Using Real-Time Control Algorithms to Operate Urban Drainage Networks, Manage Urban Runoff, and Reduce Flooding

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1. Introduction

Urban drainage networks (UDNs) play a fundamental role in today's world. These infrastructure systems, consisting of pipelines, pumping stations, and various other components, are designed to manage the urban water cycle while balancing public needs with environmental protection. Without these systems, contemporary societies as we know them would struggle to function and eventually cease to exist.

Historically, as settlements developed into cities, natural landscapes - largely composed of greenery and permeable soils - were replaced by buildings and paved areas, effectively sealing the ground and altering the urban water cycle (see Figure 1). Over time, this transformation has introduced various challenges that had not been anticipated and now demand ongoing management. One of these challenges - urban flooding - is the centrepiece of this blog post.

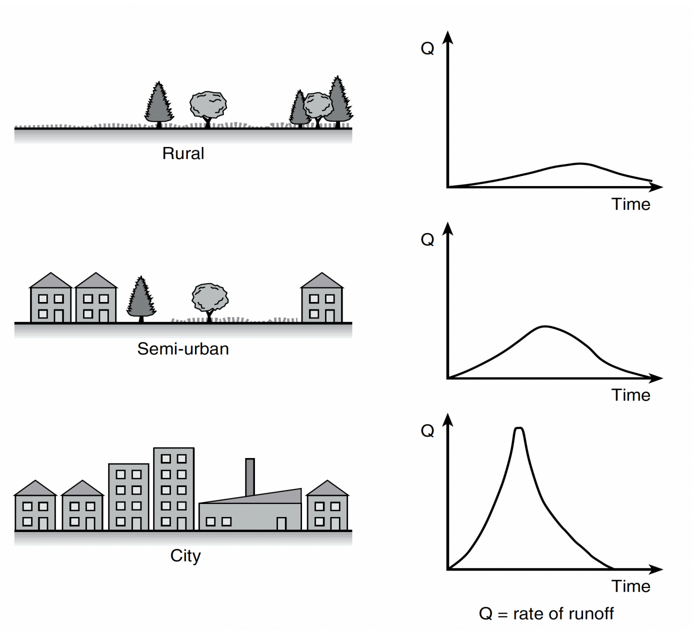

Figure 1. Effect of urbanisation on peak rate of runoff [1].

Available meteorological data suggests that, as a result of climate change, extreme weather events, including rainfall, are increasing in intensity, duration, and frequency [2]. This trend places significant stress on existing UDNs that: 1) are ageing and approaching the end of their useful life cycles, and 2) were designed with different operating conditions in mind.

If not properly drained and treated, excess rainwater will inevitably cause inconvenience, damage public and private property, and pose potential public health risks due to environmental pollution. In fact, over the past two months, multiple devastating rainfall-induced floods have occurred worldwide [3-7].

Municipalities and local utilities, typically responsible for operating and maintaining urban drainage networks, face increasing pressure to enhance these systems' resilience against climate-related stresses. Simultaneously, they must manage budget limitations, regulatory requirements, rising service expectations, and societal demands - each adding complexity to the balance between immediate needs and long-term sustainability.

Since peak flows (in urban flooding scenarios) are both sudden and short-lived (see Figure 1), completely overhauling urban drainage systems to handle increased hydraulic loads is neither practical nor financially viable. Instead, the preferred approach focuses on runoff management by: a) retaining as much runoff as possible at its source, and b) controlling flow within pipeline networks to reduce the risk of flooding in downstream areas.

In this blog post, we will explore recent advancements in real-time control (RTC) algorithms used to manage existing UDNs. We will highlight cases where this technology has successfully reduced or even eliminated urban flooding and pollution. Additionally, we'll discuss potential risks associated with the use of RTC and examine key challenges limiting its broader adoption in the water services industry.

The rest of this blog is organised as follows. In Section 2, we provide an overview of the technological readiness of RTC systems for UDNs, including their core components, practical applications, and notable implementations, such as Copenhagen's Skybrudsplan initiative. Section 3 explores the strengths of RTC solutions, highlighting benefits like real-time monitoring, predictive analytics, resource optimization, and resilience to extreme weather events. Section 4 addresses the challenges and risks associated with RTC deployment, focusing on cybersecurity vulnerabilities, legacy infrastructure integration, data privacy, and operational risks. Section 5 concludes with a discussion on the broader barriers to RTC adoption, including financial constraints, the reluctance toward digitalization within the water sector, and regulatory challenges, particularly for smaller municipalities, while emphasising the importance of interdisciplinary collaboration in making RTC systems widely accessible and effective.

