Qureshi, M., Feng, Z., Kumar, V., Lovreglio R., & Abdelmegid, M. (2024). A Review of the Role of Digital Twin Applications for Water Sustainability. In D. B. Costa, F. Drevland, & L. Florez-Perez (Eds.), *Proceedings of the 32nd Annual Conference of the International Group for Lean Construction (IGLC32)* (pp. 731–742). doi.org/10.24928/2024/0185

A REVIEW OF THE ROLE OF DIGITAL TWIN APPLICATIONS FOR WATER SUSTAINABILITY

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ABSTRACT

This paper investigates the convergence of Digital Twin (DT) applications, Lean Construction (LC) principles, and water sustainability. The DT concept, which originated in the 2000s, has gained momentum across various industries. Yet, integrating DT into the construction industry, particularly in water systems, is at an early stage. A comprehensive literature review is conducted to explore the potential benefits of DT in water management, aligning with the principles of LC.

The exploration reveals the integration of DT into diverse water systems, encompassing distribution networks, sewage systems, river and lake management, dam systems, and wastewater treatment plants. The identified benefits extend beyond operational efficiency to water sustainability, addressing climate change adaptation, disaster risk reduction, and resource optimization. The study also explores the tools and technologies employed in DT applications, emphasizing their alignment with LC principles of reducing waste and fostering collaboration.

Nevertheless, limitations exist in the identified tools and technologies, such as data interoperability, computational complexities, and data reliability, underscoring areas for future research to enhance DT application effectiveness. Despite these limitations, the synthesis of DT, LC, and water sustainability holds promise for transforming water resource management.

This study offers guidance on achieving efficient, sustainable, and collaborative water management across various contexts. It provides essential insights for scholars, practitioners, and policymakers, emphasizing the importance of policy support and technological innovation to overcome current challenges. Furthermore, it suggests avenues for future research to evaluate the long-term effects and enhance the effectiveness of DT systems.

KEYWORDS

Digital Twin, Water Management, Water Sustainability, Lean Construction

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INTRODUCTION

The inception of the Digital twin (DT) concept dates back to early 2000 when Professor Michael Grieves introduced it during a Product Life cycle Management Course at the University of Michigan (Grieves, 2005). Since its introduction, DT has gained substantial traction, becoming a cornerstone in various industries. According to Kritzinger et al. (2018), the core of DT lies in the cyber-physical connection, termed the Digital Thread, enabling bidirectional communication between physical and digital spaces.

DT adoption in the construction industry is at a nascent stage; however, it is highly regarded for its significant benefits. It holds the potential to diminish waste through effective decision-making and analysis facilitated by real-time monitoring and control. DT also offers a comprehensive solution that harmonises lean thinking, computing, and monitoring technologies within the construction sector (Altan & Işık, 2023). This technological advancement is in line with the principles of LC, an approach that underscores efficiency, collaboration, and waste reduction throughout the construction process. The integration of DT technology into LC practices can significantly amplify operational efficiency by fostering collaboration among stakeholders and streamlining processes.

Indeed, while lean construction principles may not directly connect to water sustainability projects, their integration into water systems can bring notable benefits. By applying LC principles to water management, efficiency can be heightened, waste reduced, and overall sustainability in water usage improved. Yang et al. (2021) emphasised the need for innovative measures within a diverse social framework, especially those integral to water. Achieving water sustainability entails efficient use of clean water and judicious reuse and treatment of rainwater and sewage water for various purposes. In recent years, water utility planning, operation, and management have seen rapid digitalization and the use of various digital tools to achieve water sustainability. DT, as a transformative tool, is gaining prominence in water infrastructure, water treatment, and networking processes (Matheri et al., 2022).

Notably, prior scholarly works predominantly discuss DT applications in the context of management and operational functions rather than explicitly addressing their relevance to water sustainability. Nonetheless, it is imperative to acknowledge that efficient and intelligent operational and managerial practices significantly contribute to the broader goal of achieving water sustainability. This study endeavours to bridge this scholarly gap by conducting a comprehensive literature review encompassing water systems and their associated DT applications using lean principles.

