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DOI
10.3390/w13040501

Publication date
2021

Document Version
Final published version

Published in
Water (Switzerland)

Citation (APA)
Nardo, A. D., Boccelli, D. L., Herrera, M., Creaco, E., Cominola, A., Sitzenfrei, R., & Taormina, R. (2021). Smart urban water networks: Solutions, trends and challenges. *Water (Switzerland)*, *13*(4), 1-8. Article 501. https://doi.org/10.3390/w13040501

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Editorial

Smart Urban Water Networks: Solutions, Trends and Challenges

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Citation: Di Nardo, A.; Boccelli, D.L.; Herrera, M.; Creaco, E.; Cominola, A.; Sitzenfrei, R.; Taormina, R. Smart Urban Water Networks: Solutions, Trends and Challenges. *Water* **2021**, *13*, 501. https://doi.org/10.3390/w13040501

Academic Editor: Enedir Ghisi

Received: 8 February 2021
Accepted: 13 February 2021
Published: 15 February 2021

1. Introduction

This Editorial presents the paper collection of the Special Issue (SI) on Smart Urban Water Networks. The number and topics of the papers in the SI confirms the growing interest of operators and researchers for the new paradigm of Smart Networks as part of the more general Smart City. The SI showed that digital information and communication technology (ICT), with the implementation of smart meters and other digital devices, can significantly improve the modelling and the management of urban water networks, contributing to a radical transformation of the traditional paradigm of water utilities. The paper collection in this SI includes different crucial topics such as reliability, resilience, and performance of water networks, innovative demand management, and the novel challenge of real time control and operation, along with their implications for cyber-security. The SI collected fourteen papers that provide a wide perspective about solutions, trends, and challenges in the contest of smart urban water networks. Some solutions have already been implemented in pilot sites (i.e., for water network partitioning, cyber-security, and water demand disaggregation and forecasting) while further investigations are required for other methods, e.g., the data-driven approaches for real time control. In all cases, a *new deal* between academia, industry, and governments must be embraced to start the new era of smart urban water systems.

The deployment of digital information and communication technologies (ICTs) in different aspects of urban life has contributed to generating the notion of the Smart City [1], recently recognized in the scientific and technical international community as a city where the use of ICT allows making "the critical infrastructure components and services—which include city administration, education, healthcare, public safety, real estate, transportation, and utilities—more intelligent, interconnected, and efficient" [2]. The implementation of new monitoring and control sensor technologies and the availability of high computational power changed the traditional approach to studying, designing, and managing water systems and enabled the development of new data-driven approaches fed by big data. The availability of low-cost devices, controlled by remote systems, is pushing the operators of urban water systems to fill the technological gap with other network utilities (i.e., electricity, gas, Internet, etc.), as reported in [3]. This transformation, triggered by ICTs, has also generated the new concept of the smart water network (SWAN) as a key subsystem of the Smart City.

In the more general framework of Industry 4.0, the recent development of Internet of Things (IoT) technologies applied to smart grids opens further novel opportunities in the management of water network systems and beyond. At the current state, it is possible to imagine novel solutions based on digital innovations to study, analyze, assess, and improve traditional approaches for leakage reduction, pressure management, optimal maintenance, water quality protection from accidental and intentional contamination, network calibration, water use identification, water demand modelling and management, water network partitioning, adaptive and dynamic control, as well as the new challenges raised in the digital era (e.g., cyber-security). This leads to a transformation of the traditional operational criteria and contributes to an increase in the resilience of urban water systems. In addition, by analyzing the cross-links between the urban water infrastructure and other systems (i.e., power grids, urban drainage, smart homes, etc.) it is possible to account for multi-sectoral interconnections in planning and management decisions for more resilient Smart Cities.

