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# Optimal rehabilitation planning for aged water distribution mains considering cascading failures of interdependent infrastructure systems

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## ABSTRACT

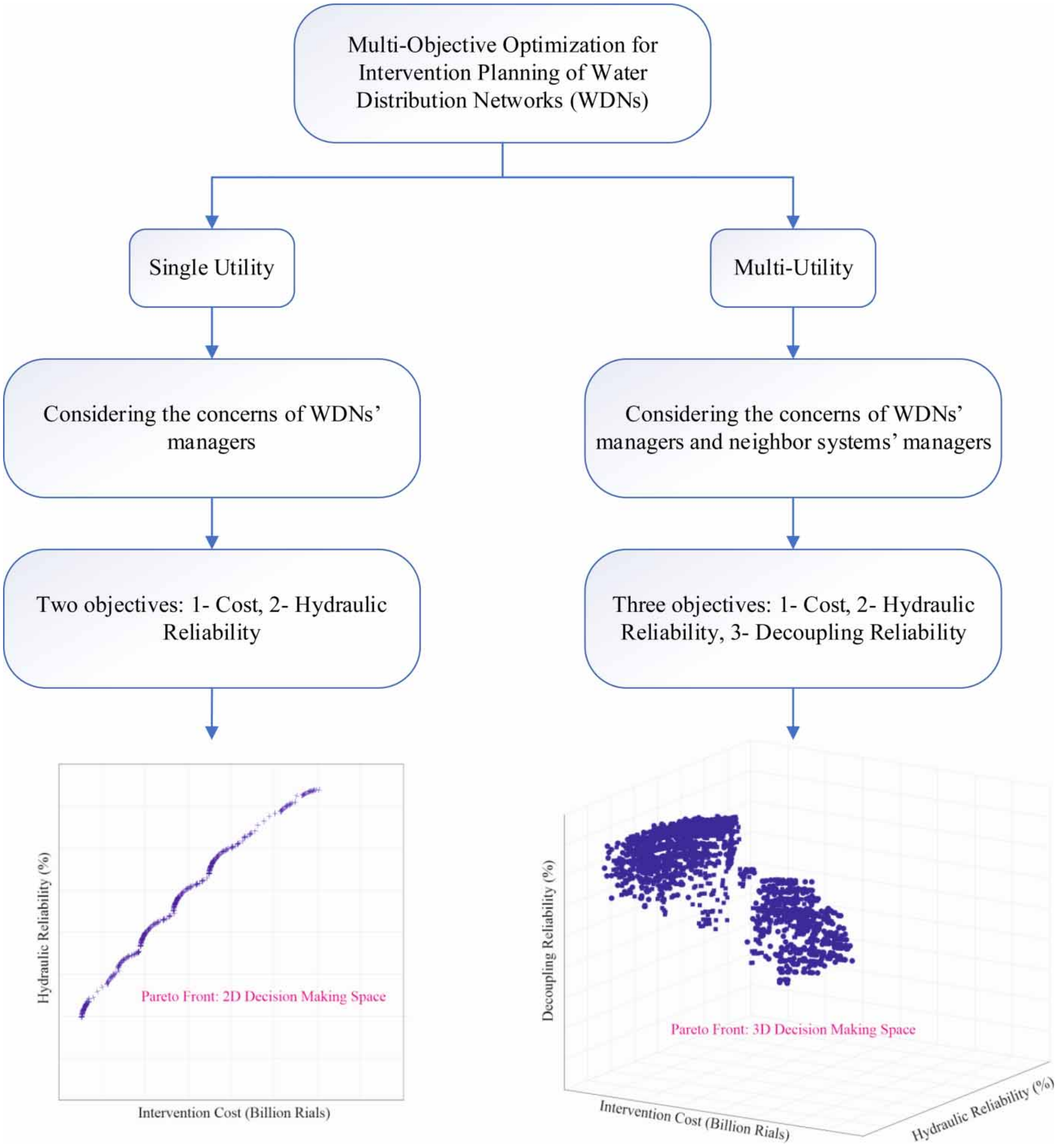
Water distribution networks (WDNs) with other infrastructures constitute a complex and interdependent multi-utility system. Considering interdependencies between WDNs and other urban infrastructures, this work proposes WDN intervention planning using a dynamic multi-utility approach to tackle the challenges of pressure deficits and cascading failures by the decoupling of different infrastructure systems. For this purpose, the study develops reliability indices representing the hydraulic and decoupled statuses of WDNs with neighbor infrastructures; the hydraulic reliability represents the robustness of the network against the water pressure deficit, and decoupling reliability represents the extent to which WDN elements are decoupled from other assets elements. A multi-objective optimization algorithm is employed to develop rehabilitation strategies by introducing three approaches for WDN upgrade following a phased design and construction method. Evaluating intervention plans based on construction cost, reliability and cascade effects shows that, under budget limitation conditions, decoupling a WDN could significantly save the cascade cost such that 1% improvement in the decoupling reliability brings about 157.42 billion Rials cascade cost saving to asset managers. On the other hand, the decoupled network is weak against hydraulic reliability, which could make it by far less resilient network than the coupled network with around 75% hydraulic reliability difference.

**Key words:** asset management, interdependent multi-utility system, multi-objective optimization, water distribution networks

## HIGHLIGHTS

- Asset management-based intervention planning of water distribution networks (WDNs).
- New approach for decoupling WDNs' elements from adjacent networks' elements.
- Three objectives optimization algorithm development for rehabilitation of complex interdependent networks.
- Dynamic topology change consideration in the optimal rehabilitation of WDNs minimizing the chance for cascading failures.

## GRAPHICAL ABSTRACT




## ACRONYMS

| | |
|---|---|
| CPM | Critical path method |
| RNs | Road networks |
| UDNs | Urban drainage networks |
| WDNs | Water distribution networks |
| A1 | Approach 1 |
| A2 | Approach 2 |
| A3 | Approach 3 |

| | |
|---|---|
| $T$ | Planning horizon year |
| $\Delta t$ | Phase interval |
| $Obj$ | Objective |
| $Con$ | Constraint |
| $Dec$ | Decision variable |
| $I^{A1}_{c_i,p}$ | Intervention strategy in Approach 1, corridor $i$ and phase $p$ |
| $n_c$ | Number of corridors |
| $I^{A2\&3}_{c_i,p}$ | Intervention strategy in Approaches 2 and 3, corridor $i$ and phase $p$ |
| $d_{c_i}$ | Diameter in corridor $i$ |
| $D_{\min}$ | Minimum commercial diameter |
| $D_{\max}$ | Maximum commercial diameter |
| $H_{j,p}$ | Pressure head at node $j$ in phase $p$ |
| $H_{\min-s,p}$ | Minimum service pressure head in phase $p$ |
| $n_n$ | Number of demand nodes |
| $EBC^{Q}$ | Demand edge betweenness centrality |
| EBC | Edge betweenness centrality |
| $W_{D_{Co-pipe_i}}$ | Weighted pipe $i$ co-location degree |
| $w_{z_i}$ | Weight of pipe $i$ for adjacent element in infrastructure network $z$ and corridor $i$ |
| $e_{z_i}$ | Edge in infrastructure network $z$ and corridor $i$ |
| $n_z$ | Total number of neighboring infrastructure systems |
| $Rel_{\text{hyd},p}$ | Hydraulic reliability in phase $p$ |
| $Rel_{\text{dec},p}$ | Decoupling reliability in phase $p$ |
| $\Gamma$ | Intervention program |
| $uc_i$ | Unit cost of the commercial diameter size assigned to the pipe in the corridor $i$ |
| $H_{kj}$ | Head at node $j$ in phase $k$ |
| $n$ | Number of phases |
| $nr_k$ | Number of reservoirs in phase $k$ |
| $Qr_{kl}$ | Discharge from reservoir $l$ in phase $k$ |
| $Hr_{kl}$ | Head at reservoir $l$ in phase $k$ |
| $pn_k$ | Number of pumps in phase $k$ |
| $P_{km}$ | Power of pump $m$ at the end of phase $k$ |
| $C_{kj}$ | Uniformity weighting coefficient for the diameter of pipes connected to node $j$ in phase $k$ |
| $DC_{c_{ip}}$ | Direct cost of the intervention decision against pipe burst in corridor $i$ and phase $p$ |
| $IC_{c_{ip}}$ | Indirect cost of the intervention decision against pipe burst in corridor $i$ and phase $p$ |
| $URC$ | Unit road resurfacing cost |
| $AC_{c_{ip}}$ | Construction area of road resurfacing for corridor $i$ in phase $p$ |
| $DU_{c_{ip}}$ | Duration of intervention plan completion in the corridor $i$ and phase $p$ |
| $AI_{c_{ip}}$ | Intervention plan area in corridor $i$ and phase $p$ |
| $A_{c_{ip}}$ | Total corridor $i$ area in phase $p$ |
| $Tr_{P_{c_{ip}}}$ | Percentage of trucks in corridor $i$ and phase $p$ |
| $AADT_{c_{ip}}$ | Annual average daily traffic in corridor $i$ and phase $p$ |
| $UUC_{Pa_{c_{ip}}}$ | Unit user cost for passenger vehicles in corridor $i$ and phase $p$ |
| $UUC_{Tr_{c_{ip}}}$ | Unit user cost for truck vehicles in corridor $i$ and phase $p$ |

## 1. INTRODUCTION

Over the past two decades, numerous researchers have shown a preference for utilizing multi-objective optimization evolutionary algorithms to address a variety of issues related to water distribution networks (WDNs). These problems encompass areas such as network design, rehabilitation, replacement, management and operations (Prasad *et al.* 2003; Farmani *et al.* 2005, 2006; Keedwell & Khu 2006; di Pierro *et al.* 2009; Siew & Tanyimboh 2012; Quintiliani *et al.* 2019; Gheitasi *et al.* 2021; Kidanu *et al.* 2023). However, in all the studies, the focus is only on WDNs where the concerns of neighbor infrastructures' managers are not considered in decision-making problems.

Water distribution, urban drainage and road networks (UDNs and RNs) have historically coevolved into an interconnected network in municipalities (Zischg *et al.* 2019). On the one hand, the relationship between such systems should be of interest to asset managers for making cost-efficient infrastructural investments through integrated multi-infrastructures asset management (IMAM) approaches (Tscheikner-Gratl *et al.* 2016; Daulat *et al.* 2022). On the other hand, this could be a challenge for asset managers due to the complexity of interactions among the interlinked networks. The complexity raises the risk of cascading failures, where failures in one system could bring about failures to other systems (Little 2002). For example, Neema *et al.* (2022) showed the effects of flooding on the deterioration rate of pavements.

