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Editorial: Special issue 'Digital Water'

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DIGITAL WATER TRANSFORMATION

Strategic digital transformation in the water industry offers a comprehensive framework for addressing the mounting pressures of climate change, aging infrastructure, urbanisation, resource scarcity, and public-health risks through systematic digitalisation (Grievson *et al.* 2022). In this context, digital transformation refers to the fundamental rethinking of processes by integrating digital technologies, both hardware and software, to enhance operational efficiency, data-driven decision-making and service delivery (Giustolisi 2023).

Key enablers of this transformation include the Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), advanced sensor technologies, and remotely sensed data, all of which have demonstrated the capacity for effective water resources management (Ansari & Vidyarthi 2025). IoT constitutes a foundational component of digital water systems, enabling real-time data acquisition and remote monitoring capabilities that facilitate the development of interconnected, adaptive, and responsive infrastructure networks (Iglesias-Rey *et al.* 2024). AI/ML algorithms leverage data collected from IoT and other sources to predict future system states. These predictions are generated by integrating outputs from physically-based hydrological models, in-situ sensor observations, and numerical meteorological forecasts. This integration supports the assessment of flood risk parameters across both rural and urban catchments, as well as the detection of anomalies in system performance (Laucelli *et al.* 2016; Vinokić *et al.* 2025). Furthermore, remotely sensed data acquired through satellites permits the systematic collection of spatially distributed information at large scales, such as river basins, enabling continuous monitoring of dynamic changes in hydrometeorological conditions and land use patterns that directly influence water quantity and quality (Abegeja 2024). In terms of water system operation, AI and automated agents (e.g., digital twins) provide advanced computational support for complex, multi-objective decision-making processes by analyzing high-dimensional datasets and enabling automated operational responses designed to satisfy multiple system functions simultaneously, including flood risk mitigation, river forecasting, water quality management, reservoir operation, hydropower generation, and ecosystem and biodiversity conservation (Kadiyala *et al.* 2025). These environmental and water-related objectives are intrinsically linked to human well-being and societal resilience (Prodanovic *et al.* 2024).

While digital technologies offer substantial benefits for the operation of water systems, their implementation must be approached with caution. Cross-industry experience highlights the critical importance of maintaining humans in the loop within increasingly automated decision-making processes, ensuring that operators remain actively engaged, well trained, and fully aware of both system capabilities and limitations (Savić *et al.* 2021). Equally important is the provision of robust and reliable manual override mechanisms that allow effective intervention when digital tools malfunction. As water systems become more interconnected and reliant on cyber-physical infrastructures, addressing cybersecurity threats inherent to digital waters becomes a requirement, particularly given the potential consequences of cyberattacks on essential public services (Tuptuk *et al.* 2021).

Finally, the growing reliance on automation and data-driven decision support raises ethical considerations that must be addressed to ensure that digital transformation remains both responsible and socially acceptable (Savić 2022). In this context, emerging regulatory frameworks are beginning to formalise these priorities. More broadly, such frameworks signal a growing consensus that trustworthy and risk-aware deployment of AI systems in critical infrastructures, including the water sector, must be anchored in clear regulatory obligations. The EU AI Act, for instance, classifies AI applications in critical infrastructure including water management as high-risk systems, thereby imposing requirements for transparency, human oversight, robustness, and accountability prior to deployment (European Parliament 2024).

It is essential to discuss both the advantages and limitations of water sector digitalisation, engaging not only researchers but also other stakeholders who utilize digital tools, as well as citizens who benefit from enhanced service reliability. In this regard, the International Water Association (IWA) is leading a global initiative for digital transformation entitled 'Towards the Next Generation of Water Systems' (Giustolisi 2023). Concurrently, regional initiatives are emerging to facilitate the development and implementation of digital water tools. For instance, the DIgital WAter (DIWA) programme in Finland promotes the transition towards digital representations of real-world water systems through digital twin technology. Other countries, such as Serbia, are also actively participating in this agenda by organising annual scientific conferences that bring together water engineers and information technology specialists to collaborate on the development of digital tools for the water sector (e.g., ICIST 2026 Digital water special track: https://www.eventiotic.com/eventiotic/conference/icist2026).

