Flexible investment planning for water distribution networks

R. Pellegrino, N. Costantino and O. Giustolisi

ABSTRACT

The present work focuses on the planning of water distribution networks (WDNs). The research proposes an innovative strategy which aims at helping water managers formulate flexible investment plans while allowing for adaptive management under the increasing unawareness of medium–long term planning. This innovative strategy differs from existing strategies accounting for flexibility in WDN design. It allows for developing flexible investment plans without assuming that statistic or deterministic assumptions can account for all unawareness. The strategy introduces the key idea of technical contiguity of actions/solutions by post-processing a Pareto front obtained by a classic optimization technique in order to obtain sequential actions. This means retrieval of a set of 'technically contiguous' actions from the Paretian solutions, namely, by increasing the investment each action needs to contain the previous one. The application to the Apulian network allows discussion of the need for post-processing the Pareto front of solutions returned by the classic multi-objective design optimization and presenting the general strategy to obtain adaptive and flexible investment plans. We discuss further perspectives of the proposed strategy based on the integration of different flexible plans, each obtained with different assumptions, which could be statistic or deterministic, for the system boundary conditions.

Key words | adaptive management, post-processing, technical contiguity, WDN investment plans

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INTRODUCTION

Water distribution network (WDN) management requires that water managers make decisions on investments *ex ante* in the face of an environment significantly changing over years in an unpredictable way. The unpredictability of such changes, which severely affects medium–long term planning of WDNs, cannot be solved by statistic or deterministic model assumptions for the system boundary conditions. It is a consequence of the unawareness about future states of the environment where WDNs work, caused by the unpredictable evolution of elements that are endogenous (e.g., customer demands, pipe deterioration, background leakages, etc.) and/or exogenous (e.g., environmental, economic, financial and contractual conditions, etc.) to hydraulic systems (Zhang & Babovic 2012; Creaco *et al.* 2014). Once built, hydraulic systems cannot significantly modify their operating conditions to adapt to new scenarios that may present themselves according to the evolution of endogenous and exogenous elements. Hence, the unawareness about future states of the WDN environment asks for a novel planning strategy.

The unawareness about the evolution of endogenous elements to WDNs (i.e., boundary system conditions), mainly due to a lack of information, determines uncertainties that are generally faced using statistic (e.g., a probability density distribution function for customer demands) or deterministic (e.g., a maximum increase of

doi: 10.2166/hydro.2017.023

customer demands as in the classic approach) assumptions. However, the unawareness of endogenous elements, although statistically or deterministically modelled, is not actually solved because of their dependence on actual environment changes over years. Furthermore, the unawareness resulting from the evolution of exogenous elements (e.g., urbanization plans, macroeconomic situation, contract evolution, etc.) cannot be faced using statistic or deterministic assumptions. The unawareness related to the lack of conception rather than the lack of information, that is, the unawareness due to the impossibility to formulate/predict uncertain scenarios about the future conditions (scenario-based uncertainties), requires the intrinsic adaptability of planned actions.

Without loss of generality, we here focus on the classic planning actions related to pipe sizing and expansion of WDNs, although the proposed strategy could be applied to any decision problem, e.g. rehabilitation, districtualization, etc., in order to obtain flexible plans.

It is well known that in WDN design the presence of uncertainty may typically result in oversized or undersized hydraulic capacity of WDNs (Basupi & Kapelan 2015). During the last decade, researchers proposed several alternatives to face the issue of uncertainty through the development of flexible design of the system components (e.g., Zhou & Hu 2009; Huang *et al.* 2010; Marques *et al.* 2014, 2015a, 2015b; Basupi & Kapelan 2015) in order to achieve hydraulic reliability. Undoubtedly, all these studies represent a significant progress in developing new strategies and methods, such as the real option theory. However, they do not address the more general issue of the adaptive WDN planning, which is strategic to support water managers in developing flexible investment plans. Furthermore, the reported efforts faced the uncertainty related to unawareness about the evolution of endogenous elements to WDNs (e.g., customer demands and pipe resistances), generally using statistic assumptions.