The objective of this Special Issue is to gather contributions advancing scientific and technical methodologies, technologies, and best practices that advance smart urban water networks by leveraging the increasingly available computational power in simulation, IoT systems, and smart meter devices. Through this open access journal, a wide community of researchers, operators, and water utilities can have access to a collection of recent cutting-edge contributions showing how some key operational challenges of water networks can be improved by coupling ICT technologies, physically-based mathematical procedures and data-driven techniques (i.e., identification, optimization, complex network theory, etc.). In other terms, this will foster the digitization of urban water networks towards the concept of smart cities and societies.

The papers in this Special Issue provided heterogeneous contributions to the topics proposed by the Editors in the call, showing a large variety of implemented and potential solutions, current trends, and challenges that remain open for future research. In the following sections, the paper collection is presented, highlighting the main proposed novelties.

2. Special Issue Paper Collection

The keywords suggested by the Editors of this Special Issues tried to identify some potential fields of applications that are being transformed by digital innovation in smart urban water networks. In this editorial, it is worth reporting some of them to attest the effort of synthesis and offer to researchers and operators a possible map of innovation in current cutting-edge research on urban smart networks, with topics including: optimal network design and management, novel modeling approaches, application of IoT, adaptive automatic control of urban water network, machine learning and big data for water utilities management, characterization and modeling of water demands at different spatial and temporal scales, divide-and-conquer techniques for water network partitioning, innovative metrics for resilience computation, actions to protect water distribution network from accidental and intentional contamination, novel approaches for water safety plans, data-driven water demand modeling, non-intrusive load monitoring, water and energy nexus, end use disaggregation of water consumption, water demand user profiling, behavioral modelling and water-energy demand management, innovative decision support systems, hydroinformatic applications, innovative intermittent uses in drought periods, pump and turbine implementations, disaggregated pricing and tariff policing, and cyber-security applications.

Many of these concepts were addressed and discussed in the papers collected in this Special Issue, which was mainly dedicated to water distribution networks but, as will be shown below, also hosted some contributions on water drainage systems, highlighting how the digital transition is affecting all subsystems involved in the urban water cycle.

Specifically, the Special Issue on Water Journal collected 12 papers, which in this editorial and, consistently, in the on-line paper collection, are categorized in four main topics: (1) Reliability, Resilience, and Performance, (2) Smart Urban Water Demand Management, (3) Smart Real Time Control and Operation, and (4) Cyber-Security in Water Systems.

Two further contributions bring the total number of submitted papers to 14: a timely review on the Smart Water Systems, inserted as the overview of the Special Issue; and a review on the state-of-the-art literature on cyber-security in the water sector, which systematically presents the existing works in this fast growing field and identifies outstanding issues.

2.1. Overview on Smart Water Systems

The first paper of the Special Issue offered the opportunity to rethink the framework of smart water systems. The design and construction of such smart water systems are still not standardized enough for massive applications, and there is a lack of consensus on the overall transformative framework.

Some authors identified from their comprehensive literature review on smart water techniques the lack of a general architecture and a systematic framework to successfully guide real-world deployment of smart water systems [4]. To fill this gap, they suggested a novel approach consisting of five layers: (i) instrument layer, (ii) property layer, (iii) function layer, (iv) benefit layer, and (v) application layer, including two newly-defined metrics, i.e., smartness and cyber wellness. Therewith, the aim of the authors was to stimulate the implementation of smart water systems in practice as a joint work of academia, industry and government.

2.2. Reliability, Resilience and Performance

Some papers of the Special Issue deal with the subtopic of reliability of water networks. In these papers, some specific water network management issues, including network partitioning, and protection from contamination and other critical events are addressed, and a comparative analysis of some reliability indices was also provided.

