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Editorial

Advances in Management and Optimization of Urban Water Networks

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1. Introduction

The effective management and optimization of urban water networks is essential for addressing the growing challenges posed by aging infrastructure, population growth, urbanization, and climate change. Given the complexity of these systems, such challenges increasingly require advanced analytical and data-driven methods, innovative technologies, and strategic planning approaches.

This Special Issue brings together contributions that address key challenges in urban water networks. At a broader level, it responds to urban water challenges from different but complementary perspectives, including advanced modeling, new optimization techniques, innovative monitoring approaches, and practical management strategies. Each contribution highlights a particular advance, and together they reflect broader progress toward improving urban water systems' efficiency, reliability, and sustainability.

With particular focus on three main domains—(1) water distribution networks (WDNs), (2) urban drainage networks (UDNs), and (3) broader urban water management perspectives—the included studies span different stages of system lifecycles, ranging from network design to operation, rehabilitation, and governance. More specifically, they reflect current research on network design and optimization (e.g., pipe sizing and layout generation), operational decision-making (e.g., control optimization), abnormal condition monitoring and detection (e.g., leak detection and overflow prediction), predictive maintenance and rehabilitation planning (e.g., failure prediction), and governance-related challenges in urban water systems.

The introduction is therefore structured around these three thematic domains of (1) WDNs, (2) UDNs, and (3) broader urban water management perspectives. For each domain, it outlines the broader background, key research gaps, and emerging needs across the relevant stages of the system lifecycle, thereby providing the context for the contributions included in this Special Issue.

1.1. Water Distribution Networks

WDN research has progressed significantly in recent decades, reflecting growing interest in both the design of new systems and the operation and management of existing ones. In this Special Issue, the contributions concerning WDNs can be broadly organized into two main areas: network design, and operation and management.

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1.1.1. Network Design

WDN design encompasses both network layout, including structural arrangement and component routing, and hydraulic design, which involves selecting physical characteristics such as pipe diameters. The evolution of hydraulic design reflects the broader trajectory of the field, moving from early linear and nonlinear programming approaches focused on cost minimization and basic hydraulic constraints [1] to increasingly advanced optimization frameworks capable of addressing multiple, often competing, objectives [2]. In particular, metaheuristic and multi-objective algorithms have enabled the inclusion of performance criteria such as resilience and reliability alongside cost [3]. However, these approaches remain heavily dependent on repeated hydraulic simulations, which limit their efficiency, particularly for large or complex systems [4]. As a result, computational demand continues to represent a major challenge in the search for optimal hydraulic designs.

In response, alternative approaches have gained increasing attention. Graph theory, for example, has been applied to different types of WDN analysis to capture structural characteristics in a computationally efficient manner [4,5], while data-driven methods, particularly machine learning, have shown strong potential for modeling complex system behavior [6]. More recently, interest has grown in combining graph-based representations with machine learning techniques in order to exploit both structural insight and data-driven pattern recognition for various types of WDN analysis [7]. Such integration appears particularly promising for hydraulic design tasks such as pipe sizing, which are inherently complex and computationally intensive. However, despite this potential, the application of these combined approaches to hydraulic design remains largely unexplored. This makes their further investigation and application in WDN design a clear and emerging research direction, as reflected in this Special Issue.

A further key aspect of WDN design concerns network layout generation, a factor inherently connected to hydraulic sizing, as network configuration directly influences hydraulic performance and, consequently, pipe-sizing decisions [8]. However, many existing methods still address these aspects sequentially, assuming a predefined layout before carrying out hydraulic design [9], and although simultaneous layout and sizing approaches have been proposed [10], they are computationally intensive and difficult to apply to large-scale and real-world systems. These challenges point to another important research direction in WDN design which is also explored in this Special Issue.

1.1.2. Operation and Management

Beyond design, the effective operation and management of WDNs require maintaining system performance under varying dynamic and often uncertain conditions. This stage encompasses several interconnected tasks, including operational optimization, system monitoring, predictive maintenance, and rehabilitation planning, which together frame the contributions presented in this Special Issue.