To guide this exploration, specific research questions were formulated:

1. What water systems have been studied, tested, or evaluated with DT applications?
2. What are the benefits of those DT applications to water sustainability?
3. What are the tools and technologies applied in those DT applications?
4. What are the challenges and barriers of applying these DT applications to water systems?

METHODOLOGY

Research methodology forms the backbone of any study, providing a structured plan that guides the investigation from start to finish. Conducting a literature review is a crucial approach for acquiring insights into the research topic and grasping the current state of knowledge in the field.

This study employs a systematic literature review approach using the PRISMA framework as outlined by Khan et al. (2003), and utilizes the Scopus database as the primary research platform. The literature review encompassed both journal articles and conference papers. The search keywords were “digital twin” OR “building information modelling” OR BIM AND water. We included building information modelling and BIM because these terms are often used interchangeably with DT, ensuring a comprehensive search for relevant literature and studies on the topic.

The second part of the search keywords is: “water”. This search strategy encompassed a broad scope by including "water" rather than "water sustainability". This deliberate choice aimed to capture a wide array of literature concerning water management and its relevance to DT. The keywords were applied to search for titles, abstracts, and keywords.

The search was executed in September 2023, resulting in 1142 initial findings retrieved from Scopus. Using the Preferred Reporting Items for Systematic Literature Reviews and Meta-Analyses (PRISMA) approach (Page et al., 2021), the results were refined as illustrated in Figure 1. Firstly, 33 duplicates (e.g., the same DT application was published in different sources) were removed. Secondly, articles were excluded based on the following criteria: (1) The article has no relation to water and DT. (2) The proposed application in the article was not designed for the water sector. (3) The article proposed theoretical frameworks without practical applications. (4) The article was not in English.

