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REVIEW

Drone-based digital twins for water quality monitoring: A systematic review

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Abstract

The rapid advancement of drone technology and digital twin systems has significantly transformed environmental monitoring, particularly in the field of water quality assessment. This paper systematically reviews the current state of research on the application of drones, digital twins, and their integration for water quality monitoring and management. It highlights key themes, insights, research trends, commonly used methodologies, and future directions from existing studies, aiming to provide a foundational reference for further research to harness the promising potential of these technologies for effective, scalable solutions in water resource management, addressing both immediate and long-term environmental challenges. The systematic review followed PRISMA guidelines, rigorously analysing hundreds of relevant papers. Key findings emphasise the effectiveness of drones in capturing real-time, high-resolution spatial and temporal data, as well as the value of digital twins for predictive and simulation-based analysis. Most importantly, the review demonstrates the potential of integrating these technologies to enhance sustainable water management practices. However, it also identifies a significant research gap in fully integrating drones with digital twins for comprehensive water quality management. In response, the review outlines future research directions, including improvements in data integration techniques, predictive models, and interdisciplinary collaboration.

KEYWORDS

digital twin, drones, environmental management, water monitoring, water quality

1 | INTRODUCTION

Water quality monitoring is a critical component of environmental management, which influences public health, ecosystem stability, and resource sustainability. Effective water quality management is essential for preventing pollution, mitigating the impacts of human activities, and preserving biodiversity. Traditional methods of water quality assessment, such as in-situ sampling and laboratory analysis, while reliable, are often labour-intensive, time-consuming, and geographically limited. These methods typically lack the ability to provide real-time insights across large or remote water bodies, leading to gaps in data coverage and delayed responses.[1] To overcome these limitations, there is a growing need for innovative technologies that can enable more comprehensive and efficient water quality monitoring.

Drones, also known as Unmanned aerial vehicles (UAVs), have emerged as a transformative technology in environmental monitoring, including water quality assessment. Unmanned aerial vehicles provide a versatile platform for accessing remote or hazardous areas that are difficult to reach with conventional methods. Equipped with an array of sensors, drones can collect high-resolution spatial and temporal data on various water quality parameters, such as temperature, turbidity, pH, and pollutant concentrations. By enabling the collection of real-time data across large and often inaccessible water bodies, drones significantly enhance the precision and scope of water quality monitoring efforts. Additionally, the ability to equip drones with different sensor payloads makes them adaptable to a wide range of environmental monitoring tasks.

Another promising technology that has gained traction across multiple industries, including environmental management, is the digital twin. A digital twin is a dynamic digital replica of a physical system that can simulate, predict, and optimise the performance of the system in real time.[1] Digital twins have already been successfully applied in sectors like manufacturing,[2] healthcare,[3] and urban planning,[4] where they enable real-time decision-making and predictive analytics. In the context of water quality monitoring, digital twins offer a continuous and dynamic representation of water bodies. It allows early detection of pollution events, real-time assessment of intervention strategies, and the optimisation of water management practices.[1]

The integration of drones with digital twins creates a powerful synergy that can revolutionise water quality monitoring and management. Drones collect real-time, high-resolution data from aquatic environments, which is then fed into digital twins—advanced models capable of simulating and predicting environmental conditions. This combination provides continuous monitoring of water quality and gives water managers the ability to track current conditions while also anticipating future changes. With this deeper understanding of water systems, managers can make informed decisions based on accurate, up-to-date data.[5] This integration improves both immediate interventions and long-term environmental planning, as the digital twin models become more precise and responsive through real-time drone data. As a result, the management of water resources becomes more proactive and adaptive to the complex dynamics of aquatic ecosystems.

However, despite the clear advantages of combining these technologies, research in this area remains limited. There is a pressing need for standardised methodologies and frameworks that can effectively integrate drone data into digital twin platforms for water quality monitoring and management.

This systematic review surveys the literature, analyses emerging trends, identifies common themes, outlines commonly used methodologies, and highlights future directions in the field. It provides researchers with an up-to-date assessment of the field, serving as a foundation for further research in the development of effective, real-time, and scalable solutions for water quality management. Moreover, the review emphasises opportunities for innovation, motivating further advancements in water quality monitoring systems. Specifically, the study makes a notable contribution to the scientific community by (a) *Identifying research gaps*: Despite increasing interest in digital twins and drones, there remains a lack of standardised methodologies and frameworks for integrating these technologies into water quality management. The review highlights the need for more research focused on combining UAV data with digital twin platforms. (b) *Highlighting the potential for interdisciplinary collaboration*: The integration of these technologies spans diverse fields, including environmental science, data science, and engineering. The review underscores the importance of cross-disciplinary cooperation to fully realise the potential of these tools for water quality management. (c) *Proposing future research directions*: Several key areas are identified for further research, such as enhancing data integration techniques, developing AI-based predictive models, and improving the scalability of digital twin platforms. These advancements are vital for addressing current technological limitations and unlocking the full potential of drone-based digital twin systems.

The rest of the paper is organised as follows: Section 2 provides a detailed description of the systematic review methodology and process. Section 3 analyses and discusses the collected literature. Section 4 outlines future directions. Finally, Section 5 concludes the review.

2 | SYSTEMATIC LITERATURE REVIEW

2.1 | Scope

In this section, we present a systematic review of drone-based digital twins for water management in various water bodies, including dams, reservoirs, rivers, watersheds, and lakes. Water management encompasses water monitoring, assessment, control, and any actions aimed at managing or controlling water in these natural environments. While the primary focus is on the utilisation of drone-based digital twins for water quality management, the study systematically covers three closely related research areas to provide a broader perspective. First, the review addresses the use of drones and digital twin technologies in water quality applications independently. Then, the review focuses on literature that integrates drones and digital twin technologies in water quality management. Thus, the systematic review of relevant literature includes the following aspects:

1. *Digital twins for water quality:* Exploring the literature of using digital twin technology for simulating, monitoring, and predicting water quality parameters in various water bodies (e.g. lakes, rivers, dams, watersheds, and reservoirs).
2. *Application of drones for water quality*: Understanding the state-of-the-art research perspectives and use cases regarding the use of UAVs or drones in managing or controlling water quality through literature.
3. *Combining drones and digital twins for water quality management:* Highlighting research utilised drone-based digital twin for water quality management in water bodies; lakes, rivers, dams, watersheds, and reservoirs.

Figure 1 illustrates the intersection of main topic with these three related domains. Understanding the emergence and trend of research in these three areas highlights the significance of their integration and underscores the potential for future studies to leverage the strengths of each field for innovative and enhanced water management solutions.

2.2 | Methodology

A PRISMA-based systematic review methodology is followed to ensure transparency and reproducibility of outcomes.[6] The methodology entails six phases, shown in Figure 2, to comprehensively compile, process, and analyse the relevant literature.

Study Scope: A rigorous definition of the study scope is essential to establish the inclusion and exclusion criteria. The study scope is divided into three key topics as specified in the *review scope*. The primary focus is on research integrating digital twins with drones for water quality management in water bodies such as lakes, rivers, dams, watersheds, and reservoirs. In this context, water management encompasses decisions related to water quality monitoring, assessment, purification, filtration, and more. Additionally, we aim to understand how each of these intersecting topics—digital twins and drones—is utilised in the literature for water quality management, specifically focussing on how the research literature emphasises the use of digital twins for water quality applications and how drones are utilised for water quality monitoring or control. Studies utilising digital twins or drones for purposes outside water quality management are excluded. Also, studies employing these technologies in applications not related to water bodies, such as water distribution networks or underground water, are outside the scope of this study. This precise focus on the study scope drives the outcome insights towards the specific topic of interest.

Article Source Identification: To gather relevant articles, we utilised three esteemed academic search engines: Web of Science (WOS), ScienceDirect, and IEEE Xplore. These search engines are known for their exclusive inclusion of high-quality, peer-reviewed journals, ensuring the credibility and reliability of the literature sources. Additionally, these platforms enable precise, targeted, and reproducible searches, which are essential for conducting a robust systematic review. Therefore, their comprehensive coverage and advanced search capabilities collectively contribute to high-quality literature review outcomes.

Developing Search Strings: Search strings for each defined subject are carefully developed to capture all relevant studies while excluding unrelated ones. Each search string consists of multiple terms used by search engines to fetch articles based on matches found in titles, abstracts, and keywords. Table 1 outlines the logical structure of the search strings for each sub-scope of the literature review. Logical operators such as OR and AND are employed to combine search terms building a search string.

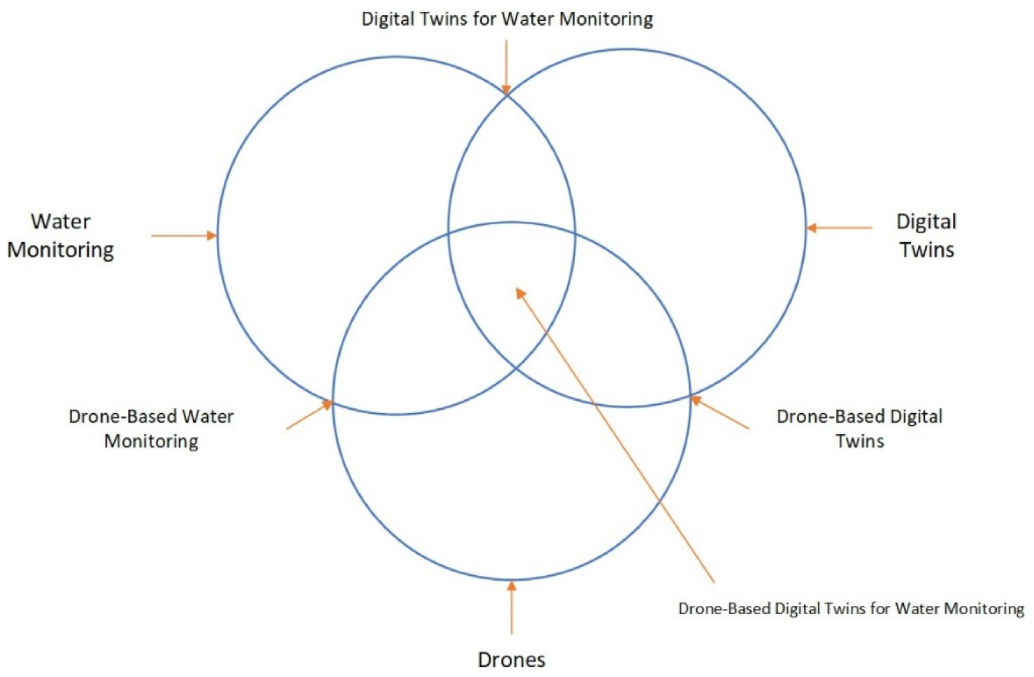

FIGURE 1 Relevant research topics.

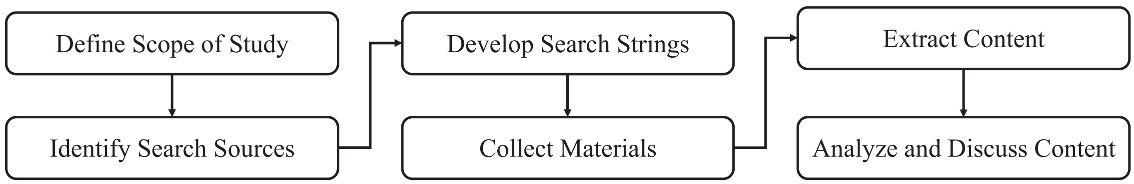

FIGURE 2 Review methodology.