A first major challenge in WDN operation concerns the optimization of control strategies and system interventions in order to balance competing objectives. However, operational problems, particularly in design-for-control applications, are often highly nonlinear, combinatorial, and strongly coupled with hydraulic behavior [11,12]. For instance, they could involve the simultaneous determination of structural interventions, such as valve or pipe placement, and operational policies, such as valve settings over time, to achieve competing objectives, including pressure-induced leakage reduction and resilience enhancement. Although optimization techniques ranging from global exact approaches [13] to heuristic methods [14] have been explored as decision-support tools for such tasks, they are often applied in isolation, limiting understanding of their comparative performance and practical implications. In particular, while exact methods often rely on model simplifi-

cations, metaheuristic approaches can better accommodate real-world complexity but do not guarantee global optimality [12,13]. Addressing these challenges and improving optimization mechanism understanding in complex operational problems, therefore, remain important research directions addressed in the contributions of the Special Issue.

In addition to control strategy optimization, effective WDN management also depends on the ability to monitor system behavior and identify abnormal conditions. In this context, leak detection remains a major challenge in many aging WDNs because of its impact on water loss, network reliability, and operational costs. At the same time, conventional methods based on visual inspection or pressure monitoring are often labor-intensive and insufficient for identifying small or intermittent leaks [15]. In response, various sensing technologies, such as acoustic, vibration, ultrasonic, and fiber-optic systems, have been developed [15,16], with acoustic-based techniques appearing particularly promising given their ability to capture leak-induced signals [17]. When combined with data-driven approaches [18], sensing technologies improve detection capability by enabling the analysis of complex and noisy data. However, many existing acoustic-based studies are based on controlled laboratory conditions [19] or focus only on isolated aspects of acoustic behavior, such as the effects of pipe diameter and material on leak-induced signals [20], limiting their applicability to real-world and large-scale networks. Moreover, the comparative performance and integration of different data-driven models for such acoustic-based techniques remain insufficiently explored. This highlights the need for comprehensive evaluation frameworks that leverage real operational data to assess and combine machine learning techniques for reliable, real-time leak detection in WDNs, an aspect further explored in this Special Issue.

Building on operational optimization and system monitoring, another key direction in WDN management involves predictive maintenance and failure forecasting to support rehabilitation and asset management decisions. Failure prediction in WDNs, particularly for pipes, has evolved from traditional statistical formulations [21] toward more advanced machine learning approaches [22], driven by the need to better capture complex deterioration patterns and support proactive asset management. Rehabilitation planning must, however, extend beyond deterioration-driven failure prediction to also account for sudden and large-scale serviceability loss caused by extreme events such as earthquakes, which demand a system-level perspective beyond what is possible with pipe-level failure forecasting alone. In this context, research has advanced from early single-objective formulations toward multi-objective and risk-averse frameworks, including approaches that optimize rehabilitation strategies while explicitly accounting for decision-makers' risk attitudes [23] and game-theoretic models that identify Pareto-optimal rehabilitation plans under competing objectives [24]. The interaction between pipe degradation and seismic vulnerability adds a further layer of complexity, as deteriorating pipes exhibit increasing seismic fragility over time, altering the relative criticality of rehabilitation targets and rendering static rehabilitation plans insufficient [25]. To address the high computational cost of hydraulic-simulation-based optimization at the city scale, topology-based surrogate methods have been proposed that substantially reduce runtimes while preserving solution quality [26]. Alongside these hazard-driven challenges, failure prediction efforts have concentrated mainly on water mains [27], whereas failures in service lines remain comparatively less studied, despite their substantial contribution to total network failures in some regions and their direct impact on customer service [28]. This highlights the need for more reliable predictive frameworks that can identify high-risk service lines and support proactive, data-driven maintenance planning, a consideration further addressed by one of the contributions presented in this Special Issue.