2. Technological Readiness

A basic RTC system (see Figure 2) is designed to perform a series of coordinated actions aimed at optimising the operation of an UDN. The main functions of an RTC system include:

1. **Data Collection**. Through a network of sensors and measurement devices installed at various points throughout the system, the RTC system continuously gathers real-time data on the current state of the UDN.
2. **State Comparison**. The collected data is compared against a predefined optimal state, which is typically based on hydraulic models and operational criteria. By assessing deviations from this optimal state, the RTC system can determine when and where adjustments are needed.
3. **System Modeling and Adjustment Planning**. Based on the observed discrepancies, the RTC system simulates the necessary adjustments required to bring the system closer to the desired state. Advanced algorithms and predictive modelling tools are often employed to evaluate different adjustment scenarios.
4. **Actuation and Control**. Once an adjustment plan is determined, the RTC system sends commands to control various components within the UDN, such as actuators, valves, pumps, and gates.

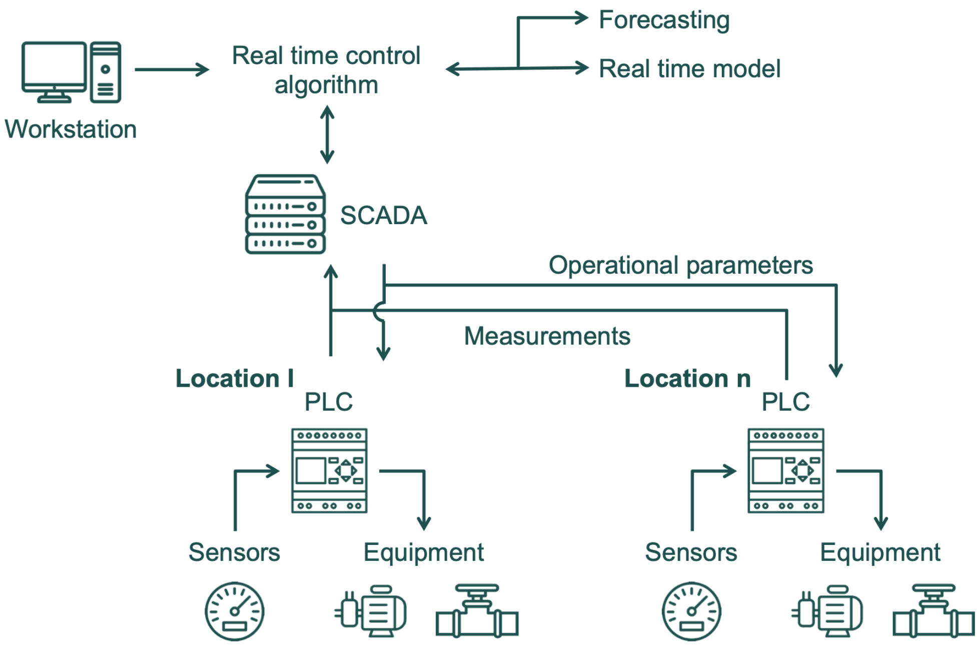

Figure 2. Common components of a RTC system [8].

Practical application of RTC algorithms for operation of UDNs has been a prominent area of research and development at leading European universities, including the Technical University of Denmark (DTU), Delft University of Technology (TU Delft), the Norwegian University of Science and Technology (NTNU), and Tallinn University of Technology (TalTech). With academia being actively involved in developing, testing, and implementing RTC solutions in real-world environments to address the challenges posed by urban flooding, this technology has reached Technology Readiness Level 9 (TRL9) [9].

One notable example of a successful RTC implementation is in the city of Copenhagen, where RTC has been integrated into daily UDN operational decisions following a severe flooding event in July 2011. After several minor rainfall events earlier that year, a sudden downpour brought two months' worth of rain to the city within a few hours, causing widespread flooding. This overwhelming rainfall led to cascading failures across multiple infrastructure systems, leaving tens of thousands without power and resulting in scalding injuries from ruptured district heating pipes [10].