Materials Collection: In this phase, articles were gathered from several academic databases, including WOS, ScienceDirect, and IEEE Xplore. After the initial collection, duplicate records were identified and removed, leading to a more refined set of unique articles. The remaining records were then screened based on their titles, keywords, and abstracts to assess their relevance and suitability for the review. Figures 3–5 illustrate flowcharts detailing the step-by-step process of screening, filtering, and selecting studies for each of the three topics, including the outcomes at each stage. The final refined set of articles selected for further processing includes.

- 8 records on *Digital twins for water quality management in natural water bodies.*[1,7–13]
- 217 records on *Drones for water quality management in natural water bodies,*[1,12–50,51–80,81–100,101–125,126–150,151–175,176–200,201–227] In this case, due to the large number of papers, 65 conference papers and non-English articles were excluded from the initial screening result of 282.

TABLE 1 Logical structure of search strings for the literature review.

Literature Review Sub-Scope	***Logical Search String Structure***
Digital Twins for Water Quality Management in Natural Water Bodies	"water" AND "digital twin" AND ("river" OR "lake" OR "watershed" OR "dam" OR "reservoir" OR "stream") AND ("purity" OR "clarity" OR "quality" OR "condition" OR "health" OR "pollution" OR "contamination" OR "standard" OR "degradation" OR "tainting" OR "spoilage" OR "defilement" OR "corruption" OR "Impurity" OR "poisoning" OR "adulteration" OR "fouling" OR "filth" OR "dirt" OR "environmental damage")
Drones for Water Quality Management in Natural Water Bodies	"water" AND ("drone" OR "unmanned aerial vehicle" OR "UAV") AND ("river" OR "lake" OR "watershed" OR "dam" OR "reservoir" OR "stream") AND ("purity" OR "clarity" OR "quality" OR "condition" OR "health" OR "pollution" OR "contamination" OR "standard" OR "degradation" OR "tainting" OR "spoilage" OR "defilement" OR "corruption" OR "Impurity" OR "poisoning" OR "adulteration" OR "fouling" OR "filth" OR "dirt" OR "environmental damage")
Drone-Integrated Digital Twin for Water Quality Management in Natural Water Bodies	"water" AND ("drone" OR "unmanned aerial vehicle" OR "UAV") AND "digital twin" AND ("river" OR "lake" OR "watershed" OR "dam" OR "reservoir" OR "stream")

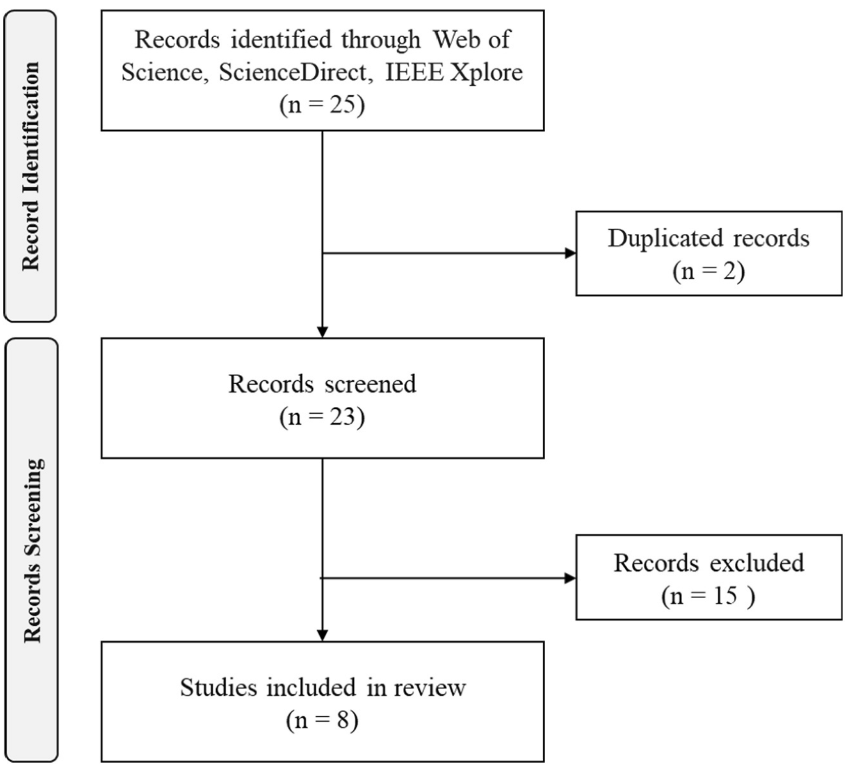

FIGURE 3 Material collection: DT for water quality management in natural water bodies.

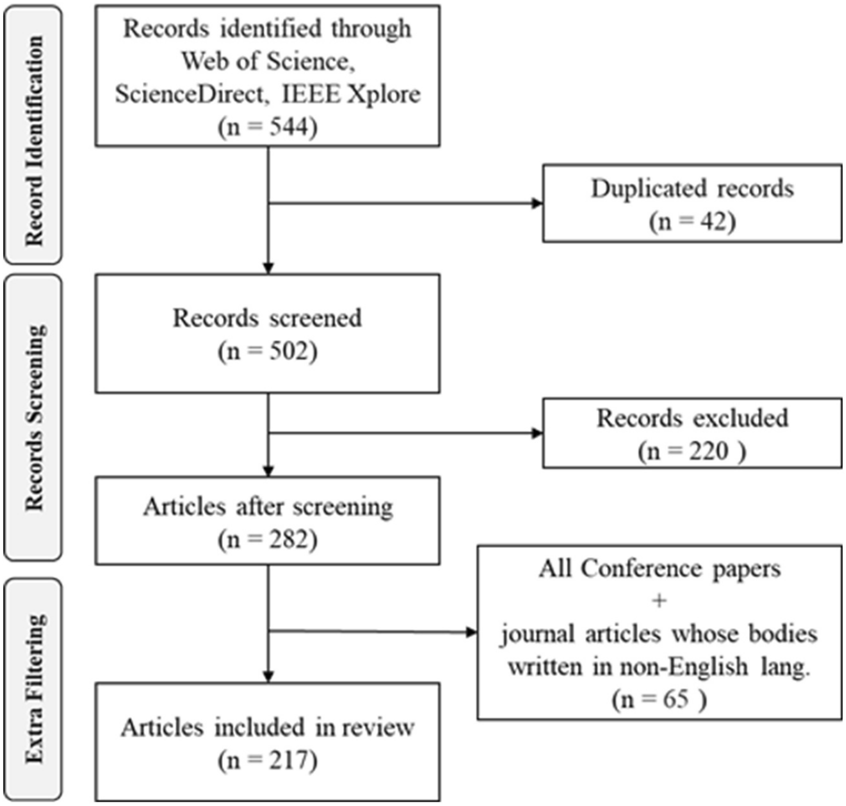

FIGURE 4 Material collection: Drones for water quality management in natural water bodies.

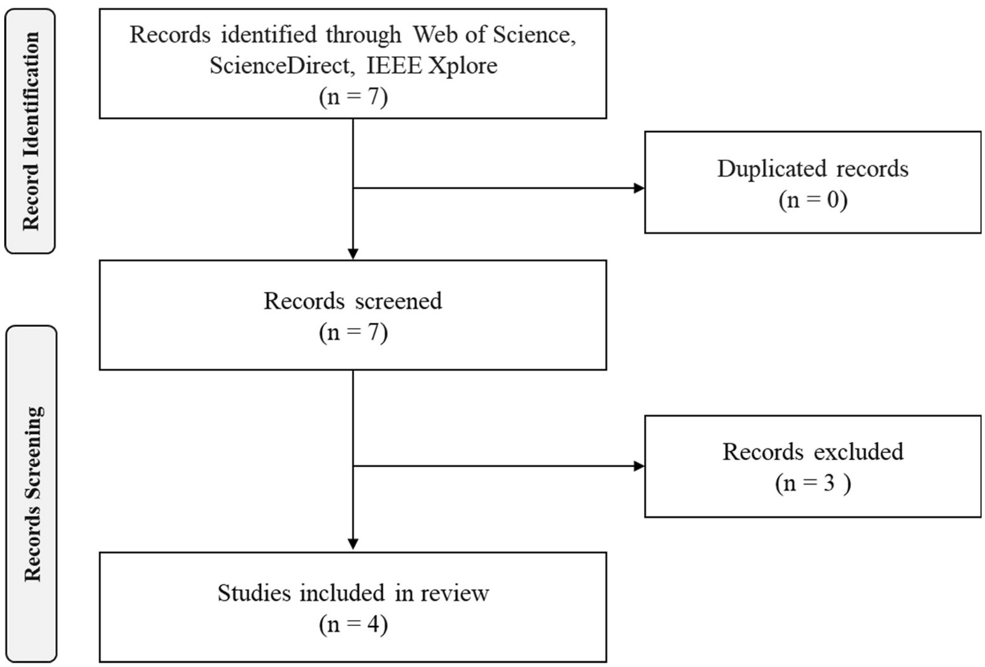

FIGURE 5 Material collection: Drone-based DTs for water quality management in natural water bodies.

- 4 records on *Drone-integrated digital twin for water quality management in natural water bodies.*[1,228–230]

Information Extraction: In this stage of the PRISMA approach, important insights, themes, findings, results, challenges, and research gaps are extracted. This structured organisation sets the foundation for the next stage, where each subarea is analysed separately.

Information Analysis and Discussion: Information Analysis: At this stage of the PRISMA-based systematic review, the extracted data is systematically synthesised to draw meaningful conclusions and highlight key bibliographical and thematic insights. To ensure effective communication with the reader, a variety of visualisation tools are employed, including authorship networks, trend charts, methodology maps, summary tables, and detailed charts.

3 | ANALYSIS AND DISCUSSION

To extract key insights and provide a comprehensive overview of the current research landscape, the collected studies are analysed both bibliographically and thematically in the following subsections. The analysis is organised into three categories based on the previously outlined research scope. This structured approach aims to offer a holistic understanding of the field's state of the art, uncover significant trends through bibliographic exploration, highlight key themes and insights, and identify areas in need of further research. The first section synthesises the role of digital twins in water quality management for natural water bodies, followed by an analysis of the use of drones in this context. Lastly, the analysis explores the integration of these technologies, focussing on their combined potential to advance water quality management for natural water bodies.

3.1 | Digital twin applications in water quality management of natural water bodies

Bibliographical Analysis: As shown in Figure 6, the literature reveals an increase in research activity related to digital twin technology for water quality management in water bodies in recent years. Notably, 2023 shows the highest number of publications, underscoring several key points. First, this is clearly an emerging field, with all relevant publications appearing within the last 3 years, starting from 2021. Second, the growing number of publications reflects a rising interest in this area, as researchers increasingly recognise the importance of applying digital twin technology to address environmental challenges. This trend is driven by technological advancements and heightened awareness of global environmental issues. Finally, despite the recent surge in interest, the overall number of studies remains limited. This limit number of literature research indicates the need for more work to bridge the research gaps, particularly, in addressing the challenges, applications, limitations, and security concerns of digital twin technology, both theoretically and technically.

The co-authorship network graph, shown in Figure 7, highlights the collaborative nature of research in this field. The connections between authors suggest active collaboration across various groups, institutions, and even countries. Such collaborations are crucial for advancing complex, interdisciplinary research topics like digital twin technology applications for water management in water bodies. Additionally, the diversity of the authors involved, spanning disciplines such as environmental science, engineering, and data science, underscores the inherently interdisciplinary nature of this research area.