On the other side, the great challenge for the technical-scientific community in the third millennium will be to develop tools and technologies to plan and manage infrastructure (Haimes 1998). The analysis of technical literature reveals that less attention has been reserved for adaptive planning considering a general strategy to face the unawareness about the evolution of both endogenous and exogenous elements as defined above. The practical challenges encountered by the water managers in planning WDNs strengthen the need for investigating this unexplored area of research. Water managers are required to provide the next year's investment plans to the regulatory agency aimed at improving the service. These plans need to report the pathways of interventions to reach the agreed contractual targets. At the same time, however, water managers should be able to modify plans, without the need to neglect past interventions. For instance, it may be opportune to continue investing although the targeted performance has been reached (due to availability of additional budget, or extension of the contact, etc.); or it can be opportune to stop investing earlier than scheduled (because the performance has been reached ahead of schedule, or the budget has been reduced, or the contract has been shortened, etc.). This asks for flexible plans enabling adaptive management along the whole life of the hydraulic system. This means, in practice, that the plan could be modified as the unawareness about the evolution of endogenous and exogenous elements resolves, allowing for alternative solutions that are technically compatible with the past interventions.

These considerations provided strong motivation to focus on the general planning of WDNs considering the evolution of endogenous and exogenous elements. In particular, the aim of this research is to propose an innovative strategy for supporting water managers in the formulation of flexible investment plans allowing adaptive management under the intrinsic unawareness of environment changes in medium–long term planning horizons. This innovative strategy differs from the others because it allows the development of flexible investment plans without asking that statistic or deterministic assumptions have to account for all the unawareness in medium–long term planning.

To this purpose, the strategy introduces the key idea of 'technical contiguity' of actions/solutions by post-processing the classical Pareto front. This means retrieval of a set of technically contiguous actions from the Paretian solutions, namely, by increasing the investment each action needs to contain the previous one. Or in other words, starting from any action, the next one has to be an 'upgrade' of the previous one.

Existing flexile design approaches (e.g., Marques *et al.* 2014, 2015a, 2015b; Basupi & Kapelan 2015) assume a predefined scenario of uncertainty evolution (e.g., high and low customer demands), develop a two/four-stage plan (described as a decision tree) where each node presents a solution that is technically contiguous with that of the previous node of the tree. Furthermore, these flexible approaches are strictly driven by the prior expectations on the scenario. In fact, the technical literature studies (Marques *et al.* 2014, 2015a, 2015b, 2017; Basupi & Kapelan 2015) assume that at predefined discrete instants of time during the considered horizon the uncertainty evolves into two possible states (e.g., high and low customer demands), and model this uncertainty evolution as a decision tree.

For instance, Basupi & Kapelan (2015) simulate a possible scenario for the demand following a two-staged decision tree depending on the states of the demand (e.g., High or Low), and, accordingly, find the solutions for this staged design of WDNs that minimize total intervention costs (capital and operational) and maximize system and resilience.

Similarly, Marques *et al.* (2014, 2015a, 2015b) consider a network planning horizon of 60 years, divide it into 4 periods, and assume that possible future conditions the network could have to cope with will change discretely within these 4 periods (i.e., some possible expansions and a 'predefined' demand increase may happen in two consecutive periods of this tree). Given these predefined scenarios of uncertainty, they optimize the WDNs design.

Marques *et al.* (2017) present an optimization method for the design and operation of WDNs that implements a multi-phase strategy to achieve a flexible design by considering uncertainty when planning short to long term investments. The multiphase design of WDNs consists of carrying out the design in phases using short-time horizons at each phase (rather than considering the full planning horizon). In this sense, existing works on optimization of WDN design seem to adopt a top-down approach to the design of WDN under uncertainty, limiting their scope to provide a flexible design for a given uncertainty scenario. Differently, the present research proposes an innovative bottom-up strategy for developing investment plans which are not built on a given uncertainty scenario, and therefore allow for adaptive management according to the evolution of unawareness about exogenous and endogenous elements.

To post-process the set of Paretian solutions obtained from any classic multi-objective optimization technique, several rules of contiguity can be implemented (Pellegrino *et al.* 2017). In the following, we discuss some of them, although the paper uses the most effective for pipe sizing.

