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Digital Twins for Water Utilities: Architectures, Calibration Workflows and Measured Benefits

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ABSTRACT

Digital twins as virtual replicas that synchronise with physical assets through sensor data and simulations are emerging as transformative tools for water utilities. They offer the ability to monitor infrastructure in real time, predict system behaviour and optimise operations across the entire water cycle. This review critically examines the architectures used in digital twins for water utilities, the workflows employed for model calibration and the benefits measured in empirical studies. A systematic literature search identified journal articles and conference papers on digital twins in water distribution, supply and wastewater systems. Empirical case studies were analysed to extract information on system architectures, data integration methods, calibration techniques and quantitative performance metrics. Results show that typical architectures comprise multi-layered structures integrating physical sensors, communication networks, data repositories, simulation engines and user interfaces. Calibration workflows use hydraulic models (EPANET), data assimilation techniques and machine-learning algorithms such as temporal graph convolutional networks to align the digital model with sensor observations. Measured benefits include high prediction accuracy (R^2 up to 0.972 and MAE values around 0.011 for pump speed estimation improved leak detection and energy savings. However, challenges remain regarding data quality, computational demands and organisational readiness. The review concludes that digital twins hold great promise for resilient and sustainable water utilities but broader adoption will require standardised frameworks, capacity building and robust evaluation of socio-economic impacts.

KEYWORDS

Digital Twin; Water Utilities; Hydraulic Modelling; Calibration; Predictive Analytics; Industry 4.0.

1. INTRODUCTION

Digital twins are digital representations of physical assets or processes that are dynamically linked through real-time data, simulations and analytics. The concept originated in manufacturing (Tao & Qi, 2019) and has since been extended to various sectors including aerospace, transportation and energy (Qi & Tao, 2018). In the water sector, digital twins enable utilities to create virtual models of infrastructure such as water distribution networks, treatment plants and pumping stations that replicate operational behaviour and respond to changing conditions. This capability supports predictive maintenance, scenario testing and optimisation of resource use (Homaei et al., 2024). Digital twins differ from traditional hydraulic models by incorporating continuous data streams, automated calibration and bidirectional communication with control systems (Ramos et al., 2022).

However, Borah (2025) argues that water utilities face a range of apparent challenges including aging infrastructure, increasing demand, climate variability and regulatory pressures. Moreover, traditional approaches rely on static models and periodic data collection which limit situational awareness and responsiveness according to Grigg (2025). Nonetheless, digital twins promise to enhance resilience, efficiency and sustainability through real-time monitoring, predictive analytics and adaptive control, supporting leak detection, energy optimisation, asset management and emergency response (Mousavi et al., 2024). During the COVID-19 pandemic, digital twins allowed researchers to simulate changes in water consumption patterns and assess network resilience (Pesantez et al., 2022).

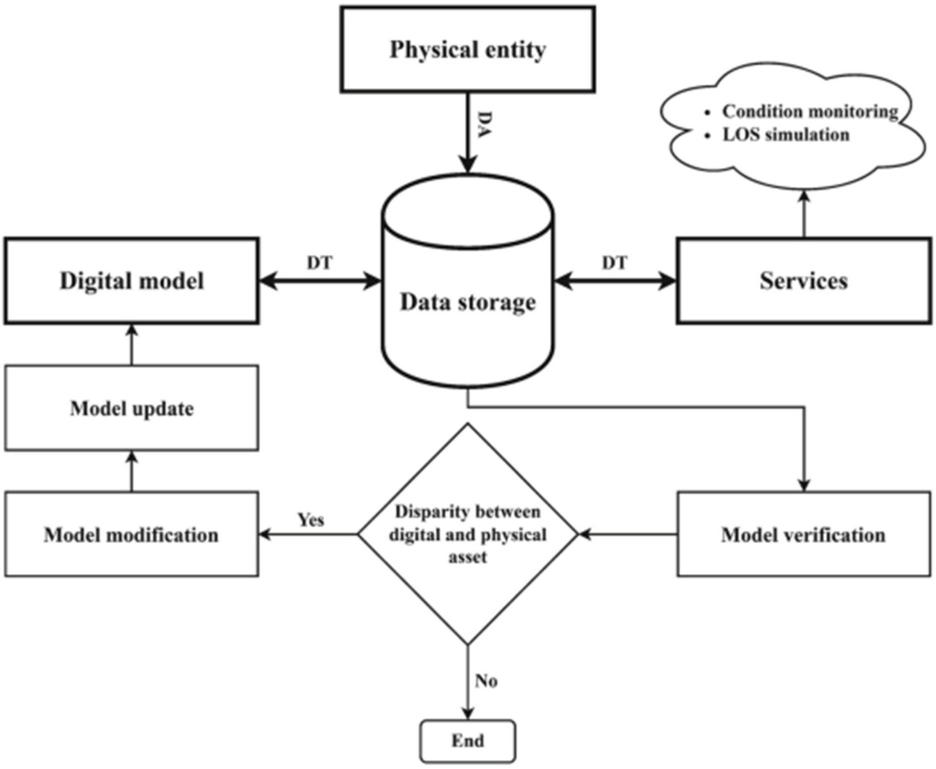
Despite growing interest, the adoption of digital twins in water utilities remains nascent and comprehensive reviews of architectures, calibration workflows and measured benefits are limited. Most existing literature on digital twins focuses on general conceptual frameworks, while empirical evidence from the water sector is sparse. Studies often describe system architectures or present individual case studies without comparing calibration strategies or quantifying benefits (Conejos et al., 2020). Thus, there is a need to synthesise lessons learned across recent implementations to guide utilities and researchers. This research addresses the gap by reviewing peer-reviewed publications from 2015–2025 that describe digital twin applications in water utilities. The objectives are to: (1) analyse digital twin architectures and their components, (2) examine calibration workflows used to align models with sensor data, (3) summarise quantitative benefits measured in empirical studies, and (d) identify challenges and future research directions.