SPECIAL ISSUE: DIGITAL WATER

This Special Issue, 'Digital Water,' addresses the digital transformation of the water sector through contributions published across several IWA journals, including *Blue-Green Systems*, *Journal of Hydroinformatics*, *Water Science and Technology*, and *Water Practice and Technology*. It comprises seven peer-reviewed papers that reflect the interdisciplinary and multidisciplinary nature of digital water research, with the dominant themes of ML, water quality monitoring, and data-driven modelling clearly reflected in the keyword landscape of the collected titles (Figure 1). The papers collected in this Special Issue are organised around three thematic areas: (1) Water quality monitoring and prediction, (2) ML for process control, calibration and flood design, and (3) Data infrastructure and governance.

Topic 1: water quality monitoring and prediction

The first group of papers focuses on data-driven water quality monitoring, demonstrating how ML models can accurately estimate key water quality indicators using readily available datasets. Tenebe *et al.* (2025) developed ML regression models to predict dissolved oxygen from in-situ measurements, applying regression, bagging, and boosting approaches, with feature selection used to identify the most influential parameters. Ilic *et al.* (2025) extended this by integrating *in-situ* measurements with Sentinel-2 satellite imagery, capturing relationships between multispectral bands and water quality parameters, including water temperature, electrical conductivity, and dissolved oxygen, through both static models (deep neural networks, Kolmogorov–Arnold networks, and XGBoost) and temporal models (long short-term memory (LSTM) and temporal Kolmogorov–Arnold networks) to account for serial dependence. Extending the data-driven paradigm to estuarine systems, Zhu & Willems (2025) compared artificial neural networks (ANN), random forest, and support vector regression for daily salinity simulation in the Scheldt Estuary, finding that combining the best-performing ANN with a hydrodynamic model (MIKE11) via ensemble methods reduced error by up to 20% in the downstream region, while also highlighting the extrapolative limitations of standalone ML models under changing boundary conditions. Together, these studies demonstrate that data-driven approaches enable scalable, cost-effective water quality assessment, supporting improved decision-making in river basin and estuarine management.

Topic 2: ML for process control, calibration and flood design

The second group of papers encompasses ML embedded within engineering workflows to drive control decisions, system optimization, or infrastructure design. Pino Santana *et al.* (2025) present a model predictive control (MPC) strategy that employs long short-term memory (LSTM) networks as internal predictive models for anaerobic digestion (AD) processes, with the primary objective of developing a data-driven control approach

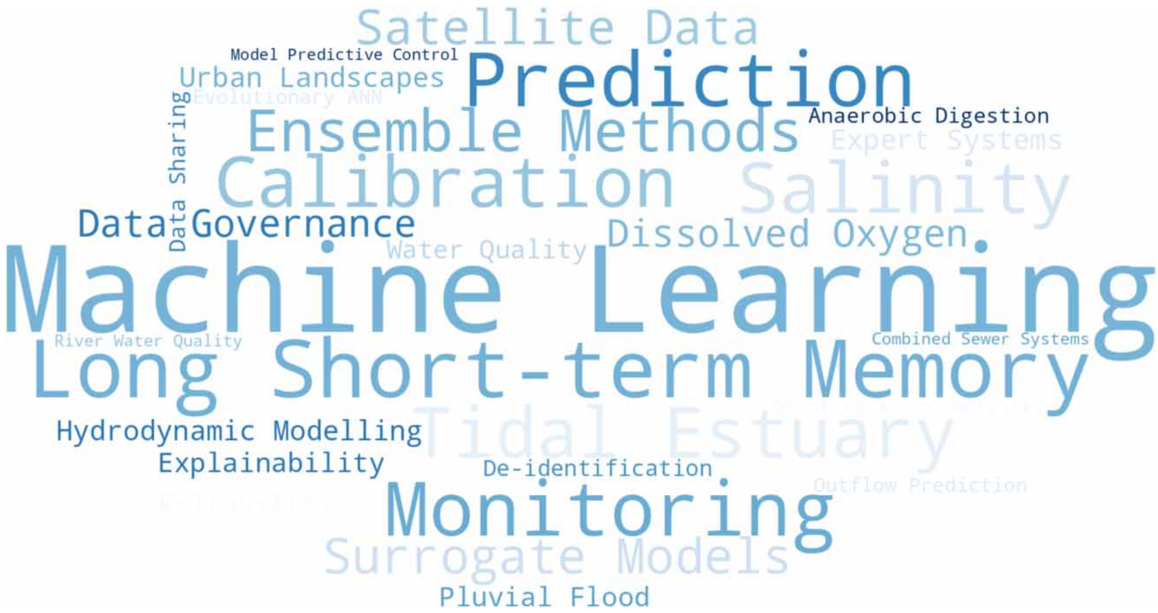

Figure 1 | Generated word cloud of paper keywords in the special issue 'Digital water'.