Another interesting problem faced in the Special Issue is the optimization of fault examination in water distribution networks. It is essential to automatically detect faults (e.g., leaks, blockages) in water distribution systems to avoid or reduce the loss of resources, non-revenue water, and operational costs. In [5] was proposed an inverse transient-based optimization approach to identify such faults. They tested their approach with models of two hypothetical water distribution systems and found that their algorithm is proven reliable and efficient in detecting faults. In the paper [6], the authors reviewed the state-of-the-art literature on water networks partitioning in district metered areas (DMAs) and provided a comprehensive overview of existing methods and approaches. They classified these methods in two steps: clustering algorithms (dividing the network) and dividing procedures (identifying the optimal positions of gate valves and flow meters). Six of the most widely adopted clustering algorithms were presented and discussed in-depth, and future research gaps were identified (e.g., considering devices, such as pumps, operations under abnormal conditions).

Furthermore, [7] presented a strategy for reducing the impacts of contamination events in water distribution systems. The authors developed a hybrid strategy which is based on water network partitioning and the installation of sensors. By testing the framework on a real water distribution system, they showed how to reduce the impact of any kind of critical events.

Finally, in the literature, there are numerous reliability indices to evaluate the performance of water distribution systems. However, the choice of which one to use is often challenging, as they rely on different assumptions and some of them are correlated. In this regard, a very useful comparative analysis of reliability indices and hydraulic measures was carried out by [8], who investigated nine different reliability indices and six different hydraulic measures with 17 hypothetical networks with various topological features under different supply scenarios. They found that selecting the indices according to the defined goals is essential and, accordingly, give guidance on how to choose the right indices for different water network configurations.

2.3. Smart Urban Water Demand Management

The Special Issue hosted some papers on the topic of water demand management, which is showing an increasing interest in the technical and scientific community.

A comprehensive review of urban water consumption datasets at multiple spatial and temporal scales was proposed by [9]. The recent technological developments and increasing number of pilot studies in smart water metering is resulting in an increasing availability of high-resolution metering datasets for research applications. Motivated by the need for tracking the type and accessibility of the existing water consumption datasets in the rapidly evolving field of smart metering, the authors reviewed and collected available dataset sources and classified them according to spatial and temporal scale, and dataset accessibility. In the work [9], the authors found that the existing datasets are very heterogeneous in terms of temporal and spatial scales, and they can serve different purposes depending on the scale of interest, data resolution, and related analytics, including, for instance, water demand forecast, end use disaggregation, behavioral modeling. After assembling the catalogue of existing smart meter datasets and characterizing them with the above mentioned criteria, the authors formulated a series of recommendations to support future research efforts and encourage the open access publication of smart water meter data.

A spatial aggregation effect on water demand peak factor was also in the Special Issue. The single water consumption is a random and highly volatile process. However, when aggregating a large number of consumers, temporal, but also spatial trends and patterns, can be observed. In the work [10] the peak factor for the water demand consumption as a function of spatial data aggregation on the basis of the statistical analysis of data of 1000 households was investigated. They found an empirical relation for estimating the peak factors. Furthermore, they proposed a procedure to analyze smart meter data regarding the occurring water demand peak factors and give guidance for network operators on how to process their data for design and operation.

In another contribution based on a least square support vector machine [11], the authors established a forecasting chaotic time series for short-term water demand with a forecasting horizon of one day and a time step length of 15 min. To improve the quality of the forecast, they transformed the time series of differences between the forecasted and measured data to a chaotic time series and implemented an error correction module to improve the accuracy. By testing this hybrid model on three real-world supply areas, they showed an improvement of the obtained forecasting solutions regarding mean absolute percentage error.

Another interesting paper on the smart water grid for micro-trading rainwater was proposed in the special issue by [12]. While there might be a local urban water shortage, local excess water might be available in supply areas. For non-potable water, some authors proposed to establish a smart water grid which allows to trade rainwater on a local level [12]. For doing that, they envisioned a distribution network connecting residential rainwater tanks that would enable to buy and sell rainwater on a local level (e.g., for irrigation purposes), and which would be monitored and controlled via numerous smart water sensors. In a hydraulic feasibility study, they analyzed these micro-trading and showed that water and energy savings are feasible across different climates.