Thematic Analysis: Figure 8 highlights the key themes and the distribution of articles across the following themes.

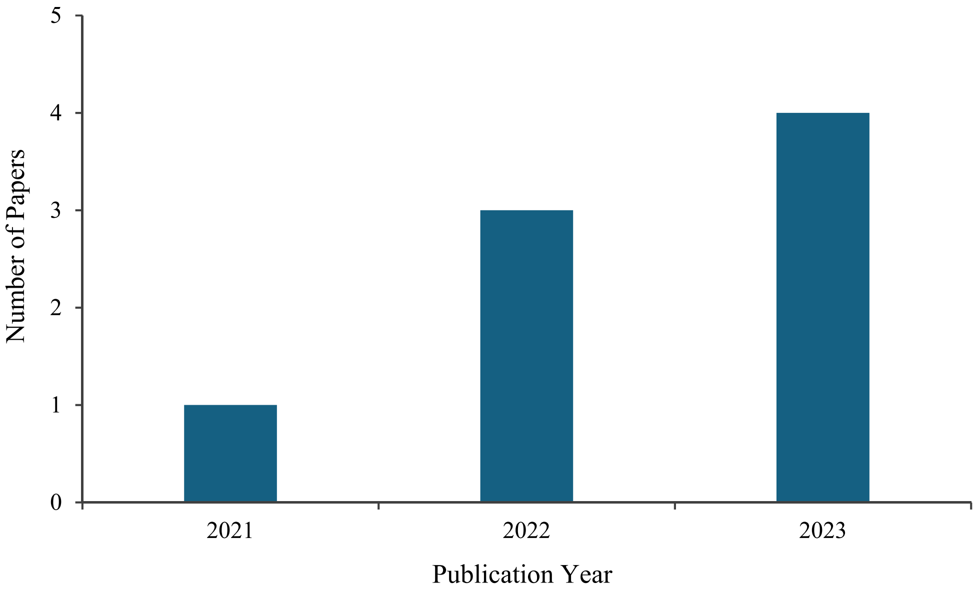

FIGURE 6 Growth of digital twin research in water quality management.

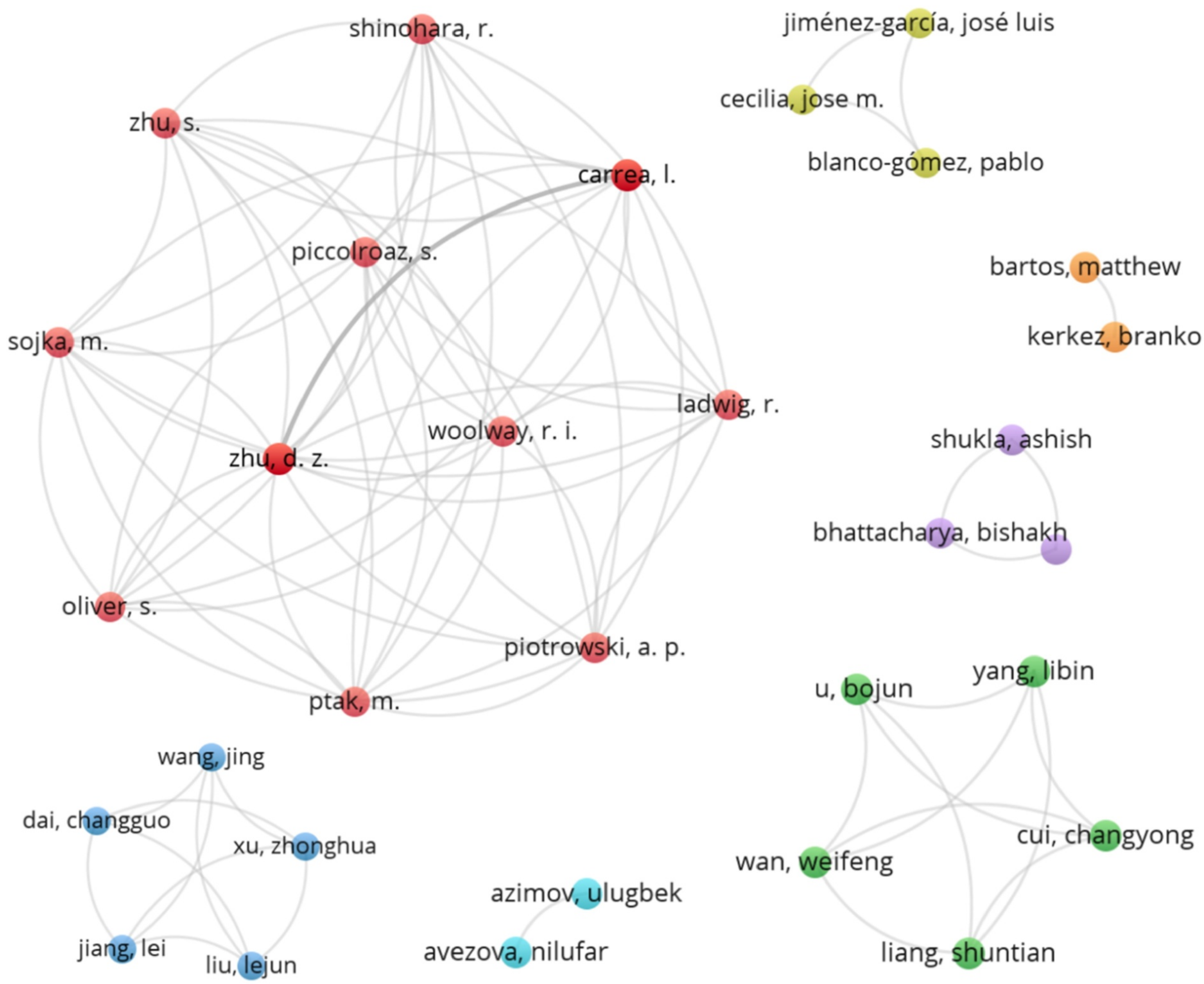

FIGURE 7 Authorship network map for digital twin research in water quality management.

- *Digital Twin Technology: All* articles,[1,7–13] are centred on the application of digital twin technology, particularly for environmental monitoring and water quality management. This theme includes the integration of IoT, real-time data, and advanced modelling to replicate and monitor natural systems.
- *Water Quality Monitoring:* Several papers,[1,8,9,11–13] focus on innovative approaches to water quality monitoring using digital twins. This includes the development of low-cost sensors, integration with IoT devices, and real-time data analysis.
- *Environmental Resilience and Management:* The use of digital twins in enhancing environmental resilience, especially in coastal areas and vulnerable ecosystems, is a recurring theme in multiple research papers.[1,7,8,11,10] The studies highlight how digital twins can aid in flood prediction, management of water bodies, and broader environmental protection.
- *Interdisciplinary Collaboration:* A theme that runs across the papers is the collaboration between different disciplines —such as environmental science, engineering, and data science—to achieve the goals of the projects. This interdisciplinary collaboration appears clearly in refs.[1,7,8,11]

Key Insights: Table 2 maps the insights into the identified themes within the literature.

- *Technological Integration:* The studies demonstrate the successful integration of various technologies, such as IoT sensors, satellite data, and advanced modelling tools, into digital twin systems. For instance, a study discusses the integration of flood models, IoT sensors, and observational data to create a comprehensive DT for managing coastal resilience.[1] Similarly, another study employs artificial neural networks to predict water quality issues, combining sensory data and IoT monitoring.[13] The use of IoT-enabled buoy technology to track water quality metrics in rivers like the Ganges is discussed in ref. 12. Moreover, a study incorporates satellite and in-situ observational data to model lake thermal dynamics, showcasing the role of integrated technologies in adapting to climate change.[11]
- *Cost-Effectiveness:* One of the significant insights is the development of cost-effective solutions for environmental monitoring. One study introduces a 190 EUR IoT-based device for water quality monitoring campaigns, designed for non-experts and encouraging citizen science.[9] Another

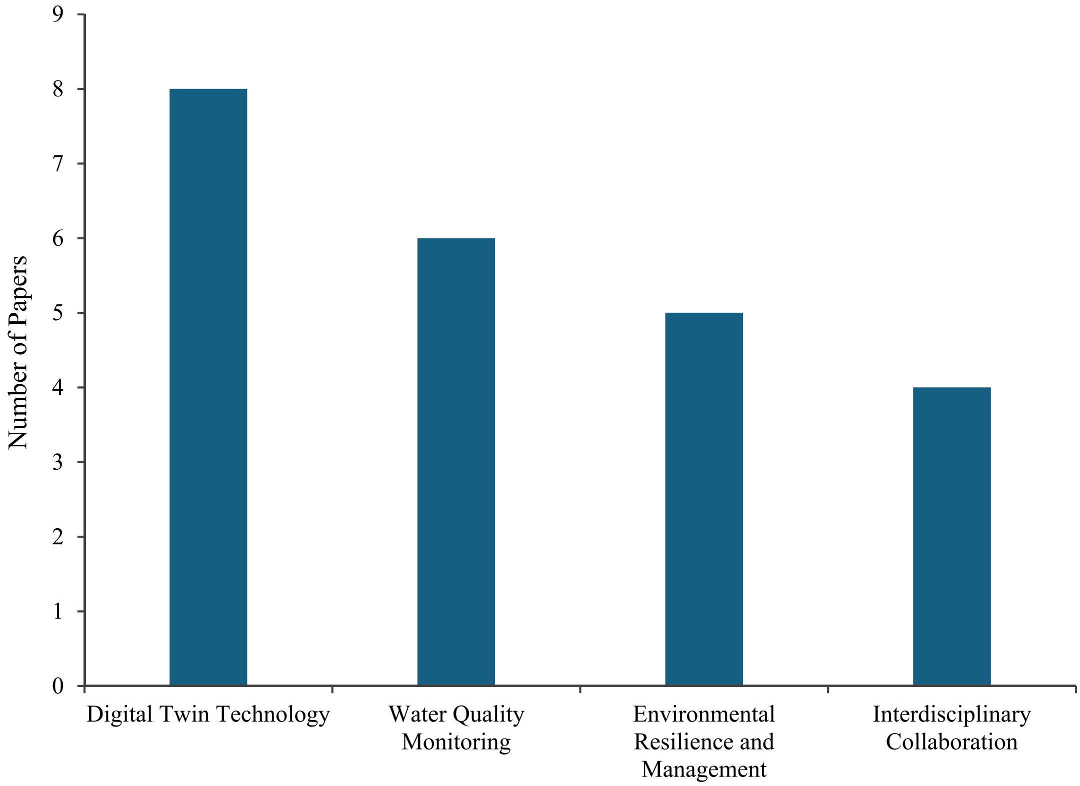

FIGURE 8 Research articles distribution across key themes.

TABLE 2 Mapping key insights to the identified themes.

