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Multi-Objective Optimal Design of Water Distribution Networks Accounting for Transient Impacts

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Abstract

Transients are commonly triggered in urban water distribution networks (WDNs) due to daily system management and operation. While these transients are unlikely to cause catastrophic consequences immediately, frequent occurrences can result in prolonged deterioration of infrastructure safety and life cycles in the long term. To account for such impacts in the design of WDNs, a multi-objective optimization method coupled with the Non-dominated Sorting Genetic Algorithm III is proposed in this paper, where two transient-based objectives are incorporated into the WDN design process. Additionally, an engineering design constraint in the decision space is developed to ensure that the sizes of upstream pipes are not smaller than those downstream, thereby improving the engineering practicality of the optimal design solutions. Two WDN cases with transient conditions triggered by pump switching are applied to demonstrate the effectiveness of the proposed method. The results show that the widely used reliability metric based on steady-state conditions is unable to fully represent the transient impacts and that upsizing pipes can reduce transient impacts but at the expense of high economic costs. It is also found that optimally designed pipe diameters can be effective to mitigate transient impacts, in addition to the use of traditional protection devices. The proposed method represents the first step in investigating the underlying relationships between WDN design and unsteady flow effects and is a supplement to current WDN design criteria.

Keywords Water distribution networks (WDNs) · Multi-objective optimization · Hydraulic transients · WDN reliability

1 Introduction

Urban water distribution networks (WDNs), generally composed of different components such as pipes, reservoirs, tanks, valves, and pumps, have been an essential part of urban infrastructure systems because of the important function of the water supply as a basic need for daily

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Extended author information available on the last page of the article life. Therefore, extensive attention has been paid to the optimal design and management of WDNs for enhancing their efficiency and sustainability over the past decades. To this end, WDN design requirements have been shifting from a single objective of economic considerations in early years to a comprehensive multi-objective design in recent years (Zheng et al. 2016). Among the various multi-objective approaches for WDN design, reliability-related approachesones have been proposed and developed as an important and essential category, which is mainly motivated by the increasing awareness of sustainability requirements for the operation and management of WDNs (Raad et al. 2010; Zheng et al. 2017). Recently, so-called reliability surrogate measures (RSMs) have been prevalent due to the strong positive correlations of these RSMs with system reliability and their capacities to assess reliability accurately and explicitly (Todini 2000; Raad et al. 2010). For example, network resilience index (*NRI*), as a RSM, has been proven to provide promising synthetic performance in terms of hydraulic reliability due to its consideration and formulation of both nodal surplus power and diameter uniformity for pipes (Raad et al. 2010). Therefore, in the formulation of multi-objective problems in the current paper, the *NRI* is selected as a separate objective to represent the overall reliability of a WDN.

While the above-mentioned approaches have made significant contributions to the optimal design of WDNs, they all are supposed to achieve the objectives in the context of steady-state conditions. However, in realistic WDNs, transient flow conditions commonly exist due to normal and/or abnormal operation in the system, such as pump switch/trip, valve manipulation, demand fluctuation, and pipe break (Meniconi et al. 2015; Rathnayaka et al. 2016; Brunone et al. 2018). According to the potential consequences, these transient conditions can be basically divided into two categories as follows (Starczewska et al. 2015). One is attributed to catastrophic failure, which is due to the potential high-magnitude (over the strength limit) forces caused by fast pressure transient events, such as pump trip, fast valve closure, and main break (Boulos et al. 2005). The other category is fatigue-like failure due to the prolonged impact of relatively small-moderate magnitude and high-frequency transient occurrences over a long time in the system (e.g., daily switching of pumps, regular valve operation and demand fluctuation). This second type of transient has been addressed and increasingly emphasized in this field (Stephens et al. 2017). Recent field surveys in the literature on transient events in WDNs have revealed that there are various random and/or repeated transients with relatively small-moderate magnitudes (e.g., in the range of 5~20 m) but high-frequency occurrences (e.g., on the order of 1 Hz) in WDNs, which have been very underrated or unexpected by water utilities (Aisopou et al. 2012; Stephens et al. 2017).

Due to the significant impact of catastrophic transient conditions on WDN safety, many design and operation approaches have been developed to evade or suppress such transient conditions, such as rerouting pipelines, regulating valve operations, and deploying air vessels or surge tanks (Boulos et al. 2005; Ghidaoui et al. 2005; Duan et al. 2010). However, so far, very little attention has been paid to coping with the impact of such high-frequency and small-amplitude transients on WDNs, which indeed commonly occur and exist in real-life WDNs. To address this issue, this paper aims to develop an improved design framework (i.e., pipe sizing) to explicitly reduce these transient impacts in WDNs by incorporating the long-term transient impacts into the design process. More specifically, given that the daily demand variations of domestic users are unlikely to produce transients with significant magnitudes, this paper considers transients generated by pump operation for a WDN with a single demand scenario because pumps are often routinely operated in many WDNs to cater to daily demand variations. It should be noted that these intentional operations frequently generate transients but often with relatively small-moderate magnitudes, which should be significantly lower than those generated by accidental events (e.g., sudden power off, Meniconi et al. 2015).

While many water hammer devices are available to handle such transients within WDNs, this paper aims to develop a method to reduce transient impacts through pipe sizing in the design stage, which can also be practically useful. This is because (i) many WDNs do not have water hammer devices installed due to the water delivery properties (e.g., for WDNs with pumps directly connected to the distribution pipes) as well as their associated high maintenance costs, and (ii) for WDNs with water hammer devices, pipe sizing during the design stage can work jointly with these devices in the operation stage to effectively reduce the transient effects. It should be highlighted that this paper does not intend to indicate that the transients can be fully controlled by pipe sizing in the design stage but that it can be considered as an alternative to partly mitigate their impacts, in addition to many other transient handling methods (e.g., protection devices).

In addition to the lack of consideration of transient impacts in the context of traditional WDN design, most previous studies in this field conducted multi-objective optimization with constraints considered only in the solution space, e.g., the minimum/maximum pressure, the velocity range, and the tank level range (Wu et al. 2013; Zheng et al. 2014; Shokoohi et al. 2017). However, these proposed constraints in the solution space may not guarantee the feasibility of solutions in the decision space. For instance, from an engineering application perspective, the size of a designed pipe in the upstream region is usually required to be not smaller (equal or larger) than the pipes in its immediate downstream connections. Nevertheless, such design criteria cannot be explicitly included as constraints in the solution space, and thus, the traditional design method is likely to result in impractical solutions that cannot be well implemented (thus become useless) in practice. As a result, implementing these constraints in the decision space becomes crucial to ensure the practicality of WDN design results, which is achieved by the improved method in this paper.

