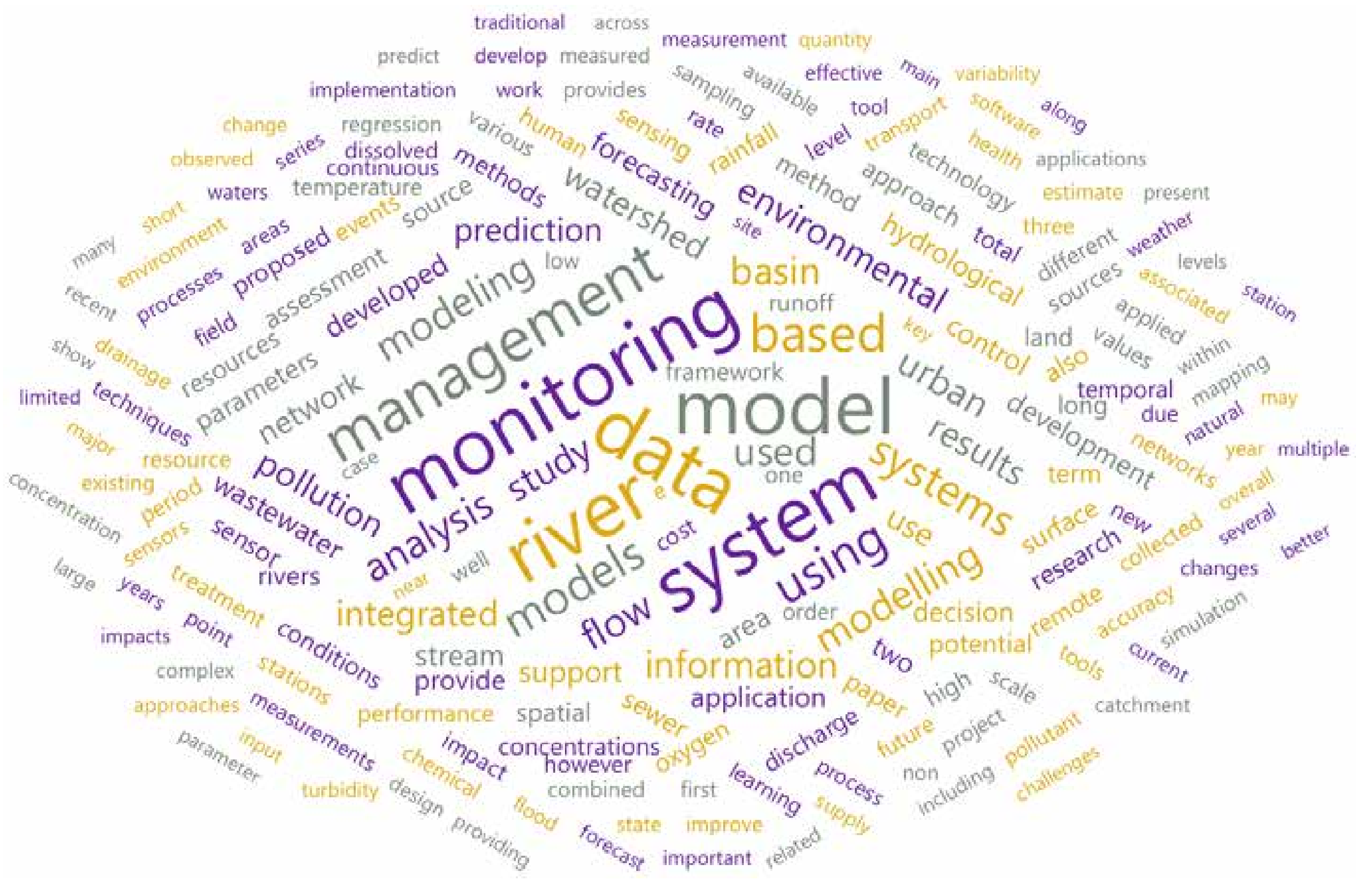

Fig. 5. Visualization of title, abstract, and author keywords modeling results via word cloud.