Underpinning the majority of operational and management challenges, especially in some of the tasks discussed above, is the need for reliable and well-calibrated hydraulic models. In this context, the calibration of large-scale water supply macrosystems remains a major challenge, particularly when applied to real networks characterized by limited data availability, complex operational rules, and uncertain topology. For this reason, many calibration studies have focused on hypothetical or benchmark models [29], which offer methodological simplicity but may not adequately represent real systems' complexity. Although several advanced calibration techniques have been proposed, including graph-based metamodels and artificial neural networks [30,31], their application to large, dynamic, real-world systems is still difficult in practice. This highlights the need for practical calibration strategies that can improve the reliability of large-scale hydraulic models while incorporating prior knowledge of actual system behavior and operational conditions, an important gap addressed by a contribution in this Special Issue.

1.2. Urban Drainage Networks

Similar to WDNs, research on UDNs, including both separate stormwater systems and combined sewer networks, can be broadly grouped into two main areas: network design, and operation and management.

1.2.1. Network Design

As in WDNs, the UDN design process typically involves defining the network layout (often assumed to be predefined) followed by the estimation of hydraulic parameters such as pipe diameter and slope, which are functions of the design flow. Traditionally, the Rational Method (RM) has been widely used to estimate design flow rates from sub-catchments due to its simplicity and limited data requirements, while Manning's equation is applied for hydraulic calculations [32]. However, the RM assumes steady and uniform flow conditions and only provides peak flow values limiting its ability to represent actual unsteady hydraulic behavior, particularly in large-scale systems. To improve design accuracy, hydrological and hydraulic-simulation-based approaches have been increasingly adopted, including SWMM-based iterative design methods [33] and various optimization techniques such as genetic algorithms [34], cellular automata [35], and ant colony optimization [36]. While these approaches enhance design precision, many still rely on RM-based assumptions for estimating design flows. Moreover, when employing detailed hydraulic models such as SWMM to estimate design flows, they must be calibrated with extensive, reliable, and complete data, which are often uncertain or unavailable in practice [37]. In addition, optimization-based methods typically depend on evaluating multiple design alternatives, leading to high computational demand as system scale increases.

These limitations highlight the need for more efficient approaches to estimating design flows that can better capture unsteady hydraulic behavior while reducing data requirements and computational complexity, a research gap addressed in this Special Issue.

1.2.2. Operation and Management

Moving beyond UDN design, effective management and operation, particularly in combined sewer systems, require reliable flow condition and overflow event predictions, which are critical for mitigating urban flooding and protecting public health. To address this, a range of modeling approaches has been developed, including physics-based simulators [38], data-driven surrogate approaches [39], and hybrid frameworks [40]. While physical models provide a detailed representation of hydrological and hydraulic processes through governing equations, they often require significant simplifications, are computationally expensive [41], and depend on detailed and frequently uncertain system information such as network topology and condition [42]. In contrast, data-driven models

offer higher computational efficiency and the ability to capture complex relationships directly from data [43], but they often lack physical interpretability and reliability [44]. Hybrid or physics-informed models attempt to combine these advantages [45], yet their complexity and implementation challenges limit their practical applicability. Despite these advances, there remains a lack of efficient and uncertainty-aware approaches capable of providing real-time prediction and anomaly detection in complex and data-scarce UDNs. Addressing this gap is essential for improving operational decision-making and is the focus of one of the contributions presented in this Special Issue.

1.3. Broader Urban Water Management Perspectives

While recent advances in WDNs and UDNs have primarily focused on technological and data-driven solutions, such as optimization, simulation, and machine learning for leakage detection, flow prediction, and anomaly identification, these efforts largely address the physical and operational dimensions of urban water systems. However, effective urban water management also depends on institutional, economic, and governance structures, which have received comparatively less attention and require further systematic investigation. In particular, practice-based and diagnostic approaches that examine how governance arrangements and managerial processes shape urban water services at the municipal level remain limited. This highlights the need for more integrated analyses that complement technical developments with institutional perspectives, an aspect explored by the final contribution to this Special Issue.

The research gaps and emerging needs outlined in the Introduction are addressed in this Special Issue through the contributions presented in the following sections. Section 2 provides an initial overview of these papers, which are then summarized in more detail in Section 3. Finally, Section 4 reflects on the main insights emerging from these contributions and highlights important directions for future research.