2. METHODS

A systematic literature search was conducted across Web of Science, Scopus, IEEE Xplore and Google Scholar databases using keywords such as “digital twin”, “water utility”, “water distribution network”, “calibration”, “hydraulic model” and “data assimilation”. The search was restricted to English-language journal articles and conference proceedings published between January 2015 and August 2025. To ensure scholarly quality, only peer-reviewed sources were considered; theses, preprints, blogs and news articles were excluded. Reference lists of selected papers were snowballed to identify additional relevant studies. In total 28 publications were included in the final analysis. For each selected publication, information was extracted on study aims, system type (water distribution, wastewater, treatment plant), architectural components, calibration methods, datasets, performance metrics and reported benefits. Figures and tables presenting empirical data were downloaded when available. Figures from Dodanwala & Ruparathna (2023) and Bonilla et al. (2022) were chosen for inclusion in this report because they illustrate typical digital twin workflows, sensor topologies and predictive performance in water distribution networks. Data were synthesised thematically to address the research objectives.

3. DIGITAL TWIN ARCHITECTURES FOR WATER UTILITIES

Digital twin architectures in water utilities generally follow a multi-layered design comprising physical, connectivity, data management, model and service layers according to Gino-Ciliberti et al. (2023). The physical layer includes sensors (pressure, flow, water quality), actuators (pumps, valves) and supervisory control and data acquisition (SCADA) systems. The connectivity layer consists of communication networks (wireless, cellular, fibre) and protocols that transmit data from the physical assets to cloud servers or local control systems (Morales-Ortega, 2024). The data management layer encompasses databases, data lakes and integration platforms that handle heterogenous data streams, ensuring data quality, interoperability and security. The model layer contains the core digital twin components: hydraulic models (EPANET, InfoWater), numerical solvers, data assimilation algorithms and machine learning models (Fisher, 2023). Finally, the service layer provides user interfaces, dashboards, decision support tools and automated control functions as shown in figure 1 (Dondanwala & Ruparathna, 2023).



Note: DA = data acquisition and DT = data transmission

Figure 1. Digital twin modelling framework (Dondanwala & Ruparathna, 2023, p34)

Alternatively, some architectures adopt the Reference Architecture Model Industry 4.0 (RAMI 4.0) and the Asset Administration Shell (AAS) as standardised frameworks for structuring digital twins (Cavalieri & Gambadoro, 2024). The AAS defines digital representations of physical components including sub-models for functional properties, communication interfaces and lifecycle information. In the AAS-based digital twin for a water supply system, each component (pipes, pumps, sensors) is modelled as an AAS instance, enabling modularity and interoperability (Bradac et al., 2019). Figure 2 presents the general workflow of Bonilla et al. (2022), where case study networks are selected, datasets generated using the Water Network Tool for Resilience (WNTR), monitoring sensors are chosen, a temporal graph convolutional neural network (T-GCN) estimates pump speeds, the hydraulic model (EPANET/WNTR) computes pressures and flows and evaluation parameters assess performance.