This paper aims to develop a multi-objective optimization framework of WDN design that includes four objectives: minimizing transient adverse impacts (for two objectives), minimizing network cost and maximizing hydraulic reliability. Additionally, the constraints defined for the decision space are implemented in the multi-objective WDN design framework to enhance the practicability of the design results. The Non-dominated Sorting Genetic Algorithm III (NSGA-III) is adopted to solve this multi-objective optimization problem. The contributions/novelties of this paper include (i) the development of a new multi-objective optimization framework to investigate the underlying relationship between WDN design and unsteady flow effects, which is a supplement to current WDN design criteria, and (ii) the proposal of an engineering design constraint in the decision space that can significantly improve the practicality of the final optimal solutions. Two WDN cases are then applied to demonstrate the feasibility and validity of the developed method and solution procedure in this study. The application results are analysed and discussed for practical applications of WDN design. Finally, the results and findings from this study are summarized at the end of this paper.

2 Methodology

The methodology of the proposed multi-objective optimization framework of WDN design accounting for transient impacts is presented. Firstly, the metrics for transient fluctuations are defined to quantify transient impacts, followed by the formulation of the multi-objective optimization model for WDN design, in which an engineering design (ED) constraint is defined and incorporated in the decision space. The NSGA-III (Jain and Deb 2014) is adopted to enable the optimization by implementing the proposed constraint in the decision space. In the following study, two cases of a hypothetical looped network and a large-scale realistic WDN are investigated to demonstrate the utility of the proposed method and application procedure, respectively.

2.1 Metrics for Transient Fluctuations

Traditional design of WDNs regarding transient impacts generally focuses on the possible transient events that may result in catastrophic failure (i.e., worst-case loadings) (Boulos et al. 2005). As a result, few explicit guidelines, rules and standards have been developed for the non-extreme transient conditions occurring frequently in the daily operation of WDNs that can result in fatigue-like failure in the long term. In this regard, it is necessary to define usable metrics to evaluate the impacts of transient pressure fluctuations in WDNs under relatively high-frequency and small-moderate amplitude transient conditions. This is the first objective of this study and is addressed in this section.

Figure 1 presents a typical process of pressure fluctuations at a node during a transient event (the solid blue lines). For transient analysis, the head trajectory for each situation can be characterized by the key parameters as follows: H_0 – the initial steady-state head before the transient condition, H_{end} – the final steady-state head when the transient state stabilizes, and H_{max} and H_{min} – the maximum and minimum heads during the transient condition, respectively (Radulj 2010). It is worth noting that H_{max} or H_{min} is not necessarily shown in the first or second oscillation peaks (as shown in the current example cases in Fig. 1) during the transient process and can also be equal to H_0 or H_{end} for the cases where the transient fluctuation does not exceed the range between H_0 and H_{end} during the transient state transition process. To quantify the transient process, the metrics for transient fluctuations are defined as follows:

$$\Delta H_{steady} = |H_0 - H_{end}| \tag{1}$$

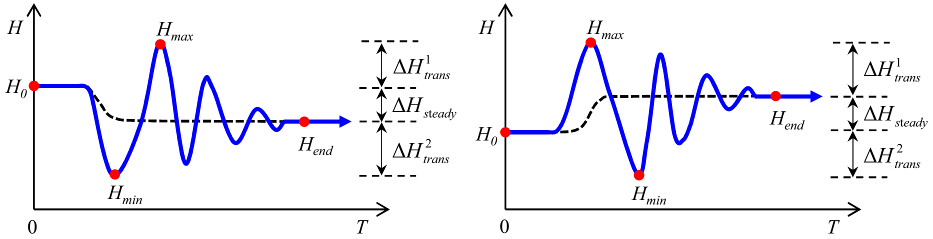
$$\Delta H^1_{trans} = H_{\max} - \max(H_0, H_{end}) \tag{2}$$

$$\Delta H^2_{trans} = \min(H_0, H_{end}) - H_{\min} \tag{3}$$

where ΔH_{steady} is the steady-state head change between the pre-transient and final states, indicating the resultant "targeted" state change by a specific operation, such as a pump switch due to demand variation, and ΔH^1_{trans} and ΔH^2_{trans} are the extra head fluctuations due to positive and negative transient conditions, respectively, revealing the extra transient impacts on the steady-state change (i.e., additional stresses on the pipe wall, fittings, supports, etc.).

For the safety and reliability of WDNs, it is preferable that the head change of state transitions from H_0 to H_{end} be small and fluctuate as little as possible (i.e., the black dotted lines shown in Fig. 1). That is, the extra head fluctuations ΔH^1_{trans} and ΔH^2_{trans} are expected to be small enough. Mathematically, the metric for quantifying the impacts of transient fluctuations can be further expressed as

$$TF = \max\left(\Delta H^1_{trans}, \Delta H^2_{trans}\right) \tag{4}$$



(a) $H_0 > H_{end}$ (b) $H_0 < H_{end}$

Fig. 1 Illustration of metrics for transient fluctuations

where *TF* is the factor indicating the transient impact that is to be minimized for the optimal design of WDNs.

Based on these explicit expressions, a transient condition induced by a specific operation/event in the system can be evaluated in the optimal design model. Among all possible sources that may trigger transient events, daily pump operation (scheduling with switching on or off) is one of the most common factors in pumping systems (Starczewska et al. 2015; Stephens et al. 2017), which is thus applied for demonstration in this paper. Note that the developed method and procedure in this study are also applicable to any other transient sources (e.g., valve operation, daily demand variation) in WDNs.

2.2 Multi-Objective Problem Formulation

The WDN design problem presented in this paper can be formulated as a multi-objective optimization problem, in which the decision variables considered are the sizes of the pipes for the given WDN layout, i.e., $\mathbf{D} = [D_1, D_2, \ldots, D_n]^T$, where D_i is the diameter of pipe i and n is the total number of pipes being considered. Within the design problem, four objectives are considered for this study, including (i) minimizing the network cost, (ii) maximizing the hydraulic reliability, and (iii) minimizing the transient impacts of daily pump switching as expressed in Eq. (4), which consists of two respective objectives, as presented in the following study. Additionally, commonly used constraints and a new constraint in the decision space are imposed in the four-objective design problem. The formulation of the multi-objective problem proposed in this paper can be given as follows.

