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Editorial

Advances in Water Distribution Networks

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Received: 4 October 2018; Accepted: 25 October 2018; Published: 30 October 2018

Abstract: This Editorial presents a representative collection of 10 papers, presented in the *Special Issue on Advances in Water Distribution Networks* (WDNs), and frames them in the current research trends. Four topics are mainly explored: simulation and optimization modelling, topology and partitioning, water quality, and service effectiveness. As for the first topic, the following aspects are dealt with: pressure-driven formulations, algorithms for the optimal location of control valves to minimize leakage, benefits of water discharge prediction for the remote real time control (RTC) of valves, and transients generated by pumps operating as turbines (PATs). In the context of the second topic, a topological taxonomy of WDNs is presented, and partitioning methods for the creation of district metered areas (DMAs) are compared. With regards to the third topic, the vulnerability to trihalomethane is assessed, and a statistical optimization model is presented to minimise heavy metal releases. Finally, the fourth topic focusses on estimation of non-revenue water (NRW), inclusive of leakage and unauthorized consumption, and on assessment of service under intermittent supply conditions.

Keywords: water distribution networks; non-revenue water; leakage; energy; real time control; pumps as turbine; pressure-driven analysis; topology; partitioning; district metered areas; water quality; trihalomethane; heavy metals

1. Introduction

The research on water distribution networks (WDNs) has recently undergone important renewal and development, due to technical progress in control systems and computational resources. In the last few decades, the research has examined in depth the well-established topics related to the quantitative simulation and optimization of water distribution systems, and it has broadened to water quality aspects.

As for water quantity, one of the most explored topics is undisputedly modelling [1]. In this context, the extended period simulation, which represents WDN behaviour as a sequence of steady states, is by far the most widely adopted modelling tool. This is because it enables obtaining good results in the trade-off between accuracy and computation burden. However, the thorough assessment of nodal outflows is an essential requirement for the accuracy of the simulation. To this end, the pressure-driven approach originally proposed by Bhave [2], which relates nodal outflows to demands and pressure-heads, proved to perform much better at reproducing WDN behaviour in a wide range of service pressure, in comparison with the demand-driven approach, in which nodal outflows are set equal to demands. However, little attention has been dedicated to the comparison of the various pressure-driven formulations available in the scientific literature, e.g., [2–7].

Besides outflow to authorized users, nodal outflows also include non-revenue water (NRW) [8], which is represented by leakage and unauthorized consumption. Numerous studies, e.g., [9–11], have been carried out on the effective parameters for characterizing WDN in terms of NRW. However, the correlation between NRW ratio to overall water production and WDN operational and physical parameters has not been thoroughly explored.

To decrease the NRW ratio, as well as to obtain other benefits such as the reduction in pipe bursts and the extension of infrastructure life, water utility managers often choose to perform service pressure regulation in WDNs. This requires the installation of control valves at suitable locations and the real time control (RTC) of these devices, to meet the demand variations in time. After the work of Jowitt and Xu [12], many other works, e.g., [13–17], in the scientific literature explored optimal location of control valves in WDNs. Nevertheless, few comparative works exist to help water utility managers choose the best algorithm for generic case studies. As for RTC, some work was done to set-up increasingly effective algorithms to regulate control valve settings as a function of the pressure at critical nodes [18] and variables, such as water discharges at valve sites [19]. An interesting idea, which can be further developed, was recently presented by Page et al. [20,21] to include water discharge forecast within the control logic.

Instead of being dissipated at control valves, the surplus of service pressure can be recovered by installing turbines or pumps operating as turbines (PATs) [22,23]. While the performance of these devices has been analysed in many contexts, e.g., [24–27], including real WDNs, e.g., [28,29], little attention has been given so far to the effects of transients generated by turbines or PAT.

Besides service pressure regulation, WDN management includes other practices such as partitioning. This is done to subdivide the WDN into sufficiently small areas, called district metered areas (DMAs) [1], to facilitate management and monitoring. Numerous algorithms, e.g., [30–35], are proposed in the scientific literature for WDN partitioning, while few comparative analyses are available. Furthermore, since WDN partitioning is generally carried out by making use of the graph theory, a study is missing on the behaviour of WDNs from the topological point of view, to characterize their basic metrics.

While the research on WDNs in the 20th century was mainly dedicated to water quantity aspects, the two first decades of the current century have seen the birth of new research lines concerning water quality. These lines have received nourishment from the changes in the regulations in many countries, which encourage the draft and adoption of water safety plans [36]. A water safety plan is a plan to ensure the safety of drinking water using a comprehensive risk assessment and risk management approach, which encompasses all steps in water supply from catchment to user. In this context, the WDN plays an important role since it can be threatened by events of accidental and intentional contaminations [37–39]. These events can cause supplied water to contain inacceptable concentrations of undesired compounds, such as heavy metals, disinfection by products and so forth. Therefore, methodologies for improving water quality and estimating the vulnerability of WDNs to these compounds should be developed.