In response, within a year, Copenhagen introduced its first *Skybrudsplan* (Cloudburst Management Plan), a policy document that fundamentally reshaped the city's approach to urban development and drainage planning [11]. Today, RTC is used to manage stormwater on a city-wide scale, resulting in a substantial reduction in combined sewer overflows (CSOs) and enhancing the city's resilience to extreme weather events [12].

However, Copenhagen is just one of many cities in the European Union (EU), and the detrimental effects of climate change are experienced across all types of urban areas. While larger cities may have the resources to implement advanced RTC systems in their UDNs, smaller municipalities - which are home to 43% of EU citizens - often lack the financial and technical capacity to adopt similar solutions [13]. As a result, state-of-the-art RTC implementations are primarily concentrated in larger cities, resulting in a limited, localised impact.

Scaling and broader adoption of RTC solutions is limited by a lack of organisational readiness within the water sector, with the most prominent reasons being:

1. Financial and Workforce Capabilities. Only large utilities typically have the financial resources and workforce capacity to: a) install the necessary sensors and actuators, b)

upkeep this new equipment, c) manage the required IT infrastructure, and d) develop and maintain the hydraulic models and data essential for powering these algorithms.

2. Reluctance Toward Digitalization in the Water Sector. As part of the legacy sector, the water industry has been slow to embrace digitalization. Furthermore, it is often an unpopular career choice among younger generations, leading to a shortage of specialists with digital expertise [14].

3. Lack of Plug-and-Play Solutions: Implementing RTC solutions requires sophisticated hydraulic models, which can be complex and time-consuming to set up, limiting ease of adoption.

This disparity in access to advanced flood management solutions highlights a critical gap in climate resilience across the EU. Without broader adoption of RTC technology, smaller cities remain vulnerable to extreme weather events, resulting in higher risks of urban flooding, environmental damage, and public health threats. To address climate-related water challenges at a wider scale, further efforts are needed to make RTC systems more affordable and adaptable for smaller cities, ensuring that all urban areas can benefit from improved resilience against climate change impacts.

3. Strengths of the Solution

The implementation of RTC algorithms in urban water networks has introduced a transformative approach to managing water resources, enhancing resilience against extreme weather events, improving operational efficiency, and benefiting communities both socially and environmentally. This section examines the primary strengths of RTC, focusing on real-time monitoring and control, advanced analytics and predictive decision support, resource optimization and environmental impact, system resilience and risk management, and the economic advantages associated with these systems.

While RTC systems have proven particularly valuable in managing urban drainage and preventing flooding, their benefits extend well beyond these primary applications. Cities worldwide have leveraged this technology to address various water management challenges through innovative solutions ranging from smart metering and leak detection to comprehensive water conservation programs. These diverse applications demonstrate how RTC solutions can be adapted to support multiple aspects of urban water management while maintaining their core strength in flood prevention and drainage control.

3.1. Real-time Monitoring and Control

RTC systems enable continuous, precise monitoring of water parameters and operational conditions across urban networks, enhancing real-time control capabilities. In Copenhagen, an integrated RTC framework was implemented following the catastrophic 2011 flood, which released two months' worth of rain within hours. This event spurred the creation of the Cloudburst Management Plan, also known as *Skybrudsplan*, which has since evolved into a comprehensive system of parks, canals, and roads designed as catchment areas capable of directing and retaining floodwaters (see Figure 3). This "sponge city" design enables rapid water absorption and flow management, significantly reducing CSOs and protecting critical infrastructure during peak events [10],[15].

While primarily designed for flood prevention, the sophistication of RTC systems enables additional benefits through comprehensive monitoring capabilities. Real-time sensors track both quantitative (flow rate, level, etc.) and qualitative (pH, turbidity, etc.) parameters, allowing for immediate adjustments through smart-enabled valves and pumps. These systems can respond to demand changes within milliseconds, as demonstrated in Copenhagen's 350

RTC projects and San Francisco's automated metering infrastructure, which covers nearly 98% of its 178,000 customers [16],[17]. These examples highlight how RTC systems can extend beyond their primary flood management role to provide broader benefits, such as managing demand fluctuations, minimising water wastage, and preventing service disruptions.