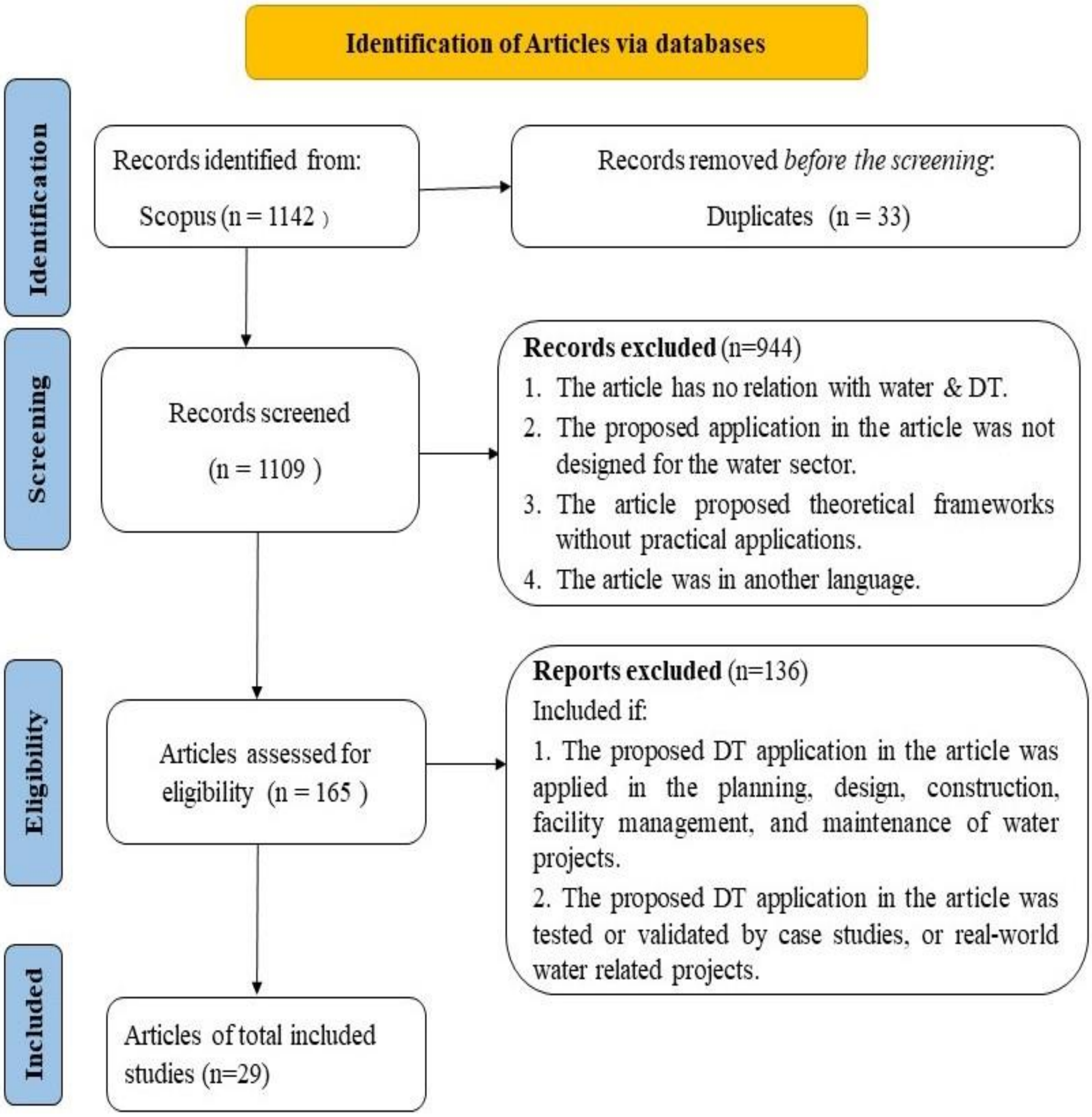

Figure 1 The PRISMA Workflow

During this step, 944 articles were excluded, leaving 165 articles for further analysis. Finally, we scrutinized the full text of these remaining articles, applying the subsequent inclusion criteria: (1) The proposed DT application in the article was applied in the planning, design, construction, facility management and maintenance of water related projects. (2) The proposed DT application in the article was tested or validated by case studies, or real-world water related projects.

This process resulted in 29 articles meeting the eligibility criteria for inclusion in this literature review. Among them, there were 18 journal and eleven conference papers, all published between 2017 and 2023 (Figure 2).

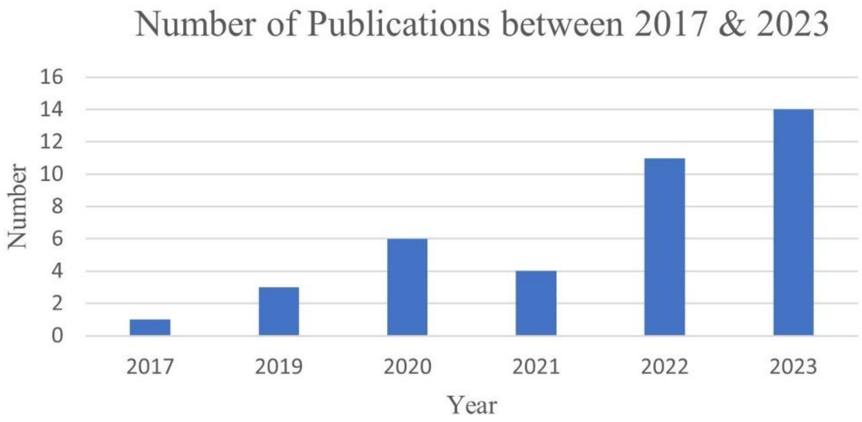

Figure 2 Number of Publications

RESULTS

This study examines the eligible articles to discover the water systems that have been equipped with DT, the benefits to water sustainability, the tools and technologies employed in DT applications, and the challenges and barriers of applying DT.

WATER SYSTEMS

The integration of DT technology into various water systems aligns with the principles of LC, emphasizing efficiency, sustainability, and continuous improvement. These systems encompass water distribution networks, river and lake management systems, dam management systems, sanitary sewage systems, water resource recovery facilities (WRRFs), wastewater treatment plants (WWTP), groundwater management systems, drainage systems, and wetlands (Figure 3).

Conejos Fuertes et al. (2020) explored DT for city management in Valencia, Spain, demonstrating a commitment to lean principles by enhancing daily operations, strategic planning, and responses to unplanned events. Ramos et al. (2023) suggested a DT application for a pumping system in Sta Cruz, targeting a decrease in water demand volume and an increase in renewable energy generation, aligned with sustainable development goals (SDGs). This reflects a lean approach towards resource efficiency.