2. Overview of Contributions

From the various submissions received for this Special Issue, a total of nine high-quality papers were accepted and published. Table 1 provides a concise overview of these contributions, summarizing them according to our three main identified domains: WDNs, UDNs, and broader urban water management perspectives. In addition, it highlights each paper's main contribution type, methodological approach, and practical applications. Collectively, these contributions reflect the research gaps and emerging needs identified in the Introduction and illustrate the diversity of current approaches being developed to address key challenges in urban water systems.

Table 1. Overview of the contributions included in this Special Issue.

Contribution No.	Main Domain	Contribution Type	Research Methods	Potential Application
1	WDN	Network design (pipe sizing)	Graph-theoretic and hydraulic feature extraction, feature selection, and ensemble machine learning	Optimal diameter design with reduced computational burden
2	WDN	Network design (layout and pipe sizing)	Fractal-based simultaneous routing and sizing with modified Murray's law	Generation of network layouts and pipe-sizing decisions
3	WDN	Operational optimization (design-for-control)	Comparative assessment of heuristic and exact optimization for optimal valve location and operation settings	Leakage reduction and resilience enhancement through design-for-control

Table 1. *Cont.*

Contribution No.	Main Domain	Contribution Type	Research Methods	Potential Application
4	WDN	Monitoring (leak detection)	Wireless acoustic noise loggers combined with machine learning and ensemble models	Real-time leak detection and leak management
5	WDN	Predictive maintenance (rehabilitation planning)	Machine learning algorithms using service-line attributes and failure history	Identification of high-risk service lines and proactive rehabilitation planning
6	WDN	Calibration (hydraulic modeling)	PSO-based calibration combined with operational-rule adjustment and engineering judgment	Improving reliability of large-scale hydraulic models for real system operation
7	UDN	Network design (hydraulic design)	Dynamic-wave-simulation-based method coupled with SWMM and iterative design	More realistic estimation of design flow, pipe diameters, and slopes
8	UDN	Operation (forecasting and anomaly detection)	Gaussian Process Regression with probabilistic prediction	Real-time flow/depth prediction and anomaly detection in sewer systems
9	UWM	Governance and institutional analysis	Case-study-based diagnostic assessment using documentary evidence and stakeholder insights	Identification of governance and institutional constraints in small municipalities

Note(s): WDN: Water Distribution Network; UDN: Urban Drainage Network; UWM: Urban Water Management; PSO: Particle Swarm Optimization; SWMM: Storm Water Management Model.

3. Summary of Contributions

3.1. Water Distribution Systems

3.1.1. Network Design

The first contribution addresses a research gap in integrating graph-theoretic approaches with machine learning methods for the optimal design of WDNs. Their goal was to approximate optimal pipe diameters without repeatedly solving computationally intensive hydraulic equations. To build a robust training dataset, the authors generated 600 synthetic WDNs and determined the optimal pipe diameter configuration for each network using a conventional single-objective genetic algorithm. From these optimized networks, they then extracted 80 diverse features, including hydraulic attributes (e.g., flow rate, flow velocity) and graph-theoretical descriptors (e.g., shortest-path metric, clustering coefficients). To refine the input space, six different feature-selection techniques were applied to identify the most influential predictors for optimal design. Using these selected features, the authors trained four machine learning models (Random Forest, Support Vector Machine, Bagging, and Light Gradient Boosting Machine), resulting in a total of 24 ensemble model combinations. The best-performing model was subsequently applied to the well-known Hanoi benchmark network, demonstrating strong predictive capability for estimating optimal pipe diameters.

The second contribution introduces a simultaneous routing and sizing (SRS) method for WDNs, adopting a cooperative approach that integrates layout routing and pipe diameter assignment. The layout generation is based on fractal geometry principles, enabling the creation of hierarchical, branching network structures that resemble patterns observed in natural systems. For pipe sizing, the method incorporates a modified form of Murray's

law [46], providing a scaling relationship that links pipe diameters to flow distribution. In this approach, routing decisions are guided by multiple criteria, including total pipe length and construction cost, with the latter being dependent on pipe diameter. This creates an interaction between layout and sizing during the iterative design process, although the method remains rule-based rather than building a global optimization framework. The approach was applied to both single- and multi-source configurations using synthetic case studies. The results suggest that the SRS method can reduce design complexity and provide a structured procedure for generating feasible network layouts.