Since early 2000, many studies have elaborated on various types of dependency and interdependency relationships between different infrastructures (Ouyang 2014). The interaction between systems could be unidirectional (dependency) or bidirectional (interdependency). Rinaldi *et al.* (2001) categorized interdependency into four types namely physical, cyber, geographic and logical. These could be the source of mutual vulnerabilities, risk and declining performance of adjacent networks (Johansson & Hassel 2010; Rogers *et al.* 2012; Alinizzi *et al.* 2018).

Except for the types and the direction, the impact magnitude and frequency of dependencies should be considered in the life cycle of systems: (1) planning, (2) design, (3) construction, (4) operations, (5) monitoring, (6) maintenance, (7) end of service and replacement. Daulat *et al.* (2022) showed two examples in this regard. The first one is the geographical interdependency between a water pipe and the pavement above it in the operation step. In this case, the leakage from the pipe washes soil particles below the pavement. The impact is minor but continuous; this example shows a bidirectional interaction between systems as the traffic frequency on the pavement could also lead to a pipe breakage. The second example is a unidirectional physical dependency in the operation step where the shut-off in the power system leads to the interruption in the pumping system of a WDN. As seen in practice, the impact is not frequent, however, its consequence could be significant. This could also indirectly and negatively affect the environment where, with a power failure, the emergency power supply system (mainly diesel generators) is used and fuel consumption causes an increase in environmental pollution.

Cascading failures could be one of the catastrophic outcomes of such dependency and interdependency of the coupled systems (Buldyrev *et al.* 2010; Havlin *et al.* 2012). Such failures could be categorized into many types. They could be horizontal when the cascade failures happen between different systems, or vertical when it occurs in an individual system. In this regard, Sitzenfrei *et al.* (2011) depicted the vulnerability maps for a single system and multiple systems under cascade failures. The former showed the extent to which the hydraulic performance of a WDN could be negatively affected under the simultaneous failures of pipes and sources; for example, pressure deficiencies at nodes caused by a simultaneous pipe failure and fire hydrant activation (a single system cascade failure). The latter demonstrated the effect of power shut-off on the performance of pumps for managing flood (a multi-system cascade failure). Untangling these types of dependencies and interdependencies is a complex asset management problem that is difficult to solve.

Using optimization algorithms for solving asset management problems has been favored by some researchers over the last two decades (Kleiner *et al.* 2010; Nafi & Kleiner 2010; Scheinberg & Anastasopoulos 2010; Rashedi & Hegazy 2016; Abu-Samra *et al.* 2020; Ramos-Salgado *et al.* 2021; Minaei *et al.* 2023b). Mostly, the studies focus on solving decision-making problems for the assets' intervention planning by optimizing the investment and the level of service (LOS). While efforts have been made toward integrating intervention plans for cost-efficient projects, Minaei *et al.* (2023a) proposed an approach for decoupling WDNs with adjacent networks, including UDNs and RNs to cope with geographic (inter-)dependency and its outcomes.

Daulat *et al.* (2022) listed some important challenges in the application of IMAM:

- Quantifying the interdependencies for asset management purposes and utilizing the benefits or minimizing the risks hidden in the interactions.
- The problem of interplay, which means a lack of tools for communication between the infrastructure managers when they have conflicting goals for implementing their asset projects.

To tackle the mentioned challenges, this study aims to introduce a novel approach to developing an intervention plan for an aged WDN. The task for the managers of the WDN is to renew the whole system to maximize the hydraulic performance while considering budget constraints. The high pipe failure rate due to pipe bursts and leaks negatively affects road performance causing frequent road excavations and traffic interruptions. Also, WDN pipe bursts prevent UDN technicians from accessing their system if simultaneous WDN and UDN failures occur in the mutual street section. To tackle these problems, the managers of RN and UDN ask for a way to minimize the impact of the WDN on their assets, i.e., to decouple the WDN from their systems. To this end, a novel decoupling reliability metric is defined for the quantification of the interdependency between the systems. This metric is introduced to the multi-objective intervention optimization formulation as an additional objective to the cost and hydraulic reliability objectives. As a result of this, new WDN layouts are considered in the optimal rehabilitation process taking the decoupling of WDN from the elements of neighboring infrastructure networks over the entire planning horizon into account. The renewal plans for WDNs are organized dynamically in such a way that not only required flows and desirable pressures are delivered to consumers, but also the chance of causing cascading failures is gradually minimized in subsequent stages until the end of the planning horizon.

## 2. METHODOLOGY

### *Overview*

To solve intervention planning for an aged WDN, three approaches are introduced as shown in Figure 1. The first approach (A1) refers to the common multi-objective rehabilitation of WDNs where two objectives of cost and hydraulic reliability are considered in the optimization process. The second and third approaches (A2 and A3) not only consider WDN performance, but also address the concerns of utility managers of adjacent networks. The difference between approaches two and three is the number of strict constraints for laying parallel pipes. While in A2, WDN nodes are free to receive parallel pipes as many as connected pipes, in A3, node degree enhancement is only allowed by one parallel pipe where the location is defined by imposing some additional practical constraints on the optimization which will be explained in the rest of the paper. In the following, the present work's methodology including dynamic concept and optimization components for multi-objective and utility intervention planning of WDN will be explained.

### 2.1. Dynamic intervention planning of WDNs

A master plan for the rehabilitation of a WDN can be made using two different approaches, static or dynamic (Minaei *et al.* 2019). While the traditional static approach considers the status of the network in year $T$, the dynamic approach applies a phased approach to design and construction as shown in Figure 2 (Creaco *et al.* 2014) where an optimization run is carried out in each phase to decide the planning of interventions for the $\Delta t$ following the beginning of the phase.

Intervention planning of a WDN starts from Phase 1. The WDN is simulated with the peak hourly demand at the end year of every phase. The multi-objective optimization problem is solved in Phase 1 generating a set of renewal plans. The intervention

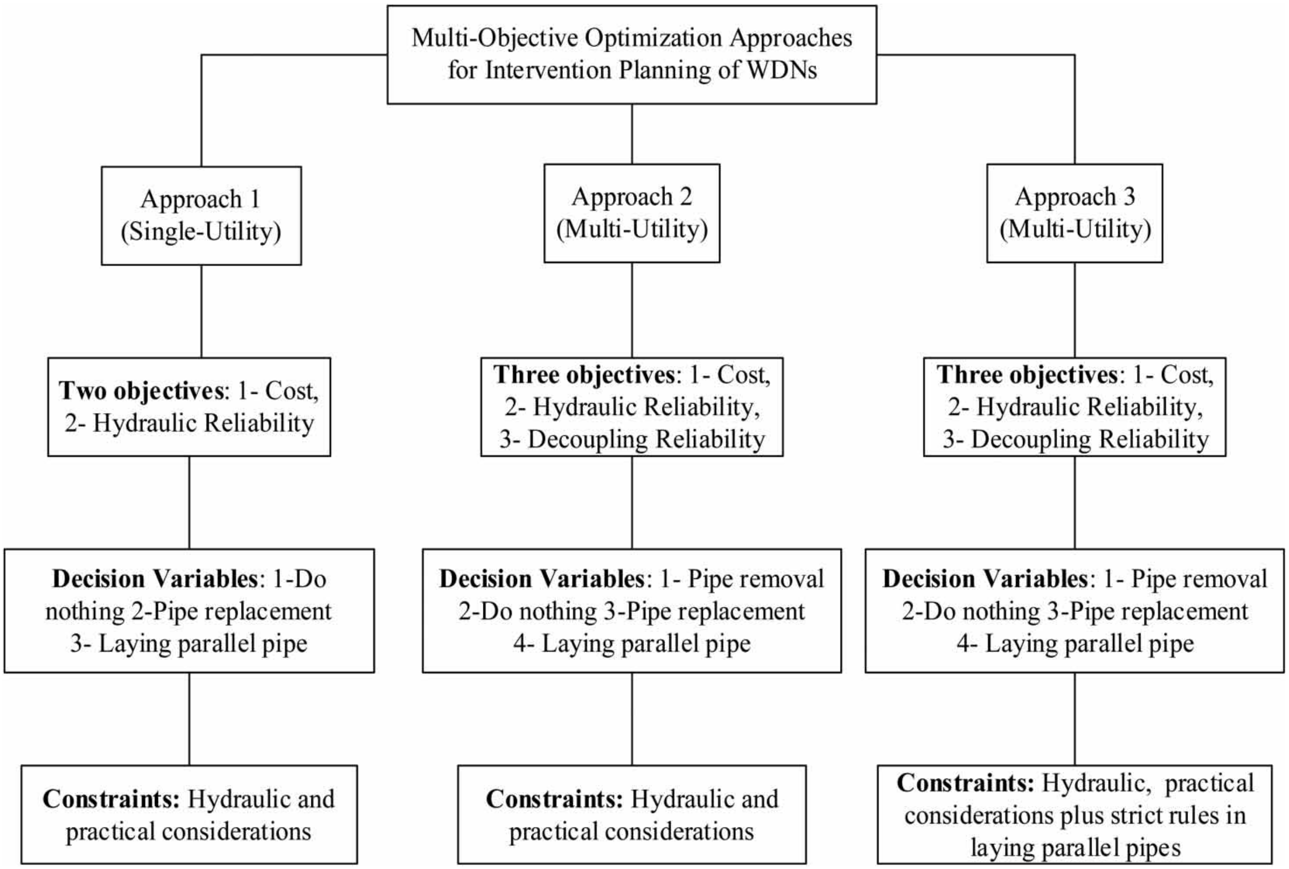



**Figure 1** | Single and multi-utility approaches for intervention planning of WDNs.

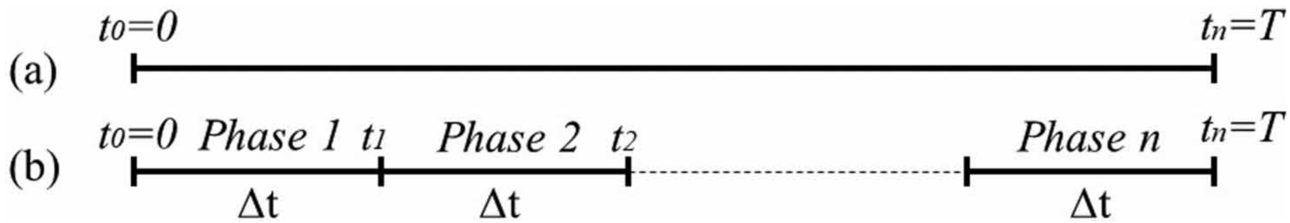



**Figure 2** | (a) Traditional approach, (b) phased approach for the design and construction periods.

master plan in every phase is designed in a way that not only meets the customers' demands estimated for the under-design phase, but also could overcome the demand increase in the subsequent phases. Hence, the demand input for the optimization is the average of peak hourly demands at the end years of the target and following phases. The network is updated at the beginning of Phase 2 and the optimization process is repeated. Updates include the new topology of the network after the construction of the rehabilitation plan in Phase 1, changes in the WDN nodes' demand and roughness coefficient of pipes. This dynamic phase-by-phase intervention continues until phase $n$ and gradually upgrades the aged WDN saving money and leading to a reliable network (Minaei *et al.* 2019). This is a nonlinear, constrained and mixed-integer optimization problem. The solution is obtained by using the Non-Dominated Sorting Genetic Algorithm (NSGA-II) (Deb *et al.* 2002). In the following sections, the decision variables, constraints and objectives of the optimization problem are explained.