Objectives:

$$\text{Minimization } C_T = \sum_{i=1}^{n} C(D_i)L_i \tag{5}$$

$$\text{Maximization } NRI = \frac{\sum_{j=1}^{m} U_j Q_j \left(H_j - H_j^{req}\right)}{\left(\sum_{r=1}^{R} q_r H_r + \sum_{k=1}^{npu} \frac{P_k}{\gamma}\right) - \sum_{j=1}^{m} Q_j H_j^{req}} \tag{6}$$

$$\text{Minimization } TF_{mean} = \sum_{j=1}^{m} TF_j / m \tag{7}$$

$$\text{Minimization } TF_{\max} = \max\left(TF_j\right) \tag{8}$$

Constraints:

$$\text{Diameter choices}: \quad D_i \in \mathbf{S}, \quad i = 1, \dots, n \tag{9}$$

$$\text{Nodal pressure constraints}: \quad H_j \geq H_j^{req} \tag{10}$$

$$\text{Pipe velocity constraints}: \quad V_i \leq V_i^{\max} \tag{11}$$

$$\text{Hydraulic constraints}: \quad \mathbf{H} = f(\mathbf{D}) \tag{12}$$

$$\text{Defined ED constraints}: \quad \max\left(\mathbf{\Omega}_j^u\right) \geq \max\left(\mathbf{\Omega}_j^d\right) \tag{13}$$

where Eqs. (5–8) present the four objectives considered in this study, Eqs. (9–12) are commonly used constraints in WDN design approaches and Eq. (13) is the newly defined constraint that ensures that the sizes of pipes upstream are not smaller than those downstream. For the objectives in Eqs. (5–8), C_T is the total cost of pipes, *NRI* is the representative RSM for the hydraulic reliability, and TF_{mean} and $TF_{\max}$ are the mean and maximum *TF* values of all the nodes in the WDN and describe the average and maximum levels of transient impacts, respectively. More specifically, in Eq. (5), L_i is the length of pipe *i*; $C(D_i)$ is the cost per unit length of pipe *i* for diameter D_i, which comprises the pipe material cost and construction cost; and, *n* is the total number of designed pipes in the given WDN. In Eq. (6), Q_j, H_j and H_j^{req} are the demand, actual head and minimum required head of node *j,* respectively; *m* is the total number of nodes; q_r and H_r are the discharge and actual head of supply source *r,* respectively; *R* is the number of supply sources (reservoirs and tanks); P_k is the power of pump *k*; γ is the specific weight of water; *npu* is the number of pumps; U_j is the diameter uniformity of node *j*, which can be expressed as $U_j = \sum_{p=1}^{npj} D_p / (npj \times \max\{D_P\})$; D_p is the diameter of pipe *p* attached to node *j*; and *npj* is the number of pipes attached to node *j*.

For the constraints in Eqs. (9–13), **S** is the set of available diameters of pipes; $V_i^{\max}$ is the maximum allowable velocity for pipe *i* (Shokoohi et al. 2017); $\mathbf{H} = [H_1, \dots, H_m]^T$ is the vector of node head; and $\mathbf{\Omega}_j^u$ and $\mathbf{\Omega}_j^d$ represent the sets; of upstream and downstream pipes connected to node *j*, respectively. Note that the hydraulic constraints in Eq. (12) consist of nonlinear equations of both steady-state and transient hydraulic models, which are solved by the freely available solver EPANET2 and the Method of Characteristic (MOC) that have been widely validated and applied in the literature (Rossman 2000; Ghidaoui et al. 2005).

The objectives C_T and *NRI* in Eqs. (5) and (6) are the traditional ones to be minimized and maximized, respectively, for the multi-objective design of WDNs, and the objectives TF_{mean} and $TF_{\max}$ in Eqs. (7) and (8) are proposed to be minimized to reduce the transient impacts of daily pump switching in the design stage. The newly defined ED constraint in Eq. (13) is implemented to ensure the engineering practicality of the optimal solutions for this multi-objective optimization problem. It should be noted that the proposed ED constraint is applicable to pipes with fixed flow directions. Therefore, an extended period simulation may be needed for WDNs considering multiple demand scenarios to exclude pipes with variable flow directions from Eq. (13).

2.3 Improvement of the Optimization Method

In this study, the up-to-date method NSGA-III, developed by Jain and Deb (2014), is used as the optimization method for the proposed WDN design framework. NSGA-III is an extension of its former version, NSGA-II, with improved performance in dealing with many-objective optimization problems. This is because NSGA-III utilizes a new selection mechanism based on reference points as well as implementing relevant operations of association and niche preservation. As a result, NSGA-III is more capable of maintaining the diversity of solutions and thus is more effective for many-objective optimization problems than NSGA-II as demonstrated by Jain and Deb (2014). In addition, the constraints in the solution space (Eqs. (10–11)) can be directly considered by a modified tournament selection operation in NSGA-III (Jain and Deb 2014).

To implement the newly proposed ED constraint in Eq. (13), a priori processing in the decision space is required to find feasible solutions with sufficient diversity, especially for large-scale WDNs. This is due to the enormous distributions of the decision space and thus the extremely low probability of finding feasible solutions that satisfy the ED constraint. To this end, this paper proposes an enhanced version of NSGA-III with an update strategy for the population prior to the evaluation of the objective functions for individuals in the population, as shown in Fig. 2.

Specifically, the update strategy is developed to satisfy the ED constraint in the decision space during the whole evolution process of multi-objective WDN design. As shown in Fig. 2, this strategy updates each individual of the offspring population generated from the recombination and mutation operations in NSGA-III by iteratively exchanging the values of the variables (i.e., pipe diameters) that violate the ED constraint given by Eq. (13) until the upstream and downstream relationships of pipes at all nodes are consistent with the calculated flow directions and the ED constraint definition. With this update strategy, the populations during the optimization process, including the initialized ones and the generated ones from the recombination and mutation operations, can always satisfy the ED constraint, which significantly improves the search efficiency of the optimization method.

