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Editorial

Resilience of Interdependent Urban Water Systems

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1. Introduction

The reliable functioning of water infrastructures is one of the key pillars for society, and it is crucial for social well-being and supports economic growth [1,2]. As recently experienced, during COVID-19 shutdowns, society has been reminded of the importance of these services to reliably cover basic needs and ensure public health [3]. Further, there is a strong need for adaptation of water infrastructure to tackle challenges like climate change, increasing urbanization, etc. [4]. It requires resilience evaluation and intervention planning, in which the former is to develop a comprehensive understanding of the inherent resilience of the entire underlying system, and the latter is to provide evidence-based strategies for optimizing water infrastructure resilience at the lowest possible cost within its life cycle.

Therefore, the enhancement of resilience of urban water management solutions is an emerging topic for water research and the water industry. Important issues for water distribution systems [5,6], as well as for urban drainage systems [7,8], have been tackled in scientific literature. However, studies on the resilience of interdependent components of the different parts of the urban water systems are rare. The different urban water infrastructures not only have spatial correlation [9] but also functional correlation [10]. This Special Issue aimed to include papers addressing the emerging research gaps in interdependent water infrastructure resilience, such as:

- Resilience of interdependent urban water infrastructures, and the interdependencies between water infrastructures and other infrastructure systems;
- Improving either attribute-based (e.g., topology; configurations) resilience or performance-based (operational) resilience or both; Revealing the correlations between the two components of resilience;
- Resilience metrics—local, system, infrastructure;
- Trade-off between different intervention strategies, as increased resilience to one failure mode may decrease resilience to another;
- Need of high-performance algorithms for resilience evaluation and intervention;
- Comprehensive methodologies/frameworks for building resilience by adaptation (e.g., design, rehabilitation, renewal and replacement) and governance of urban water infrastructures;
- Comprehensive cost-effectiveness evaluation of resilience intervention plans.
- Impact of COVID-19 on the water infrastructure (impact of shut-downs, emergency operation, management strategies, reducing vulnerability to implications).

From this call, the papers published in this Special Issue provide heterogeneous contributions to the resilience of interdependent water infrastructure, 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 and further discussions.

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Citation: Sitzenfrei, R.; Diao, K.; Butler, D. Resilience of Interdependent Urban Water Systems. *Water* **2022**, *14*, 440. https://doi.org/10.3390/w14030440

Received: 19 January 2022
Accepted: 21 January 2022
Published: 1 February 2022

2. Paper Collection in this Special Issue

From numerous submissions, in total, eight high-quality papers are published in this Special Issue. Thematically, four different sub-topics are tackled within the published manuscripts (Figure 1). First, two papers within the sub-topic of integrated resilience assessment are discussed (Section 2.1). Then, contributions on (smart) green infrastructure solutions as linking parts between different water infrastructures are presented (Section 2.2). Concluding, resilience assessment and enhancement methods are shown for water distribution systems (Section 2.3) and urban drainage systems (Section 2.4).

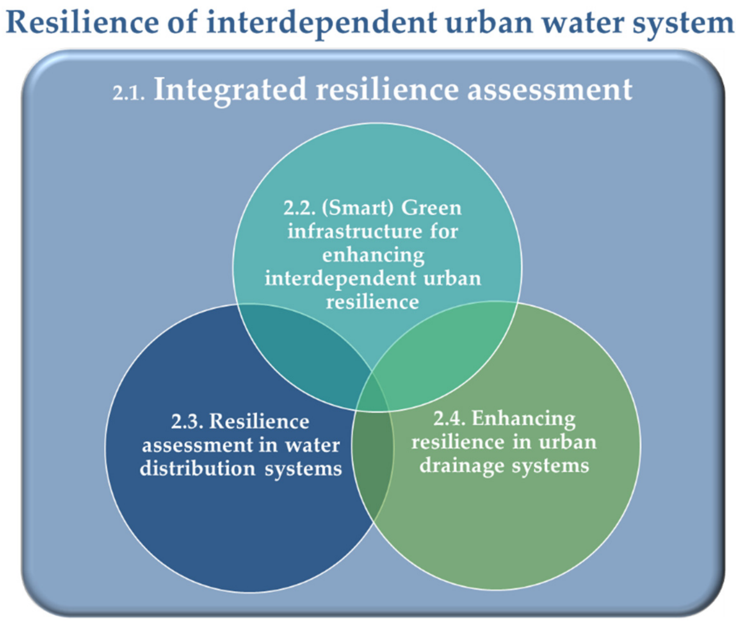

Figure 1. Sub-topics on the resilience of interdependent urban water systems tackled in this Special Issue.