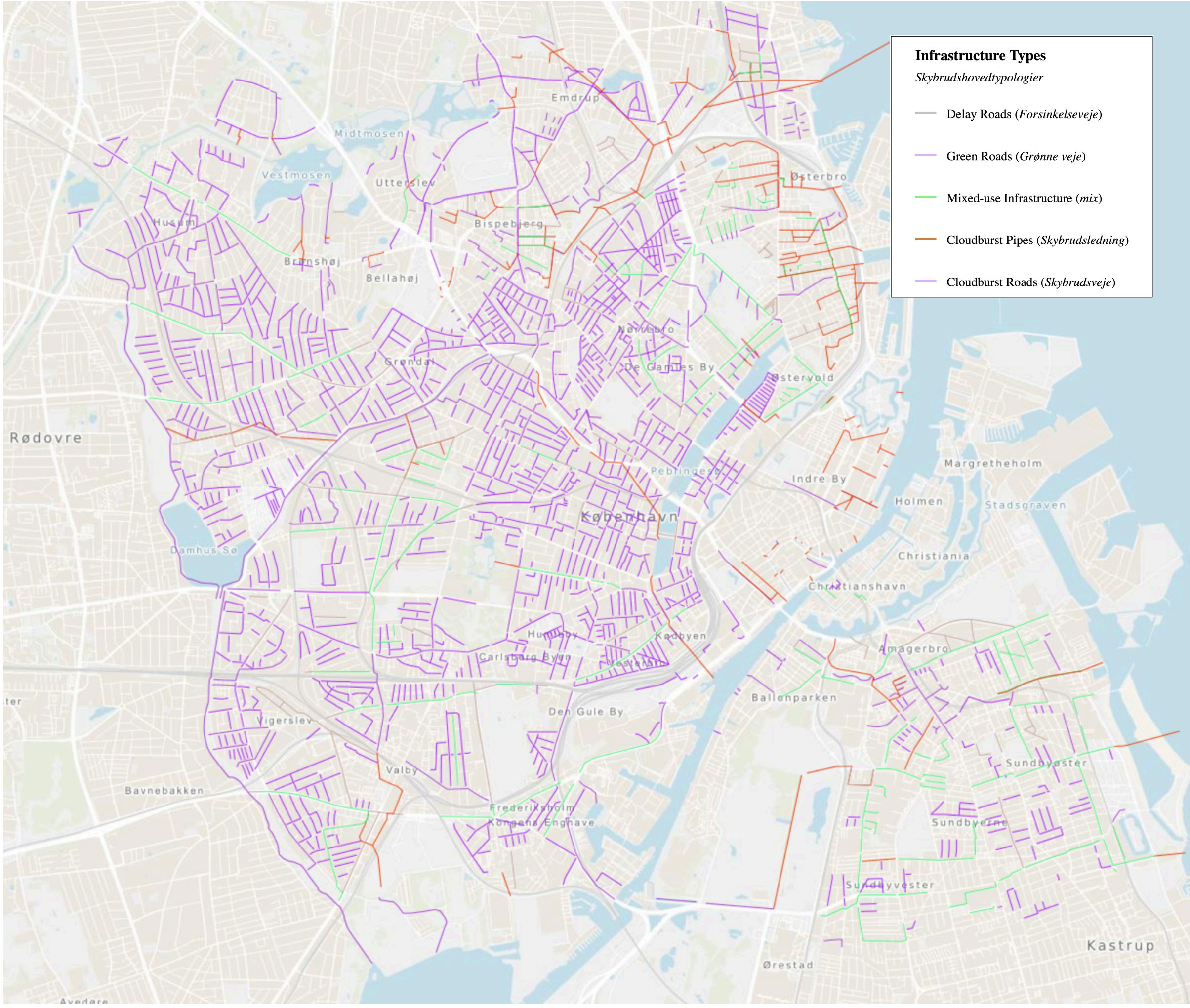

Figure 3. *Skybrudsplan*. Map of Copenhagen's cloudburst infrastructure, showing the network of water management solutions across the city. Green Roads and Cloudburst Roads share the same colour designation in the official plan, reflecting their complementary roles in the water management system. [18],[19].