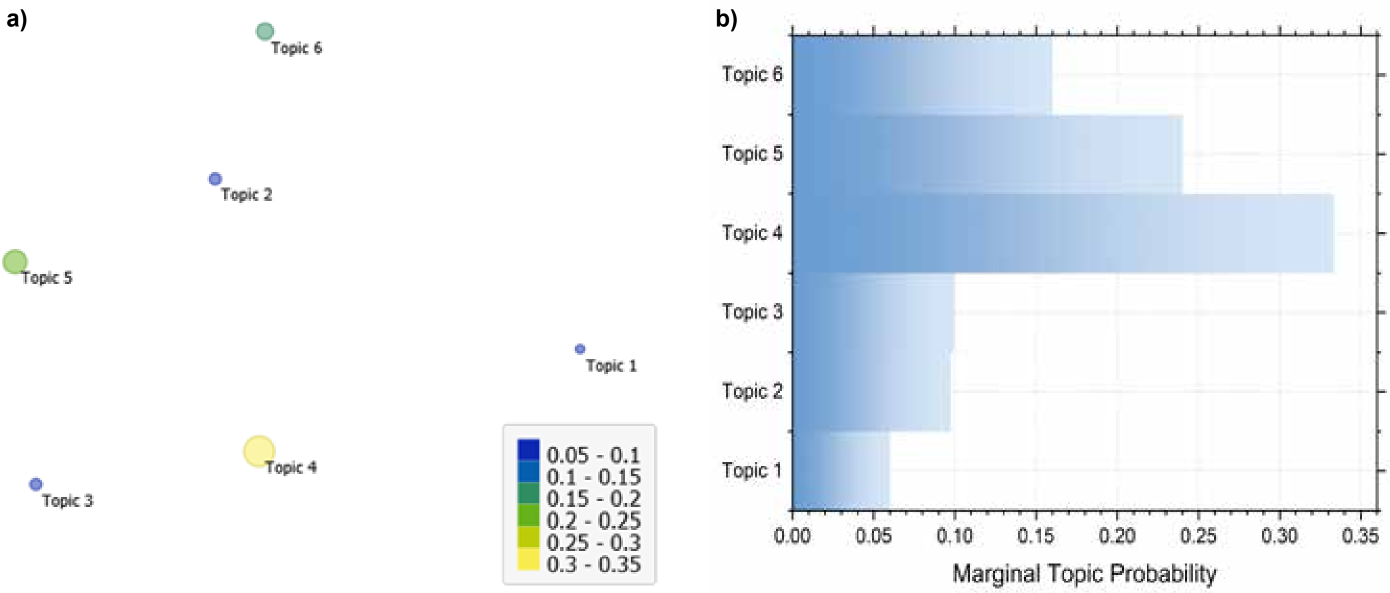

Fig. 6. Outcome of topic analysis: (a) Multidimensional scaling and (b) Marginal topic probabilities.

for effective environmental management. The prominence of terms such as 'river', 'management', and 'watershed' reflects the significance of water resource monitoring in addressing challenges posed by urbanization and advancing environmental sustainability (Pham-Duc et al. 2023). Furthermore, the focus on terms such as 'prediction' and 'forecasting' signals a growing interest in developing predictive models to anticipate environmental changes (Budihardjo et al. 2023). The integration of advanced technologies is evident through terms such as 'sensing' and 'technology,' which highlight efforts to enhance monitoring capabilities. Interdisciplinary collaboration is suggested by terms like 'hydrological' and 'biological,' emphasizing the need for diverse expertise to address complex environmental issues. However, the presence of terms such as 'challenges' and 'variability' suggests ongoing difficulties that require resolution to refine and optimize methodologies.

The comparison between keyword frequencies from the word cloud analysis in Orange Data Mining and co-occurrence data from VOSviewer reveals common themes, such as the importance of 'data', 'monitoring', and 'water quality', highlighting a consensus on the significance of data-driven approaches in environmental management. However, VOSviewer provides a deeper understanding of keyword relationships and research gaps, while also offers a more comprehensive understanding of keyword relationships and research gaps, while also tracking temporal trends in research interests, thus complementing the insights gained from the word cloud analysis. Despite the wealth of information from previous studies, there is a noticeable scarcity of research specifically addressing pollution sources, such as point source emissions or wastewater, diffuse emissions from agriculture and livestock, and landscape metrics. This gap may arise from previous studies' broader focus on general environmental impacts rather than targeting specific sources of pollution. Moreover, the complexity of integrating pollution sources with landscape metrics may have constrained research efforts in these areas, leading to their underrepresentation in the literature.