This paper is organized as follows. The following section describes the challenges faced when using traditional Pareto fronts during the medium–long term planning of WDNs. After that, the case of the Apulian network is presented, discussing the need for post-processing of Pareto front solutions returned by standard multi-objective optimal pipe sizing assuming that the customer demands will double in the future. Then the innovative strategy to obtain flexible plans from original Paretian solutions is presented, followed by showing the results of the analysis varying the assumption about the future demand. These results demonstrate the technical effectiveness and robustness of the strategy with respect to this assumption. Finally, further research perspectives of the proposed strategy are discussed followed by the concluding report on the findings of this paper.

PROBLEM FORMULATION

Without loss of generality, we here discuss the challenges faced when using traditional Pareto front during the medium–long term planning of WDNs considering, as example, the optimal pipe sizing of an existing system in order to increase the hydraulic capacity.

In the last decades, in fact, researchers have extensively studied the problem of WDN design, adopting two different approaches. The first viewed the WDN optimization problem as a single-objective, least-cost optimization problem where pipe diameters are the primary decision variables, with no reliability constraint (Simpson *et al.* 1994; Savic & Walters 1997). The second comprises studies which address the minimization of design/rehabilitation costs and take into account the maximization of benefits through reliability assessment (Walski 2001). The latter uses multi-objective optimization to consider extra and conflicting objectives, such as hydraulic and mechanical reliability (e.g. Prasad & Park 2004; Tolson *et al.* 2004; Babayan *et al.* 2005; Farmani *et al.* 2005; Kapelan *et al.* 2005; Setiadi *et al.* 2005; Filion *et al.* 2007; Giustolisi *et al.* 2009; Filion & Jung 2010; Torii & Lopez 2012; Giustolisi *et al.* 2014; Ivetić *et al.* 2016).

In both cases, the outcome of WDN optimization is a Pareto front representing different technical actions of interventions. For instance, in the case of pipe sizing aimed at increasing the hydraulic capacity, each point on the diagram returned by a two-objectives optimization (intervention cost vs. hydraulic capacity) corresponds to a subset of pipes to be replaced or parallelized. In this sense, each point on the diagram is a sort of 'one-off solution/action' providing a certain level of net benefits (hydraulic capacity) against a certain level of investment (intervention cost). The Pareto front obtained by the classical optimization is therefore well suited when water managers make a single (i.e., one-off) investment decision which will become effective almost immediately.

Beyond one-off investment, WDN planning needs, i.e., the design of an investment pathway, come up very often. For example, water managers are required to provide the plans for the coming next year's investment to the regulatory agency aimed at improving the service (hydraulic reliability). Consequently, more actions on WDN must be identified and implemented not immediately, but in more than one stage, considering the unawareness about endogenous and exogenous elements. It becomes, therefore, mandatory to formulate such investment plans allowing for adaptive management along the whole life of the network, under the increasing unawareness in medium–long term planning.

In this scenario, the problem to be solved is not just the identification of the optimal one-off intervention (as in the classical optimization). It is needed to design an investment pathway, which is adaptive, given that the evolution of endogenous and exogenous elements is generally not known at the time of making the decision on the investment pathway. Hence, the classical Pareto front cannot be used to formulate an investment plan, since it solves the problem of one single investment decision. In other words, once a population of Paretian solutions has been obtained through any kind of multi-objective optimization procedure, starting from the lowest solution cost and increasing it, the following solutions are, in general, not sequential, i.e., not contiguous from a technical standpoint.

In practice, if water managers would like to intervene on the network to reach a predefined level of performance (on y-axis of Figure 1), they cannot intervene 'gradually' on the network following the classical Pareto front. They cannot start with the technical solution associated to the first point of the diagram and then decide to move to the next one. Being non-contiguous means that the pipes replaced in the next solution, in order to further increase the WDN performance, are generally different from the previous one. At the extreme, each solution requires restoring the old conditions (related to the initial state of the WDN) in order to be applicable (in terms of expected performance and cost of implementation) (path dependence issue).