### 2.2. Optimization structure

The multi-objective optimization problem is formulated as follows:

$$\text{Minimize}(Obj_1,\ Obj_2,\ \ldots,\ Obj_m) \tag{1}$$

Subject to:

$$\text{Constraints} = \{Con_1,\ Con_2,\ \ldots,\ Con_{m'}\} \tag{2}$$

$$\text{Decision Variables} = \{Dec_1,\ Dec_2,\ \ldots,\ Dec_{m''}\} \tag{3}$$

where $Obj$, $Con$ and $Dec$ stand for objective, constraint and decision variables of the optimization problem, and $m$, $m'$ and $m''$ are the number of objectives, constraints and decision variables, respectively. The following subsections describe the various methodological elements in detail.

#### 2.2.1. Decision variables of optimization for dynamic intervention planning of WDNs

Every deteriorated pipe in a WDN needs an intervention for upgrading the network while the requirements of adjacent networks are met in terms of minimizing the chance of geographical cascading failures. In this regard, there are some intervention decisions such as pipe removal, replacement, parallelizing and no action on the pipe in every corridor $i$ (in this study, every corridor is assumed to include one element from WDN, UDN and RN, which are pipe and road segments). The suitable strategy depends on the desired targets the water utility and adjacent networks' managers request. In the current study, the requests are assumed to be (1) optimal intervention program with the decoupling of the WDN from adjacent infrastructures (this is done by applying topology changes to WDN from looped to branched networks as this decreases the number of co-located pipes with road segments) and (2) improving the hydraulic performance of the network to cope with pressure deficit due to the increase in demands and pipe aging. Every solution in the optimization represents a decision vector with $n_c$ length where the decision variables are decoded with 0,1,2,3 as follows:

$$I_{c_i,p}^{A1} \in \{1, 2, 3\}, \quad i = 1{:}n_c \tag{4}$$

$$I_{c_i,p}^{A2\&3} \in \{0, 1, 2, 3\}, \quad i = 1{:}n_c \tag{5}$$

$$d_{c_i} \in \{D_{\min},\ \ldots,\ D_{\max}\},\ i = 1{:}n_c \tag{6}$$

where $I_{c_i,p}^{A1}$ is intervention indicator actions for the pipe in corridor $i$, phase $p$ and A1 where $i$ changes from 1 to $n_c$, which is the total number of corridors in the interdependent networks. Intervention decisions could be integer numbers between 1 and 3. Similarly, $I_{c_i,p}^{A2\&3}$ is an intervention indicator for A2 and A3, which could get integer numbers between 0 and 3, as explained in Table 1; $d_{c_i}$ is the pipe $i$ diameter in corridor $i$ belonging to the set of commercial diameters which are real values changing from $D_{\min}$ (the minimum available commercial diameter in the market) to $D_{\max}$ (the maximum available commercial diameter in the market).

The first decision contributes to making the network robust against interconnectivity with adjacent networks as removing pipes changes the topology of the WDN layout toward a branched shape and therefore less geographically co-located elements are achieved in every corridor. The second decision contributes to saving the intervention project costs. Here, the main assumption is neglecting the pipe maintenance and operating costs. The third and fourth decisions are for improving the hydraulic performance of the network.

### 2.2.2. Optimization constraints for dynamic intervention planning of WDNs

The hydraulic simulation of WDN is carried out by EPANET 2.2. Therefore, the simulation model automatically satisfies the physical constraints of the pipe network hydraulics, i.e., the conservation of mass and energy. Moreover, every solution is feasible as long as it keeps the piezometric pressure head of WDN nodes above the minimum service pressure level, Equation (7), below which the demand of the node is not fully satisfied (Wagner *et al.* 1988). In Equation (7), $H_{j,p}$ is the pressure head at node $j$ in phase $p$, $H_{\min -s,p}$ is minimum service pressure head in phase $p$ and $n_n$ is the number of demand nodes in the WDN layout (it is assumed that there would be no development (expansion) in the layout, hence, $n_n$ is fixed over the phases).

$$H_{j,p} \geq H_{\min -s,p}, \ \ j = 1{:}n_n \tag{7}$$

Some decision constraints for intervention decisions arise from logical judgment and graph analysis of WDN layout topology. To explain them, first, knowledge about some terms is needed, described as follows:

- *Node degree*: it is defined for every node and equal to the total number of connected pipes to the node (Hwang & Lansey 2021); for example, a node with three connected pipes has a node degree = 3.
- *Hubs*: nodes with the highest degree in a WDN layout are called hubs that usually refer to the high-traffic rated spots in urban areas (Yazdani *et al.* 2011) which could include hospitals, commercial and administration offices.
- *Shortest paths*: this measure can be used to identify the least expensive route between two nodes (the sum of positive edge weights is minimal). In the context of a WDN, our main concern is to discover the most optimal pathways for water to travel between sources and demand nodes. This involves seeking out the shortest routes that ensure efficient water flow.
- *Demand edge betweenness centrality* ($EBC^Q$): the number of times edge $i$ (pipe $i$) is a part of the shortest paths between demand nodes pairs $j$ and the source node is known as the source edge betweenness centrality (EBC). This metric was modified by Sitzenfrei *et al.* (2020), as demand EBC ($EBC^Q$). The $EBC^Q$ of pipe $i$ finds the shortest path connecting the reservoir (source node $S$) and all demand nodes $j$, and weighs the EBC counting with the nodal demand $Q_j$. $EBC^Q$ ($i$) is formulated as follows (to find more about this index, refer to Sitzenfrei *et al.* (2020) and Hajibabaei *et al.* (2023)).

$$EBC^Q(pipe_i) = \sum_{j=1}^{n_n} shortest\ path_{S,j}(pipe_i) \cdot Q_j \tag{8}$$

**Table 1** | Strategies for the intervention planning of an aged water distribution network

| Intervention indicator | Explanation |
|---|---|
| $I_{c_i,p} = 0$ | The old pipe is removed from corridor $i$ in phase $p$ |
| $I_{c_i,p} = 1$ | The old pipe is kept in corridor $i$ to continue its service in phase $p$ |
| $I_{c_i,p} = 2$ | The old pipe is replaced with the new pipe in corridor $i$ with a new diameter $d_{c_i}$ in phase $p$ |
| $I_{c_i,p} = 3$ | The old pipe gets a parallel pipe in corridor $i$ with a diameter $d_{c_i}$ in phase $p$ |

– *Weighted pipe i co-location degree* ($W_{D_{Co-pipe_i}}$): every pipe $i$ in a WDN can be located adjacent to other infrastructure elements; for example, pipe $i$ with a parallel pipe under a street and next to a UDN pipe has a co-location degree of three. Equation (9) mathematically explains how this is calculated where $w_{z_i}$, $e_{z_i}$ and $n_z$ represent weight, pipe $i$ adjacent element in infrastructure network $z$ and corridor $i$, and the total number of neighboring infrastructure systems, respectively. Weights for the pipes and roads are estimated based on the level of importance categorized with different diameter sizes and types of roads (residential, tertiary, secondary and primary roads to motorways):

$$W_{D_{Co-pipe_i}} = \sum_{z=1}^{n_z} w_{z_i} e_{z_i} \tag{9}$$

The following explains the constraints of the problem based on the concept of five above-defined terms.

The first intervention decision (removing the pipe from the WDN layout) cannot be applied to the pipe whose main role is supplying water to an associated node. Those pipes that belong to the shortest path set are marked as critical pipes (where an edge weight is considered the Euclidean length divided by the diameter as a representative of head loss in WDNs) and cannot be removed. Moreover, pipes with service connections cannot be removed. Non-critical pipes can be removed. Once a pipe has been removed in a phase and a corridor, it is not allowed to be replaced with a new pipe in the same corridor in the next subsequent phases and other intervention decisions (do nothing, replacement and laying parallel pipes) are not feasible there anymore.

Once intervention three (pipe replacement) is adopted for pipe in corridor $i$ and phase $p$, $p = 1{:}n$, repeating the same strategy or pipe removal is avoided in corridor $i$ and the following phases, $p+1, p+2, \ \ldots, \ n$. These decision constraints are implemented because multiple pipe replacements or removing a recently renewed pipe is not cost-effective. When an old pipe is strengthened by a parallel pipe, the associated corridor will not have any other parallel pipes until the last phase because laying numerous parallel pipes next to each other is not reasonable. However, the old pipe beside the parallel pipe is no longer among the critical pipe sets and could be removed in the next phases.

There is a trade-off between various objectives of the current rehabilitation problem where different intervention decisions play different roles in reaching the objectives. For example, while removing a pipe could decouple a WDN from the co-located systems, it could also worsen the hydraulic reliability of the network; or laying pipes in parallel can increase the hydraulic capacity of the network, while it makes the rehabilitation program expensive and increases the risk of cascading failures. Consequently, A2 and A3 differ from each other in the rules for laying pipes in parallel:

- In A2, the node degree can increase with parallel pipes, and *all* connected pipes to the node can be strengthened by one parallel pipe over the phases.
- In A3, node degree can increase with parallel pipes, and only *one* connected pipe to the node can be strengthened by a parallel pipe over the phases.