3 Case Studies

3.1 Description of Studied Cases

To demonstrate the effectiveness and applicability of the proposed method, two case studies with different complexity levels of WDN configurations are used in this paper. The first case is a relatively simple hypothetical network system with 32 pipes, 29 nodes and a supplied pump station at the source node (i.e., node 1), as shown in Fig. 3a. This case with a limited number of pipes and nodes is mainly applied to demonstrate the principle and procedure of the developed method framework in this study. The second case represents a real-world WDN (Fig. 3b) and is adapted from He et al. (2018). The WDN in this case consists of 449 pipes, 300 nodes and

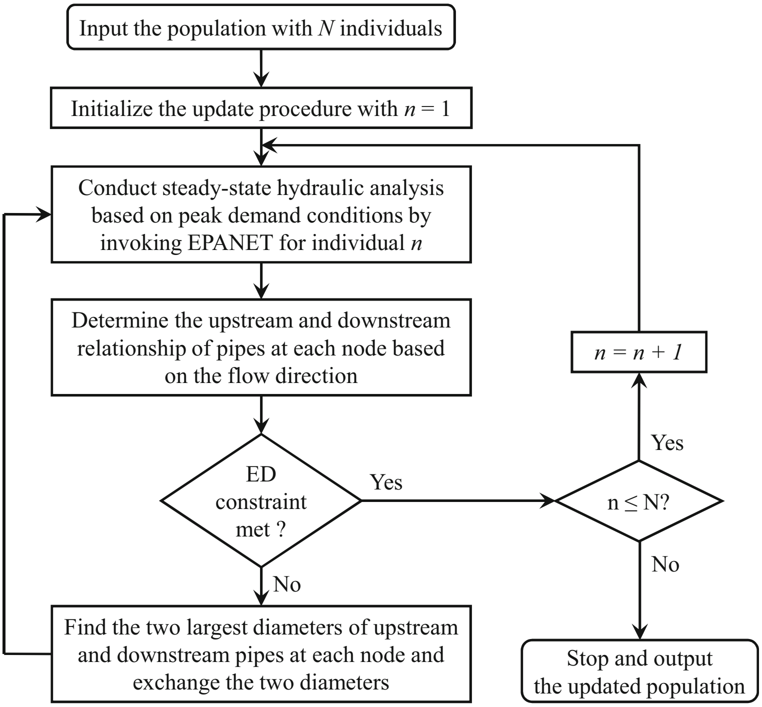


Fig. 2 The proposed update strategy for implementing the new ED constraint in multi-objective optimization-based WDN design

two supplied pump stations at two water supply sources and is applied in this study to demonstrate the feasibility and effectiveness of the developed method for practical applications. For demonstration, the three pump stations in these two WDNs are assumed to have similar configurations, consisting of a source reservoir, two parallel pumps and two control valves downstream of each pump for delivering water through a transmission line, as illustrated in Fig. 3.

The transient conditions triggered by the pump switching off during the daily pump scheduling, combined with the initial steady-state conditions of peak demand, are selected to determine the transient-based objectives in the optimization method in this paper. The rationale behind this approach is that this combination is more likely to be the "worst case" in terms of the transient effects, as the pipe velocities are high overall in the peak demand scenario, which can result in relatively large transients (Boulos et al. 2005; Rathnayaka et al. 2016). Specifically, it is assumed that the prescribed transient event for the two cases is triggered by the switching off of a pump at the pump station with the downstream control valve closing in 10 s. Moreover, the most unfavourable operation condition of case 2, with synchronous pump switch-offs at both pump stations, is used for the analysis. However, as transient dynamics within WDNs can be very complex due to wave reflections and overlaps at different boundary conditions induced by various point sources, a future focus along this research line should be the identification of the true "worst case" with the consideration of more likely transient conditions (Starczewska et al. 2015).

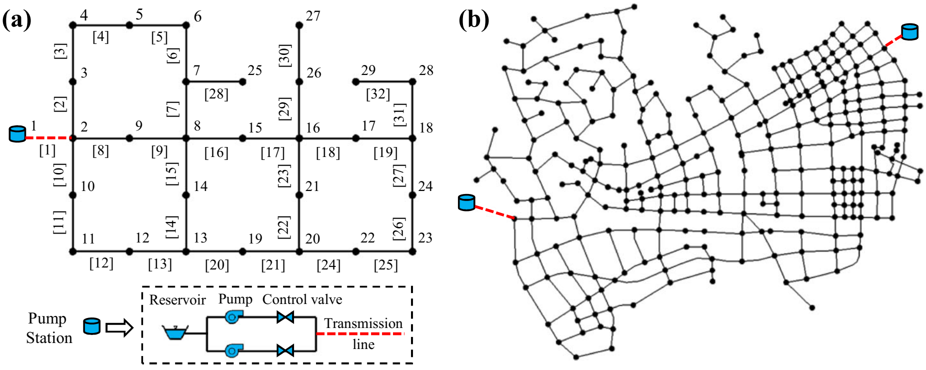


Fig. 3 Network layouts of the two cases

3.2 Design Information and Conditions

The proposed multi-objective optimization method is applied to each of the two cases shown in Fig. 3. Note that the diameters of transmission lines connected to the pump station can be directly determined based on the system requirements and engineering knowledge, as they are very short in length (the red lines marked in Fig. 3). As a result, the number of decision variables (i.e., the diameters of pipes to be determined) for these two cases is 31 and 447, respectively. In addition, the minimum allowable pressure for each node is set to 15 m and the maximum allowable velocity for each pipe is set to 3.0 m/s in this study (Shokoohi et al. 2017). The diameter of each pipe is selected from a set of commercially available pipe sizes: [150, 200, 250, 300, 350, 400, 450, 500, 600, 700, 750, 800, 900, 1000] mm, with the corresponding cost per unit length taken from Kadu et al. (2008) for illustration purposes in this study. Accordingly, the total search space is 14^{31} and 14^{447}, respectively, for these two cases and is to be optimized by the method developed in this paper to obtain the most suitable design results. Furthermore, considering that the wave speed of a pipe is related to the pipe diameter (assuming that the pipes used for WDN design are all ductile iron pipes with common commercial sizes for wall thickness), the wave speed for each pipe type is estimated for each of the available pipe sizes listed above as follows: [1300, 1300, 1200, 1200, 1200, 1100, 1100, 1100, 1000, 1000, 1000, 900, 900, 900] m/s. The consideration of varying wave speeds for different designed pipe sizes aims to achieve more realistic design results.