2. Overview of the *Special Issue*

The *Special Issue* was established to point out the recent trends on WDNs, with emphasis on the opportunities introduced by technical progress for simulation, design, and management of water distribution systems. The collected papers are representative of some current main research topics in WDNs.

2.1. WDN Simulation and Optimization

Four papers form part of this topic:

- Ciaponi and Creaco [40] present the comparison of five pressure-driven formulations in the context of WDN modelling. The results of two case studies show that the formulations tend to behave similarly in terms of nodal outflows. The formulations with smooth relationship between nodal outflow and pressure head tend to guarantee faster algorithm convergence, in comparison with a relationship with derivative discontinuities. The results yielded by the formulations for low values of the nodal pressure head can be very different;

- Creaco and Pezzinga [41] present the comparison of two different algorithms for the optimal location of control valves for leakage reduction. The former is based on the sequential addition (SA) of control valves: at each step, the optimal combination of valves is searched for, while containing the optimal combination found at the previous step. Therefore, the former algorithm searches for only one new valve location at each step, among all the remaining ones. The latter algorithm consists of a multi-objective genetic algorithm (GA), in which valve locations are encoded inside individual genes. The results obtained on two WDNs show that SA and GA yield identical results for small number of valves. When this number grows, GA performs increasingly better than SA. However, the smaller computation time of SA may make this algorithm preferable in the case of large WDNs;
- Creaco [42] explores the benefits of water discharge prediction in the RTC of WDNs. An algorithm aimed at controlling the settings of control valves and variable speed pumps, as a function of pressure head signals from remote nodes in the network, is used. Two variants of the algorithm are considered, based on the measured water discharge in the device at the current time and on the prediction of this variable at the new time, respectively. The RTC algorithm attempts to correct the expected deviation of the controlled pressure head from the set point, rather than the currently measured deviation. The results of the applications prove that RTC benefits from the implementation of the prediction, in terms of closeness of the controlled variable to the set point;
- Pérez-Sánchez et al. [43] characterize the water hammer phenomenon in the design of PAT systems, emphasizing the transient events that can occur during a normal operation. This is based on project concerns towards a stable and efficient operation associated with the normal dynamic behaviour of flow control valve closure or by the induced overspeed effect. The analysis shows how precise evaluation of basic operating rules depends upon the system and component type, as well as upon the required safety level during each operation, with emphasis on the analysis of transients.

2.2. WDN Topology and Partitioning

Two papers belong to this topic:

- Giudicianni et al. [44] apply Complex Network Theory to characterize the behaviour of WDNs from a topological point of view. A tool of analysis is provided to help in finding solutions to several problems of WDNs. The application of the methodology to 21 existing networks and 13 literature networks highlights some topological peculiarities and the possibility to define a set of best design parameters for ex-novo WDNs. Also, the interplay between topology and some performance requirements of WDNs is discussed;
- Liu et al. [45] present a comparative analysis of three partitioning methods, including Fast Greedy, Random Walk, and Metis, which are commonly used to establish the DMAs in water distribution systems. A complex water distribution network is used for comparison considering two cases, i.e., unweighted and weighted edges, where the weights are represented by the demands. The results obtained from the case study network show that the Fast Greedy method is more effective in the weighted graph partitioning. The study provides an insight for the application of the topology-based partitioning methods to establish district metered areas in a water distribution network.

2.3. Water Quality

Two papers are concerned with water quality issues:

- Quintiliani et al. [46] propose a methodology for estimating the vulnerability with respect to users' exposure to disinfection by-products (DPBs) in WDNs. The presented application considers total trihalomethane (TTHM) concentrations, but the methodology can be used also for other types of DPBs. Five vulnerability indexes are adopted. The results obtained on five case studies suggest that the introduced indexes identify different critical areas in terms of elevated concentrations of TTHMs. This allows identification of the higher risk nodes in terms of different kinds of exposure (short period of exposure to high TTHMs values, or chronic exposure to low concentrations);

- Peng and Mayorga [47] propose a statistical multiple objectives optimization, namely Multiple Source Waters Blending Optimization (MSWBO), to find optimal blending ratios of source waters for minimizing three heavy metals (HMR) in a WDN. Three response surface equations are applied to describe the reaction kinetics of HMR, and three dual response surface equations are used to track the standard deviations of the three response surface equations. A weighted sum method is performed for the multi-objective optimization problem to minimize three HMRs simultaneously. The experimental data of a pilot distribution system are used to demonstrate the model's applicability, computational efficiency, and robustness.