There are some controls for laying parallel pipes in A3. The introduced indices, $EBC^{Q}(pipe_i)$ and $D_{Co-pipe_i}$, represent the hydraulic and co-location criticality of a pipe, respectively. The algorithm for A3 is shown in Figure 3. In short, if node $j$ is the hub, the associated pipes cannot be strengthened by laying pipes in parallel with them. If a pipe can be duplicated (i.e., it is connected to a node with a degree lower than the hub node), priority is given to the pipe with the lowest co-location degree. Finally, if all connected pipes to node $j$ have the same co-location degree, the pipe with the highest $EBC^{Q}$ gets a parallel pipe. Moreover, if in the construction process over time, a node becomes the hub (the node with the highest degree), a parallel pipe cannot be connected to it over the subsequent construction phases. These constraints were formulated through discussions between the clients of different co-located infrastructures. Finally, comparing optimization solutions from A1, A2 and A3 helps clients to agree on the final intervention plan.

### 2.2.3. Optimization objectives for dynamic intervention planning of WDNs

The current multi-objective optimization problem is formulated with three objectives as follows:

$$\text{Minimize}\,(Obj_1 = Cost_p(\Gamma_p(I, d), \ Obj_2 = -Rel_{\text{hyd},p}, \ Obj_3 = -Rel_{\text{dec},p}) \tag{10}$$

where $Cost_p$ is the rehabilitation cost of the intervention program $\Gamma$ (Rials), indicating the budget for upgrading the network at

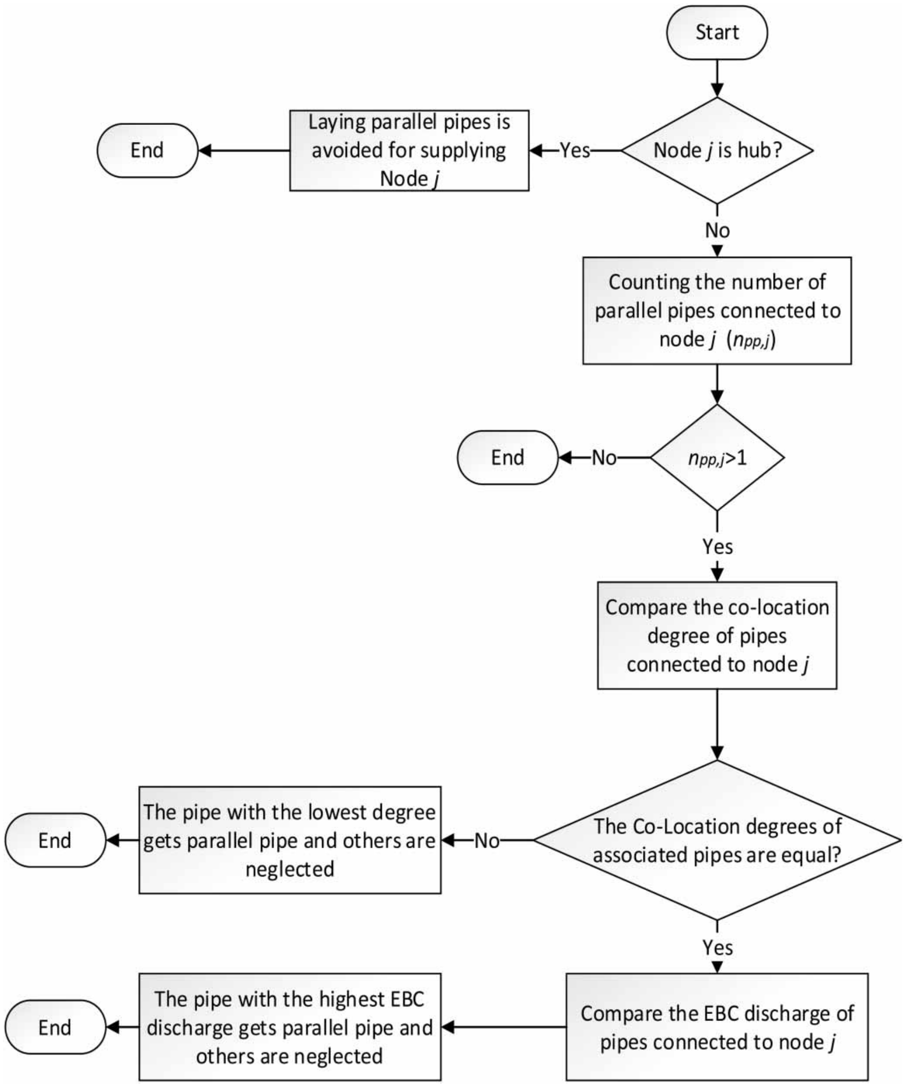



**Figure 3** | The decision-making algorithm of laying parallel pipes in A3 for intervention planning of WDN.

the beginning of phase $p$ where $I$ and $d$ stand for the intervention type and diameter size, and evaluated by Equation (11):

$$Cost_p(\Gamma(r, d)) = \sum_{i=1}^{n_c} uc_i L_i \tag{11}$$

where $uc_i$ is the unit cost of the commercial diameter size assigned to the pipe in the corridor $i$ with a length $L_i$ (Rials/m). Hydraulic reliability is the second objective of optimization calculated by a hybrid index which is the combination of two indices in hydraulically weak and robust conditions, respectively (Minaei *et al.* 2019). The first one is the frequency index that counts the number of demand nodes with water pressure above the desired level, which is calculated by Equation (12):

$$Rel1_{\text{hyd},p} = 1 - \frac{\sum_{k=p}^{n}\sum_{j=1}^{n_n} \max(0, \ -\text{sign}(H_{kj} - H_{\text{des}}))}{n_n(n-p+1)} \tag{12}$$

where $Rel1_{\text{hyd},p}$ represents the frequency hydraulic reliability index of the network in phase $p$, and $H_{kj}$ is the actual head at node $j$ in phase $k$, where $k$ changes from $p$ to $n$ and $H_{\text{des}}$ is desirable pressure. The second part of the hybrid reliability is the resilience index introduced by Todini (2000) and then modified by Prasad *et al.* (2003):

$$Rel2_{\text{hyd},p} = \frac{\sum_{k=p}^{n}\left(\frac{\sum_{j=1}^{n_n} C_{kj} \times q_{kj}(H_{kj} - H_{\text{des}})}{\left[\sum_{l=1}^{nr_k} Qr_{kl} \times Hr_{kl} + \sum_{m=1}^{pn_k}\left(\frac{P_{km}}{\gamma}\right)\right] - \sum_{j=1}^{n_n} q_{kj} H_{\text{des}}}\right)}{(n-p+1)} \tag{13}$$

where $q_{kj}$ is the design demand at node $j$ at the end of phase $k$, $nr_k$ is the number of reservoirs in phase $k$, $Qr_{kl}$ and $Hr_{kl}$ are respectively the discharge from and head at reservoir $l$ in phase $k$, $pn_k$ is the number of pumps in phase $k$ and $P_{km}$ is the power of pump $m$ at the end of phase $k$. Also, $C_{kj}$ is a weighting coefficient associated with the uniformity of the diameter of pipes connected to node $j$ in phase $k$ as follows:

$$C_{kj} = \frac{\sum_{r=1}^{np_{kj}} D_r}{np_{ij} \times \max\{D_r\}} \tag{14}$$

where $np_{kj}$ and $\max\{D_r\}$ are respectively the number of pipes and the maximum pipe diameter size connected to node $j$ in phase $k$. According to the above equation, $C_{kj} = 1$ if only one pipe is connected to node $j$ or all pipes connected to that node have the same diameters and $C_{kj} < 1$ if pipes connected to node $j$ have different diameters.

In each phase $p$, the two indexes are calculated and the final hydraulic reliability would be as follows:

$$Rel_{\text{hyd},p} = \begin{cases} Rel1_{\text{hyd},p}, & Rel1_{\text{hyd},p} < 1 \\ 1 + Rel2_{\text{hyd},p}, & Rel1_{\text{hyd},p} = 1 \end{cases} \tag{15}$$

Using the hybrid reliability index (Equation (15)), the upgrade program becomes more flexible and manageable so that the system can be gradually upgraded from a weak state ($Rel1 < 1$ or 100%) to a normal state ($Rel1 \approx 1$ or 100%) and then to a robust state ($Rel2 > 1$ or 100%) depending on the funds invested in the project and the reliability expected. Hence, the value of $Rel_{\text{hyd},p}$ ranges between 0 and 2 or 0 to 200%.

The third objective refers to the degree of decoupling of WDN from other infrastructure systems in phase $p$ (Equation (16)):

$$Rel_{\text{dec},p} = 1 - \frac{\sum_{i=1}^{n_c} \frac{W_{D_{Co-pipe_i}}}{n_z}}{n_c} \tag{16}$$

where $Rel_{\text{dec},p}$ calculates the average weighted co-location degree for the WDN pipe in corridor $i$ and phase $p$ over the whole corridors, meaning that for a water network adjacent to two other networks (e.g., RN and UDN), if a pipe element is co-located with only one out of three elements (WDN parallel pipe, UDN pipe and RN element), the average degree for the pipe is 0.33 (assuming that the weight of edges are equal to one). This index gives an overall view of the geographical decoupled status of WDN pipes from co-located systems' elements, where its values change between 0 and 1 (or 0 to 100%).

When considering the objectives, it can be argued that objectives one and three are solely estimated for the target phase. However, objective two is estimated for both the target phase and subsequent phases throughout the optimization problem. This distinction arises from the fact that objective two measures the robustness of each solution by addressing pressure deficiencies in a network. Consequently, this metric is defined across multiple phases to generate solutions that not only enhance the hydraulic performance in the target phase but also ensure that the network possesses sufficient excess supply capacity in subsequent phases. This capacity is necessary to handle uncertainties like interruptions in the implementation of intervention plans in the next phases.