Key Insights	*Number of Mapped Themes*	*Digital Twin Technology*	*Water Quality Monitoring*	*Environmental Resilience and Management*	*Interdisciplinary Collaboration*
Technological Integration	3	✓		✓	✓
Cost-Effectiveness	1		✓		
Real-Time Monitoring	3	✓	✓	✓	

study offers a cost-effective predictive tool by using pre-existing water quality data to reduce the need for expensive field surveys.[13] Furthermore, a study emphasises the development of modular hydropower systems and affordable digital twins for optimising water and energy resources.[17]

- *Real-Time Monitoring:* Real-time data collection and analysis is a critical component across all studies. For instance, one research uses real-time hydrodynamic simulations to optimise stormwater and flood management in urban areas.[8] Real-time, satellite and in-situ data are utilised to predict lake temperature changes, helping mitigate the effects of climate change.[11] A study demonstrates how real-time flood and sensor data integration improves response strategies for coastal emergencies.[1] Finally, a study showcases real-time IoT-based data collection for continuous water quality analysis.[12]

3.2 | Drone-based water quality management in natural water bodies

Bibliographical Analysis: Figure 9 demonstrates a clear upward trend in research activity related to drone-based water quality management. It shows a steady increase in the number of published articles from 2014 to 2023. This research topic first began to gain interest around 2014, and the number of publications has increased steadily each year, with a particularly sharp rise in the last few years. This surge reflects the growing recognition of drones as valuable tools for monitoring and improving water quality in natural water bodies, indicating that the field has gained significant momentum recently. The data for 2024 indicates a decline; however, this is due to many published papers for the year not yet being available at the time this systematic review was conducted.

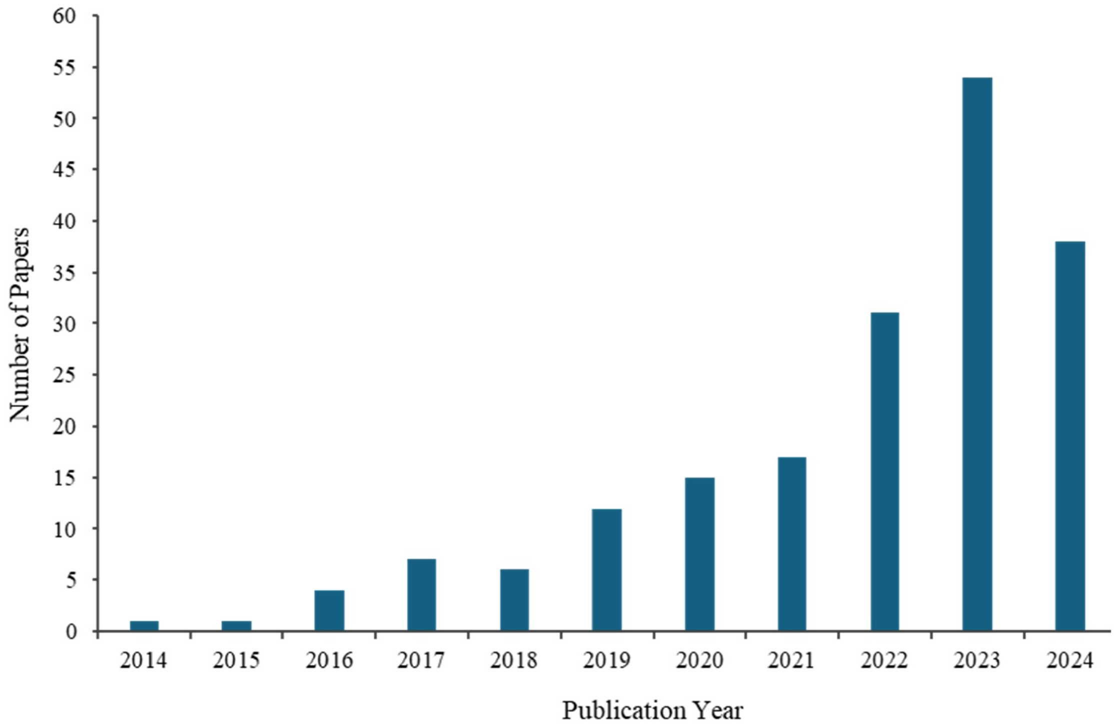

FIGURE 9 Growth of drone-based water quality management.

Drone-based water quality management is an important research topic with growing momentum. The continuing growth demonstrates that this field remains highly in demand, with significant potential for further advancements and broader applications. Such an evolving and dynamic area of research indicates the opportunity for the development of innovative solutions, exploration of new technologies, and adoption of more advanced methods. Figures 10 and 11 illustrate the co-authorship network for drone applications in water monitoring as a graph, where nodes represent individual authors and edges signify co-authorship relationships. Different colours indicate distinct clusters or communities of authors who are more closely interconnected. The visualisation highlights the extensive scope and diversity of collaborations within this rapidly expanding field. The analysis identifies approximately 759 interdisciplinary researchers from around the world, organised into 132 independent connected sets. Notably, the largest connected set of co-authors includes 26 researchers, as shown in Figure 12. While a small number of researchers work independently, the overall network reflects the inherently collaborative and multidisciplinary nature of research in this domain, spanning fields such as environmental science, engineering, and remote sensing. The co-authorship network underscores that the field of drone applications in water monitoring is highly cooperative, with distinct yet interconnected research clusters. As this area of research continues to grow, collaborations between clusters will play an increasingly critical role in driving innovation, particularly in advancing integration of UAV technology with environmental science to address complex global challenges in water monitoring and management.

Thematic Analysis: Figure 13 presents an overview of the key themes identified in the literature on the use of drones for water quality management in natural water bodies. This figure also provides a visual distribution of research papers across the four major themes. The subsequent sections offer a detailed elaboration on each theme, highlighting the most significant insights derived from the research. Furthermore, Table 3 maps these key themes to their corresponding insights.

- *Water Quality Monitoring and Management:* The dominant theme revolves around water quality, with a strong focus on monitoring and management. Many studies (e.g. [21,22,54]) highlight the application of advanced technologies like UAVs and remote sensing to improve the accuracy and effectiveness of water quality monitoring.
- *Methodological Development:* There is a strong focus on developing and refining research methodologies in environmental science. The large number of papers (e.g. [54,58,80]) suggests that significant effort is being invested in improving the accuracy, efficiency, and applicability of various scientific methods. This is crucial in water quality monitoring and environmental modelling where there is a need for more sophisticated and accurate research methodologies. The application of machine learning models is a recurring topic, often discussed in the context of enhancing environmental monitoring techniques.
- *Application of UAVs and Remote Sensing:* The use of UAVs and remote sensing is a critical theme, reflecting the growing interest in these technologies for environmental monitoring. These tools are particularly valued for their ability to gather high-resolution data over large areas, making

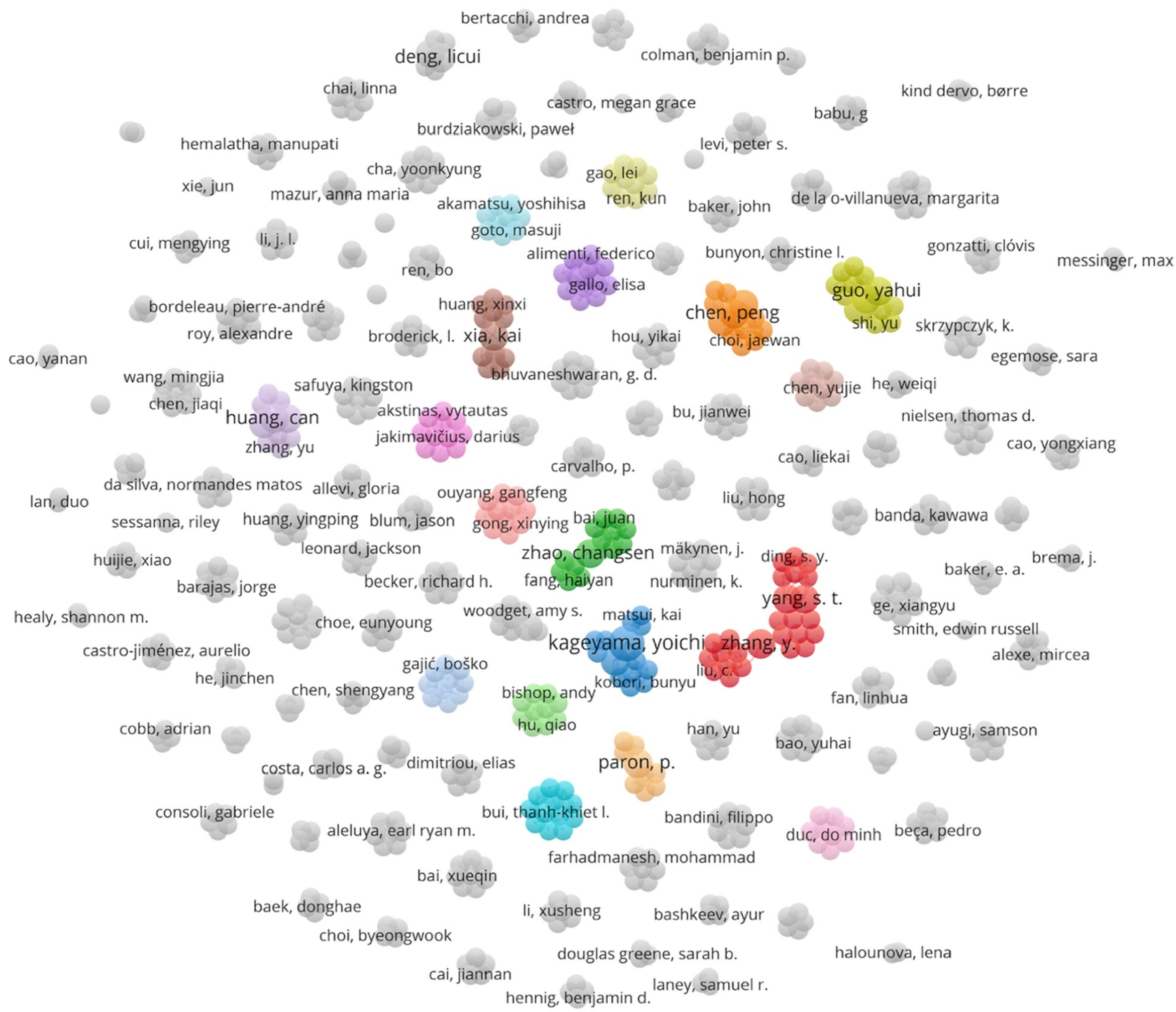

FIGURE 10 Authorship network map for drones in water quality management in natural water bodies.

them indispensable in modern environmental research, particularly in challenging environments like rivers and large water bodies (e.g. [60,80,103]).

- *River and Ecosystem:* Several studies (e.g. [58,68,103,129]) focus on river ecosystems, indicating a specialised interest in understanding and managing riverine environments. These studies often involve the application of methodologies and technologies to monitor and protect these vital ecosystems.

Key Methodologies: This section analyses the predominant methodologies and techniques highlighted across the research papers. These approaches underscore the interdisciplinary nature of environmental research, where advanced data analysis, modelling, and monitoring techniques converge to tackle complex environmental challenges. The growing prominence of UAVs and remote sensing technologies signifies a shift towards high-tech, precision-driven methods in the field. Table 4 provides an overview of these methodologies and associated techniques, which are further discussed in detail below.

Analysis and Modelling Techniques: Several studies emphasise the importance of accurate data analysis, particularly in the context of environmental monitoring and modelling. Common modelling and analysis techniques are.