3.1.2. Operation and Management

The third contribution addresses the need to better understand the underlying mechanisms of metaheuristic and exact optimization approaches for the design-for-control of water distribution networks. To this end, it investigates the simultaneous determination of structural interventions, such as the installation of valves and/or pipes, together with valve operational settings in existing networks, with the aim of optimizing two conflicting objectives: minimizing pressure-induced background leakage and maximizing network resilience. The authors apply an upgraded Multi-Objective Simulated Annealing with new Generation and Reannealing procedures (MOSA-GR) [47] and compare its performance with the exact global optimization spatial branch-and-bound method previously proposed for the same problem [13]. Using the same case studies and evaluation framework, the paper provides a structured comparison of the two approaches and offers insight into their mathematical and hydraulic implications. The results show that the metaheuristic approach can generate high-quality solutions in a shorter computational time while avoiding the model simplifications required by the exact method, thereby demonstrating strong potential for addressing complex real-world design-for-control problems.

The fourth contribution addresses the limited real-world applicability of many existing leak detection studies by integrating wireless acoustic noise loggers with machine learning models for real-time leakage detection in water pipelines. Unlike earlier work, which often relied on laboratory or testbed datasets, this study is based on 2110 acoustic signals collected in real urban environments in Hong Kong, comprising 992 leak and 1118 non-leak cases. The authors evaluate several machine learning algorithms, with Random Forest achieving the highest accuracy (93.68%) and K-Nearest Neighbors and Multi-Layer Perceptron also performing strongly, offering robust alternative approaches. An ensemble model combining these top-performing methods further improved detection performance. By contrast, YamNet, a general-purpose deep audio classification model based on pre-trained deep learning for sound recognition [47], showed weaker results, likely due to its sensitivity to urban background noise and its lack of adaptation to leak-specific acoustic patterns. Overall, the study demonstrates the strong potential of data-driven acoustic monitoring for practical and sustainable leak management in WDNs.

The fifth contribution presents a machine learning-based rehabilitation framework for forecasting the likelihood of failures in service lines within WDNs, with the aim of supporting proactive decision-making. Using 11 years of service-line data, including variables such as diameter, length, age, material, pressure, and demand, together with more than 88,000 recorded failures, the study evaluated three predictive models: Random Forest (RF), Extreme Gradient Boosting (XGB), and Long Short-Term Memory (LSTM). The first nine years of data were used for training, while the final two years were reserved for validation, and the analysis was repeated to examine the effect of training data length on prediction performance. It was shown that the tree-based models, RF and XGB, outperformed LSTM, mainly because the available inputs were dominated by static service-line attributes rather than rich temporal signals. Overall, the study highlights the potential of machine learning

for identifying high-risk service lines and supporting predictive asset management. The authors also indicated that future improvements could be achieved by incorporating measured pressure data, environmental variables such as soil conditions, and more detailed information on failure type and severity into the models.

The sixth contribution addresses the challenge of calibrating large-scale real water supply macrosystems by considering not only physical parameters, but also the influence of actual operational behavior on model performance. Focusing on the metropolitan water supply system of Fortaleza, Brazil, the authors calibrated absolute pipe roughness and base demand multiplication factors using 50 pressure-head monitoring points and 40 flow-rate monitoring points over a 48 h period. In addition, the calibration process accounted for the operating rules of several pressure-reducing valves, reflecting the complexity of real system operation. To achieve a realistic model, pre-calibration operational adjustments were carried out by reviewing model outputs, revising valve control settings, and evaluating their effects on network behavior before applying Particle Swarm Optimization (PSO) to minimize the objective function. By combining engineering judgment with optimization, the study achieved acceptable agreement between simulated and observed data, highlighting the importance of practical calibration strategies for improving the reliability of large-scale hydraulic models in water-scarce urban systems.