2.1. *Integrated Resilience Assessment*

Urban water systems are usually grown over decades resulting in complex and interacting systems. However, analyses often focus only on a sub-system for simplicity, neglecting these multi-faceted dependencies. This aspect becomes even more important when extending the initial design to uncertain future conditions. Therefore, it is important to understand how urban water systems behave when they fail and to ensure that they can recover quickly. To enhance the knowledge on under which conditions urban water systems can work with a sufficient level of service, Nikolopoulos et al. [11] introduced a source-to-tap simulation model for stress testing. With this modelling chain, it is feasible to assess the resilience of urban water systems in a standardized way under long-term uncertainties. Specifically, the framework considers a water resources management model, a hydraulic water distribution model and a water demand generation model including a stochastic assessment methodology to model disturbances. On a synthetic case study, the proposed framework was applied, giving valuable new insights into the complex behavior of the underlying urban water system. The proposed methodology can be a valuable tool for decision making and long-term planning of water infrastructure.

For engineering sciences, it is of great interest to work with as realistic case studies as possible. Urban water infrastructure, more specifically water distribution systems, belongs to critical infrastructure. Hence, often access to such case studies is restricted due to general data protection issues or due to critical infrastructure protection. Therefore, researchers often use synthetic case studies. In the literature, there are many different methods for manually or automatically creating such synthetic models [12]. However, the quality of the creation process is of great relevance, as all subsequent analyses rely on the quality of the case study created. The study of Rehm et al. [13] enhances such a generation process by a highly automated approach, using different sources of available geo-referenced data. With the generated synthetic data, a more in-depth resilience analysis of such systems can be performed also in an integrated way.

2.2. (Smart) Green Infrastructure for Enhancing Interdependent Urban Resilience

Green infrastructure can play an important role to enhance the sustainability of (grey) urban drainage systems and also their resilience. In contrast to grey infrastructure, green infrastructure is much more flexible in terms of installation and adaptation, bringing multi-functions and other benefits such as flood risk reduction or improved water quality to urban drainage management. However, the interplay of green infrastructure and traditional urban drainage networks is often unknown, especially in the context of overall resilience and urban patterns. Rodriguez et al. [14] developed an approach to better understand the resilience enhancement due to green infrastructure implementations in urban drainage systems. For a case study in the UK, they found significant positive correlations between different locations of green infrastructure and service loss scenarios. Further, spatial performance clusters were also identified with the proposed method. The developed approach could play an important role in urban planning and resilience-based water infrastructure planning.

Another approach to make the urban water systems more resilient is to use different smart approaches to gain better (data-driven) insights into the system performance and also use decentral real-time control options of smart components. Smart rain-water harvesting can play an important role when reducing potable water consumption and also improving urban drainage performance. When operating rain-water harvesting systems, the objective is, in general, that the storage unit is always fully filled so that water can be withdrawn (e.g., for irrigation) at any time. However, from a drainage network perspective, the objective for such a storage unit is to be, in general, empty so that runoff from rain events can be (at least partly) intercepted and stored. Smart rain-water harvesting addresses these two contradicting objectives by releasing, based on weather forecasts, (some) stored rain water prior to new storm events. By that, during a rain event, runoff entering the drainage network can be reduced, and a full rain-water harvesting system is ensured after the rain event. Oberascher et al. [15] implemented that concept in a smart rain barrel approach and evaluated the resilience of the integrated system on a large-scale implementation. For the resilience of such smart systems, the authors considered an integrated resilience assessment consisting of the performance of the combined sewer overflows, rain-water harvesting efficiency, and irrigation volume. Moreover, the smart systems also rely on the quality of digital parameters, such as the reliability of the communication technology and the quality of weather forecasts, for control strategies. Therefore, in this study, these disturbances of usually optimal working conditions were implemented in an integrated resilience analysis of a large-scale implementation of smart rain-water harvesting. The authors identified that digital disturbances could significantly reduce the performance, and a coordinated integration is required for smart rain-water harvesting systems in order to ensure that the potential of such systems is fully utilized and degradation of system performance is avoided.

2.3. Resilience Assessment in Water Distribution Systems

Resilience assessment in water distribution systems requires measuring the systems' performance under many failure scenarios [2,5,16]. However, current methods simulate the failure scenarios by imposing stresses on the system (e.g., pipe failure) without considering any possible changes of other attributes in the system during the failure, e.g., relocation of water demands caused by moving people to evacuation shelters during a critical event, such as bomb disposals, that require evacuations or natural catastrophes [17,18]. Given the importance of emergency planning in critical events, a deeper understanding of the systems' changes in the events is crucial for more accurate and comprehensive resilience evaluation, which will avoid misleading emergency solutions.

Logan, Leštáková, Thiessen, Engels and Pelz [18] identified that many critical events may cause demand relocation within a water distribution system and thus developed a historically informed method of assessing resilience for water distribution systems under critical events. The water distribution system has thus been considered an interdependent, socio-technical system in which the social and the technical system interact: the technical system has to maintain its service during a critical event despite the social system accounting for strong changes in demand distribution. More specifically, the critical event is modeled as an event during which the population leaves consumer nodes within the evacuation area, where the required demand drops to zero, and the equivalent demand is relocated according to three sheltering schemes. This study addressed five research questions, i.e., the effect of the size of the evacuated area, the feasibility of different sheltering schemes, vulnerability of particular parts of the system, and the suitability of nodes to serve as shelter nodes. The results show that the developed approach can be the basis of describing and analyzing socio-technical systems.