- Regression Analysis: It is frequently used for predicting environmental outcomes based on historical data. Techniques like linear regression, multiple regression, and logistic regression are often employed. These techniques are effective in identifying relationships between environmental variables and predicting future trends. For instance, linear regression might be used to examine the relationship between nutrient levels and algal bloom occurrences, while multiple regression could analyse the impact of several variables, such as temperature, rainfall, and land use, on water quality.[25,68,232]
- Machine Learning Models: Machine learning models are utilised in UAV-based water quality assessments to predict environmental outcomes with high accuracy. Models such as Random Forest, Support Vector Machines, and Neural

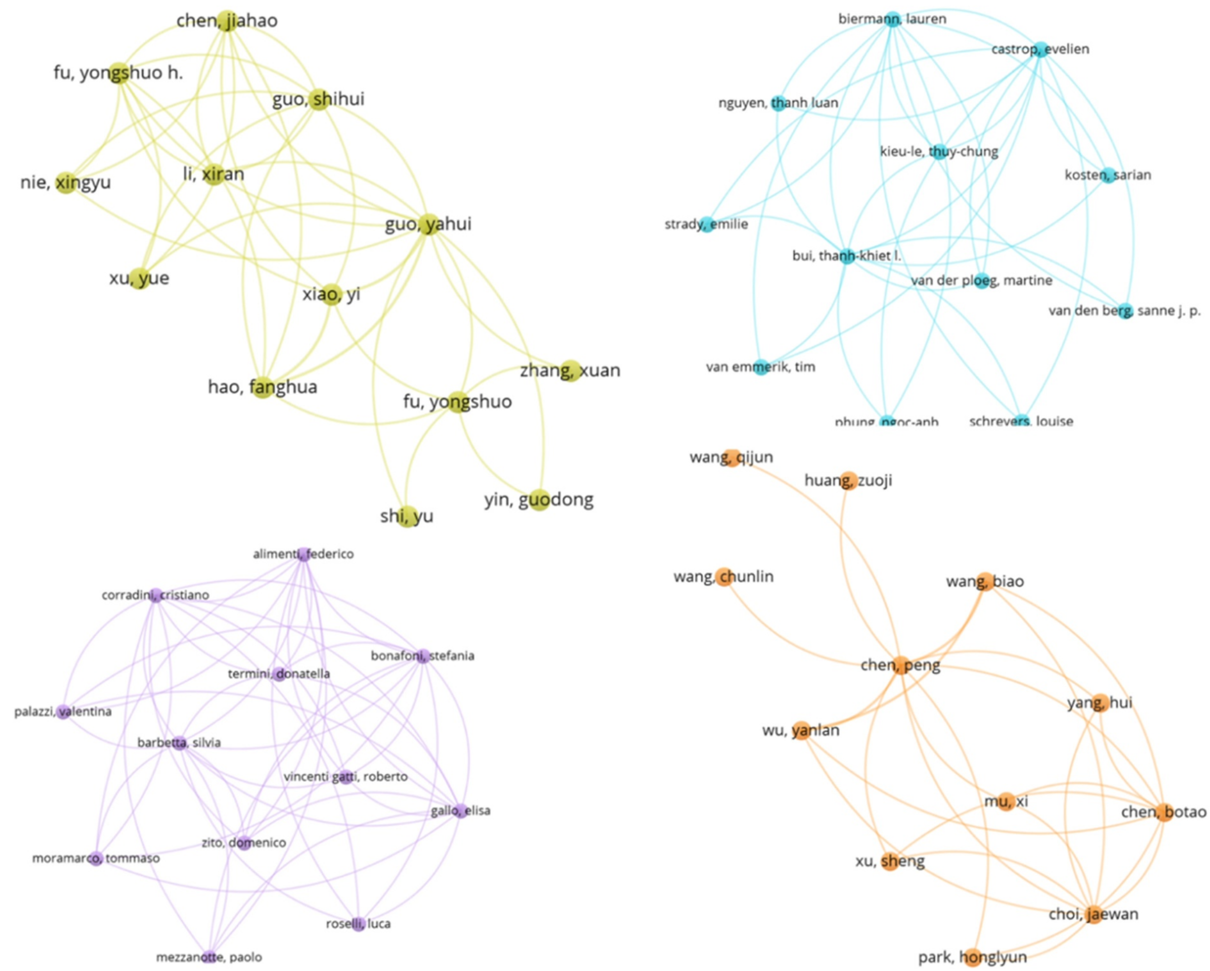

FIGURE 11 Highlighted four connected sets of the co-authorship map for drone applications in water quality management in natural water bodies.

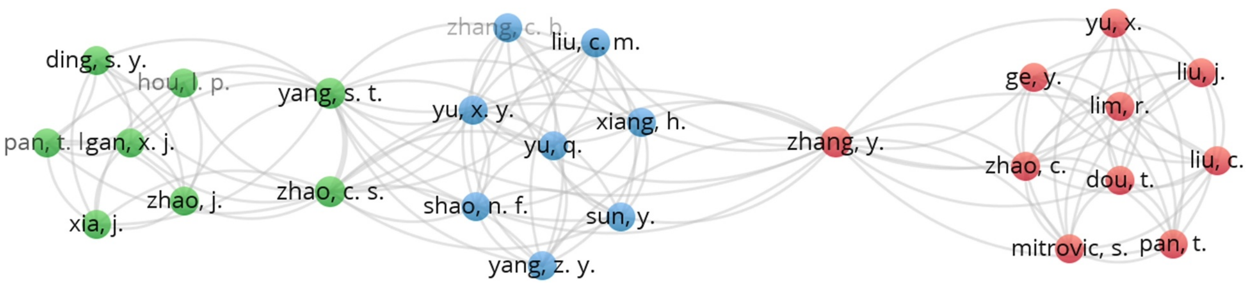

FIGURE 12 Largest connected set of co-authors network.

Networks are particularly effective in analysing complex environmental data, identifying patterns, and making predictions about water quality parameters such turbidity, nutrients, and algal blooms. These models learn from historical data and can handle non-linear relationships often found in environmental systems.[26,68]

- Spatial Analysis: It involves the analysis of spatial data, often using Geographic Information Systems to study environmental patterns and distributions. These techniques help understanding the spatial distribution of environmental phenomena, such as pollution or habitat degradation.[26,131]
- Multivariate Analysis: Techniques like Principal Component Analysis and cluster analysis are used to reduce dimensionality and identify key variables influencing environmental outcomes. These techniques are effective in simplifying complex datasets and identifying underlying patterns.[25,232]
- Statistical Modelling: This involves using statistical techniques to build models that explain and predict environmental processes. Commonly used for hypothesis testing and to validate environmental theories.[26,68]
- Hydrological and Water Quality Models: Hydrological and water quality models like SWAT (Soil and Water Assessment

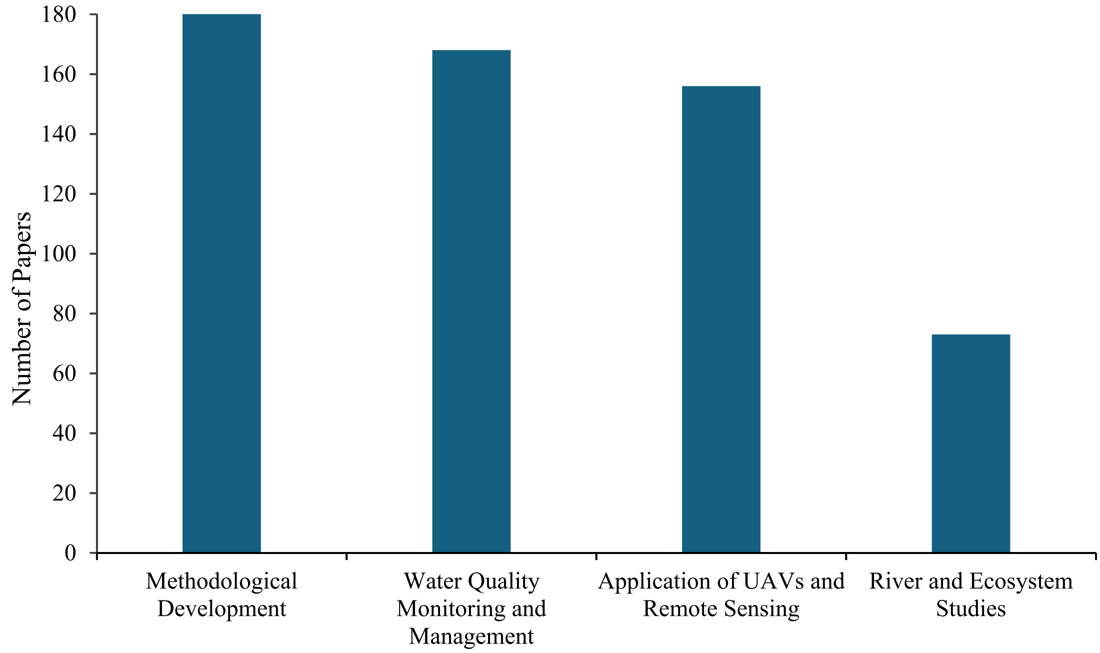

FIGURE 13 Research articles distribution across key themes in drones for water quality management.

TABLE 3 Mapping of key insights to identified themes in drone-based water quality management.

Theme	Key insights
Water quality monitoring and management	Use of UAVs for water quality monitoring
	Advanced technologies in monitoring
Methodological development	Development of machine learning models like random forest, support vector machines, decision tree, etc.
	Advanced technologies in monitoring
Application of UAVs and remote sensing	Use of UAVs for water quality monitoring
	Remote sensing for environmental monitoring
River and ecosystem	Impact of human activities on river ecosystems
	Remote sensing for environmental monitoring

Tool), HSPF (Hydrological Simulation Program – Fortran), and WASP (Water Quality Analysis Simulation Program) are extensively used in simulating the impact of land use, climate change, and other factors on water quality and hydrology. These models are particularly valuable in predicting how different scenarios—such as deforestation, urbanisation, or climate change—will affect water bodies over time.[26,131]

- Remote Sensing-Based Models: Models that incorporate remote sensing data, often using UAVs, are increasingly popular for large-scale environmental monitoring. These models leverage high-resolution imagery and other sensor data collected by UAVs to monitor and predict environmental conditions across vast areas. They are particularly useful in tracking changes in land cover, vegetation health, and water quality parameters over time, enabling large-scale assessments that are both detailed and timely.[26,232]

TABLE 4 Common methodologies and associated techniques.

Methodology	Technique
Accuracy and precision	Calibration techniques[231]
	Error analysis[181]
	Sensitivity analysis[178]
Data analysis	Machine learning models[1,28,55,71,86,123,129,154,158,165,166,199,227]
	Regression analysis[50,54,130,107,129,155,162,165,199,203,212]
	Spatial analysis[119,193,226]
Modelling techniques	Neural networks[25,31,59,82,124,140,141,152,155,162,173,215]
	Random forest[14,25,28,29,36,53,55,58,80,123,128,129,138,165,166,177,189,215,227,232]
	Support vector machines (SVM)[128]
Monitoring and quality assessment	In situ measurements[19,64,113,132,154,159,163,191,209,212,216,233]
	Remote sensing technologies[26,55,60,90,94,139,150,155,171,176,183,189,209,212]
	Sensor networks[56,216]
Research and study design	Comparative studies[29,69,208]
	Field surveys[18,42,53,57,111,141,190]
Use of UAVs	GIS integration[215]
	High-resolution data collection[72,195]
	Real-time monitoring[25,56,68,74,86,94,106,119,132,137,175,204,234]

Use of UAVs: The Use of UAVs in water quality management has proven to be an invaluable tool for collecting high-resolution data, particularly in remote or difficult-to-access areas. Unmanned Aerial Vehicles are equipped with advanced sensors capable of capturing detailed imagery and environmental data, enabling researchers to monitor key water quality parameters such as turbidity, chlorophyll, and surface temperature with exceptional precision. The ability of UAVs to fly at low altitudes and cover extensive areas makes them especially effective for monitoring regions that are otherwise challenging to study using traditional methods. This is well-documented in studies like[25] and.[26] One of the most significant advantages of UAVs is their capacity to access remote or inaccessible locations, where conventional monitoring techniques would be difficult or impossible to implement. Unmanned Aerial Vehicles can be deployed in challenging terrains, such as mountainous regions, dense forests, or areas with hazardous conditions, allowing for the collection of crucial environmental data without exposing researchers to potential risks. This capability has considerably expanded the scope of environmental monitoring, as demonstrated in papers like[68] and.[232] Furthermore, UAVs offer the advantage of real-time monitoring and rapid data acquisition, which is essential for time-sensitive environmental assessments. By equipping UAVs with live data transmission capabilities, researchers can monitor water quality parameters in real-time. This allows for immediate responses to environmental changes or emerging issues. This real-time capability is particularly valuable in dynamic environments where conditions can change rapidly, as discussed in ref. 26.