### 2.3. Pipe bursts cascade consequences in coupled and decoupled WDN topologies

The optimization results from different approaches are Pareto fronts including a wide range of solutions referring to WDN intervention plans with different construction costs, level of decoupling and hydraulic reliability metrics. Due to the pipe removal and laying parallel pipe decisions, the under-designed WDN could get a new topological feature after applying the optimal intervention plan to the network. The solutions that provide the decisions for removing pipes from some corridors make a new topology for the WDN decoupled with adjacent networks (this is a partial decoupling as 100% decoupling is not practically feasible in many cases). To show and compare the benefits between coupled and decoupled WDN layouts, the consequences of pipe bursts in both WDN topology types are estimated, which are direct and indirect costs on the co-located infrastructure elements. The direct cost refers to road resurfacing (sub-base, basement and asphalt construction) costs (Equation (17)) arising from pipe-burst repair activities, and the indirect cost indicates customers' cost due to the traffic interruption (Equation (18)). Abu-Samra *et al.* (2020) developed a deterministic mathematical model estimating the indirect cost of intervention planning for the three correlated systems of WDN, UDN and RN based on the traffic rate and occupied area of intervention construction activities on the associated corridor.

$$DC_{c_{ip}} = \sum_{j=p}^{n} \sum_{i=1}^{n_c} URC \times AC_{c_{ip}} \tag{17}$$

$$IC_{c_{ip}} = DU_{c_{ip}} \times \frac{AI_{c_{ip}}}{A_{c_{ip}}} \times [((1 - Tr_{P_{c_{ip}}}) \times AADT_{c_{ip}} \times UUC_{Pa_{c_{ip}}}) + (Tr_{P_{c_{ip}}} \times AADT_{c_{ip}} \times UUC_{Tr_{c_{ip}}})] \tag{18}$$

where $DC_{c_{ip}}$ and $IC_{c_{ip}}$ stand for the direct and indirect cost of the intervention decision against pipe burst in corridor $i$ and phase $p$ (Rials), $URC$ and $AC_{c_{ip}}$ stand for unit road resurfacing cost (Rials/m$^2$) and construction area of road resurfacing (dependent on pipe diameter size) for corridor $i$ in phase $p$(m$^2$), respectively; $DU_{c_{ip}}$ is the duration of intervention plan completion in the corridor $i$ and phase $p$ (days), $AI_{c_{ip}}$ and $A_{c_{ip}}$ are the intervention plan area (the area of a corridor's part occupied for intervention construction activities) and the total corridor $i$ area in phase $p$, respectively (m$^2$); $Tr_{P_{c_{ip}}}$ represents the percentage of trucks in corridor $i$ and phase $p$ (%), $AADT_{c_{ip}}$ is annual average daily traffic in corridor $i$ and phase $p$; $UUC_{Pa_{c_{ip}}}$ and $UUC_{Tr_{c_{ip}}}$ are unit user cost for passenger and truck vehicles in corridor $i$ and phase $p$.

Post-pipe-burst rehabilitation activities could be major (pipe replacement) or minor (repairing pipe). In this study, only major action is considered for such failure events. For this purpose, pipe burst is tried on every old pipe one by one (recently replaced and parallel pipes are excluded), and its consequences are estimated for both coupled and decoupled WDN topologies. Here, the main assumption is that a single pipe failure happens with a 100% chance for all the remaining old pipes (after completing the intervention plan in a target phase) over the remaining phases. For example, if after Phase 1, 30% of old pipes remain in the network, every old pipe fails only once in the next phases. This assumption comes from the fact that new pipes burst less frequently while old pipes have already experienced multiple failures in the network.

In order to calculate the time to complete all the activities for pipe replacement, the standard critical path method (CPM) was used to (1) break the activities and come up with a total duration for each scenario; (2) determine whether those activities can be undertaken in parallel or not based on the schedule; and (3) determine the critical path to calculate the total duration to complete the intervention for each corridor (varies according to the type of soil, length of the corridor, etc.) (Abu-Samra *et al.* 2020). The total duration for the pipe replacement project is equal to the sum of sub-activity durations for commuter notification, traffic control systems, excavation and shuttering, pipe bedding and replacement, backfilling and compaction and site reinstatement (please refer to the Supplementary material for the standard time per unit for completing every intervention plan activity).

### 2.4. Case study

To investigate the proposed approach, an aged WDN, the Baghmalek network (Figure 4), located in the southwest of Iran, is considered for intervention planning. The network has 90 pipes and 72 consumption nodes; hence, there are 90 corridors. The network is fed by one reservoir (node 1) located at the highest elevation of the region. The network's current hydraulic performance is in urgent need of rehabilitation and upgrading and the old pipes' structural condition is at a poor level with a high risk of failure (Minaei *et al.* 2019). It is assumed that the network is co-located with a UDN and RN. The multiplex system is conceptualized in Figure 4 representing the co-locations and the network configuration. The full information about the network can be found in Minaei *et al.* (2019) and is available upon request.

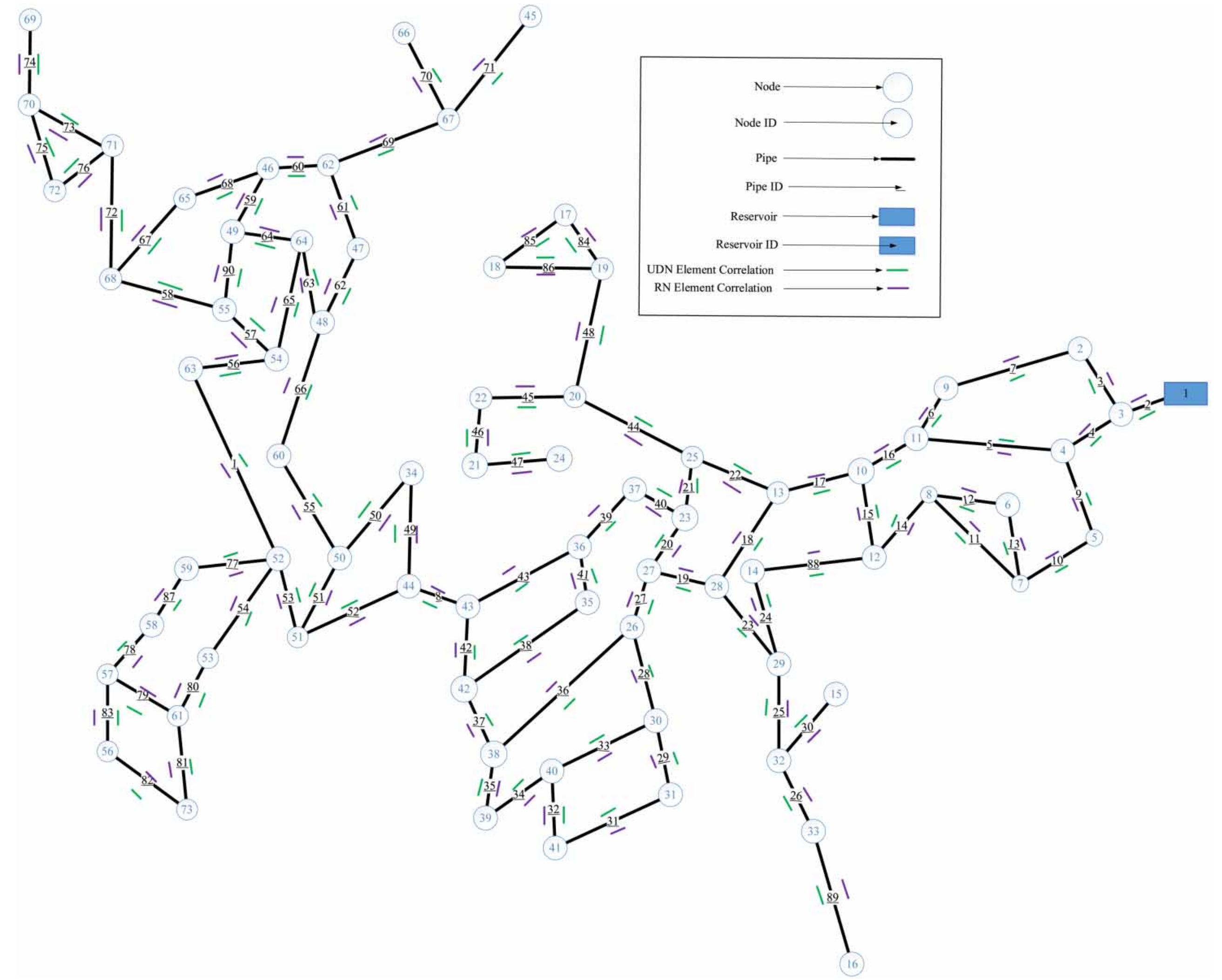



**Figure 4** | Baghmalek WDN and correlation with adjacent networks' elements in year 0.

The network is first analyzed for the existing conditions at the beginning of the planning horizon (i.e., year 0). Currently, the hydraulic performance of the WDN is weak and only 36% of the consumption nodes meet the desirable pressure of 18 m, as required according to the national regulations ($Rel1_{\text{hyd}} = 36\%$). Also, the decoupling reliability for the current topology of the network is about 44%. Hence, the hydraulic reliability and decoupling degree should be improved through network intervention actions. There are some main assumptions for the Baghmalek Network, captured from Minaei *et al.* (2019, 2023a) work, and considerations for intervention planning of the current network as follows:

- A 25-year design period is considered for upgrading the network ($T = 25$).
- The design period is divided into five construction phases, 5 years each.
- During the design period, the network is not expected to expand spatially. The network layout is fixed over time.
- A list of 14 discrete diameter sizes with their unit cost for polyethylene pipes is shown in Table 2, which are considered for intervention planning of the WDN. The discount rate is 2% for present worth cost evaluation.
- The Hazen–Williams coefficient is set to 130 for all new pipes in year 0. Also, the Hazen–Williams coefficients are assumed to change linearly with time, with an annual reduction rate of −0.6%.
- The installation of a parallel pipe is more difficult and expensive than installing a new pipe. To take this issue into account, the unit cost of parallel pipes is 20% higher (Creaco *et al.* 2014).