Fargas and Cornellà (2023) addressed a DT application in managing water distribution pipes for asset management purposes, highlighting the challenge faced by the Tarragona Water Consortium (Consorci d'Aigües de Tarragona - CAT). This application aligns with lean principles, addressing specific challenges and streamlining asset management processes.

Another application of DT towards river, lake, and dam management, presented by Wang et al. (2022), emphasizes lean principles by upgrading conventional water systems to enhance efficiency and reduce energy consumption in the Weihe River Basin (WRB) in Shaanxi province, China. Additionally, Park and You (2023) introduced an innovative DT platform for dam and watershed management, enabling real-time data utilization for flood response and water resource management for Sumjin Dam and its river water system in Korea. This proactive approach embodies one of the principles of LC, which leverages efficient response to environmental challenges.

Moreover, the DT concept was employed to mitigate the impacts of climate change on groundwater levels in distinct water systems. Henriksen et al. (2023) presented a Danish case study introducing the Hydrological Information and Prediction Digital Twin (HIP DT) for Denmark, reflecting a lean focus on climate change adaptation, water security management, and disaster risk reduction.

Three papers specifically focused on wastewater treatment plants and water resource recovery facilities. Bellandi et al. (2022) investigated the DT of an advanced wastewater treatment plant in the Netherlands, aimed at improved performance and water safety. In the context of lean management, this approach enhances operational effectiveness.

Melo et al. (2019) studied the Sanitary Sewage System of Piumhi, a city in Brazil. They applied the framework of City Information Modelling (CIM), a management model leaning on preventive actions and a decision-making process based on accurate information. Payne et al. (2023) used Machine Learning (ML) for surrogate groundwater modeling in Barbados (Caribbean region), showcasing a lean use of technology for efficient groundwater management.

Moving towards natural systems, Ruangpan et al. (2023) explored smart solutions and DT to manage flooding and irrigation systems in the Rangsit Area, Thailand, to enhance urban resilience. Similarly, the environmental improvement project in the Green Water Wetland in the Yangtze River, China, by Huang et al. (2023), integrates technology for lean water system management, emphasizing connectivity, hydrodynamics, and modeling for analysis and verification.

The exploration of DT water management extends to buildings, with Batista et al. (2023) designing a specialized framework for optimizing water efficiency in the Central Market of Belo Horizonte, Brazil. Yang et al. (2021) devised a framework employing advanced technology and algorithms for maintaining water dispensers within campus settings. These frameworks showcase the potential for enhanced water conservation and management, which is a lean approach contributing to sustainable water practices in constructed spaces.

By aligning with lean principles and focusing on continuous improvement, DT technology not only addresses current water management challenges but also paves the way for innovative solutions that could significantly impact resource efficiency and sustainability in both natural and constructed environments.