3.2. Advanced Analytics and Predictive Decision Support

RTC systems utilise advanced analytics and machine learning algorithms to process sensor data and forecast water demand patterns, providing utility operators with predictive decision support. For instance, predictive analytics in San Francisco’s water management system enables early detection of leaks, optimising maintenance efforts before issues escalate [17].

Similarly, Copenhagen's Dynamic Overflow Risk Assessment (DORA) system integrates RTC with weather forecasting to predict overflow risks, dynamically adjusting water flow to avoid flooding during storms. This proactive control significantly reduces CSO occurrences and enhances the resilience of the water distribution network [10],[12].

Moreover, advanced RTC systems leverage Supervisory Control and Data Acquisition (SCADA) platforms to manage large data sets from diverse sources, enabling automated responses and pattern recognition. While primarily supporting flood management, these systems demonstrate broader utility- the Western Municipal Water District in California reported energy savings of 30% and water loss reductions of 20% due to SCADA-based RTC applications, showcasing how predictive analytics can optimise multiple aspects of water management [20].

3.3. Resource Optimisation and Environmental Impact

RTC-driven resource optimization improves both water and energy efficiency, contributing to environmental sustainability. At its core, Copenhagen's deployment of RTC in its drainage and stormwater systems has achieved significant water conservation by dynamically adjusting water flows and leveraging green infrastructure for retention. Parks and roads have been redesigned as temporary reservoirs, allowing water to gradually percolate or redirect to the harbour [18]. The plan has thus transformed urban infrastructure into multifunctional assets, addressing both flood management and urban greenery needs [10].

Beyond flood control, RTC systems deliver significant additional benefits in resource management. They facilitate substantial energy savings through smart pump controls, which dynamically adapt to flow requirements, reducing energy consumption by as much as 66% compared to fixed-speed operations [16]. Similarly, in Singapore, the WaterWiSe initiative demonstrates how RTC's capabilities can extend to broader resource management goals. By enabling real-time monitoring of consumption and potential water quality issues, the system supports sustainable urban growth while maintaining public health standards [17], showcasing how RTC solutions can simultaneously address multiple water management challenges beyond their primary flood control function.

3.4. System Resilience and Risk Management

RTC enhances the resilience of urban water systems by enabling real-time risk management, especially in mitigating the impacts of climate-induced extreme events. The *Skybrudsplan's* design, incorporating an underground network of channels and retention parks, exemplifies this approach. It enables Copenhagen to withstand significant rainfall events, preventing overflow by channelling excess water through designed pathways. This system aligns with climate resilience goals by safeguarding urban infrastructure against the long-term risks of severe weather events [10],[12].

Cybersecurity and data integrity are also integral to RTC system resilience. Advances in IoT-driven water management systems address vulnerabilities by employing Statistical Process Control and multivariate analysis for anomaly detection, securing the system against potential cyber threats. This cyber wellness, combined with predictive control, supports continuous water quality monitoring and system reliability, as seen in the Western Municipal Water District's SCADA-based RTC [17],[21].

3.5. Economic and Operational Benefits

RTC systems offer substantial cost savings over traditional infrastructure expansion. Retrofitting water networks with smart RTC components, such as sensors and SCADA platforms, is more economically feasible than constructing new pipelines and reservoirs to manage excess capacity. In Copenhagen, the cost of implementing the Skybrudsplan was around 1.8 billion euros, a considerable but necessary investment compared to the estimated 2 billion euros in flood-related damages over the next century without the plan. Additionally, most of the financing was raised through water levies, making the project financially sustainable and minimising the burden on taxpayers [10].

RTC's operational benefits extend beyond cost savings. By enabling predictive maintenance and efficient resource allocation, RTC reduces operational costs and prolongs infrastructure lifespan. Studies show that real-time monitoring and optimised pressure control can extend pipe network life by up to 20%, further reducing capital expenditures over time [22].

3.6. Future Possibilities and Transformative Potential

Smart water systems represent a paradigm shift in urban water management. Cities like Copenhagen demonstrate how these technologies can transform urban water infrastructure into more resilient and sustainable systems. The integration of smart water management with broader smart city initiatives creates opportunities for comprehensive urban sustainability improvements [10].