Steady-state hydraulic simulations are performed for the single demand scenario of peak demand (which is commonly used for WDN design) with the aid of the EPANET2 solver (Rossman 2000). Taking the steady-state simulation results as the transient initial conditions, the transient simulations are carried out by the classic 1-D water hammer model, with the widely used MOC coupled with a quasi-steady friction term (Ghidaoui et al. 2005). To enable reliable transient simulations for the two cases in the optimization process, the computational time steps are set to be sufficiently precise (i.e., 0.05 s for both cases) to satisfy the Courant condition. The total durations of the simulation scenarios are set to 150 s and 100 s, respectively, which are sufficient to achieve the final steady-state pressure (i.e., H_{end}).

With regard to the implementation of the NSGA-III algorithm, an initial population of 1000, which results in 969 reference points in the four-objective space, is used for both cases to maintain a well-spread diversity of solutions on the basis of results from a number of test runs. A maximum generation of 1000 (thus, a maximum evaluation of 969,000) is adopted to obtain the final solutions. Three random-seed replicate runs are conducted to avoid the influence of the randomness underlying the nature of GAs, and the obtained non-dominated solutions are then aggregated to yield a final optimal solution set by using the selection mechanism of NSGA-III. It is noted that the WDNs in both cases only have one demand scenario (peak demand); hence, the flow directions are determined using this single demand scenario to enable the application of the proposed ED constraint. For such implementations, PlatEMO, a MATLAB platform for evolutionary multi-objective optimization developed by Tian et al. (2017), is used to facilitate the coding work.

For comparative analysis, another implementation of the proposed method framework without the ED constraint is also performed for these two cases so that the results can be compared with those obtained by the method with the ED constraint. This comparison may provide a direct demonstration and highlight the improvement of the solution practicality by the new ED constraint proposed in this paper.

4 Results and Discussion

4.1 Tradeoffs of Different Design Objectives

Based on the improved NSGA-III in Fig. 2, Pareto approximate sets of 969 solutions are generated for each of the two studied cases respectively for quantitative analysis. Figures 4 and 5 show all the bi-objective subsets retrieved from the results of the four-objective optimization for the two cases, respectively, with the approximate Pareto fronts of cost versus the other three objectives highlighted by marked solutions (i.e., blue for cost versus the *NRI*, orange for cost versus TF_{mean}, and pink for cost versus TF_{max}). The arrows on the axes indicate the directions of increasing preference for the design. As shown in Figs. 4a–c and 5a–c, clear tradeoff relationships between network cost and any of the other three objectives can be observed for both studied cases, indicating that an increase in the network cost would generally benefit the performance of both steady-state-based and transient-based objectives in WDN design (i.e., enhancing the hydraulic reliability and reducing the transient impacts). This is unsurprising because an increase in network cost may enlarge the pipe sizes and thus slow down the flow velocities in the pipelines, improving the system capacity of adapting to demand fluctuations, pipe failures and pressure fluctuations.

However, the three approximate Pareto fronts (as marked by the solutions in blue, orange and pink colours) shown in Figs. 4 and 5 for both cases appear to barely overlap or be close together according to their discrete distributions in the solution spaces in the figures. This implies relatively complex relationships among the objectives of the *NRI*, TF_{mean} and TF_{max}. That is, the solutions that are high performing for one objective may fail for the other two objectives. Such conflict among the design solutions for different objectives reveals the importance of multi-objective design of WDNs with consideration of both steady and transient impacts in the system.

In addition, an interesting trend can be observed in Figs. 4d–f and 5d–f for cases 1 and 2, respectively, in which the subsets of the *NRI* versus TF_{mean}, the *NRI* versus TF_{max} and TF_{mean} versus TF_{max} appear as funnel-shaped solution spaces with the bottoms oriented towards the directions of increasing preference of the design objectives. This general trend indicates that weak correlations exist among the objectives of the *NRI*, TF_{mean} and TF_{max}, implying the relative independence of these three objectives for WDN design. In addition, the bottom directions of the funnel-shaped solution spaces reveal that the competitive tradeoffs of these three objectives become less intense in the directions of their increasing preferences. Hence, it is more likely to select solutions with fewer such tradeoffs among these objectives that are close to the bottom regions of the funnel-shaped solution spaces. With these complex relationships among different design objectives, it is necessary to further explore specific solutions to analyse the WDN performance, as presented in the following section.

4.2 Discussion of the Design Schemes

Figure 6 demonstrates four globally high-performing solutions (denoted as S1, S2, S3 and S4) from the multi-objective optimization results of studied case 1 to further explore the underlying system characteristics related to the objectives. As shown in Fig. 8a–c, these solutions represent different sets of quasi-optimal solutions with the highest performance for one objective (i.e., S1 and S3 are the approximate Pareto solutions of cost versus the *NRI*, and S2 is the approximate Pareto solution of cost versus TF_{mean}) or with a performance compromise for all objectives (i.e., S4 achieves well-balanced tradeoffs among all four objectives). Figure 6d shows a parallel line plot of the four selected solutions to clarify the differences among these solutions. Moreover, the corresponding network layouts of WDN design for the four solutions are shown in Fig. 7 to investigate the detailed system characteristics.

As shown in Fig. 6, schemes S1 and S2 have similar network investment costs but show very different performance in the other three design objectives. Comparatively, S1 provides a relatively higher *NRI* (i.e., benefitting the hydraulic reliability) and higher TF_{mean} and TF_{max} (i.e., failing the transient-based objectives) than S2. Accordingly, the network configurations of these two solutions shown in Fig. 7 reveal very different characteristics in the distributions of designed pipe diameters (denoted by different colours). Overall, the distribution of pipe