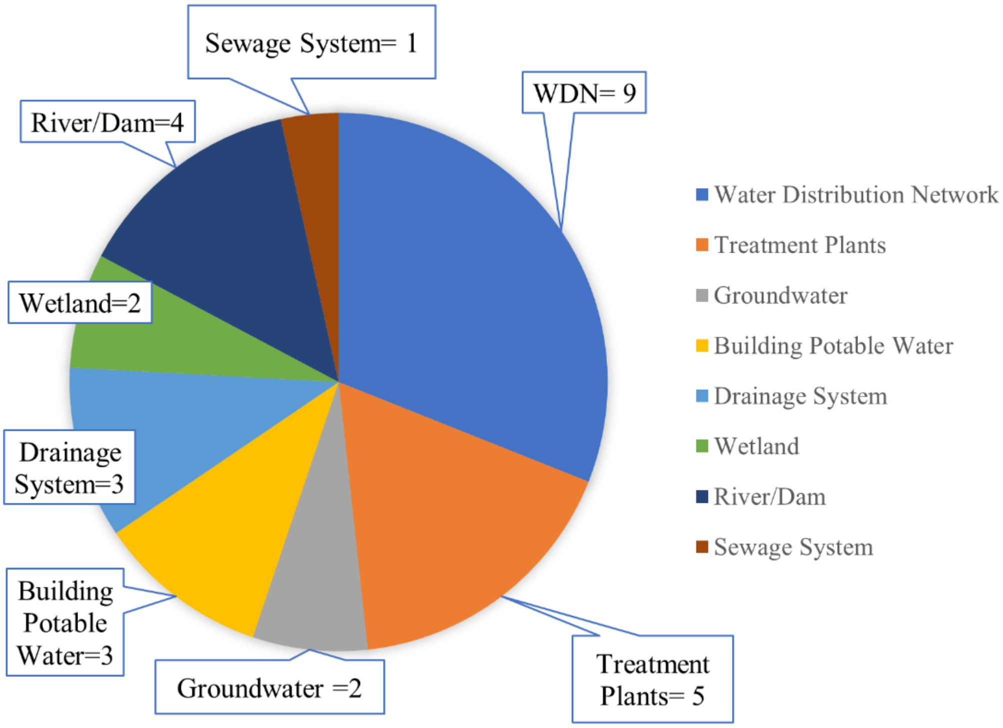

Figure 3 Digital Twin Publications: Water Systems Classification

BENEFITS TO WATER SUSTAINABILITY

The exploration of DTs across diverse water systems presents a multitude of benefits that align with water sustainability and resonate with LC principles. They enhance resilience through proactive monitoring, anticipating, and mitigating challenges. DTs also contribute to sustainability, preserving water quality and promoting long-term sustainable development objectives. For instance, Conejos Fuertes et al. (2020) showcased how DTs contributed to efficient water resource management in city operations, daily activities, and strategic planning. These applications embody LC's emphasis on minimizing waste and optimizing processes.

Similarly, Fargas and Cornellà (2023) highlight the role of DTs in asset management that exemplifies LC commitment to effective asset utilization for streamlined project delivery. DT applications in preserving water quality, flood prevention, and mitigation align with sustainable water practices and LC principles of minimizing inefficiencies (Park & You, 2023; Wang et al., 2022). Moreover, DTs play a pivotal role in adapting to climate change and reducing the risks associated with disasters, as demonstrated by Henriksen et al. (2023). The application of DTs in this context reflects both LC's focus on adaptability and the broader goal of sustainable water resource management.

Treatment plants optimization presented by Bellandi et al. (2022); Remigi et al. (2022) showcase the DT's capacity to enhance overall performance, aligning with LC's principles of continuous improvement. City-specific water solutions proposed by Ramos et al. (2023 a); Ramos et al. (2023 b) reflect a focus on sustainability, renewable energy, and system efficiency. These applications correspond with LC's goal of optimizing resources and improving overall system efficiency.

The use of DTs in groundwater management under changing climates (Payne et al., 2023) aligns with LC's adaptive project management approach. Additionally, the optimization of urban water cycles using Cyber-Physical Systems mirrors LC's emphasis on efficiency (Sun et al., 2020). Smart solutions for flooding and irrigation proposed by Huang et al. (2023); Ruangpan et al. (2023) emphasize resilience and integration of nature-based solutions, aligning with LC's focus on adaptability and resilience in the face of challenges.

Finally, the applications of DTs in buildings by Batista et al. (2023); Yang et al. (2021) optimize water efficiency within commercial structures and campus settings, aligning with LC's principles of efficiency and resource optimization. In summary, the highlighted benefits emphasize the versatility of DT applications, making substantial contributions to both LC practices and sustainable water management. DT technologies significantly contribute to water sustainability, closely aligning with LC principles by optimizing resource use, enhancing resilience, and supporting sustainable development through a wide range of applications across water systems management and infrastructure efficiency.

TOOLS AND TECHNOLOGIES

The eligible articles introduced various tools and technologies employed for developing and implementing DT applications in water management (Table 1). Many of these tools, readily available in the market, have been integrated into new platforms or adapted for use in existing systems to facilitate integration and management.

Conejos Fuertes et al. (2020) extensively detailed the tools and technologies applied in managing the drinking water management system of Valencia, Spain, with the GO2HydNet serving as a foundational platform. The system seamlessly integrated the hydraulic model with various information sources, like Geographical Information System (GIS), Automated Meter Reading (AMR), Computerized Maintenance Management Systems (CMMS), and field data stored by the Supervisory Control and Data Acquisition (SCADA) system. Specialized algorithms facilitated high-efficiency model construction, exemplified by the creation of a comprehensive model with 32,000 nodes in about a minute.