The analysis using LDA identified six distinct topics with no overlap (**Fig. 6a**), supported by MDS visualization, which highlights clear topic separation (Lee et al. 2022). MDS illustrates that similar topics are positioned closer together, indicating stronger relationships (Yao et al. 2022). In comparison to VOSviewer, Orange Data Mining revealed a more complex overlap of keywords across topics. Notably, 'data' appearing in all six topics, emphasizing its broad relevance (Ikhlas and Ramadan, 2024). The topics were subsequently labeled as follows: 'Watershed Flow Modeling', 'Data-Driven Monitoring Systems', 'Urban Drainage Monitoring', 'River Pollution Management', 'Decision Support for River Management', and 'Data-Driven Prediction Models.' Differences between VOSviewer and Orange Data Mining suggest varying interpretations of the topics. However, thematic connections, such as 'River Pollution Management' linking to 'Eutrophication Management' and 'Water Quality Forecasting', were evident. The results from both MDS and MTP analyses reveal clear patterns in research focus (**Fig. 6b**). Among the topics, 'River Pollution Management' emerges as the most prominent, with the highest MTP score, indicating a significant concentration of research in this area. Conversely, 'Watershed Flow Modeling' has the lowest MTP score, highlighting a notable gap in research attention. This suggests opportunities for further exploration and development in areas like hydrological modeling and real-time data integration.

The MDS visualization further shows that 'Decision Support for River Management' and 'Data-Driven Prediction Models' are closely related, while 'Data-Driven Monitoring Systems' and 'Watershed Flow Modeling' are positioned further apart, signifying distinct research directions (Daenekindt and Huisman, 2020, de Vries et al. 2020). These findings suggest that data-driven models are more likely to be employed than physical models. While physical models provide a more comprehensive understanding of phenomena, their application is often more challenging. In contrast, data-driven models, although potentially fragile in terms of causality, require robust datasets. This highlights the importance of improving data quality to enhance monitoring efforts.

Qualitative content analysis

Studies concerning RMS and SM in developing countries

Recent innovations in real-time water quality monitoring have significantly enhanced our ability to track and manage water resources more effectively. Cham et al. (2020) introduced UMH2O, a web-based monitoring system that utilizes Google Earth and the National Water Quality Index (NWQI) to present a user-friendly graphical representation of water quality. Designed for the Langat River in Malaysia, UMH2O uses varying shapes and colors to make water quality data more accessible to both the public and experts alike (Cham et al. 2020). By visualizing trends and pollution sources through interactive heart-shaped icons, the system raises public awareness and supports environmental conservation efforts. It also provides valuable insights into spatial and temporal variations in water quality (Cham et al. 2020).

Building on technological advancements, Sarminingsih et al. (2024) developed a real-time water quality monitoring tool for the Garang Watershed, using IoT technology. This system continuously measures parameters such as temperature, pH, turbidity, and dissolved oxygen, integrating the data into a publicly accessible platform (Sarminingsih et al. 2024). By coupling these real-time measurements with the Storm Water Management Model (SWMM), the tool evaluates the impact of land-use changes on water quality, offering actionable insights for effective watershed management (Sarminingsih et al. 2024). The integration of IoT sensors and SWMM software in the system exemplifies how modern technology can enhance both water quality monitoring and modeling (Sarminingsih et al. 2024).

Taufik and Nuqoba (2019) focused on improving river water quality monitoring by combining real-time data acquisition with spatial-temporal visualization tools. Their approach uses Wireless Sensor Networks (WSN) and Geographic Information Systems (GIS) to overcome limitations of traditional methods, such as delays in data collection and susceptibility to human error (Taufik and Nuqoba, 2019). The comprehensive system they developed combines data acquisition, communication, and visualization components, which facilitate accurate and timely monitoring (Taufik and Nuqoba, 2019). By integrating GIS with real-time data, their system supports better environmental management and decision-making, particularly for analyzing pollution sources and their impacts (Taufik and Nuqoba, 2019).

In another study, Zulkifli et al. (2022) explored the application of IoT technology to enhance the performance and efficiency of water supply networks. Their system incorporates a solar-powered GSM TTGO sensor logger and cloud-based real-time data visualization to provide accurate and timely water quality data (Zulkifli et al. 2022). By addressing technical challenges and integrating advanced IoT solutions, the study offers a cost-effective approach to water quality monitoring (Zulkifli et al. 2022). Continuous data collection, combined with comparison against laboratory results, ensures reliable feedback and alerts, further improving water quality management practices (Zulkifli et al. 2022).