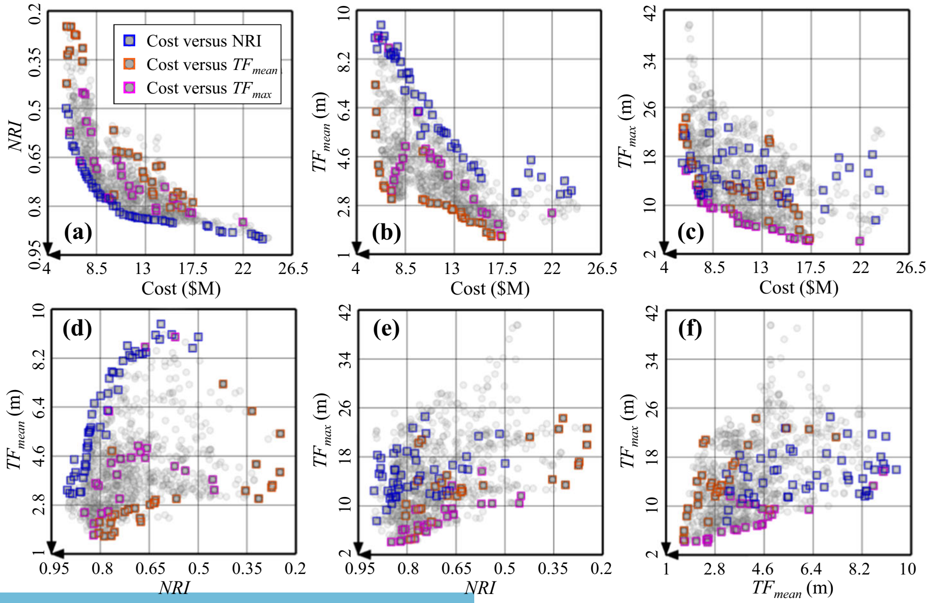


Fig. 4 Bi-objective subset plots in the context of the four objective-based WDN design for case 1 (axial arrows indicate directions of increasing preference)

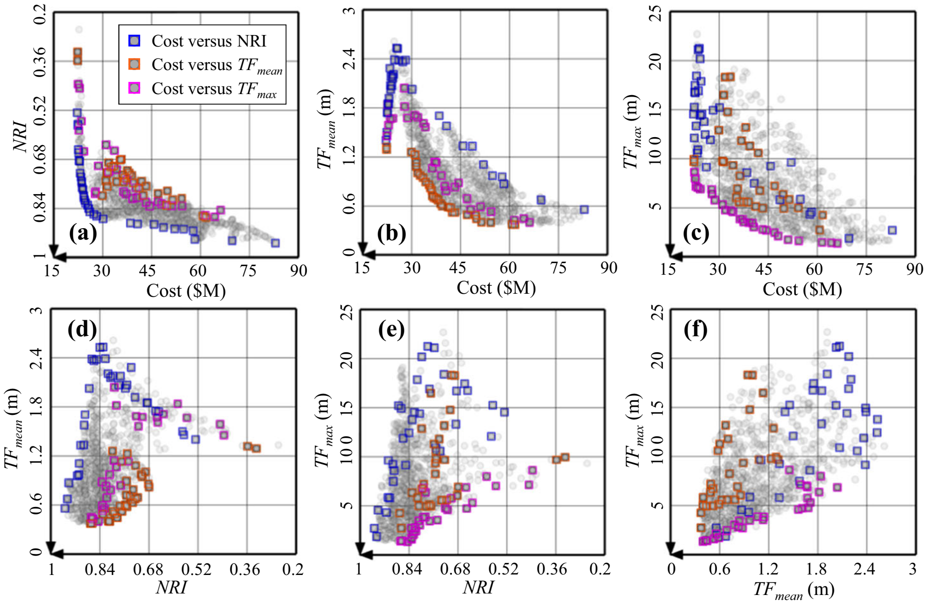


Fig. 5 Bi-objective subset plots in the context of the four objective-based WDN design for case 2 (axial arrows indicate directions of increasing preference)

diameters at nodal connections in S1 is more regular than that in S2. Therefore, it is understandable that the hydraulic reliability of S1 is much greater than that of S2 according to the WDN design assessment criteria. An underlying reason for the difference between the transient-based objectives for the two solutions could be attributed to the influence of these different system characteristics on the propagation of transient pressure waves. In detail, a larger difference in pipe attributes (e.g., pipe diameters) at nodal connections may result in more intense transmission and reflection of pressure waves at this boundary when travelling through it. For this general propagation mechanism, the pipe network of S2 has a greater diversity of pipe diameters and presents more intense wave transmission at boundaries; thus, the overlapping of pressure waves through loops and branches attenuates the transient fluctuations at a faster rate.

Compared to S1 and S2, S3 has a much greater network cost and thus achieves a substantial improvement in the *NRI*, as shown in Fig. 6. However, S3 shows relatively poorer performance for TF_{mean} and TF_{max} than S2, which implies that increasing the network cost may not necessarily be effective in reducing transient impacts. In contrast, with a reduced network cost, S4 performs better in the transient-based objectives than S3, with very little performance reduction for the *NRI*. In addition, compared to S2, S4 achieves comparable TF_{mean} and TF_{max} even with increasing network cost and *NRI*. As a result, the comparison of S2, S3 and S4 suggests that the transient-based objectives would thoroughly compromise with the traditional steady-state-based objectives (i.e., the network cost and *NRI* in this paper) to obtain solutions with well-balanced and good overall performance (e.g., S4 in this case). In addition, S2 is not practical from an engineering design perspective due to the relatively large differences in the designed pipe diameters at some joint connection nodes (e.g., node 10 with diameters of 1000 mm and 150 mm). Such impractical solutions would often be excluded through a decision-making process as that performed in this paper; hence, S4 is ultimately selected for this design problem.

Furthermore, as shown in Fig. 7, the system characteristics of S3 and S4 are significantly different in the distributions of pipe diameters, especially for the pipes at the bottom left of the networks. Specifically, the diversity of pipe diameters is much greater in S4 than in S3, which is similar to the case in S1 and S2. Therefore, it can be inferred that increasing the diversity of pipe diameters could yield a reduction in transient impacts for this particular network structure. To further confirm this, an example from case 2 is also presented herein and shown in Fig. 8. For illustration, two solutions with nearly identical network costs are selected: the one in Fig. 8a showing a relatively high *NRI*, TF_{mean} and TF_{max} and the other in Fig. 8b having a well-balanced overall performance in these three objectives. As shown in Fig. 8, the first solution achieves a network with a relatively uniform distribution of pipe diameters (i.e., most pipe diameters are within 500~800 mm), while that in the second solution shows a much greater diversity of pipe diameters, with much lower values of TF_{mean} and TF_{max} as well. Hence, this again confirms the influence of transient-based objectives on WDN design with regard to the diversity of pipe diameters.