Monitoring and Quality Assessment: Continuous environmental monitoring and quality assessment are central methodologies in these studies. This often involves the use of advanced sensors, remote sensing technologies, and in situ measurements. *Advanced sensors* integrated into UAVs collect high-resolution data on key water quality parameters such as temperature, turbidity, and Dissolved oxygen (D.O.). These sensors enable efficient monitoring of large water bodies, as discussed in studies such as 68 and 131. *Remote sensing technologies* extend the monitoring capabilities by offering broad spatial coverage, capturing trends and patterns over time through various spectral bands. This approach is particularly effective for monitoring algal blooms, sediment plumes, and vegetation changes, as explored in refs. 26 and 232 *situ measurements* are crucial for validating the remotely collected data, providing ground-truth references that ensure the accuracy of the monitoring efforts. This technique is emphasised in refs. 235 and 26.

Research and Study Design: The studies focus on robust research design and methodology. This includes the development of new study protocols and the refinement of existing methods to ensure accurate and reliable results. One of the critical aspects of this design is *Experimental Design*, where the structure of the study is carefully planned to yield valid and reliable results. This includes selecting appropriate study sites, determining the frequency, and timing of UAV flights, and choosing the correct sensors and parameters to measure, as discussed in papers such as 26 and 25. Another vital technique is the *Sampling Strategy*, which ensures comprehensive data coverage by capturing the spatial and temporal variability of water quality in natural water bodies. This strategy involves decisions on the number of samples, their locations, and the intervals at which they are collected, and is explored in studies such as 68 and 131. Finally, *Data Collection Protocols* are established to maintain consistency and accuracy throughout the study. These protocols include standard operating procedures for UAV operation, sensor calibration, data logging, and handling environmental variables, ensuring that all researchers follow the same procedures, thus enhancing the repeatability and reliability of study outcomes. This is well-documented in refs. 25 and 232.

Accuracy and Precision: There is notable emphasis on achieving high accuracy in measurements and predictions. This is particularly important in environmental research, where small inaccuracies can lead to significant errors in outcomes. Among techniques used in this regard.

- Calibration Techniques: Calibration techniques are employed to adjust the UAV sensors so that their readings are accurate and consistent with known standards or environmental benchmarks. This process typically involves using reference samples or ground-truth data to correct any deviations in sensor measurements. For instance, studies often calibrate sensors before deployment to ensure that they accurately measure water quality parameters such as turbidity, pH, and temperature.[25]
- Error Analysis: This involves assessing the differences between repeated measurements, identifying systematic errors (such as biases introduced by the measurement process), or evaluating random errors due to environmental factors.[68]

3.3 | Integration of drones and digital twins for water quality management in natural water bodies

This section analyses the integration of drones with digital twins for water quality management in natural water bodies, a relatively novel area of research. Due to the limited number of studies focussing directly on this topic—only one paper specifically addresses the integration of both drones and digital twin technologies for water quality monitoring—three additional papers that explore the integration of these technologies in water management, specifically for flood and water level monitoring, are also included. These additional papers emphasise the technical feasibility of such integrations in the same context. A relevant study comprehensively explores how remote sensing technologies, including drones, can be integrated into digital twin models for water bodies.[230] The study describes how drones are vital tools for collecting high-resolution, real-time data on key environmental parameters such as water temperature, precipitation, and soil moisture, which are then fed into a digital twin system for detailed simulation and analysis of water quality. This system enables a continuous and interactive feedback loop between the physical environment and the virtual model, facilitating advanced decision-making processes in water management. While this study offers the most direct application of digital twins and drones for monitoring water quality in basins, other studies focus on integrating these technologies for flood and water level management. Although the three studies do not address water quality directly, they remain relevant to this survey because they showcase the technical feasibility and benefits of combining digital twins and drones for large-scale water management. For instance, one study discusses how drones capture data on water levels and flow rates, feeding this information into digital twin models for predicting floods and managing infrastructure.[228] Another study highlights the importance of integrating real-time drone data into digital twins for simulating water behaviours in coastal regions.[1] Lastly, a third study explores the use of UAV-collected data for wetland management in constructing digital twin models, which simulate water level variations and wetland ecosystem changes.[229] By reviewing these related works, it becomes evident that there is substantial potential for future research to focus on integrating these technologies to address pressing water quality issues in natural bodies of water. The studies collectively show the technical benefits of drone-based data collection and digital twin modelling, suggesting that future research can adapt these techniques for water quality management in natural water bodies. Though the number of research studies in this area is minimal, the timeline of their publication dates indicates that we are only at the very nascent stage of integrating drones with digital twin technology.

Core Concepts Analysis: The concept map presented in Figure 14 synthesises the integration of drones and digital twins, as extracted from the related literature in 1,228–230. These studies explore the synergy between drones and digital twin technologies applications in water quality management, flood monitoring, and ecosystem simulation. The map identifies core concepts such as remote sensing, geospatial data, and 3D visualisation, along with their interconnections. The concept map highlights several core concepts central to the integration of drones and digital twins.

- Digital Twins: Serves as the core framework for modelling and simulating water systems. It integrates data from various sources to enable real-time decision-making and predictive analysis.
- Drones: Essential tools for high-resolution and real-time data collection. They gather critical parameters such as water temperature, soil moisture, and precipitation, feeding these inputs into digital twin systems.
- Remote Sensing: Complements drones by covering larger areas and providing data for hydrological and water quality simulations.
- 3D Visualisation: Enhances understanding by translating complex data into intuitive visual representations.
- Ecosystem Simulation: Models changes in ecosystems, including water quality, sedimentation, and nutrient flow, using data collected by drones and other sources.
- Flood Management: Demonstrates the ability of digital twins to simulate water flow and infrastructure responses, a functionality that can be adapted for water quality applications.

These concepts and their interconnections underscore the collaborative role of drones and digital twins in advancing water quality and resource management. Their relationships are summarised in Table 5, which highlights the connections and insights derived from the concept map.

3.4 | Limitations and challenges

Integration limitations: Despite their potential, drone-integrated digital twin systems face inherent limitations that restrict their widespread application in water quality management. These limitations include issues with data processing capacity, operational range, and consistency in challenging conditions.

- Scalability of High-Resolution Data: Processing and analysing detailed, high-resolution data can be computationally intensive and may lead to delays in providing real-time insights.[228]
- Data Accuracy and Latency: Ensuring data accuracy and minimising latency during the integration of drone and remote sensing data can be difficult, particularly for real-time applications.[230]
- Limited Coverage in Harsh Conditions: Drones may have reduced effectiveness in extreme weather or over vast areas, limiting their operational applicability.[230]

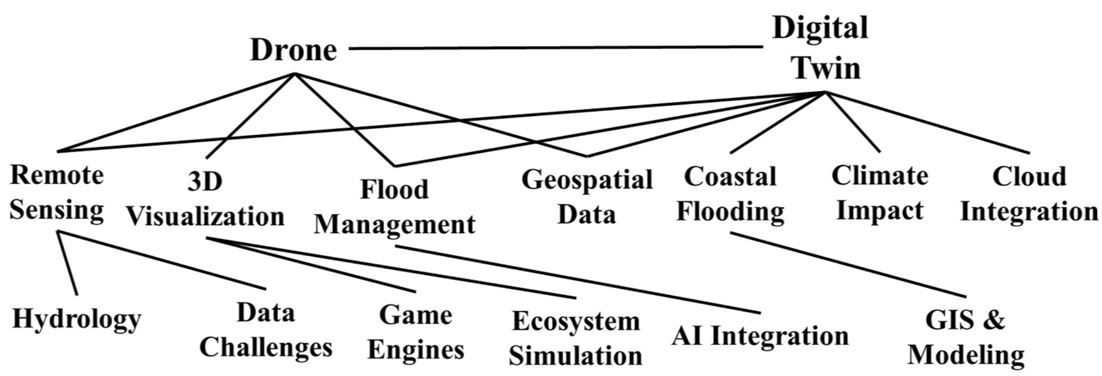

FIGURE 14 Concept map of drone-integrated digital twins.

- Resource Intensity: The continuous use of drones for monitoring can be resource-intensive in terms of power consumption, operational time, and maintenance.[229]

Integration challenges: The integration of drones with digital twins for water quality monitoring poses several significant challenges that arise from complex environmental conditions, technical expertise requirements, and cybersecurity risks associated with interconnected monitoring systems. These challenges impede seamless operation and data synthesis.

- Data Integration and Compatibility: Combining drone data with other sensor data in real time requires a robust infrastructure that ensures data synchronisation and interoperability.[1]
- Environmental Variability: The dynamic nature of weather and water bodies can affect the reliability and consistency of drone-collected data, complicating integration.[229]
- Technical Expertise and Logistics: Operating drones over large areas demands skilled personnel for drone maintenance and data interpretation.[230]
- Cybersecurity Concerns: IoT-based integration introduces cybersecurity risks, such as data breaches and unauthorised access.[1]
- Simulation and Modelling Complexity: Developing real-time models that accurately capture water quality parameters and natural system interactions is a complex task.[228]

3.5 | Impact on environmental management and policymaking

Digital twin technology and its integration with water management systems provide significant insights that impact environmental management and policymaking. Digital twin platforms facilitate data-based smart water management by integrating real-time data visualisation, simulation models, and predictive analytics. This approach supports policymakers and environmental managers by offering enhanced tools for proactive flood management, resource optimisation, and infrastructure resilience. These capabilities help in understanding complex environmental interactions and assessing the impact of policy decisions on ecosystem health, water distribution, and disaster mitigation.[228] Moreover, digital twins demonstrate how integrated earth observation data, IoT sensor networks, and UAV imagery enhance situational awareness and decision-making for coastal resilience and flood management. These technologies empower urban and regional planners to address the consequences of climate change.[1]

TABLE 5 Key connections and insights.

Connection	Insights
Drones ↔ remote sensing	Drones enhance remote sensing by providing localised, high-resolution data critical for water quality and hydrology.
Digital twin ↔ flood management	Enables real-time simulation of floods and infrastructure impacts; adaptable for water quality management.
3D visualisation ↔ ecosystem simulation	Offers advanced representations of ecosystem changes, such as nutrient dispersion or sedimentation patterns.
Drones ↔ digital twin	Creates a dynamic feedback loop between physical environments and virtual models, enabling real-time updates and predictions.
Remote sensing ↔ geospatial data	Combines large-scale environmental data with high-resolution drone imagery for comprehensive water quality analysis.
Cloud integration ↔ digital twin	Ensures seamless processing and storage of large-scale data, allowing real-time updates and global accessibility.