Ramos et al. (2023) employed similar tools but integrated them into the hydraulic model via Artificial Intelligence (AI) algorithms and Information and Communication Technology (ICT). Conversely, Bonilla et al. (2022) utilized Python libraries to estimate pump speed and derive pressure and flow rate information for non-monitored pipes using EPANET 2.2. Fargas and Cornellà (2023) explored the integration of online monitoring technologies such as Acoustics Fiber Optics (AFO) and electromagnetic pipe inspection in the implementation of DT for the Tarragona Water Consortium (Consorci d'Aigües de Tarragona - CAT).

Distinct tools were utilized for managing rivers, lakes, and dams compared to water distribution networks. For instance, Park and You (2023) utilized the K-Twin SJ platform for dam and watershed management, integrating 3D Geospatial Reality Modelling with Aerial LiDAR Survey & Drone, hydraulic and hydrological simulation models. Qiu et al. (2022) developed a web-based interactive twin platform for watershed management using Virtual Geographic Environment, integrating geospatial data with terrain visualization, unmanned aerial vehicle (UAV) tilt photography, and 3D modeling. Furthermore, real-time video monitoring and water quality data were integrated into a 3D scene, enabling a detailed representation of the area and aiding in precise watershed management.

Henriksen et al. (2023) developed a DK-model employing the MIKE SHE-MIKE Hydro software, simulating various hydrological processes, and supplementing it with machine learning (ML) algorithms for enhanced accuracy. The DT for Water Resource Recovery Facility developed by Remigi et al. (2022) comprised components such as MIKE OPERATION for real-time data, WEST model for simulation, and a user-friendly dashboard for operator control. Melo et al. (2019) proposed a combination of technologies for the operation and maintenance of the sanitary sewage system of Piumhi. He utilized GPS GNSS RTK L1/L2 for high-precision positioning survey and designed the sewage network on AutoCAD Civil 3D and QGis.

Various articles explored groundwater sustainability, irrigation and drainage system behavior, wastewater management, and wetland simulations, utilizing software tools such as FEFLOW, MIKE 11, GAMS with CPLEX solver, and Unreal Engine. Huang et al. (2023)

recommended using BIM & GIS as a communication platform during the construction period, while Batista et al. (2023) proposed AquaBIM, a web-based application integrating BIM-IOT-FM for water sustainability within buildings.

This review highlights the diverse tools and technologies employed across various projects, showcasing the versatility of DT applications in the realm of water resource management. Furthermore, the utilization of AI, ML, and streamlined data integration contributes to the lean principles of reducing waste, enhancing productivity, and fostering collaborative decision-making processes. Notably, Geographical Information System (GIS) emerges as the most prevalent technology across these water management systems, employed for managing, analyzing, and visualizing geographic data. Similarly, Supervisory Control and Data Acquisition (SCADA) systems are widely used for control, monitoring, and analysis purposes.

Table 1 Tools and Technologies

Water System	**Platform**	**Tools and Technologies**
Drinking Water Management System Valencia (Spain)	GO2HydNet	Hydraulic Model on EPANET, Geographical Information System (GIS), Automated Meter Reading (AMR), Computerized Maintenance Management System (CMMS)
Dam and Watershed Management-Korea	K-Twin SJ Platform	3D Geospatial Reality Modelling, Aerial LiDAR Survey & Drone, Hydraulic and Hydrological simulation Model
Water Resource Recovery facility (WRRF)-Italy	MIKE OPERATION	SCADA, WEST model
Water Distribution Network Madeira Portugal	Big Data Platform	GIS, Sensors, SCADA, Smart Metring, CMMS integrated in EPANET via AI algorithms
Watershed Environment of Chaohu Lake	Web-based platform using Virtual Geographic Environment	geospatial system, unmanned aerial vehicle UAV tilt photography, 3D modelling, video monitor
Hydrological Information and Prediction (HIP) Model Denmark	SHE-MIKE	Supplemented with Machine Learning (ML) algorithm
Water Management systems Belo Horizonte, Brazil.	AquaBIM	Revit Model, Smart Meters

CHALLENGES AND BARRIERS

he authors of the eligible articles have demonstrated various challenges faced by researchers and practitioners in implementing DT within water systems. These challenges span technical, data-related, organizational, and practical aspects.