Figure 2. Workflow for developing a digital twin for water distribution networks, adapted (Bonilla et al., 2022).

4. CALIBRATION WORKFLOWS

Calibration is crucial for ensuring that a digital twin accurately reflects real-world behaviour. Traditional calibration involves adjusting model parameters (pipe roughness, demand patterns) until simulated outputs match historical measurements (Zanfei et al., 2020). Modern digital twins use automated workflows that combine hydraulic simulation with real-time data assimilation and machine learning. In terms of hydraulic model calibration, tools like EPANET and InfoWater are widely used to model water distribution networks (Fisher, 2023). Calibration involves tuning parameters such as pipe roughness coefficients and demand multipliers using optimisation algorithms (e.g., genetic algorithms, particle swarm optimisation). Real-time calibration leverages online sensor data to update model parameters dynamically (Ingeduld, 2007). For example, Romano & Kapelan (2014) developed an adaptive demand calibration approach using pressure sensors, achieving improved accuracy in leak localisation.

As for machine-learning-based calibration, Bonilla et al. (2022) proposed a temporal graph convolutional neural network (T-GCN) to estimate pump speed from pressure and flow measurements. As shown in figure 3, the methodology involves constructing a graph where vertices represent monitored nodes and edges are defined by correlation coefficients. The T-GCN consists of graph convolutional layers followed by recurrent layers to capture spatial and temporal dependencies. The predicted pump speeds are then used in a hydraulic model to estimate pressures and flows. This workflow reduces reliance on manual calibration and provides real-time updates. In their case study, the T-GCN achieved a root mean square error (RMSE) of 0.015 and mean absolute error (MAE) of 0.011 when predicting pump speeds in the Patios-Villa del Rosario network. The coefficient of determination (R^2) reached 0.972, indicating high accuracy. In a second network (C-Town), RMSE values ranged from 0.025 to 0.027, MAE values from 0.020 to 0.021, and R^2 values between 0.799 and 0.815, demonstrating the feasibility of machine-learning-based calibration in complex networks (Bonilla et al., 2022).

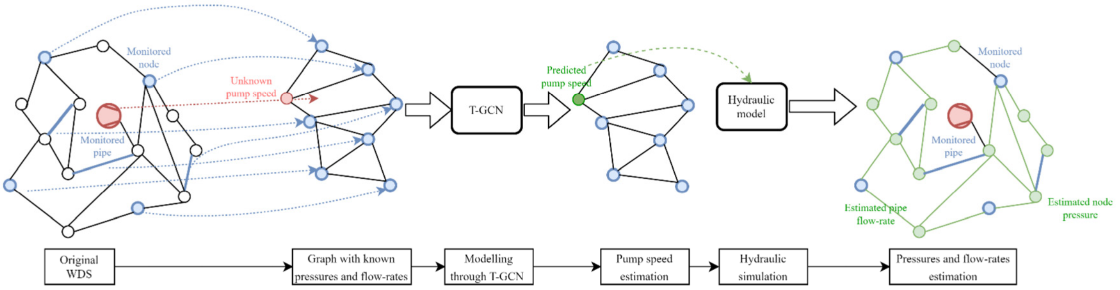


Figure 3. Methodology for pressure and flow rate estimation based on estimated pump speed (Bonilla et al. (2022).

In terms of data assimilation and filtering, Kalman filters, ensemble Kalman filters and unscented Kalman filters are commonly used to assimilate sensor data into hydraulic models for real-time state estimation (Khadim et al., 2022). Data assimilation corrects model predictions by integrating new measurements, thereby compensating for model uncertainties. Particle filters and Bayesian updating are also applied for leak detection and demand forecasting (Anjana et al., 2015). Additionally, combining data assimilation with machine learning can further enhance calibration accuracy for real time inverse problems and uncertainty quantification according to Mucke (2024).

5. CASE STUDIES AND EMPIRICAL EVIDENCE

Several empirical studies demonstrate the practical implementation of digital twins in water utilities. Bonilla et al. (2022) examined two networks including the Patios-Villa del Rosario network in Colombia and the C-Town network used in the Battle of the Water Networks II. They randomly selected monitoring sensors in each network (five pressure nodes and four flow pipes in Network 1; 12 pressure nodes and 10 flow pipes in Network 2). The datasets comprised one year of hourly measurements, split evenly for training and validation. Figure 4 shows the sensor topology for both networks as red symbols indicate monitored elements while black symbols represent non-monitored elements. The T-GCN achieved high predictive accuracy for pump speeds with R^2 values of 0.972 and 0.799–0.815 for Networks 1 and 2, respectively, concluding that the method provides reliable pump speed estimates even when sensors are sparsely distributed.