2.4. Smart Real Time Control and Operation

Some papers inserted in the Special Issue regarded the innovative topic of implementation of real time control and operation of smart devices in water networks. This aspect represents one of the main operational challenges for water utilities to definitively shift towards the paradigm of a smart water network.

A first contribution of this section of the Special Issue dealt with the optimal placement of pressure sensors using fuzzy logic. Indeed, smart pressure sensors can be used to detect leakage in water distribution systems. However, it is challenging to find a suitable location for such sensors to gain the maximum benefit, while considering budget and other constraints. In [13] the optimal placement of pressure sensors in water distribution systems was investigated by considering the nodal sensitivity to leakage, data uncertainties and node entropy in order to cover a maximum area by a sensor. The authors successfully showed the application of their approach to a benchmark system and also to a real-world case study.

In the work of [14], the authors presented an interesting application on real-time pressure control by analyzing different stochastic consumptions. As known, pressure management in water distribution systems is important to supply water in sufficient quantity and quality in a cost efficient and reliable way. If there is an excess pressure in a water distribution system, pressure control valves can be used, but the challenge is to cope with many different water consumption states. The researchers performed a numerical investigation of flow-dependent pressure controllers from the literature and assessed their performance based on a stochastic demand model to mimic realistic conditions. They found that different controller schemes perform quite similar. Therefore, they suggested using the scheme with a simple structure without performing any forecast of future demand.

2.5. Cyber-Security in Water Systems

One paper regarded the very interesting topic of the state of the art of cyber-security in water systems [15]. It is clear that also in water systems the evolution from isolated bespoke systems to those that use general-purpose computing hosts, IoT sensors, edge computing, wireless networks, artificial intelligence, and IoT devices will increase significantly the risk of cyber-attacks. The authors highlighted the importance of protecting water infrastructure from malicious entities that can conduct industrial espionage and sabotage against these systems. The review of [15] focused on the aspects of the system vulnerability, of the actual measures, and the perspective to improve the cyber-security of water systems. The authors found that the majority of cyber-security studies were carried out on drinking water systems, others on drinking water treatment systems, and only a few on non-drinking water systems (i.e., canal automation systems used for irrigation and wastewater systems). However, while the impacts of cyber-physical attacks are increasingly discussed in the literature, only few studies address the problem of how to efficiently protect micro components in smart water systems. Therefore, it was concluded that further works should specifically focus on making smart water systems reliable and safe. To successfully enable smart water systems in practice, future research should focus on efficiently protecting micro components by including cyber-physical components in the resilience assessment of urban water systems.

Finally, the last two papers hosted in the Special Issue were not fully aligned to the topic of water distribution networks, but they are very interesting in the more general paradigm of smart networks and big data collection with innovative smart sensors.

The first paper proposed the usefulness of hydrological time-series water depth clustering that can be extended to other smart measures. Specifically, clustering of recorded information is a meaningful statistical method to gain knowledge out of a multitude of real-time measured data. For urban drainage systems, where an increasing number of sensors are installed, this information might also be of great interest for the detection and forecasting of flooding events. The researchers [16] investigated how data-driven unsupervised machine learning algorithms can be used to group hydraulic-hydrological data of measurements in storm water drainage systems. By investigating different clustering and performance evaluation methods, suggestions are given about what kind of method should be applied according to the type of detection events (e.g., short-duration or long duration). This can be implemented as a flood early warning system.

Although not aligned to the topic of water distribution network, the last paper on IoT for wastewater treatment plants also provided useful suggestions to the technical and scientific community about the application of wireless sensor networks that can be a promising approach for different fields of urban water management. In [17] was presented a low-cost IoT system for water quality monitoring for wastewater treatment plants at a close-to-market stage. With a novel ion chromatography detection method, they integrated and tested a nitrate and nitrite analyzer under real conditions. The results of comparing laboratory and low-cost IoT systems revealed the reliability of the proposed device.