3.2. Urban Drainage Networks

3.2.1. Network Design

The seventh contribution addresses key UDN design limitations by proposing a dynamic-wave-simulation-based method that aims to improve design flow estimation while reducing reliance on the simplifying assumptions of the Rational Method (RM). The approach bridges the gap between simple empirical methods and data-intensive hydraulic simulations by transforming traditional RM input parameters into an equivalent time-varying runoff hydrograph. This is achieved through the development of a runoff yield and flow concentration model that preserves consistency with RM while enabling unsteady flow simulation. The generated hydrograph is then used within the dynamic wave module of SWMM to compute pipe flows more realistically, and an iterative procedure is applied to determine pipe diameters and slopes across the network. The method was validated on two case studies, where results showed that design flow rates obtained using the dynamic approach were generally higher than those from the RM. Overall, the study demonstrates that incorporating unsteady hydraulic behavior into design flow estimation can enhance the reliability of UDN design while maintaining practical applicability for engineering use.

3.2.2. Operation and Management

The eighth contribution introduces an uncertainty-aware, data-driven framework for probabilistic forecasting and anomaly detection in sewer networks. The study employs Gaussian Process Regression to predict flow and water depth in a (combined) sewer system while simultaneously identifying abnormal conditions such as blockages. A key innovation lies in the design of a customizable composite kernel (i.e., the core function that defines how the model learns patterns), which is tailored to reflect underlying physical processes. The approach is demonstrated on a hypothetical sewer network, where time and precipitation are used as primary inputs, enabling the model to effectively capture both dry- and wet-weather dynamics. Results show that the model performs well even with limited training data, achieving high predictive accuracy and reliable uncertainty bounds. In addition, anomaly detection is achieved by identifying deviations beyond confidence thresholds, allowing early detection of abnormal events. Overall, the study highlights the potential of

probabilistic, uncertainty-aware models for real-time monitoring and decision support in urban drainage systems.

3.3. Broader Urban Water Management Perspectives

The ninth contribution to this Special Issue shifts the focus from technological advancements to the institutional and governance dimensions of urban water management, with particular attention on small municipalities. The study addresses the limited consideration of small and rural service areas in both the literature and policy debates by contrasting their conditions with those of larger, better-resourced systems. Using a case-study-based diagnostic approach supported by documentary evidence, expert input, and stakeholder insights, the authors systematically analyze the structural, financial, and institutional challenges affecting water services. The findings reveal that deficiencies, such as low hydraulic performance, inadequate infrastructure, limited human capacity, and conflicts of interest, are not isolated technical issues but are deeply interconnected with governance and resource constraints. These challenges are organized into six key domains—regulation, resource availability, infrastructure, financing, stakeholder involvement, and innovation. Based on this integrated diagnosis, the authors propose a set of coordinated measures, ranging from infrastructure improvement to institutional reform. Overall, the paper highlights governance as a central lever for addressing systemic challenges and calls for a reassessment of regulatory and institutional frameworks to improve water service delivery in small municipalities.

4. Discussion and Conclusions

This Special Issue's overall aim was to respond to urban water network challenges from different but complementary perspectives. Taken together, the contributions reflect broader progress toward improving the efficiency, reliability, and sustainability of urban water systems. Across the papers, several recurring challenges emerged, including high computational demands, limited data availability and quality, the need for more accurate and transferable data-driven approaches, and difficulties in representing real-world system complexity. The following discussion highlights some of the main remaining research gaps and future directions that emerge from the Special Issue:

- **Integrating Topology, Data-Driven Methods, and Design:** The contributions in this Special Issue reflect a broader shift toward more integrated approaches to network design, combining structural, data-driven, and generative methodologies. The integration of graph theory with machine learning techniques is increasingly recognized as a powerful strategy for supporting design decisions; however, key challenges remain, particularly regarding the robustness and generalizability of such models, which depend strongly on the quality and representativeness of training data. While the Special Issue's first contribution demonstrates promising results, it is based on synthetic networks, and future work should therefore focus on improving transferability through the inclusion of real-world systems with diverse configurations, operational conditions, and components such as pumps and valves.