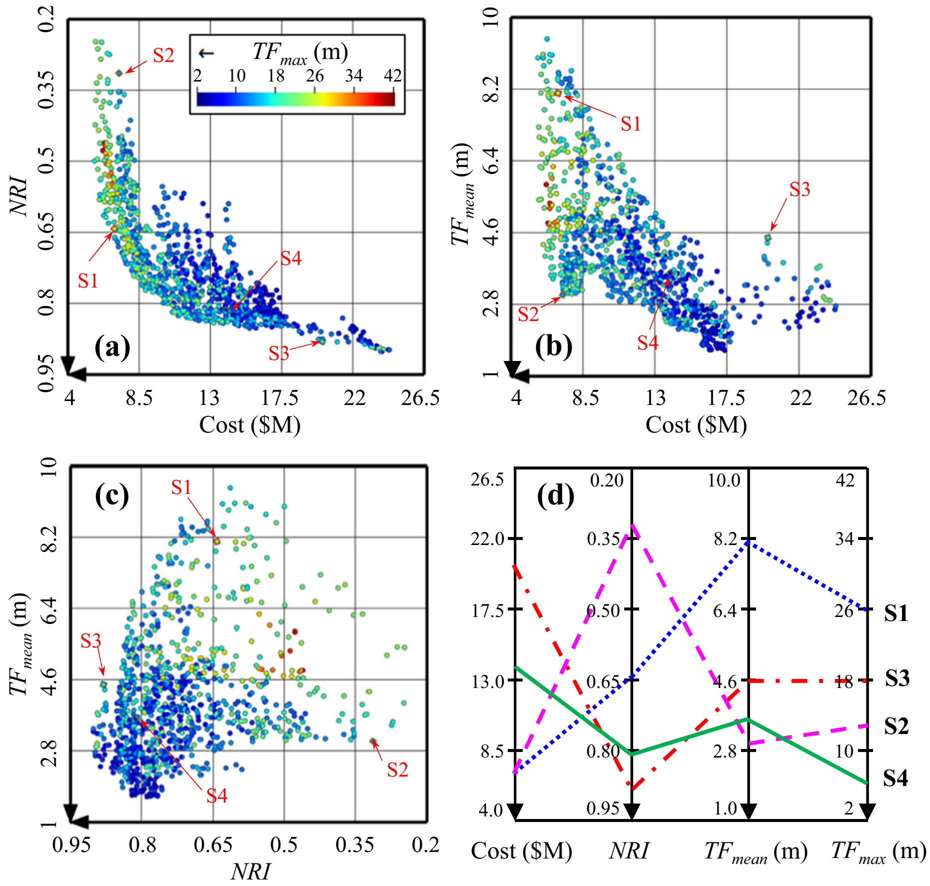


Fig. 6 Illustration of four high-performing solutions for case 1 with **a**–**c** 2-D plots of cost versus the *NRI*, cost versus TF_{mean} and the *NRI* versus TF_{mean}, respectively, and **d** a parallel line plot with each line across four objectives representing a solution (axial arrows indicate directions of increasing preference)

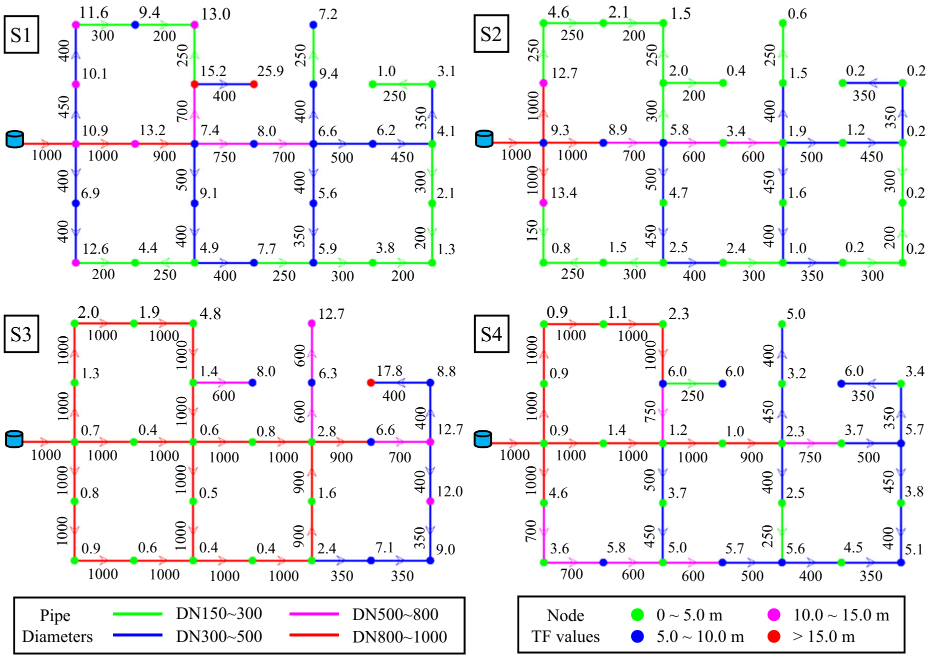


Fig. 7 Layouts of WDN design for the four selected solutions for case 1 (arrows on the pipes indicate the steady-state flow directions)

4.3 Improvement of Solution Practicality by Implementing the ED Constraint

For quantitative analysis of the effect of the newly proposed ED constraint in the decision space (i.e., Eq. (13)), WDN design has been conducted for the two studied cases with and without including this ED constraint, and the obtained Pareto approximate sets are retrieved for comparative analysis in this section. The optimal solutions are shown in Fig. 9 with different circles in the bi-objective subsets for the two cases, i.e., the solid grey circles represent solutions with the ED constraint, and the solid blue and red circles represent the practical and impractical solutions without the ED constraint, respectively, based on posteriori.

Figure 9 shows that the majority of solutions produced by the traditional optimization method without the ED constraint are impractical; that is, most of the obtained solutions have violated the ED constraint (i.e., red circles in the figure). More specifically, the statistical analysis of the WDN design results without the ED constraint indicates that approximately 84.3% and 98.3% of the feasible solutions from the multi-objective optimization processes for cases 1 and 2 are not practical for engineering design, respectively, according to realistic design requirements (e.g., the ED criterion). In comparison, 100% of the feasible solutions obtained by the developed design method implementing the newly proposed ED constraint are practical for this engineering purpose. In this regard, it can be concluded that the solution practicality could be greatly improved by applying the ED constraint in the decision space based on the WDN design results of the two studied cases in this paper. It is also necessary to note that the extent of improvement of the solution practicality by incorporating this ED constraint may vary with different design conditions of WDNs in practice, such as the system scale, hydraulic conditions, and design requirements.