**Table 2** | Commercial polyethylene pipes with their unit construction cost in year 0, $D_C$: Commercial diameter, $D$: Internal diameter (Minaei *et al.* 2019)

| $D_C$ (mm) | $D$ (mm) | Unit cost (Rials/m) |
|---|---|---|
| 63 | 53.60 | 163,473.90 |
| 75 | 63.80 | 192,204.30 |
| 90 | 76.60 | 232,484.70 |
| 110 | 93.80 | 300,636.10 |
| 125 | 106.60 | 374,078.20 |
| 160 | 136.40 | 543,685.60 |
| 200 | 170.60 | 769,448.30 |
| 250 | 213.20 | 1,147,234.00 |
| 315 | 268.20 | 1,752,000.00 |
| 400 | 341.20 | 2,734,489.00 |
| 450 | 383.89 | 3,455,312.00 |
| 630 | 537.50 | 6,466,257.00 |
| 710 | 605.77 | 8,102,474.00 |
| 800 | 682.58 | 10,187,126.00 |

- The network consumption is assumed to change linearly over time. The annual rate of consumption increase is estimated at 0.0332 l/s/year and is uniformly distributed spatially.
- There are no leakages in the network's pipes.
- The desirable and minimum service pressure heads remain spatially uniform and constant over time, set at 18 and 10 m, respectively. Nodes with pressures below 10 m experience unmet demands (0 demand), while nodes with pressures ranging between 10 and 18 m receive partial supply. Nodes with pressures exceeding 18 m receive complete supply.
- In their study, Daulat *et al.* (2022) noted that numerous studies within the field of IMAM literature assume that water pipes and UDN pipes are fully co-located with streets (road elements) in all corridors. This assumption is also acknowledged in the present paper. This is a strong assumption as Mair *et al.* (2017) discovered that, on average, 50% of the street network length correlates with 80–85% of the total WDN and UDN network for an Alpine case study.
- The network in its current topology does not have any pipe in parallel and this decision is considered only in the optimal intervention planning.
- The corridor information including road types and area was captured by the contribution of Google Map Street. The pipes' physical characteristics, including diameter and age, were retrieved from the work of Minaei *et al.* (2019). Pipe diameters are used for the estimation of the excavation area, the proportion of corridor occupation and traffic interruption. All those data are provided in the Supplementary material.
- The standard pipe replacement sub-activity durations (commuter notification, traffic control systems, excavation and shuttering, pipe bedding and replacement, backfilling and compaction, site reinstatement, road resurfacing and manhole installation (hours/unit)) were obtained from the project database of Abu-Samra *et al.*'s (2020) work. These data are subjective with high uncertainty. The duration of completing an activity depends on many factors such as workforce quality, national regulation, the accuracy of population data, the efficiency of traffic systems, and soil and pavement types, which vary case by case. Therefore, we reconstructed and tuned data for the Baghmalek network's corridors based on every street type, area and diameter of the co-located pipe (a rational relationship analysis between the corresponding real data in the project database and the reconstructed ones was implemented).
- The unit passenger and truck vehicle costs were retrieved from the work by Abu-Samra *et al.* (2020), which are 22.09 and 32.26 (CAD/user), respectively. The prices were changed to Rials based on the currency exchange rate at the time of Baghmalek WDN intervention planning (1 Canadian Dollar = 100,000 Rials). The same approach was followed for the road resurfacing unit cost, which is 65 CAD/m$^2$.
- Every corridor weight is estimated based on the road type and diameter of pipes (Zischg *et al.* 2018), as shown in Table 3.

**Table 3** | Assigned weights to the elements of corridors from different infrastructures (Zischg *et al.* 2018)

| Pipe diameter (mm) | Weight | Road type | Weight |
|---|---|---|---|
| < 80 | 0.2 | Residential | 0.2 |
| > =80 and <200 | 0.4 | Tertiary | 0.4 |
| > =200 and <400 | 0.6 | Secondary | 0.6 |
| > =400 and <600 | 0.8 | Primary | 0.8 |
| > =600 | 1 | Motorways | 1 |

- The budgets for the WDN intervention plan construction are limited for Phases 1 and 2, which are approximately 6.75 and 4.00 billion Rials, respectively.
- According to Vertommen *et al.*'s (2022) work, the topology of WDNs could be categorized into three parts: (1) Primary, (2) Secondary and (3) Tertiary. The Primary has a transport function with a looped design and no direct connections, the Secondary has a distribution function with a looped design and customer connections if needed and the Tertiary has a connecting function with a branched design. In the present work, the pipes in the loops belong to the Primary and Secondary parts with no direct connections; hence, they are free to take pipe removal action.

## 3. RESULTS

Figures 5(a) and 5(b) display the outcomes of multi-objective optimization achieved by A1–A3 for Phases 1 and 2. These results demonstrate a clear trade-off among the three objectives: WDN intervention planning cost, hydraulic reliability and decoupling reliability metrics. To maintain simplicity, only the optimization results for two phases are presented here, however, when it comes to delivering the results to the Baghmalek network's asset managers, optimization results for all five phases should be provided for the decision-takers. Figure 5(e) represents the solutions in Figure 5(a) in three-dimensional format for better interpretation of solutions. We only showed the 3D Pareto solutions for Figure 5(a) due to space limitations.

The Pareto solutions obtained from the optimization process serve as inputs for the cascade cost model. Subsequently, the cascade costs are illustrated in Figure 5(c) and 5(d), plotted against hydraulic and decoupling reliability metrics. As evident from the figures, a significant trade-off exists between the three objectives. Enhancing hydraulic reliability comes at the expense of reduced decoupling reliability. This trade-off arises because of the inclusion of a decoupled WDN layout, which involves removal of pipes, thus negatively impacting the capacity of the WDN to supply consumers.

When comparing the solutions obtained from different Pareto fronts in Phase 1, it is evident that the decoupling reliability values indicate a high risk to the UDN and RN from the WDN layout in the case of A1. Conversely, the solutions achieved by A2 and A3 show lower risk to them well shown in Figure 5(e). The Pareto fronts show the decoupling reliability of the WDN topology initially at 44% (at year 0), decreasing to lower values due to the introduction of new topologies with parallel and replaced pipes in A1. Figure 5(e) illustrates a comparison between the trends of decoupling and hydraulic reliability metrics. The analysis reveals that as hydraulic reliability increases, decoupling reliability tends to decrease. However, at certain points, the trends align. This can be attributed to the number of parallel and replaced pipes in the solutions. It is observed that a lower number of parallel pipes in the solutions leads to improved decoupling reliability. This improvement clearly is shown in the solutions of A1 in Figure 5(e) where a vertical jump occurs at a point between 20 and 25 billion Rials, whereas the horizontal jump refers to rapid improvement in the hydraulic reliability from weak to resilient conditions.

However, when considering a network in hydraulically weak conditions (when there are nodes with pressure lower than the desirable pressure), all solutions from A1 outperform those from A2 and A3. The reason for the higher costs associated with A2 and A3 compared to A1 is that the decoupling layout is significantly weaker in maintaining the nodes' piezometric pressure head above the minimum service pressure. This weakness necessitates larger pipe diameter solutions for both replaced and parallel pipes.

Analyzing the solutions from A1 reveals that the preferred intervention plan is also the most expensive one, resulting in a robust network with approximately 99% resiliency (or hybrid reliability of around 199%) which has associated construction cost of around 186 billion Rials (as the Pareto is truncated in Figure 5(a), this point is not obvious in the figure, but in Figure 6,

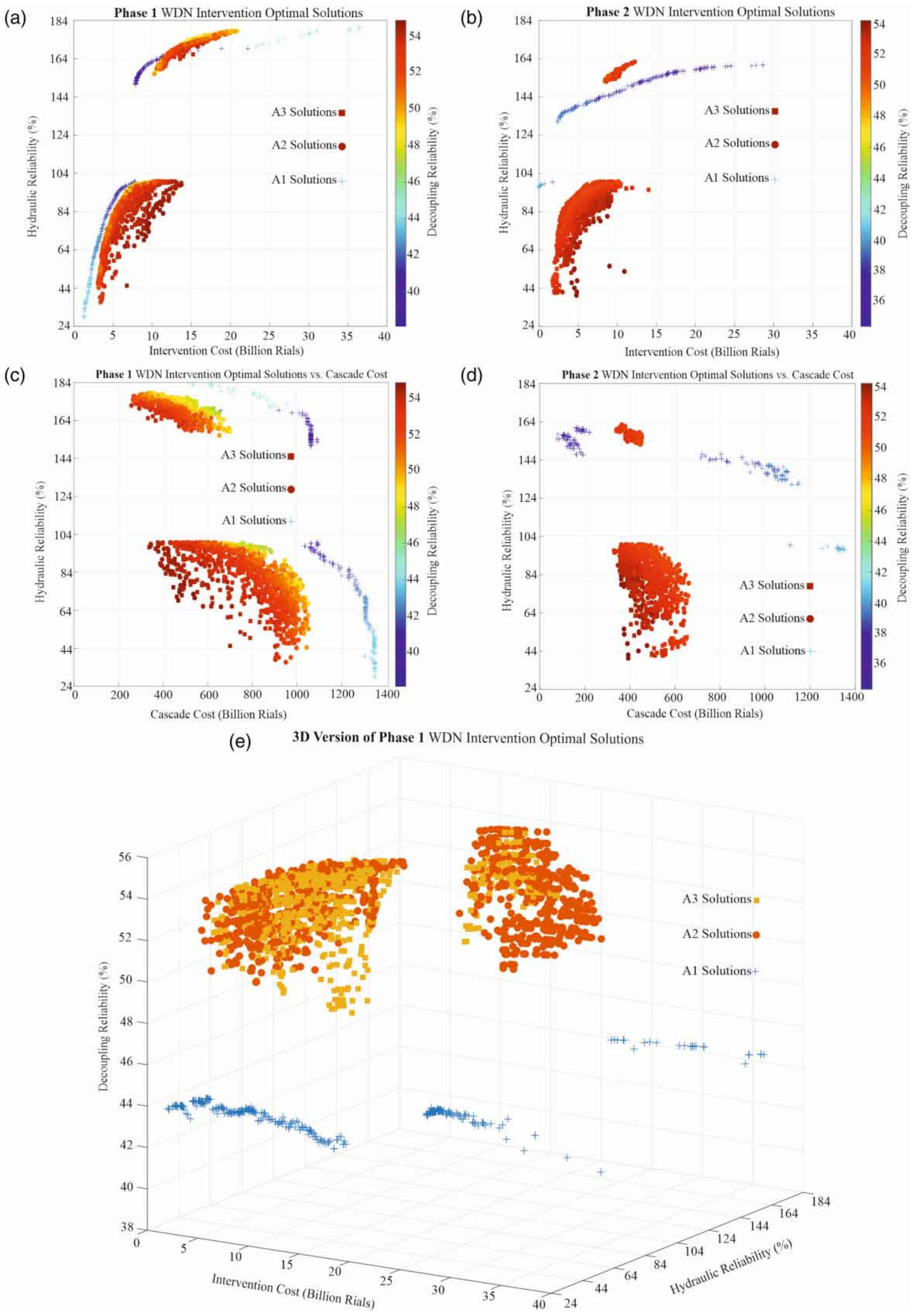



**Figure 5** | Pareto fronts solutions from different approaches. The solutions with hydraulic reliability lower than 100% are in the weak set, while the ones with hydraulic reliability over than 100% are in the robust set (the gap between distinct regions means jumping from weak to robust (resilient) condition).

it is clearly visible). However, due to budget constraints, the corresponding plan with a cost of 6.75 billion Rials is selected for Phase 1, with 0% resiliency (hybrid reliability of 97%) – meaning 61% improvement. This emphasizes the significance of budget availability in Phase 1 for making a resilient network.