At the same time, these developments point toward a broader need to move beyond simplified and sequential design practices. In particular, the network design involves not only pipe sizing but also layout configuration, two inherently interconnected processes. Emerging approaches that address layout and pipe sizing simultaneously demonstrate the potential to improve efficiency while capturing the interaction between network structure and hydraulic performance. Nevertheless, further research is required to enhance these methods by incorporating hydraulic simulation, real-world constraints, and more complex network configurations, ultimately moving toward more reliable and globally

optimal design solutions. In this context, the integration of design strategies with advanced data-driven techniques, including graph neural networks, together with improved model transparency through explainable AI tools, could offer promising directions for developing more robust, interpretable, and practical design frameworks.

- **Bridging Exact and Heuristic Optimization:** The contributions in the Special Issue show that neither metaheuristics nor exact global optimization can be viewed as a universal solution for complex network management problems. While exact (global) methods offer mathematical rigor, they often rely on simplifications that may affect hydraulic realism; metaheuristics, in turn, can better accommodate real-world complexity but do not provide formal guarantees of global optimality. This suggests an important future direction: the development of hybrid frameworks that combine the strengths of both paradigms—global rigor, hydraulic realism, and flexibility. In particular, for complex design-for-control and operational tasks, cooperative schemes integrating exact and heuristic methods could offer more reliable and practically meaningful solutions, as also suggested in [12]. Further research could therefore focus on understanding problem structure and exploiting combinatorial properties to build more efficient and intelligent optimization strategies for network management.
- **Toward More Transferable Acoustic Leak Detection:** A key direction emerging from this Special Issue's fourth contribution is the need to improve the transferability of data-driven leak detection methods across real-world systems. Although the study demonstrates strong results using a large set of real acoustic measurements, further validation is still needed under a wider range of network characteristics, operating conditions, and background noise environments. The weaker performance of general-purpose deep audio models such as YamNet also shows that models trained on broad audio datasets, which include many types of sounds but not specifically leak-induced signals in pressurized pipelines, may not be directly suitable for this task. Future research should therefore focus on more representative datasets, improved robustness under diverse field conditions, and better tailoring of data-driven models to sensing-based leak detection tasks. This would support the development of more reliable and practically deployable real-time monitoring systems for WDNs.
- **Advancing Efficient Stormwater Design:** While the seventh contribution to this Special Issue proposes a promising approach to reducing reliance on fully calibrated and data-intensive inputs for estimating dynamic design flows, its broader applicability still requires validation across diverse catchment characteristics and rainfall patterns. Thus, future research should focus on testing such approaches under varying real-world conditions to enhance their robustness. In addition, coupling dynamic flow estimation with more computationally efficient approaches, such as physics-guided graph-based methods [48], which have recently shown strong potential for efficient flow routing in pipes, offers a promising direction.
- **Integrating Governance Frameworks and Technical Innovation**: This Special Issue primarily focuses on technological innovations and emerging approaches for urban water system management, including AI-driven optimization and related advancements. While these contributions highlight the transformative potential of technical solutions, future research should move beyond purely technology-centered perspectives. Increasingly, there is a need to integrate institutional governance and policy dimensions into urban water management frameworks. As emphasized in the final contribution, many existing challenges, particularly in small municipalities, are rooted in structural and organizational constraints that can hinder the effective implementation of technological solutions. Addressing these challenges requires bridging

engineering innovations with governance frameworks alongside fostering meaningful stakeholder engagement.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
LSTM	Long Short-Term Memory
MOSA-GR	Multi-Objective Simulated Annealing with Generation and Reannealing procedures
PSO	Particle Swarm Optimization
RF	Random Forest
RM	Rational Method
SRS	Simultaneous Routing and Sizing
SWMM	Storm Water Management Model
UDN	Urban Drainage Network
UWN	Urban Water Network
WDN	Water Distribution Network
XGB	Extreme Gradient Boosting

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