Heege et al. (2014) presented a novel approach to water quality monitoring in large river systems using multispectral satellite sensors. Their study, focused on the Mekong River, utilized physics-based spectral inversion algorithms to measure turbidity and total suspended matter from satellite reflectance spectra (Heege et al. 2014). This method provides standardized, accurate data across extensive regions, overcoming the limitations of traditional in situ methods (Heege et al. 2014). The Modular Inversion and Processing System (MIP), integrated with the EOMAP Workflow System, demonstrated the effectiveness of satellite-based monitoring in capturing seasonal trends and supporting long-term environmental management (Paraskevopoulos and Singels, 2014). This approach underscores the potential of remote sensing as a scalable and cost-effective solution for water quality assessment (Paraskevopoulos and Singels, 2014). Additionally, the integration of real-time soil water data into irrigation systems by Paraskevopoulos and Singels (2014) demonstrates significant progress in water management technologies. These developments aim to enhance environmental monitoring and promote efficient resource utilization, marking notable progress in sustainable water management practices.

In recent years, spatial modeling and remote sensing have become essential tools for addressing complex water resource management challenges, particularly in developing regions where environmental and climatic pressures are most acute (Chawla et al. 2020). These techniques provide advanced methods for monitoring various aspects of water systems, including snow cover, pollution, and water quality – areas where traditional approaches often fall short (Kamyab et al. 2023). A notable application of remote sensing lies in managing seasonal snow cover, which is crucial for understanding hydrological cycles, especially in high-altitude regions where snowmelt significantly influences river flow (Chen et al. 2022). For instance, the use of MODIS snow cover data and the MODSNOW software has proven effective in analyzing snowmelt patterns in the Naryn River basin in Kyrgyzstan (Chen et al. 2022). This methodology facilitates accurate assessments of snow cover across different altitudinal zones, leading to improved forecasts of river flow and seasonal water availability (Chen et al. 2022).

Climate change exacerbates threats to water quantity and quality, necessitating more advanced management techniques (Ahmed et al. 2022). While the SWAT model is widely used, its application in developing countries is often hindered by data limitations and geographical challenges (Amalia et al. 2024). A study focusing on the Rawa Pening Catchment Area in Indonesia utilizes Google Earth Engine (GEE) and machine learning to enhance SWAT modeling (Amalia et al. 2024). By comparing models based on GEE and different Digital Elevation Models (DEMs), the research aims to improve the accuracy of hydrological modeling and provide actionable insights for water resource management (Amalia et al. 2024).

Managing accidental hazardous substance spills into rivers presents significant challenges, as these incidents can cause extensive environmental, economic, and social damage (Ye et al. 2024). Effective spill management requires advanced predictive models to understand contaminant dispersion (Ramadan et al. 2024). A study focusing on the Nile River employs the Delft3D model to simulate potential spill scenarios, aiming to provide detailed data on contaminant movement and impact (Ramadan et al. 2024). By integrating hydrodynamic and water quality modeling, the study helps decision-makers develop more effective response strategies to mitigate the consequences of spills in complex river systems (Ramadan et al. 2024). The integration of water and waste load allocation is crucial due to rising pollution concerns and dwindling freshwater supplies (Giri, 2021). Traditional models often address water quantity and quality separately, but recent research emphasizes the importance of simultaneous management (Giri, 2021). For example, a study employing a factorial interval optimization model for the Dez River system in Iran explores the impact of uncertainties in agricultural return flows (Tavakoli et al. 2014). Using the SWAP agro-hydrologic model, this research aims to develop robust water management policies that account for these uncertainties, ultimately improving water quality management (Tavakoli et al. 2014).

Socio-economic development is closely tied to water quality, especially in low-income countries where inadequate sanitation infrastructure contributes to contamination (Duttagupta et al. 2020). A study examining groundwater quality in India's Western Bengal basin explores the correlation between socio-economic factors and fecal coliform (FeC) concentrations (Duttagupta et al. 2020). By analyzing long-term trends and employing a particle tracking model, the research seeks to understand the impact of socio-economic development on groundwater contamination. Its findings aim to support progress toward achieving Sustainable Development Goal 6, which focuses on clean water and sanitation (Duttagupta et al. 2020). In Khartoum, Sudan, inadequate water consumption and untreated wastewater discharge pose significant environmental and water quality challenges (Shakak, 2022). A study using the Water Evaluation and Planning (WEAP) model in conjunction with GIS software assesses pollutant loads and their impact on water resources (Shakak, 2022). By evaluating different management scenarios and analyzing satellite imagery, the research provides valuable insights for improving water quality and reducing environmental impacts in the Nile catchment area (Shakak, 2022).