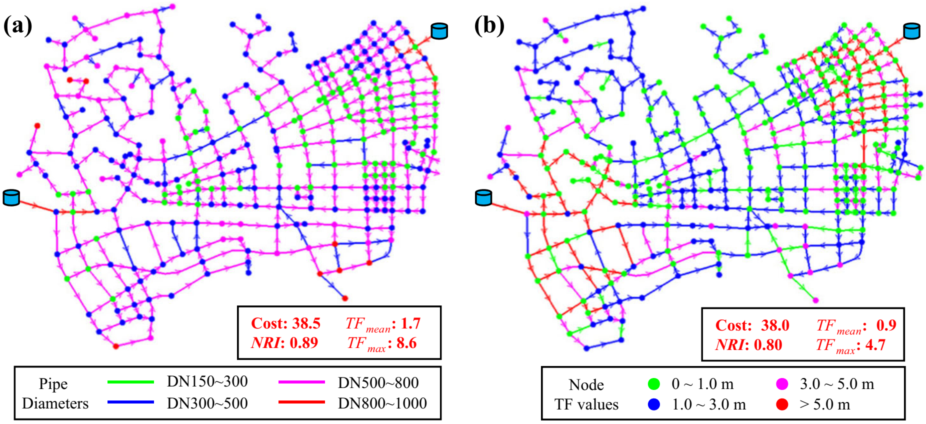


Fig. 8 Layouts of two selected solutions for case 2 (arrows on the pipes indicate the flow directions)

5 Summary and Conclusions

Urban water distribution networks (WDNs) often present relatively high complexities in their topological configurations and hydraulic performance. The optimal design of WDNs, with many different objectives, may provide many benefits in urban development. To this end, a multi-objective-based optimal design process is necessary for better operation and management of WDNs. This paper develops a four-objective optimization framework for WDN design by accounting for transient impacts through upgrading the optimization method (NSGA-III) and implementing a newly proposed engineering design (ED) criterion. The four objectives include minimizing network cost, maximizing hydraulic reliability (i.e., the network resilience index, *NRI*) and minimizing transient impacts (i.e., the mean transient fluctuation, TF_{mean}, and the maximum transient fluctuation, TF_{max}). Two WDN cases with different system complexities (one is a hypothetical system, and the other is a real-world system) are applied for different demonstration purposes. From these applications, the main results and findings can be summarized as follows.

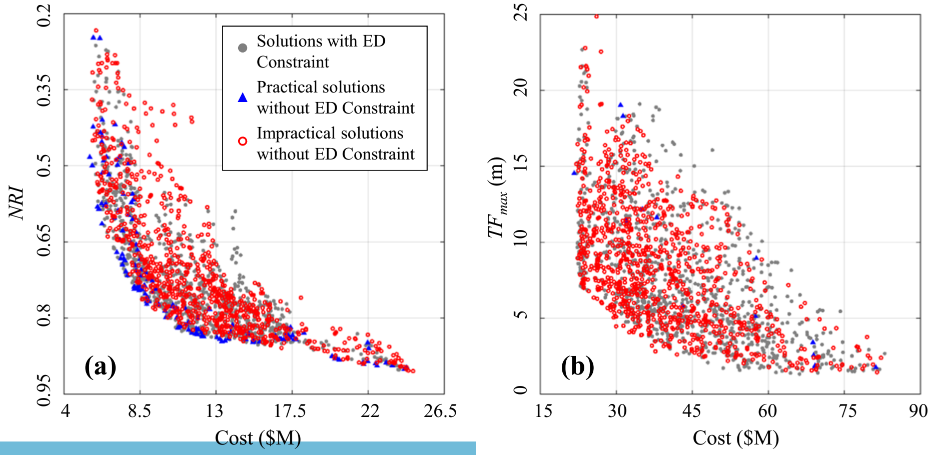


Fig. 9 Comparison of the bi-objective subsets of **a** cost versus the *NRI* for case 1 and **b** cost versus TF_{max} for case 2 for the WDN design results with and without the ED constraint in the decision space

(1) Clear tradeoff relationships exist between the network cost and any of the other three objectives (i.e., the NRI, TF_{mean} and TF_{max}) for both cases. This indicates that the use of the proposed multiple-objective method is highly necessary and important to explore the underlying balances between the network cost and other design objectives. Such a tradeoff is practically meaningful, as it can offer more design options for decision makers than a single-objective design method, where only one single solution is typically provided.

(2) The objectives of the NRI, TF_{mean} and TF_{max} are weakly correlated with each other, implying that the widely used NRI derived from the steady-state assumption is unable to fully represent the system reliability in the context of transient dynamics in WDNs. Therefore, it is important and necessary to incorporate objectives of transient impacts into the optimal design of WDNs.

(3) The influence of transient-based design objectives is significant to the design results of the system characteristics, such as the sizes and diversity of pipe diameters. The tradeoff relationships between the cost and transient objectives indicate that upsizing pipes can reduce transient impacts but at the expense of increasing network cost, which may be a practically poor solution. For the design solutions with similar network costs, it is found that a designed WDN with a greater diversity of pipe diameters tends to have lower transient impacts (i.e., lower TF_{mean} and $\mathrm{TF}_{\mathrm{max}}$) for the two case studies considered.

(4) The comparative results of WDN design with and without implementing the ED constraint proposed in this study indicate that this new ED constraint in the decision space is helpful for improving the solution practicality of the many-objective-based WDN design.

In conclusion, the developed multi-objective optimization framework in this study is effective for WDN design accounting for both steady and transient conditions and may provide useful guidelines for the operation and management of urban WDNs and other infrastructure systems. It is noted that the optimal solutions obtained in this paper are conditioned on transients being generated by pump operations in the case studies, and these solutions may vary if the source that triggers transients changes. Hence, the proposed method in this paper is not a complete and general tool to design WDNs but a first step to investigate the underlying relationships between WDN design and unsteady flow effects.

Future studies along this research line should focus on a combination of the proposed optimization method with the use of traditional protection devices to analyse the conjoint effect of pipe sizing and protection devices for transient mitigation, as well as extension of the proposed approach to deal with transients from different sources. Another important future focus is to further extend the proposed method with the consideration of more design objectives (e.g., the pump energy, water quality, and fire-fighting capacity) and validate it using existing WDNs with the aim of improving their maintenance and resilience in handling transients, as only new design problems are considered in this paper.

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Compliance with Ethical Standards

Conflict of Interest The authors declare no conflict of interest.

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