The success of these systems is also tied to their technological and societal readiness. The TRL framework emphasises the importance of technological maturity alongside societal considerations for public services, underscoring the role of smart water systems in public infrastructure resilience [9]. Furthermore, a reconceptualised Responsible Research and Innovation (RRI) approach advocates for adaptable, community-driven systems that integrate local knowledge with data-based decision-making, enhancing environmental sustainability in diverse urban settings [23]. By leveraging these frameworks, RTC solutions can achieve both technological efficacy and community acceptance, bringing a more holistic approach to urban resilience.

Looking forward, these systems will play crucial roles in addressing global water challenges. The ability to precisely monitor and control water distribution networks enables cities to better manage scarce water resources, adapt to climate change impacts, and ensure water security for growing populations. As technologies continue to advance and costs decrease, smart water systems will become increasingly essential for sustainable urban development.

4. Challenges and Risks of Implementing Real-Time Control in Urban Water, Sewerage, and Drainage Networks

4.1. Increased Vulnerability Through Internet of Things (IoT) Integration

The integration of IoT devices in smart water management systems (SWMS) enables real-time data collection and system responsiveness but also introduces cybersecurity vulnerabilities [24]. As these systems shift from isolated infrastructure to networked environments, they become susceptible to cyberattacks targeting various system components. [25] highlights that IoT integration expands the attack surface, allowing adversaries to infiltrate through multiple entry points, such as sensors, controllers, and communication networks. [14] gives the idea that in legacy sectors like urban water management, IoT integration expands the attack surface, creating multiple entry points for adversaries to exploit.

This interconnectedness can expose critical functions to attacks, such as data exfiltration, system manipulation, and even physical sabotage, with potentially devastating consequences for public health and safety. A case in point is the discovery in 2020 that more than 100 smart irrigation systems around the world had been installed without changing the factory's default, unencrypted settings. This oversight left them vulnerable to malicious attacks and potentially allowed adversaries to manipulate water delivery [26].

4.2. Legacy Infrastructure and Unpatched Systems

A major challenge in implementing RTC in water management lies in the existing legacy infrastructure, much of which was not designed to handle the demands of modern, data-driven systems. [9] analyses that while essential for assessing a technology's development stage, the TRL framework must be extended to include other readiness aspects like societal, organisational, and legal, especially when retrofitting old infrastructure with new technologies.

Many water systems rely on outdated hardware and software that lack the necessary cybersecurity protocols to protect against advanced threats. As a result, integrating RTC capabilities with legacy systems is problematic, as it can lead to compatibility issues and weak points in cybersecurity [27]. For example, older components may lack secure communication protocols or may not support the regular software updates required to address vulnerabilities. The inability to patch these systems promptly leaves them open to known exploits, creating a cyber risk for RTC applications.

4.3. Data Privacy Concerns and Potential Misuse

The SWMS' continuous collection of real-time data on water quality, usage patterns, and system operations increases the risk of data privacy breaches. Storing and transmitting sensitive data, such as consumer water usage information, poses potential privacy risks if unauthorised parties access this information [28]. This risk is of concern given the water infrastructure, which can be a target for espionage or misuse. Furthermore, data privacy concerns can lead to public mistrust, as communities may resist adopting such technologies if they feel that their data could be compromised. Ensuring data privacy and limiting access to only authorised personnel can be necessary for security and public acceptance.

4.4. Operational Disruptions and Public Safety Risks

Operational disruptions caused by cyberattacks on RTC systems can have direct impacts on public safety and the environment. An attack that targets the control systems within a water management network could interfere with critical processes such as chemical dosing, water purification, or flood management [29]. For instance, if RTC controls are manipulated to alter water treatment levels, this could lead to contamination and unsafe water reaching consumers. Furthermore, RTC systems are often designed to operate autonomously, minimising the need for on-site personnel. In the event of a cyber incident, this reliance on remote control can complicate or delay response efforts and potentially worse the impact of the outage.

4.5. Potential Social, Ecological, and Regulatory Barriers

The use of RTC in water management faces various social and regulatory barriers. Socially, the public may be wary of such technologies due to privacy concerns or fear of cyberthreats [30]. Regulators, meanwhile, may be cautious in approving RTC systems given the potential for ecological damage in cases of failure, such as the discharge of untreated water due to control manipulation. Furthermore, achieving compliance with data protection laws like the

General Data Protection Regulation (GDPR) in the EU adds another layer of complexity, as these systems must be designed to handle personal data responsibly [31].