3.6 | Performance metrics

Assessing metrics such as accuracy, reliability, and robustness of frameworks, technologies, algorithms, and models to ensure that the data used in digital twins meet the spatial and temporal requirements for accurate, real-time analysis and forecasting is essential for environmental assessments and decision-making in policy and management.[230] In this regard, different approaches reveal diverse evaluation strategies across various domains. Table 6 provides a glimpse of such metrics used in the literature of drone-integrated digital twins for water monitoring.

3.7 | Sensors and drones for drone-based digital twins for water quality monitoring

The market offers a range of sensors and drones designed for assessing and monitoring water quality by measuring various physical, biological, and chemical parameters. Tables 7 and 8 summarise the common market sensors and drones used for water quality monitoring.

TABLE 6 Performance metrics in drone-integrated digital twins for water monitoring.

Metric	Dataset/ Technology	Spatial resolution	Temporal resolution
Surface temperature[1]	Modis, landsat, himawari-8	30 m to 1 km	10 min to 16 days
Evapotranspiration[230]	Mod16, glass_v4, gleam	500 m to 1 km	8 days to 1 month
Precipitation data[228]	Imerg, trmm, persiann	Various (high precision)	Monthly to seasonal
Water level monitoring[1]	Jason satellites, sentinel series	10 cm accuracy	10–30 days
Vegetation retrieval[230]	Modis, sentinel-2, landsat	1 m to 1 km	5–26 days

TABLE 7 Market sensors for water quality monitoring.

Sensor/ Instrument	Key features	Measurement capabilities	Applications
ProDSS[236]	Handheld multiparameter metre	pH, ORP, chloride, algae, turbidity, ODO, conductivity	General water monitoring
EXO2 Multiparameter Sonde[237]	Water quality sonde with seven sensor ports and a central wiper port	Conductivity, temperature, DO, fDOM, nitrate, pH, turbidity	Comprehensive water analysis
IQ SensorNet 20203G Controller[238]	Modular system for sensor networks	DO, pH, conductivity, turbidity, TSS, ammonium, nitrate	Varied environmental applications
Pontoon Vertical Profiling System[239]	Automated data collection with YSI EXO & 6-series sondes	Various water quality parameters	Reservoirs, research, surveillance
ProSolo Optical Dissolved Oxygen[240]	Handheld optical dissolved oxygen metre	Optical dissolved oxygen measurement	Portable water monitoring

TABLE 8 Market Drones for water quality monitoring.

Drone model	Key features	Capabilities	Use case
SplashDrone 4[241]	Waterproof, fixed-angle camera, payload release	Aquatic data collection	General water body monitoring
DJI Phantom 4 Pro[1]	High-resolution camera, stability	Detailed aerial imaging	Water body inspection
DJI Mavic 2 Pro[33]	Portability, Hasselblad camera	High-quality aerial photos/ videos	Environmental monitoring
DJI Matrice 350 RTK[242]	Industrial-grade, multiple payload capacity	Thermal and visual data collection	Comprehensive analysis
Parrot ANAFI USA[243]	32x zoom, thermal imaging	Detailed inspections	Water and surrounding areas
SenseFly eBee X[244]	Fixed-wing, large-area mapping	High-resolution, extensive mapping	Large water region monitoring
AquaDrone[245]	Water-specific design, land on water, optional sensing attachments	Water quality sensing, underwater exploration	Specialised water environments
HyDrone-ASV[246]	Autonomous surface vehicle	Water sampling and mapping	Ponds, lakes, rivers

3.8 | Common water quality parameters

The concept of 'good' water quality is relative, varying according to the specific purpose of the water, whether for drinking, recreation, agriculture, industrial processes, or supporting aquatic life. Scientists select measurements from a broad range of biological, chemical, and physical characteristics to evaluate water quality effectively. Table 9 outlines water quality parameters and measurements that could be integrated into the design of drone-based digital twins for water quality monitoring.

3.9 | Case study: A digital twin for dam and watershed management in Korea

The K-Twin SJ digital twin platform is a state-of-the-art system designed to enhance water management, particularly in the context of dam and watershed operations. Built for the Sumjin River basin in South Korea, this platform integrates a broad range of technologies to ensure comprehensive monitoring, predictive modelling, and automated responses for improved flood management and decision-making.[228] Figures 15 and 16 show the digital twin platform and the architecture of the digital twin, respectively.

Key Technological Components: (a) 3D Geospatial Reality Modelling: The platform features a high-precision 3D model of the 173 km river and its infrastructure, generated using LiDAR and drone photogrammetry. This model integrates topographic data to enable real-time flood simulation and water flow analysis (Figure X). The use of LiDAR allowed for detailed mapping with a point density of over 25 points/m^2, which was essential for precise terrain representation. (b) Drone-Based Monitoring: Drones equipped with optical and thermal cameras provided real-time surveillance and data collection capabilities, see Figure 17. These unmanned aerial systems were capable of operation in adverse weather, withstanding up to 10 mm of rainfall and wind speeds of 10 m/s. Automated drone stations facilitated continuous monitoring by enabling automatic vertical take-off and landing, as well as remote charging and long-distance mission capabilities. (c) Flood Simulation Models: The platform incorporates three types of flood analysis models—K-Drum for rainfall-runoff, K-River for river flow, and K-Flood for two-dimensional flood inundation. These models, driven by real-time sensor data, simulate potential flood events and predict river behaviour during varying dam operation scenarios. The simulation results, figure X, are validated using historical flood data, achieving high accuracy metrics like an NSE value of 0.95, which indicate strong reliability. (d) AI-Enhanced Monitoring and Analysis: An AI-driven CCTV analysis system was developed to detect and respond to abnormal conditions, such as rising water levels and potential flooding. The platform employs deep learning models (YOLOv4 for vehicles and people, YOLACT for watermarks), achieving over 90% detection accuracy, and processes video at more than 1 fps for real-time decision support.

Operational Highlights and Validation: The platform demonstrated its efficacy during the August 2020 flood, where its models accurately predicted water inflow and river

TABLE 9 Common water quality parameters.

Parameter	Description	Significance
Ammonia ($NH4+$)[247,248]	Impacts nutrient dynamics and toxic above 40 µg/L	Protects aquatic life
Turbidity[249]	Indicates cloudiness of water	Water clarity assessment
Bacteria[250]	Quick reproduction under optimal conditions	Contamination indicator
Water quality index (WQI)[251]	Consolidates multiple water quality parameters	Simplifies water health assessment
Plankton[252]	Evaluates abundance of microscopic plants and animals	Supports aquatic life balance
Secchi disk transparency[251]	Measures depth for water clarity	Water transparency indicator
Light transmission[251]	Depth where 1% of surface light reaches	Assesses photosynthesis limit
pH[251]	Measures acidity of water	Water quality and aquatic health
Biochemical oxygen demand (BOD)[250]	Indicates oxygen needed by microorganisms	Organic pollution indicator
Chemical oxygen demand (COD)[250]	Quantifies organic matter in water	Total pollution assessment
Dissolved oxygen (D.O.)[251]	Essential for aquatic life respiration	Key for aquatic health
Phosphorus[251]	Influences algae and plant growth	Nutrient level indicator
Algae[250]	Contribute to oxygen production	Impact on water taste and odour
Viruses[250]	Cause diseases like hepatitis	Water safety concern
Fluoride[250]	Promotes dental health, excess causes fluorosis	Dental health indicator
Chlorine[250]	Disinfects water, 0.2 mg/L for safety	Water disinfection
Sulphate[250]	Affects taste, laxative at high levels	Taste and usability factor
Photosynthetic active radiation (PAR)[250]	Measures photosynthesis-related sunlight	Ecosystem health
CDOM[253]	Absorbs UV spectrum	Aquatic ecosystem monitoring
Acidity[250]	Influences corrosion, reactions	Water usability
Chloride[250]	Signals pollution, salty taste	Taste regulation
Protozoa[250]	Consume organic matter, resistant cysts	Contamination and treatment
Taste and odour[250]	Indicate potential contamination	Consumer acceptability
Nitrogen[251]	Essential for plant growth	Nutrient management
Temperature[250]	Affects taste, smell, purity, chemical processes	Key parameter for processes
Colour[250]	Affected by organic/ inorganic materials	Water appearance
Toxic Inorganic substances[250]	Heavy metals, cyanides	Water quality assessment
Toxic organic substances[250]	Insecticides, solvents	Contamination control
Rhodamine[254]	Tracks water flow, pollutant movement	Dispersion studies
Radioactive substances[255]	Pose health risks, damage tissues	Regulated for safety
Chlorophyll-a[256]	Indicator of algal biomass	Ecosystem health
Iron and Manganese[257]	Cause taste, stains	Turbidity and aesthetic impact
Copper and zinc[257]	Essential but affect taste at high levels	Water acceptability
Oil, Hydrocarbon[258]	Monitored near oil-related activities	Contamination tracking
Total organic carbon (TOC)[259]	Measures organic contaminants	Safety and biological growth control
Conductivity[251]	Measures ion content and electrical conduction	Water classification
Cyanide[260]	Toxic with carbon-nitrogen bond	Health protection
$CO2$[261]	Alters pH and mobilises substances	Risk assessment
Solid[250]	Includes TDS and TSS	Organic content indicator
Hardness[250]	Caused by calcium, magnesium	Safe up to 500 mg/L
Alkalinity[256]	Water's capacity to resist pH change	Maintains stable conditions

levels, closely matching observations at key monitoring points. The AI flood prediction system provided optimised dam discharge strategies to alleviate downstream damage while maintaining dam safety (Figure 18). Integrated tools for safety analysis allowed for assessments of slope stability and seepage to monitor and reinforce potential failure points.

Impact on Water Management and Decision-Making: The K-Twin SJ digital twin serves as a comprehensive tool for water resource management, combining data synchronisation, AI, and real-time monitoring to inform proactive flood response strategies. This integration of advanced technologies supports seamless decision-making, improves operational efficiency, and enhances resilience against extreme weather events. As such, it sets a benchmark for digital transformation in environmental management and policy development.