3. Discussion

The interest of researchers for the Special Issue was high with 14 published papers (4 review papers and 10 research papers).

The review papers showed that some topics, such as innovative procedures for water network partitioning [18], smart meters and tools for water demand measuring [19], end use disaggregation and forecasting [9], and applications for cyber-security [15] are already available for water utilities. However, as appropriately reported in [4], and confirmed by [15], more coordination between academia, industry, and government is required to guide real world deployment of smart urban water systems. In order to meet the demands of industry and government and successfully turn this new paradigm into practice, the researchers [4] showed that it is necessary to obtain a consensus from conceptual, technical, and practical perspectives. However, also for more consolidated innovations (like softwares, best practices, and procedures) no comprehensive consensus exists. Accordingly, the five-layer framework proposed by the authors aims to simplify the implementation of smart water technologies in novel solutions and case studies, and, for the first time, to better characterize the peculiar features of smart water systems.

Besides presenting new approaches and solutions to smart water networks, the works presented in this SI also highlight the open challenges that should be prioritized in future research.

First, the achievement of a shared definition of resilience of water systems and a shared formulation performance indices for the management represent a key priority to further advance the concept and standardization of smart water networks. In fact, with the help of smart meters and the analysis of big data it will be possible to define novel metrics and consequently improve calibration phases and maintenance plans and better face water crisis periods through water demand management. With reference to the latter point, this Special Issue highlights that the technologies and the methodologies proposed are mature to start pilot sites on a large scale. It is worth highlighting that in [4] was identified that widely applied concepts of resilience of urban water infrastructure are lacking smart components and that there is a need for novel concepts for smart water systems as these are even more complex than traditional systems. By defining two conceptual metrics (smartness and cyber wellness), a first step in this direction was taken, but comprehensive further research is required to successfully tackle these short-comings in current smart water applications.

Further, the more advanced challenges delineated in the SI are the topic regarding real-time control and operation of water systems, also with the possibility to activate dynamic changes in the network operation using smart devices controlled in real-time (e.g., regulation valves, on-off valves).

The availability of a large amount of data collected by smart sensors in IoT framework brings up valuable information and knowledge from the system and speeds up the spreading of data-driven applications in water industries. Some solutions offer new visions when well calibrated hydraulic models are difficult to obtain. In these cases, it could be possible by analyzing the learning system behavior only using data collected from hydraulic, maintenance, and economic information (i.e., length of pipes, diameter, type of material, age, flow, costs, etc.) and the know-how of the operators recorded in maintenance journals (i.e., date and time, type and causes of disservice) without any physical modelling.

This aspect is very interesting and data-driven approaches also represent a new challenge for the future of smart water systems.

4. Conclusions

This Special Issue shows that the multi-faceted paradigm of smart urban water networks can be declined in different ways and applications. While the digital transformation of water networks still presents several open challenges, many solutions can be considered ready to be implemented by water utilities and operators. However, the technological transfer from research laboratories to the water market is still slow for many reasons, mainly due to the delay of the standardization processes and a common regulatory framework.

Overall, the papers collected in this SI offer to the technical and scientific community a wide overview of the solutions and possibilities offered by the implementation of smart meters, IoT, innovative modelling, and simulation approaches fostered in the last years by the availability of high computational power and new digital technologies. The digital transition of water networks towards smart systems is an ongoing and incremental process. Yet, radical changes have been already observed in the last years and more advances leveraging the state of the art, including the contributions presented in this SI, can be expected if a *new deal* between academia, industry, and governments will be embraced to reap and materialize all the benefits of the digital transformation.

Author Contributions: Writing—original draft preparation, A.D.N. and R.S.; review and editing, all authors. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no direct external funding.

Institutional Review Board Statement: The study did not require ethical approval.

Informed Consent Statement: No required.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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