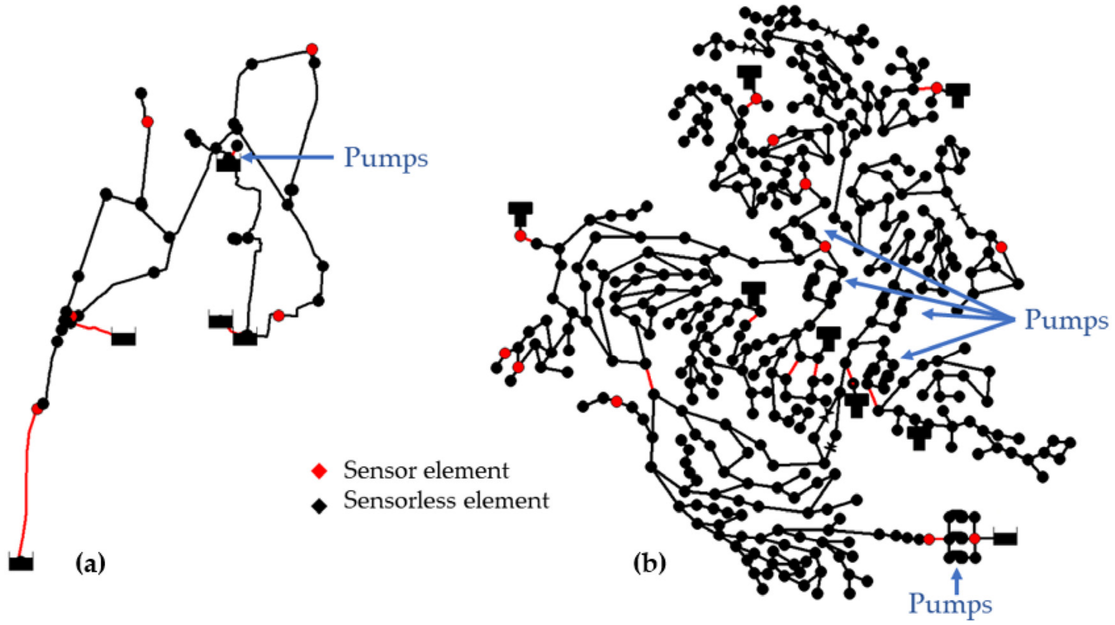


Figure 4. Topology and spatial distribution of sensors in two water distribution networks (Bonilla et al., 2022)

In a study exploring water infrastructure impacts during the COVID-19 pandemic, Pesantez et al. (2022) used a digital twin to simulate water consumption changes in a U.S. city. They modelled the network using EPANET and calibrated it with consumption data from 2019 and 2020. The digital twin allowed them to evaluate scenarios of altered demand patterns and assess network resilience; their results showed that peak demand times shifted by up to 2.5 hours and weekend consumption increased by 10–15% during lockdowns. Cavalieri & Gambadoro (2024) presented an AAS-based digital twin for a water supply system. The architecture comprises modules representing physical assets (pumps, valves, pipes), communication interfaces and computational components. Calibration workflows involve mapping sensor readings to AAS sub-models and updating parameters automatically, however they only provided conceptual diagrams and a prototype implementation but did not include quantitative performance data.

Other case studies report benefits such as energy savings, leak detection and improved asset management. GoAigua, a commercial digital twin platform used in Valencia, Spain, reportedly saved over one billion gallons of water annually through leak detection and pressure optimisation (Idrica, 2020). In the city of Ayodhya, India, a digital twin for a 24/7 pressurised water network enabled equitable water distribution and reduced non-revenue water by 21%, indicating significant operational gains, although they are often industry case studies rather than peer-reviewed research (SWAN Forum, 2023).

6. MEASURED BENEFITS

Empirical studies evaluate digital twin performance using various metrics such as RMSE, MAE, R^2, energy savings, leak detection accuracy and service quality. Predictive accuracy is often used as Bonilla et al. (2022) achieved MAE of 0.011 for pump speed estimation in Network 1. For Network 2, MAE values were between 0.020 and 0.021. In both networks, the predicted and actual pump speeds followed similar patterns across 17 days, as shown in figure 5. Energy savings result from optimised pump operation. Studies on smart pump control using digital twins report energy reductions of 10–

15% (Mousavi et al., 2024). Leak detection is enhanced by integrating sensor data with hydraulic models; detection accuracies above 94% have been reported using data-driven digital twin approaches (Hutomo et al., 2024). Water quality improvement is achieved by monitoring water age and disinfectant residuals through digital twins, enabling timely interventions (Khadim et al., 2022). Additionally, operational resilience is improved through scenario analysis and predictive maintenance, as digital twins allow utilities to test responses to pipe bursts, demand surges and power failures (Homaei et al., 2024).