2.4. Service Effectiveness

Two papers consider service effectiveness aspects:

- Jang and Choi [48] estimate the NRW ratio, that is the ratio of losses from unbilled authorized consumption and apparent and real losses to the total water supply. NRW is an important parameter for prioritizing the improvement of a WDN. The paper shows that the accuracy of multiple regression analysis (MRA) is low compared to the measured NRW ratio, where the accuracy of estimation by an artificial neural network (ANN) with the optimal number of neurons, is higher;
- Mokssit et al. [49] propose a methodology for assessing the effectiveness of water distribution service in the context of intermittent supply, based on a comparison of joint results from literature reviews and feedback from drinking water operators who had managed these networks, with standards for defining the effectiveness of drinking water service. The results are used to structure an evaluation framework for water service and to develop improvement paths defined in intermittent networks. The resulting framework highlights the means available to water stakeholders to assess their operational and management performance in achieving the improvement objectives defined by the environmental and socio-economic contexts in which the network operates. Practical examples of intermittent system management are collected from water system operators and presented for illustration purposes.

3. Discussion

All the papers of the special issue are focussed on topics that are at the forefront of the research in WDNs. Besides achieving the expected objectives, they are founded on very accurate reviews of the most recent works in the scientific literature.

Four papers in the special issue namely [40,41,45,49] have the merit of presenting comparative analyses. The results of these works may become a benchmark for future reference and may also offer precious information to orientate future research efforts.

Another merit of the papers in the special issue lies in the fact that the methodology proposed are applied to real WDNs, considering complete or skeletonized layouts. This confers reliability to the results obtained.

The methodologies adopted are multi-faceted, ranging from hydraulic [40–43] and water quality [46,47] modelling, to the graph theory [44,45], statistical [42,48], and optimization [41,47] techniques.

However, the special issue feels the effect of a strong and widespread tendency in the scientific literature, which has recently been producing many more numerical models and mathematical methods than experimental studies for model validation. In fact, only one of the ten papers, namely [43], reports novel experimental results. The others, instead, use literature data for model validation. It is the Authors' idea that the collection of new data from laboratory and in-situ experiments, by means of modern and accurate equipment available nowadays, could enable more accurate validation of numerical models and mathematical methods developed so far.

4. Conclusions

The paper presents an overview on the present research topics on WDNs through the analysis of the literature and of the papers presented in the *Special Issue on Advances in Water Distribution Networks*. The analysis of existing literature is carried out to put in evidence the aspects covered by the research in WDNs. With regards to water quantity, one of the most explored topics is the modelling, both for simulation and for optimisation purposes. Attention is focused on: demand models, pressure driven formulation, hypotheses on flow. In the context of WDN simulation, a paper presented in the special issue compares various pressure driven formulations [40]. With regards to optimisation, although there is a wide consideration of aspects to be optimised, in recent years the regulation of pressure by valves and the recovery of energy surplus by micro-turbines or PATs have assumed a fundamental role. As for WDN optimization, a paper in the special issue presents the comparison of deterministic and probabilistic algorithms for the location of control valves [41]. Another paper of the special issue shows the extent to which RTC of valves can benefit from implementation of water discharge prediction at valve site [42]. Staying in the context of WDN modelling, a paper presented in the special issue concerns energy recovery by means of PATs, with emphasis on the analysis of transients [43].

Along with service pressure regulation, another commonly adopted practice in WDN management is partitioning, which consists of WDN subdivision into small areas, which can be easily monitored and managed. A topic very closely related to partitioning is topology. Numerous algorithms were proposed in the scientific literature for WDN partitioning, generally carried out by making use of the graph theory. A paper presented in the special issue compares WDN partitioning algorithms [45]. Another paper proposes a topological taxonomy of WDNs [44].

The research lines considering water quality aspects have received recent attention from the adoption of water safety plans, to ensure safety of drinking water. Methodologies are currently being developed to improve water quality and to estimate the vulnerability of WDNs, to avoid the risk of contamination of supplied water by undesired substances. As for water quality, two papers were presented in the special issue, concerning assessment of vulnerability to trihalomethane [46] and development of a statistical optimization model to improve drinking water quality through the minimization of heavy metal releases [47], respectively.

Aspects related to service effectiveness have also received increased attention. This is because water authorities need to save water resources and to optimize their financial resources, while meeting users' satisfaction. Besides traditional issues, such as those associated with guaranteeing the suitable service pressure at users' connections, subjects as NRW, and intermittent supply conditions have recently been explored. In the context of the analysis of service effectiveness, the special issue includes two papers. The former concerns estimation of NRW, inclusive of leakage and unauthorized consumption, using multiple regression analysis and artificial neural networks [48]. The latter, instead, proposes a methodology for assessing service effectiveness under intermittent supply conditions [49].

Each of these papers gives contributions on the research in WDNs and gives possible research topics to be developed in the future.

Funding: This research received no external funding.

Acknowledgments: This research was conducted using the funds supplied by the University of Pavia and by the University of Catania.

Conflicts of Interest: The author declares no conflict of interest.

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