The global challenge of freshwater scarcity and water quality degradation are increasingly intensified by anthropogenic activities and natural events. In tropical regions, agricultural expansion and extreme runoff events contribute to eutrophication and water quality decline (Latwal et al. 2023). A study analyzing chlorophyll-a (Chl-a) concentrations in tropical reservoirs, using Sentinel-2 satellite data focuses on the Bhadra Reservoir in India (Latwal et al. 2023). By mapping Chl-a distribution and examining the impact of land use/land cover, the research provides insights into aquatic ecosystem health and variations in water quality influenced by surrounding land use practices (Latwal et al. 2023). Eutrophication remains a significant issue for freshwater bodies, as seen in the Vaal Dam reservoir in South Africa (Obaid et al. 2021). Traditional in-situ measurements are inadequate for large-scale monitoring, prompting the use of advanced satellite remote sensing technologies (Obaid et al. 2021).

A study employing Sentinel-2 and Landsat 8 data evaluates chlorophyll-a and other water quality parameters, aiming to enhance monitoring accuracy and support the management of biomass productivity and water quality in the Vaal Dam (Obaid et al. 2021). Water temperature regulation is another critical aspect of managing aquatic ecosystems, yet conventional surveys are costly and time-consuming (Lamaro et al. 2013). Remote sensing with thermal infrared imagery offers a more practical alternative, as demonstrated by a study using Landsat 7 ETM+ thermal bands to estimate water surface temperature in the Embalse del Río Tercero reservoir in Argentina (Lamaro et al. 2013). The research assesses the impact of thermal plumes from a nuclear power plant on reservoir temperature and aquatic biota, validating the Single Channel Generalized Method (SCGM) with in-situ measurements (Lamaro et al. 2013).

Conclusion

To summarize, the bibliometric analysis from 2005 to 2024, conducted utilizing the PRISMA 2020 approach, shows a rising trend in real-time monitoring and spatial modeling publications, with the United States leading in volume and citation impact. This growth is characterized by strong international collaboration and increasing availability of open-access resources. Despite fewer publications, Canada and Italy stand out for their high citation counts. Co-occurrence keyword analysis identifies key research areas such as water quality, monitoring, and modeling, with recent trends showing increased focus on topics like rivers and recreational water quality. The study utilized LDA, MDS, and MTP methods to identify six primary research areas in water quality management, revealing a preference for data-driven models over physical models due to their practical ease of application. However, data-driven models require high-quality datasets to mitigate their causal limitations effectively. Among the identified topics, 'River Pollution Management' emerged as the most prominent, while 'Watershed Flow Modeling' showed the lowest prevalence, indicating a significant research gap. Developing countries face challenges in water resources management due to technological, human, and financial constraints. Nonetheless, advancements in RMS and SM offer promising solutions. Innovations such as UMH2O and IoT-based tools have enhanced water quality monitoring, while remote sensing techniques, like those used in the Mekong River and Bhadra Reservoir studies, have improved spatial and temporal assessments. Research utilizing SWAT, Google Earth Engine, and advanced satellite data addressed critical gaps in water quality management and predictive modeling. Furthermore, socio-economic factors and the impacts of anthropogenic activities remain crucial considerations. Studies focusing on groundwater contamination and agricultural runoff have shed light on their effects on water quality.

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Achleitner S., De Toffol S., Engelhard C., Rauch W.	Model based hydropower gate operation for mitigation of CSO impacts by means of river base flow increase	2005	Water Science and Technology	52	5
Vandenberghe V., Goethals P.L.M., Van Griensven A., Meirlaen J., De Pauw N., Vanrolleghem P., Bauwens W.	Application of automated measurement stations for continuous water quality monitoring of the Dender river in Flanders, Belgium	2005	Environmental Monitoring and Assessment	108	01-Mar
South S.	Water quality analyser provides real-time total phosphorus measurement in Everglades	2005	Water and Wastewater International	20	1
Dorner S.M., Anderson W.B., Slawson R.M., Kouwen N., Huck P.M.	Hydrologic modeling of pathogen fate and transport	2006	Environmental Science and Technology	40	15
Yang T.C., Kao C.M., Yeh T.Y., Lin C.E., Lai Y.C.	Application of multimedia model for the development of watershed management strategies: A case study	2006	WSEAS Transactions on Mathematics	5	4
Quinn N.W.T.	Bottom-up, decision support system development: A wetland salinity management application in California's San Joaquin Valley	2006	Proceedings of the iEMSs 3rd Biennial Meeting," Summit on Environmental Modelling and Software"		
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Seo D., Lee E.H.	Development of vertically moving automaticwater monitoring system (VeMAS) for lake water quality management	2009	Atmospheric and Biological Environmental Monitoring		
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