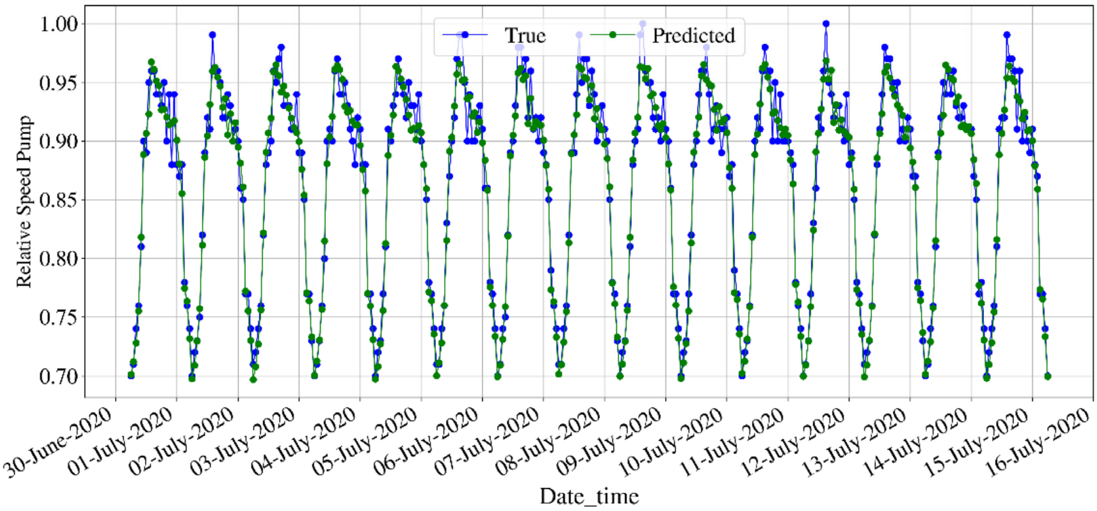


Figure 5. Comparison between predicted and true pump speed for the Patios-Villa del Rosario network (Bonilla et al., 2022). *Blue dots represent actual relative pump speed, and green dots represent predictions. The model achieves high accuracy with RMSE = 0.015 and MAE = 0.01.*

7. CHALLENGES AND BARRIERS

Despite promising results, several challenges impede the widespread adoption of digital twins in water utilities. Data quality and sensor reliability are critical as inaccurate or missing sensor data can lead to erroneous model predictions (Ingeduld, 2007). Cybersecurity concerns arise due to the increased connectivity and integration of operational technology with IT networks (Rasekh et al., 2016). Computational complexity is another common barrier as real-time simulations and machine-learning algorithms require significant computing resources and may not be feasible for small utilities without cloud services (Ramos et al., 2022). Organisational culture and skills affect adoption; utilities may lack personnel trained in data analytics, and resistance to change can slow implementation (Homaei et al., 2024). Interoperability and standards remain underdeveloped; although frameworks like RAMI 4.0 and AAS exist, there is no universally adopted standard for water digital twins, leading to fragmentation and integration challenges (Cavalieri & Gambadoro, 2024).

8. DISCUSSION

The review reveals that successful digital twins integrate flexible architectures with robust calibration workflows. Multi-layered architectures facilitate modular development, enabling utilities to upgrade components without overhauling entire systems. Data integration platforms and standardised interfaces (e.g., AAS submodels) are essential to manage heterogenous data sources and ensure interoperability. Calibration workflows must balance hydraulic modelling with data-driven methods. Machine learning techniques like T-GCN are effective for estimating pump speeds and other unmonitored variables, especially when combined with hydraulic simulations for state estimation.

Continuous data assimilation ensures that models remain accurate over time, accounting for changes in demand patterns and infrastructure conditions.