Lessons Learnt from K-Twin SJ Implementation: The development and application of the K-Twin SJ platform

FIGURE 15 K-Twin SJ platform.[228]

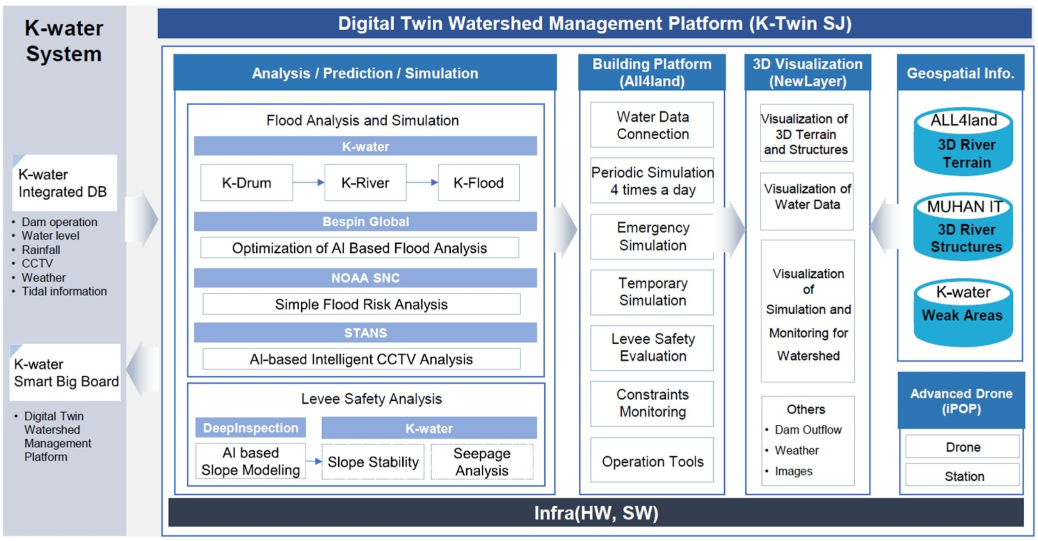

FIGURE 16 Architecture of the K-Twin SJ digital twin.[228]

FIGURE 17 Development of a drone and station system for monitoring dams and rivers.[228]

offer several critical takeaways that underline the value of integrating digital twin technology into water management systems. These lessons provide a blueprint for enhancing resilience, operational efficiency, and decision-making in similar projects globally. *(a) Value of Multi-Source Data Integration:* The success of K-Twin SJ hinges on its ability to merge diverse datasets, including LiDAR surveys, drone photogrammetry, IoT sensors, and historical flood records. This multi-source integration ensures a comprehensive, real-time understanding of the watershed, which is critical for

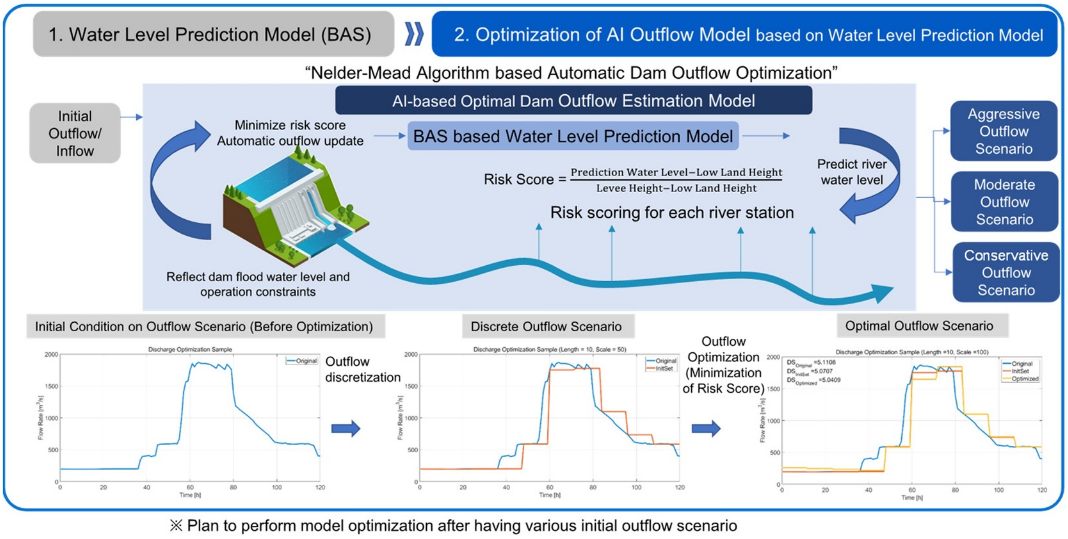

FIGURE 18 Simulation and prediction for flood management.[228]

accurate modelling and prediction. Future projects can replicate this approach to improve data fidelity and actionable insights. *(b) Critical Importance of Model Validation:* Validating models with historical flood events, like the August 2020 flood in the Sumjin River basin, demonstrated the platform's predictive accuracy and reliability. Regular validation against diverse environmental conditions and datasets ensures models remain robust and adaptive, fostering stakeholder confidence in their outputs. *(c) Significance of Automation and AI:* The inclusion of AI-driven tools such as intelligent CCTV analysis and optimised dam discharge models revolutionised response times and decision-making efficiency. By automating critical functions like anomaly detection and flood prediction, the platform significantly reduces the burden on human operators while improving accuracy and speed. *(d) Role of User-Centric Design:* Developing an intuitive interface and providing training to operational teams was pivotal in ensuring the platform's usability. A user-centric approach enhances adoption rates, reduces the learning curve, and ensures stakeholders can fully leverage the platform's capabilities. *(e) Scalability as a Strategic Goal:* Designing the platform with scalability in mind allows for its adaptation to larger watersheds or other geographic regions. Modular components, such as simulation models and AI tools, can be customised for different hydrological and infrastructural contexts, making the platform a versatile solution for global water management challenges. *(f) Collaborative Frameworks Drive Success:* Collaboration among government agencies, research institutions, and private sector partners was instrumental in K-Twin SJ's development. This partnership model ensures that the platform addresses real-world challenges while benefiting from the latest technological innovations. *(g) Proactive Climate Adaptation:* K-Twin SJ highlights the need for proactive, rather than reactive, approaches to managing climate-induced risks. Its predictive capabilities enable preemptive actions, reducing the socioeconomic impacts of extreme weather events and positioning the platform as a critical tool in global climate adaptation strategies.

4 | FUTURE DIRECTIONS

The integration of digital twin technology with drones for monitoring water quality in natural water bodies like rivers, lakes, reservoirs etc. is an emerging field with significant potential. Current research and pilot projects provide a foundation for understanding future directions in this domain, and several key trends and areas for development have been identified.

4.1 | Integration of water quality sensors with digital twins

Most current digital twin implementations for water management focus on hydrodynamic modelling, flood management, and infrastructure monitoring, as seen in platforms such as K-Twin SJ.[228] Sheng Lu et al. emphasise the use of drones for high-precision environmental monitoring, including terrain and vegetation mapping.[229] Furthermore, authors discuss the integration of drones with real-time data collection for water management.[228] Building upon that, the potential to extend these platforms by incorporating more sensors and measurements to monitor chemical and biological parameters in real-time is a promising future direction. Drones, equipped with water quality sensors for measuring parameters, such as pH, turbidity, D.O., and nutrient concentrations, can provide high-frequency, spatially detailed data across large water bodies. This data can be fed into the digital twin for real-time monitoring and long-term trend analysis. For example, by integrating drone-collected water quality data into a digital twin, management authorities could monitor the spread of pollutants, track sedimentation, and respond to harmful algal blooms, which is crucial for water quality management.

4.2 | AI and machine learning for predictive analytics

Building on the *Poyang Lake project*,[229] the application of AI and machine learning for predicting water quality changes is a promising next step. By leveraging predictive analytics, it would be possible to anticipate environmental events such as harmful algal blooms, hypoxic conditions, and pollutant dispersion by analysing historical data, drone observations, and real-time sensor inputs. Machine learning algorithms could be trained to identify early warning signs of water quality degradation, such as shifts in pH, turbidity, or nutrient levels, and predict future trends based on a combination of physical, chemical, and meteorological data. This advancement would enable water managers to take proactive, preventative actions before a crisis occurs, significantly improving response times and management strategies. The potential of AI in water resource management is vast, as demonstrated by its successful application in flood prediction and infrastructure monitoring in platforms like *K-Twin SJ*,[228] and *Hampton Roads coastal resilience project*.[1] By integrating AI with digital twins, predictive models can provide critical insights for maintaining ecological balance of water bodies to ensure sustainable and effective management.

4.3 | Automation and continuous monitoring via drone networks

The use of drones in current digital twin platforms is often limited to periodic, manual monitoring missions, which means continuous real-time data is still lacking in many applications. Future systems could automate drone missions, triggered by real-time conditions such as changes in water levels, turbidity, or detected anomalies via the digital twin. For example, drones could automatically be deployed to collect water samples or monitor areas with suspected pollution. K-Twin SJ,[228] is an example of a platform that uses drones to monitor infrastructure during floods, but this concept could be extended to water quality monitoring, enabling continuous or event-triggered surveillance. Autonomous drones, with enhanced navigation capabilities, could fly in adverse weather conditions, offering real-time monitoring even during critical environmental events.

4.4 | Improved data fusion and interoperability

A challenge for expanding digital twin applications to water quality monitoring is ensuring that all data sources, including IoT sensors, drone observations, satellite imagery, and hydrological models, can seamlessly integrate into a single platform. Future digital twins will need to support a wide range of data formats and standards, enabling comprehensive monitoring and management. K-Twin SJ,[228] already integrates data from multiple sources (e.g. rainfall sensors, CCTV footage, LiDAR, and drones) for flood management, but a similar approach could be adopted for water quality. Furthermore, Earth observation data and real-time drone imagery could be combined to track pollution sources and flow patterns over time 5 Scalability and Customisation of Digital Twin Platforms. As digital twin technologies continue to develop, one critical direction will be enhancing the scalability and adaptability of these systems. While existing platforms such as K-Twin SJ,[228] focus on specific river systems, future digital twins could be designed to manage various water bodies, from small lakes to vast watersheds. This scalability would require flexible architecture capable of accommodating different environmental conditions, data sources, and monitoring objectives. Customisation of digital twins to local contexts, integrating specific environmental challenges (e.g. heavy industrial pollution and agricultural runoff), will also be crucial for their successful deployment.

4.5 | Focus on ecosystem health and biodiversity

In addition to water quality and hydrodynamics, future digital twin systems could integrate data related to ecosystem health, such as biodiversity metrics, habitat quality, and species distribution. These ecological data, collected via drones or remote sensors, would provide a holistic understanding of the water body's health. In projects such as the Poyang Lake,[229] Digital Twin, drones are already being used to collect vegetation and land cover data, which could be expanded to include biodiversity monitoring and integrate ecological indicators into the water management strategy. This would enable a more integrated approach to managing water resources, combining physical, chemical, and biological monitoring within a single digital twin platform.

4.6 | Development of an integrated framework

A crucial future direction is the development of an integrated framework that connects drones, digital twins, laboratories, remote sensing technologies, and decision-makers. This framework would enable the seamless flow of real-time data across different platforms, enhancing both monitoring precision, decision-making, and autonomy. By incorporating real-time water quality sensors, satellite data, laboratory validation, and predictive models, this integrated system would empower decision-makers to manage water bodies more effectively. It would also allow for better communication between environmental agencies, scientists, and government entities. Figure 19 shows a proposed integrated drone-based digital twin framework for water quality management.

FIGURE 19 An under-construction framework for developing the drone-based digital twin for water system management.

5 | CONCLUSIONS

This systematic review discussed the promising potential of leveraging drone-based digital twin technology for water quality monitoring and management in natural water bodies. The convergence of digital twins and drones presents a powerful combination. The growing trend towards utilising digital twins in water resource management highlights their capacity to provide dynamic, real-time models that can simulate, predict, and optimise water quality parameters. Meanwhile, drones have emerged as an effective tool in capturing high-resolution spatial and temporal data from hard-to-reach water bodies that allow for continuous and precise monitoring. Together, they enhance the capacity for real-time insights into both physical and ecological aspects of water bodies. Despite these clear advantages, this review has revealed that the integration of UAVs with digital twin technology remains under-researched. There is a pressing need for further exploration of deeper synergies between these two technologies, particularly in developing standardised methodologies and improving data integration techniques. Such advancements will be key revolutionise the management of water bodies by incorporating real-time water quality sensors, automating data collection with drones, and utilising AI for predictive analytics. These systems will not only provide comprehensive, real-time insights but also enhance the ability to respond to environmental challenges such as pollution, algal blooms, and habitat degradation, offering water managers the tools for more effective and sustainable water resource management.

AUTHOR CONTRIBUTIONS

Abdulmughni Hamzah: Writing – original draft; methodology, conceptualization. **Faisal Aqlan:** Conceptualization; methodology; resources; writing – review & editing; supervision. **Sabur Baidya:** Writing – review & editing; supervision.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing does not apply to this article as no datasets were generated or analysed during the current study.

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