based on readily available online measurements. LSTM networks were trained to predict methane flow rates from simulated data, including stochastic disturbances, and tested in two simulated AD environments: the simplified Anaerobic Model No. 2 (AM2) and the detailed Anaerobic Digestion Model No. 1 (ADM1). The integrated LSTM-MPC framework demonstrated robust setpoint tracking and process stability under nonlinear operating conditions, while remaining computationally feasible for real-time applications, offering a practical alternative to traditional model-based approaches that often rely on complex and less accessible measurements. Gomez *et al.* (2025) develop an automatic calibration methodology that integrates an expert system with NeuroEvolution of Augmenting Topologies to solve high-dimensional calibration problems in drinking water distribution networks. Since traditional backpropagation is not feasible due to the absence of explicit target outputs, genetic algorithms are employed to evolve both network topology and connection weights, effectively embedding domain-specific knowledge from multiple stakeholders into a flexible and scalable calibration framework that outperforms alternative optimisation strategies. Extending this engineering design perspective to urban flood management, Guo & Leitão (2025) developed a differentiable surrogate flood modelling framework that replaces computationally expensive flood simulations and enables gradient computation for urban flood-risk optimisation. Using urban surface elevation and building layout data as raster inputs, the surrogate model supports terrain modification through gradient-descent optimisation rather than trial-and-error simulations, demonstrating strong potential as an effective tool for developing pluvial flood-safe urban layouts. Together, these studies illustrate how ML, whether applied to process control, infrastructure calibration, or spatial design optimization, can substantially reduce computational burden while enhancing performance across diverse water engineering challenges. In each case, ML is not used merely to make predictions, but is integrated into engineering workflows to support real operational and design decisions. Specifically, ML is embedded as a predictive controller within an anaerobic digestion process (Pino Santana *et al.* 2025), as an evolutionary calibration engine for drinking water distribution networks (Gomez *et al.* 2025), and as a surrogate model enabling optimisation of flood-safe urban environment (Guo & Leitão 2025), collectively demonstrating its role as an active decision-making component.

Topic 3: data infrastructure and governance

The third group addresses the data governance challenges underlying data-driven applications in the water sector. Sjöstedt *et al.* (2026) present the Utility Customer Data Aggregation Standard (UCDAS), a software framework that standardizes, quality controls, de-identifies, and aggregates utility customer data to enable responsible sharing while ensuring compliance with legal and ethical requirements for handling personally identifiable and business-confidential information. Applied to water consumption data from the City of Flagstaff, Arizona, UCDAS demonstrates how publicly accessible utility data can generate public value without compromising individual privacy, while reducing compliance risk and facilitating FAIR (Findability, Accessibility, Interoperability, and Reusability) data principles. While distinct from the predictive and optimisation-focused papers in the preceding groups, this work addresses a foundational prerequisite for their broader deployment.

CONCLUSION

The seven papers gathered in this Special Issue collectively illustrate the breadth and vitality of digital water research at a pivotal moment for the sector. From ML-driven water quality monitoring and satellite-enhanced sensing to surrogate modelling for flood-safe urban design, intelligent process control, and data governance frameworks, these contributions demonstrate that digital transformation is no longer a distant aspiration but an active, multidisciplinary endeavour reshaping how water systems are monitored, managed, and designed. At the same time, they underscore that technological progress must be accompanied by careful attention to human oversight, cybersecurity, ethical responsibility, and equitable data access. As global initiatives such as the IWA's 'Towards the Next Generation of Water Systems' and regional programmes like DIWA continue to gain momentum, it is our hope that this Special Issue serves as both a reflection of current advances and a catalyst for the next wave of innovation which will place digital tools firmly in the service of resilient, sustainable, and socially responsible water management. First, the development of digital twins for water systems moving beyond static representations towards dynamic, self-updating environments that integrate real-time sensor data, predictive models, and automated control, holds considerable potential for transforming operational decision-making across water industry. Second, generative AI presents new opportunities for the water sector, both in addressing data scarcity challenges and in making digital twin environments more adaptive and responsive over time.

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