Hou, Ma, Diao, Zhong and Wu [17] analyzed the relocation of water demands in water distribution systems under earthquake disasters and found that during post-earthquake rescue and restoration, the water demands at user nodes may change significantly from those of daily service under normal conditions. For example, household and commercial water demands will reduce dramatically or even disappear, while water demands for post-earthquake rescue will increase tremendously, which is also more urgent than the others. Based on these understandings, Hou, Ma, Diao, Zhong and Wu [17] developed a multi-index framework to assess the criticality of individual user nodes in terms of their roles for daily life service, emergent rescue service, and water transmission to other nodes, respectively. This multi-index measure can identify critical nodes for post-earthquake rescue service, which may be ignored by single importance index approaches. Thus, a better seismic renovation plan of pipelines can be developed based on the multi-index method to improve the seismic performance of critical user nodes.

2.4. Enhancing Resilience in Urban Drainage Systems

Wastewater management is usually based on central drainage networks, transporting the sewage flow to a central point that is usually a wastewater treatment plant. It is well known that, besides the benefits of these solutions, such systems are vulnerable to failures, and flexibility and adaptiveness to new boundary conditions, such as urbanization, are limited. Therefore, Zahediasl et al. [19] suggest using a decentralized approach with smaller entities of drainage networks and wastewater treatment plants. To find optimal degrees of decentralization, the authors developed an optimization framework that considers the optimal network layout and the optimal design. In their approach, the costs are minimized, and at the same time, the structural resilience is maximized with different degrees of centralization. It was found that an increased decentralization increases structural resilience, while at the same time, reductions in costs can be achieved. With these obtained optimal trade-offs, decision makers can pick the best designs for their considerations and limitations.

As a link between urban drainage and water supply systems, the reuse of treated wastewater for non-potable purposes can be seen. However, deciding where to optimally reuse treated graywater and treated wastewater in an existing water system is a challenging task. Therefore, Dev et al. [20] developed two screening models for reuse options that can be used in the planning stage for optimal implementation. The goal of their study is to reduce stress on the existing water supply system by substituting freshwater consumption with reuse options. In an integrated economic analysis of a case study, it was determined with the proposed models that the price for providing water can be significantly reduced as the freshwater demand is decreased.

3. Discussion and Conclusions

From the papers published in this Special Issue, in summary, four important needs for further research emerged:

(1) *Standardized methodology is required*: There are still no standard methods for defining and measuring the resilience of water infrastructures. Different cities may also respond differently to critical events. For example, as indicated by Logan, Leštáková, Thiessen, Engels and Pelz [18], the presented study was carried out using just one water distribution system, and thus, the results cannot yet be generalized for all networks. Hence, further methods for generalized models and subsequent analysis need to be explored to meet this limitation.

(2) *Need for an interdependent view*: Commonly, the urban water cycle begins with the abstraction of water from rivers and aquifers to reservoir storage. The water is then processed through filtration and chlorination to a potable quality before being transported through an extensive pipework system to residential, commercial and industrial developments. After its use by humans, much of this water becomes wastewater and, along with some surface water runoff, is transported through a network of sewers to treatment plants, which, after treating it, discharge effluent into receiving waters, such as rivers and the sea. It is clear that, in this chain of processes, there are interdependencies. To generate a holistic view of urban water cycle and test solutions, the computer-based models should integrate all the urban water systems and their interactions, the relevant hydraulic and hydrology processes, and social–economic–environmental factors. Nevertheless, simply integrating everything into one model may make the already very complex system become too complex to be efficiently analyzable. In this regard, understanding the interdependencies among different systems will be a critical starting point for setting up such holistic models and improving the performance from an integrated view.

(3) *Lack of (consumption) data during critical events*: Although the simulation of failure scenarios is the basis for resilience assessment and intervention planning, the creation of the scenarios is usually a customized process. For example, failure scenarios created following traditional concepts for water distribution systems do not consider demand relocations under critical events, as indicated in [17,18]. The reason mainly lies in the lack of systematic studies on the behaviors of urban water systems under failure states due to the high uncertainties. Hence, addressing this challenge to develop standard methodologies for the creation of representative failure scenarios is important. This task will, however, be more challenging when cascade failures in interdependent systems need to be considered.

(4) *Further exploiting potential of information and communication technology (ICT)*: The rapid development of the ICT along with big data analytics is facilitating the development of a Measurement-Analysis-Decision (MAD) framework [21] that is shifting traditional urban water systems to smart water systems [22]. Collecting extensive datasets to support modeling-based analysis has been increasingly used. Particularly, data collected during failure states will help develop an understanding of how to accurately model failure scenarios. In this regard, there is a great need for new approaches and further models to obtain better insights into the integrated behavior or urban water systems and finally exploit the full potential of this technology while, at the same time, not increasing the exposure to cyber-physical threats, e.g., power blackouts.

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

Funding: This research was conducted within the project RESIST (FO999886338), which is funded by the Austrian security research programme KIRAS of the Federal Ministry of Agriculture, Regions and Tourism (BMLRT).

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

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