Moving on to Phase 2, the trend of improving hydraulic and decreasing decoupling reliability can also be observed in solutions from A1. While the solutions from A2 and A3 do not guarantee an increase in hydraulic reliability, they maintain a good level of decoupling reliability. As more pipes are removed in an effort to create a decoupled WDN in Phase 2, the number of robust solutions captured from A2 and A3 is lower compared to Phase 1. However, this outcome depends on the initial condition of the network in Phase 2, which is obtained after implementing the selected intervention plan in Phase 1.

Regarding the cascade costs associated with solutions from A1, A2 and A3 in Phases 1 and 2, it is expected that solutions based on A1 exhibit higher cascade costs compared to those from A2 and A3. This is due to the higher interconnectivity of infrastructure in A1 solutions as opposed to A2 and A3. However, some solutions in A1 demonstrate lower cascade costs despite having higher hydraulic reliability. These solutions correspond to intervention plans that involve a significant number of replaced pipes, resulting in robust networks with a lower number of pipe bursts (it is important to note that pipe-burst scenarios are not considered for new pipes). An interesting observation from the graphs is the greater variance in hydraulic reliability compared to decoupling reliability. The former relies on pipe conditions and the number of customers, while the latter depends on the existence of redundant paths within the network (which can be estimated by the reduction of pipes outside the shortest path tree). For instance, in a network where the current topology resembles a complete tree shape, the variance of decoupling reliability would be zero.

In order to gain deeper insights into the disparities among solutions derived from various optimization approaches, Figure 6 presents statistical indices computed for all solutions obtained from each approach in both Phase 1 and Phase 2.

In terms of hydraulic and decoupling reliability, solutions from A1 generally exhibit higher hydraulic reliability compared to those from A2 and A3. Conversely, A2 and A3 solutions indicate better decoupled WDNs. When comparing A2 and A3 solutions, it becomes apparent that strictly adhering to rules for laying parallel pipes generally not only fails to significantly improve the decoupling reliability of solutions but also keeps the network hydraulic reliability in a weakened state during Phase 2. This underscores the importance of carefully considering the placement of parallel pipes to achieve a favorable balance between hydraulic and decoupling reliability when WDN decoupling is a desired objective in intervention planning.

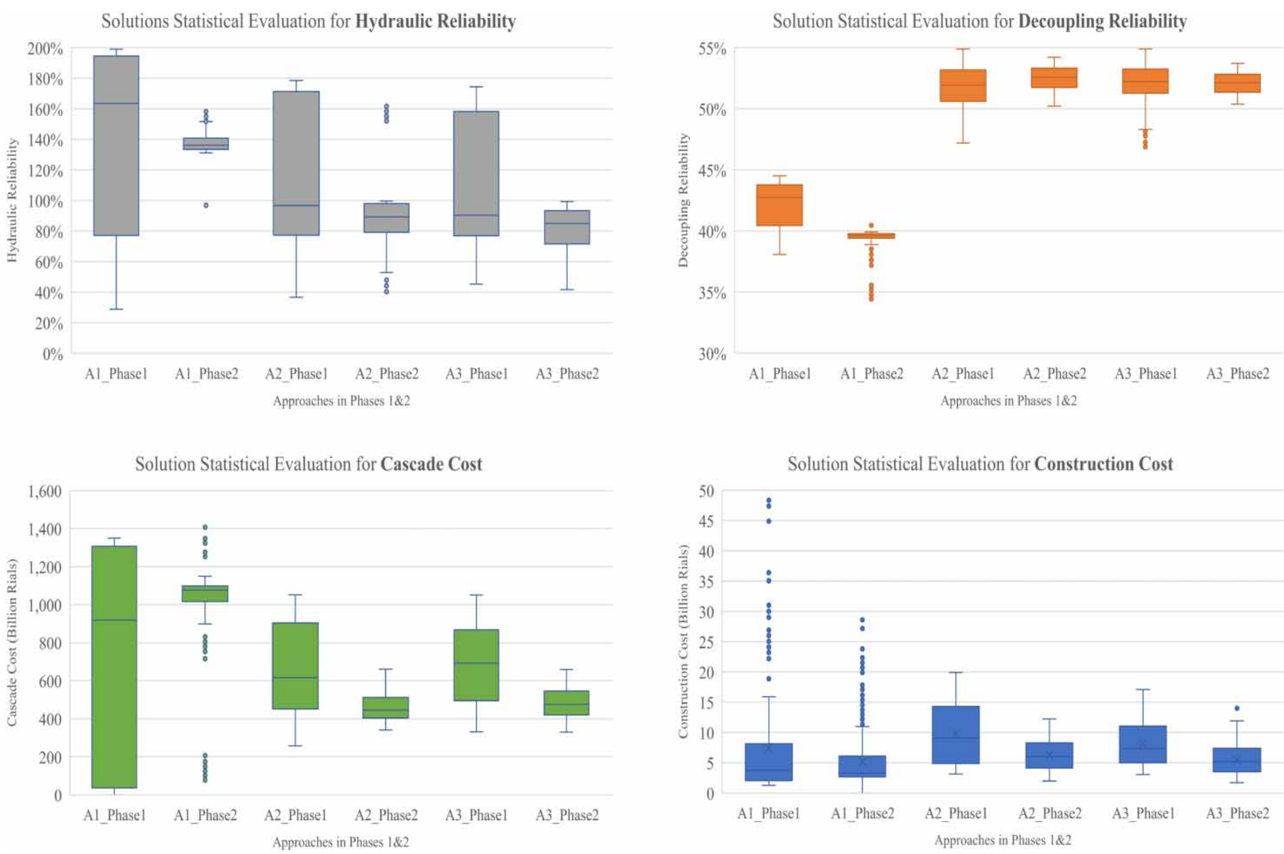



**Figure 6** | Descriptive statistics of Pareto fronts in Figure 5 through box plots.

Furthermore, when examining all three approaches, the solutions in Phase 1 exhibit a wider variance compared to the solutions in Phase 2. This indicates that the intervention plans in the forward phases are greatly influenced by the plans implemented in the previous phases in the dynamic approach. For example, if the network's pipes completely get renewed in Phase 1, except for some maintenance activities, there will be no major intervention activities in the subsequent phases.

In terms of direct (construction cost) and indirect cost (cascade cost), it is observed that solutions within A1 yield intervention plans with higher cascade costs. However, these solutions have lower construction costs compared to the ones associated with A2 and A3. For both Phases 1 and 2, the construction cost of solutions in A3 is slightly lower than that of solutions in A2. This indicates that adhering to strict rules for laying parallel pipes can have a positive impact on minimizing costs within the framework of decoupling the WDN. However, this difference in construction cost does not significantly affect the cascade cost between the intervention plans of A2 and A3. An additional notable observation pertains to the scale of costs associated with construction and cascade cost values. It is evident that the cascade cost significantly surpasses the construction cost, emphasizing the need for asset managers to give due attention to this aspect.

The higher variance and presence of outliers in solutions related to A1, compared to those associated with A2 and A3, suggest the influence of constraints in the optimization process for generating various intervention plans. In other words, altering the topology of the WDN and ensuring compliance with pressure constraints limits the number of available alternatives for the client in A2 and A3, compared to A1.

Table 4 presents the selected solutions from the corresponding Pareto fronts for Phases 1 and 2, meeting the budget constraints of 6.75 billion Rials and 4.00 billion Rials, respectively. The most expensive cascade costs, encompassing both phases, are associated with the plans generated by A1, totaling 1,977.51 billion Rials (present worth cost). Conversely, the least expensive cascade costs are attributed to the plans produced by A3, totaling 1,127.56 billion Rials (present worth cost). This indicates that decoupling while restricting the laying of parallel pipes could result in a safer network in terms of the consequences of pipe bursts and intersystem cascading failures.

Furthermore, after the two-phase rehabilitation, the intervention plans from A1 resulted in a resilient network with 137% hydraulic reliability, effectively overcoming the weak hydraulic condition of the system. In contrast, solutions from A2 and A3 maintain the WDN in a weak condition, with hydraulic reliability values of 82 and 62%, respectively. Notably, when comparing the solutions from A2 and A3 in Phase 1, a 1% improvement in decoupling reliability corresponds to a cascade cost savings of approximately 157.42 billion Rials. This highlights the significance of even marginal improvements in decoupling reliability for the asset managers of the current case study. Although the variance in decoupling reliability is not as high as in hydraulic reliability, small enhancements in decoupling reliability can lead to substantial benefits. However, in Phase 2, a marginal improvement in decoupling reliability dramatically results in a weak WDN with only 62% of nodes maintaining water pressure above the desired level. Nevertheless, this is still an improvement compared to the pre-rehabilitated hydraulic reliability, where only 36% of nodes have adequate pressure heads. Ultimately, the decision-makers have the task of selecting the final decision by considering whether they prioritize hydraulic reliability over decoupling reliability, or vice versa.

Figure 7 illustrates all the intervention plans discussed in Table 4, showcasing the dynamic changes in the network topology over the two phases by removing and inserting parallel pipes. It is evident that in A1, no decision to remove pipes has been made. Therefore, only the three decisions of 'do nothing', 'pipe replacement' and 'inserting parallel pipes' have been implemented.

**Table 4** | The selected intervention plans based on the available budget from different Pareto fronts together with their performances

| | **A1** | | **A2** | | **A3** | |
|---|---|---|---|---|---|---|
| | **Phase 1** | **Phase 2** | **Phase 1** | **Phase 2** | **Phase 1** | **Phase 2** |
| Construction cost (BRI) | 6.65 | 3.93 | 6.74 | 3.95 | 6.74 | 3.98 |
| Present worth cost * sum (BRI) | 10.21 | | 10.32 | | 10.34 | |
| Cascade cost (BRI) | 1,060 | 1,013 | 814 | 520 | 739 | 429 |
| Present worth cost * sum (BRI) | 1,977.51 | | 1,284.98 | | 1,127.56 | |
| Hydraulic reliability (%) | 97 | 137 | 93 | 82 | 90 | 62 |
| Decoupling reliability (%) | 40 | 39 | 51 | 52 | 52 | 53 |

BRI, Billion Rials. Present worth cost=Cost/(1 + discount rate)$^{p.\Delta t}$.