4.6. Technical Skills Gap and Workforce Limitations

The effective deployment and operation of RTC systems in urban water management face challenges due to a growing skills gap in the water sector. RTC technology requires expertise in both water management and digital technologies, including skills in IoT, data analytics, cybersecurity, and hydraulic modeling. However, the water sector has been slow to attract young professionals with digital expertise, in part due to limited awareness of career opportunities within the industry and a traditional reluctance to embrace digital transformation. As a result, many utilities lack the in-house capabilities needed to install, maintain, and optimize RTC systems. Addressing this gap will require targeted training programs, collaborative partnerships with tech-focused academic institutions, and incentives to encourage digital talent to enter the water sector. Until this skills gap is bridged, the potential of RTC systems to transform urban drainage and flood management remains limited.

5. Conclusion

Urban drainage networks encapsulate some of the most pressing environmental challenges of our time. The need for cost-effective, socially acceptable, and technically sound improvements in existing systems is more critical than ever. RTC algorithms offer a promising path toward sustainable and resilient solutions for managing urban runoff and reducing flooding. However, the journey toward fully realising the potential of RTC is not one that engineers or technologists can undertake alone.

Addressing the complexities of urban drainage requires a collaborative approach that transcends individual professions. Policy-makers, engineers, urban planners, builders, environmental specialists, and citizens all have vital roles to play. Policy-makers must craft regulations that encourage innovation while ensuring public safety and environmental protection. Engineers and technologists need to design systems that are technically robust and socially responsible and accessible to those who operate them.

Environmental specialists can provide insights into the ecological impacts, ensuring that solutions align with sustainability goals. Urban planners and builders must thinkfully integrate these technologies into the fabric of city development. Most importantly, citizens need to be engaged and informed, fostering a community-wide commitment to embracing new technologies that serve the public good.

These roles must be played in partnership. Engineers must broaden their perspectives to understand societal concerns and environmental implications. Conversely, those influencing policy and public opinion should seek to grasp the technical challenges and possibilities inherent in RTC technologies. Through mutual understanding and interdisciplinary collaboration, we can overcome barriers such as cybersecurity risks, legacy infrastructure constraints, and social apprehension.

While RTC technologies have benefits, it is important to recognize the challenges and risks associated with their implementation. The integration of RTC into urban water, sewerage, and drainage networks brings potential vulnerabilities, such as cybersecurity risks, dependency on legacy infrastructure, and data privacy concerns as we defined in Section 4. These systems also require investments, which can be prohibitive for small municipalities. Moreover, public concern about the digitization of essential services and the complexity of regulatory compliance may hinder wider adoption. We find that addressing these weaknesses through flexible design, cybersecurity measures, and regulatory frameworks is important to ensure that RTC systems fulfil their potential without compromising public safety or infrastructure reliability.

In embracing this collective effort, we pave the way for urban drainage systems that are not only more efficient and resilient but also more attuned to the needs and values of the communities they serve. By harnessing the strengths of RTC while conscientiously addressing its challenges, we can make significant strides toward mitigating the impacts of climate change, safeguarding our cities, and promoting a sustainable future for all.

Acknowledgements

We would like to acknowledge the assistance of ChatGPT for providing proof-reading and syntactic structure validation for this document. Additionally, we used Claude.ai to translate sections of the Cloudburst Management Plan to support our research on the Copenhagen *Skybrudsplan* project. [18]

List of Abbreviations

Abbreviation	Full Description
CSO	Combined Sewer Overflow
DORA	Dynamic Overflow Risk Assessment
DTU	Technical University of Denmark
EU	European Union
GDPR	General Data Protection Regulation
IoT	Internet of Things
NBS	Nature Based Solutions
NTNU	Norwegian University of Science and Technology
RRI	Responsible Research and Innovation
RTC	Real Time Control (algorithm/solution/system)
SCADA	Supervisory Control And Data Acquisition
SWMS	Smart Water Management Systems
TalTech	Tallinn University of Technology
TRL	Technology Readiness Level
TU Delft	Delft University of Technology
UDN	Urban Drainage Network
WWTP	WasteWater Treatment Plant

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