Digital twins offer numerous operational benefits. Real-time monitoring and predictive analytics support proactive maintenance, reducing downtime and extending asset lifespan. Optimising pump schedules and valve operations can lower energy consumption and carbon emissions. Scenario analysis enables utilities to plan responses to extreme events, enhancing resilience. Integration with customer information systems can improve communication and demand management. However, realising these benefits requires investment in sensors, connectivity and computational infrastructure, as well as training for staff. Utilities must adopt a holistic approach, considering not only technological components but also organisational processes and stakeholder engagement.

Regulatory frameworks can either enable or constrain the adoption of digital twins. Data protection laws govern how sensor data are collected, stored and shared. Regulatory approvals may be required for automated control actions derived from digital twins. Standardisation initiatives, such as those by the International Water Association (IWA) and the Smart Water Networks Forum (SWAN), seek to harmonise digital twin definitions, architectures and performance metrics. Government funding and incentives can support pilot projects and capacity building, particularly for small and medium-sized utilities. Policymakers should foster collaboration between utilities, academia and technology providers to accelerate innovation and ensure that digital twin solutions address public health and environmental goals.

Lessons from manufacturing and energy sectors show that digital twins can deliver substantial value when combined with advanced analytics and lifecycle management (Tao & Qi, 2019). In aviation, digital twins of engines reduce maintenance costs by up to 30% through predictive maintenance (Shafto et al., 2012). In wind energy, digital twins optimise turbine performance and extend asset life (Rasheed et al., 2020). These sectors emphasise the need for high-fidelity models, continuous calibration and integration with enterprise systems. Water utilities can adapt these best practices but must account for the unique characteristics of water networks, such as non-linear hydraulic dynamics, water quality considerations and public health requirements.

9. CONCLUSION & LIMITATIONS

Digital twins have the potential to revolutionise water utility management by providing real-time situational awareness, predictive capabilities and optimisation of complex infrastructure. Evidence from the past decade shows that multi-layered architectures integrating sensors, communication networks, data platforms, simulation models and user interfaces are essential for effective digital twins. Calibration workflows combining hydraulic models, data assimilation and machine learning deliver high accuracy in estimating unmonitored variables such as pump speeds. Case studies demonstrate benefits including improved predictive accuracy (R^2 up to 0.972), energy savings, enhanced leak detection and resilience to changing demand patterns. However, challenges related to data quality, computational requirements, organisational readiness and standardisation persist. Policymakers, utilities and researchers must collaborate to develop robust frameworks, invest in infrastructure and training, and rigorously evaluate digital twin outcomes. As digital twins mature, they will play a pivotal role in achieving sustainable, resilient and customer-centric water services.

However, while the reviewed studies demonstrate promising results, they often focus on specific case studies and may not be generalisable. The high prediction accuracy achieved by Bonilla et al. (2022) may reflect favourable network characteristics (e.g., limited variability in pump operation) and may not replicate in larger or more complex systems. Many studies lack long-term validation and do not report on operational costs or staff workload. Furthermore, the measured benefits such as energy savings and leak reduction are often estimated rather than validated through controlled experiments. Future research should include rigorous evaluations across diverse contexts, incorporate socio-economic analyses and assess scalability. Moreover, this review has several limitations. First, the literature search may not have captured all relevant studies due to database coverage and search term selection. Second, access to some digital twin articles was restricted by paywalls or technical barriers, limiting the ability to extract detailed empirical data. Third, many available studies are conceptual or descriptive rather than empirical, making it challenging to compare performance metrics. Fourth, the review focused on digital twins for water distribution and supply systems; wastewater and stormwater applications were less represented. Fifth, the rapid pace of technological development means that findings may quickly become outdated as new methods and platforms emerge. Despite these limitations, the review provides a comprehensive overview of architectures, calibration workflows and benefits based on accessible evidence.

10. IMPLICATIONS FOR FUTURE STUDIES

Future research should pursue standardisation of digital twin frameworks for water utilities, building on models like RAMI 4.0 and AAS. Developing open-source libraries and reference implementations will facilitate interoperability and adoption. Scalability studies are needed to evaluate digital twin performance in large, complex networks and across multiple utility districts. Research should explore integration with emerging technologies such as edge computing, 5G networks, blockchain for secure data sharing, and advanced sensing (e.g., fibre optic sensing, satellite remote sensing). Hybrid calibration approaches that combine hydraulic modelling, machine learning and physics-informed neural networks could improve prediction accuracy while preserving physical constraints. Socio-economic assessments are essential to quantify benefits in monetary terms, evaluate cost–benefit ratios, and examine impacts on workforce and customer satisfaction. Finally, longitudinal studies should monitor digital twin implementations over time to understand adoption dynamics, organisational learning and long-term outcomes.

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