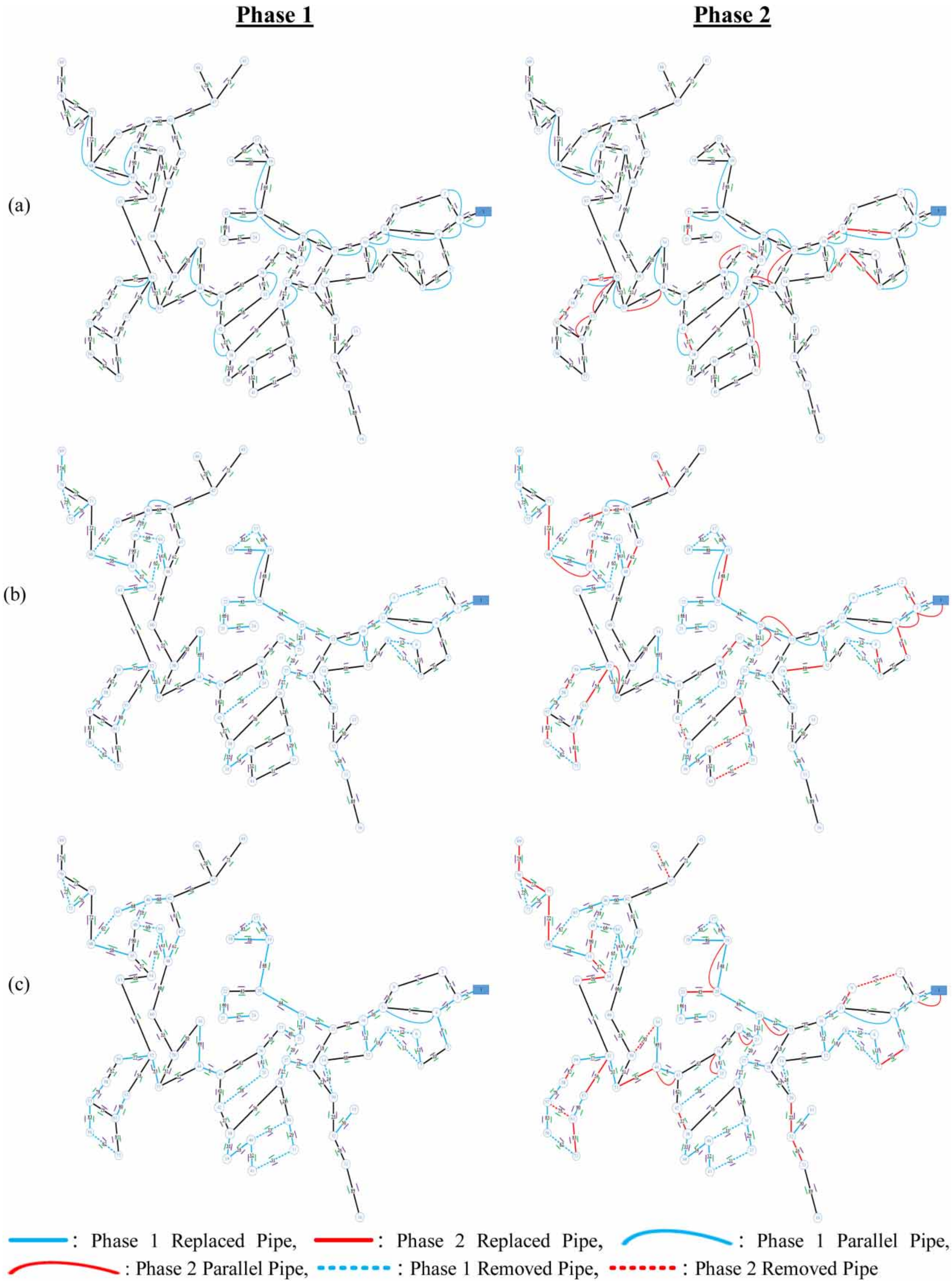



**Figure 7** | Manifestation of constructed intervention plans in Phases 1 and 2 offered in Table 4, (a) A1, (b) A2 and (c) A3.

In Phase 1, the old pipes remain in service in all corridors, and the network is reinforced solely by adding parallel pipes. Consequently, this topology is not decoupled and carries a high risk of pipe failures. As a result, the solution from this approach in Phase 1 incurs the highest cascade cost among all the solutions.

In Phase 2, the network continues to be upgraded by including parallel pipes and replaced pipes, resulting in a more resilient network. However, this approach significantly increases the degree of pipe co-location in many corridors, which is undesired for RN and UDN managers.

Solutions derived from A2 and A3 demonstrate decoupled topologies across phases by removing pipes in specific corridors. Figure 7 presents several examples of pipe removal, such as corridors 7, 11 and 12 in Phase 1 for A2, and corridors 31 and 32 in Phase 2 for both A2 and A3. Comparing the topologies resulting from A2 and A3 solutions, it is evident that A3 exhibits fewer parallel pipes compared to A2, and there are no enhanced-degree nodes with more than one parallel pipe in A3 intervention plans (which is a notable distinction between A2 and A3). This difference is demonstrated by examining Node 3 in Phase 2 for both A2 and A3 topologies.

Furthermore, it is important to consider the impact of the intervention plan in Phase 1 on the plan in Phase 2. For instance, in Phase 1, four corridors (5, 17, 48 and 60) feature parallel pipes in A2, whereas in the corresponding topology of A3, only corridor 5 has a parallel pipe. This allows Phase 2 optimization in A2 to generate resilient solutions, which is not observed in Phase 2 optimization of A3 (as depicted in Figure 6, hydraulic reliability). Therefore, while laying parallel pipes may not be beneficial in terms of cascade and construction costs, it can significantly enhance the hydraulic performance when the network's topology changes from a loop to a tree shape.

## 4. DISCUSSION AND CONCLUSION

This study developed a new approach to intervention planning for aged WDNs when there are budget limitations and the goal is to improve both hydraulic resilience and decoupling from spatially co-located infrastructures, thereby reducing the risk of intersystem cascading failures. The approach uses a multi-objective optimization methodology to include the three objectives. Three formulations of the optimization problem (A1, A2 and A3) were developed, each with distinct objectives, decision variables and constraints. A1 adopts a single utility perspective, focusing on minimizing construction costs and maximizing the hydraulic reliability of the system. Hydraulic reliability is evaluated using a hybrid index that considers the system's performance under weak and robust conditions. The decision variables for intervention activities on old pipes include 'do nothing', 'pipe replacement' and 'laying parallel pipes'.

In A2, an additional objective of decoupling reliability is introduced, and a new decision variable, 'pipe removal', is included. A novel definition of decoupling reliability was developed for WDNs, considering the co-located degree of each existing pipe in the network and assigning weights based on pipe diameters and road types. Decoupling reliability is then calculated by multiplying the weights and averaging the co-located degree minus one. A3 is similar to A2 but includes stricter rules for laying pipes in parallel, particularly avoiding such activities in densely populated urban areas. However, considerations are made for hydraulic improvement in those areas by assigning weights to pipes that are part of the shortest path and play a crucial role in network supply.

Overall, these approaches provide different perspectives and strategies for intervention planning in WDNs, considering the trade-offs between construction costs, hydraulic reliability and decoupling reliability while addressing the unique constraints and objectives of the system.

NSGA-II was utilized as the optimization engine to generate intervention plans for a real water WDN located in the southwest of Iran. The Pareto fronts were evaluated based on four criteria: intervention plan construction cost, hydraulic reliability, decoupling reliability and cascade cost. A cascade cost model was developed to assess the performance of both decoupled and coupled network topologies resulting from the implementation of each approach's solutions. The model considered the consequences of pipe-burst scenarios on the co-located systems, incorporating both direct and indirect costs. The direct cost accounted for road resurfacing construction work required after interventions to repair pipe bursts, while the indirect cost estimated the time lost by passengers and drivers due to traffic interruptions.

Once the Pareto solutions were obtained, they were used as inputs in the cascade cost model to determine the cascade cost associated with each solution. To implement the intervention plan for the water system, a dynamic approach was developed, dividing the design period into multiple phases. The optimization process was performed phase by phase, considering the evolving network changes over time.

The results revealed that the best approach for enhancing the hydraulic performance of the network is A1, which solely focuses on the WDN. However, the intervention plans derived from this approach gradually increase the interconnectivity of the WDN, resulting in a less secure topology as the cascade cost significantly rises. Conversely, solutions from A2 and

A3 exhibit lower hydraulic reliability values compared to A1, but they effectively decouple the water network by increasing the decoupling reliability. This leads to a notable reduction in cascade costs under pipe failure scenarios. Nevertheless, in general, solutions from A2 and A3 are more expensive than those from A1 since a tree-shaped network is less resilient in supplying water compared to a loop-shaped network. Consequently, larger pipe diameters are designed in A2 and A3 to compensate for this vulnerability.

Comparing the solutions of A2 and A3 reveals that when the focus is on decoupling the WDN, the strategy of laying parallel pipes can somewhat compensate for the hydraulic deficiencies resulting from the removal of pipes in certain corridors. Ultimately, selecting the best plan based on budget constraints and priorities is a decision that rests on asset managers.

To sum it up, the main outcomes of the approaches proposed in the current study are listed as follows:

- The intentions of RN and UDN managers could be conflicting with the desire of WDN managers, which is exhibited via trade-offs (Pareto fronts) obtained using multi-objective optimization approaches.
- Decoupling a WDN from the neighbor infrastructures could significantly save the cascading failure cost under single pipe burst events.
- While removing a WDN's pipes in some corridors could improve the decoupling reliability, hydraulic reliability can significantly decrease, which could be somewhat compensated by laying parallel pipes in other corridors.
- When asset managers face decision making under budget limitations, Pareto fronts obtained by using multi-objective optimization for WDN intervention planning are robfust decision-making tools for increasing the hydraulic and decoupling reliability metrics of WDNs.

To the best of our knowledge, this study is the first to propose the concept of decoupling in the context of intervention planning for WDNs. The focus of the study goes beyond improving hydraulic aspects of the WDNs and also emphasizes the reduction of spatial interdependencies between the WDN and adjacent RN and UDN, aiming to minimize the likelihood of cascading failures. However, it is important to acknowledge the challenges and simplifying assumptions made in the study, including data quality, uncertainties in modeling and decision-making, comparability of assets, and the integration of diverse assets within a single corridor. The authors intend to gradually establish a robust framework for asset managers involved in intervention planning, addressing these challenges and assumptions in future work.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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