Conejos Fuertes et al. (2020) addressed challenges related to GIS data integration and model requirements by developing algorithms, ensuring a seamless blend between spatial data and modeling needs. Notably, their proactive approach involved creating supplementary systems to store crucial data, rectifying errors, and modifying EPANET software. This reflects a sophisticated strategy to overcome technical obstacles and enhance the robustness of DT applications.

Tomic et al. (2022) focused on challenges encountered in city implementation, emphasizing the critical role of accurate data. The authors recognized the importance of addressing data challenges for effective DT application, showcasing a meticulous approach to city-level water system management.

In a distinct scenario, Qiu et al. (2022) identified challenges associated with prolonged computational durations in 3D modeling. Their response involved advocating for accelerated approaches in model computation, demonstrating an understanding of the need for agility and efficiency.

Henriksen et al. (2023) viewed establishing explicit project goals, objectives, and comprehensive plans as prerequisites for implementing DT at a national level, emphasizing the importance of clear objectives and efficient resource utilization. The authors recognized the substantial investment in resources and expertise required for national-level DT implementation, showcasing a holistic and strategic mindset.

Similarly, Melo et al. (2019) encountered challenges in surveying the sanitary sewage system and explored alternative surveying methods. Some studies posed challenges and barriers in applying DT in real-world scenarios. Ramos et al. (2023) faced challenges related to the reliability of data used to develop the DT model. They emphasized the need for accurate data related to system configuration. The authors recognized the crucial role of accurate data in the success of DT applications, highlighting the importance of close collaboration between researchers, designers, and municipal management.

Bonilla et al. (2022) rendered challenges in obtaining monitored data on the relative operating speed of pumps. Payne et al. (2023) addressed calibration limitations in spatial coverage of data and challenges in predicting transient groundwater response. Their approach involved advanced calibration technologies, emphasizing accuracy and efficiency in spatial coverage.

Sun et al. (2020) highlighted the challenge of ensuring effective management of routine interactions among subsystems within efficient computational timeframes. Lu et al. (2023) recognized the challenge of collecting data from the extensive Poyang Lake wetland and focused on optimizing data collection strategies.

In the building context, Yang et al. (2021) emphasized challenges in proposing BIM applications for water dispensers’ maintenance. Their acknowledgment of interoperability and staff unfamiliarity showcases an understanding of the importance of improved computerization.

Despite these challenges and barriers, innovative solutions and strategic approaches showcased by researchers underline the critical importance of accurate data, streamlined computations, and clear objectives in advancing DT applications for more effective water systems management.

CONCLUSION

This literature review explores the synergy between DT applications, LC principles, and water sustainability. The analysis of diverse water systems demonstrates that integrating DT with LC fosters efficiency and sustainability. The identified benefits, spanning optimized operations and resource management, resonate with LC principles, showcasing a commitment to waste reduction and collaborative decision-making.

Despite challenges in technical, data-related, organizational, and practical realms, the authors exhibit resilience and innovative problem-solving, aligning with the ethos of LC. This synthesis of DT, LC, and water sustainability holds promise for transformative advancements in water resource management. As the confluence of DT and LC principles evolves, this study provides foundational insights for scholars, practitioners, and policymakers navigating the complex landscape of water systems.

The review underscores the importance of incorporating advanced technologies such as AI, ML, and GIS into DT applications, indicating a move towards more nuanced and interdisciplinary approaches. It suggests the necessity for policy development that encourages sustainable practices and allocates resources to surmount technical hurdles, thereby guiding investments in water management technologies.

Additionally, the review points out existing gaps in DT application, such as data integration and model accuracy, suggesting a direction for future research that focuses on closing these gaps to boost DT system efficiency and reliability. The call for longitudinal studies to evaluate the long-term impacts of DT on water sustainability, system efficiency, and environmental outcomes suggests an avenue for future research that could shape the continuous improvement and scaling of DT applications.

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