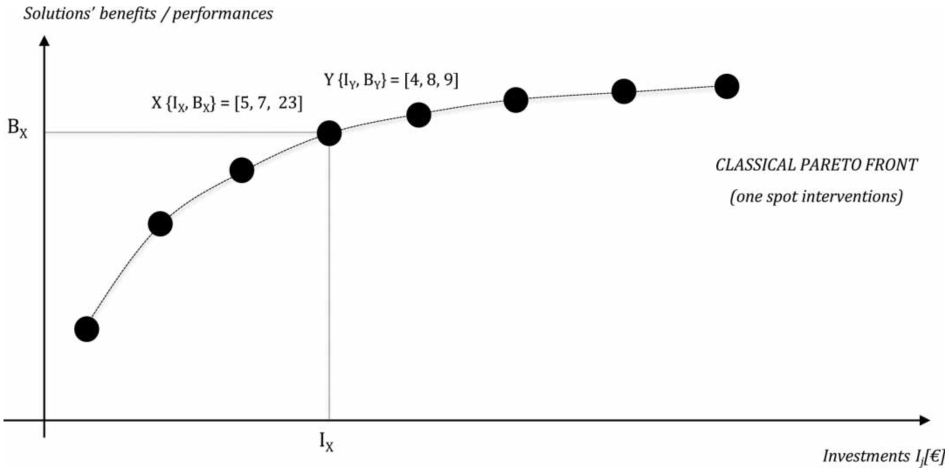

Figure 1 | Example of a one-off Pareto front.

Let us, for example, consider the intervention on the WDN identified by point X in the Pareto front represented in Figure 1. Implementing the technical solution X, this means that we expect a performance B_X against an investment I_X. If after this intervention, the water company would make another action, it would not be possible to use the same Pareto front and move, for instance, just to the next point, since the technical solutions in that front are not 'technically contiguous'. At the extreme situation, the points of the Pareto front may be even mutually exclusive: in this sense, it is a 'one-off' Pareto front developed to answer the issue of single interventions on WDNs. For instance, it may happen that the point X technically is a solution consisting in the replacement of pipes 5, 7 and 23 (see Figure 1), while the next point in the diagram (Y) consists in replacing pipes 4, 8 and 9 (with pipes 5, 7 and 23 being equal to those in the pre-intervention scenario); hence, they are not contiguous. Besides, to make it possible that the technical solution Y produces the benefits B_Y, the first intervention X should be 'cancelled' in order to bring the network back to the initial condition. In other words, a new optimization accounting for the new conditions occurred after the intervention X, which has modified part of the network, is required. This process might be very burdensome and not useful for the decision maker that aims at developing a plan of interventions/investments.

WDN SIZING EXAMPLE

The mathematical formulation of a WDN model for simulating a single steady-state snapshot of a given hydraulic system composed of n_p pipes, n_n nodes and n_0 reservoirs, is based on $(n_p + n_n)$ energy and mass balance equations is,

$$\begin{cases} \mathbf{A}_{pp}\mathbf{Q}_p + \mathbf{A}_{pn}\mathbf{H}_n = -\mathbf{A}_{p0}\mathbf{H}_0 \\ \left[\begin{array}{l} \mathbf{A}_{np}\mathbf{Q}_p = \dfrac{\mathbf{V}_n}{\Delta T} \text{ demand-driven analysis} \\ \mathbf{A}_{np}\mathbf{Q}_p - \dfrac{\mathbf{V}_n(\mathbf{H}_n)}{\Delta T} = 0_n \text{ pressure-driven analysis} \end{array}\right. \end{cases} \quad (1)$$

where the vectors $\mathbf{Q}_p$ contains the pipe flow rates, $\mathbf{H}_n$ contains the unknown nodal heads, $\mathbf{H}_0$ contains the known nodal heads of reservoirs, and $\mathbf{V}_n$ contains the volumes of water withdrawals in the nodes during ΔT, which is the time interval of the real hydraulic system snapshot.

The network graph of the hydraulic system is defined $\mathbf{A}_{pn} = \mathbf{A}_{np}^T$ and $\mathbf{A}_{p0}$ topological incidence sub-matrices of size $[n_p,n_n]$ and $[n_p,n_0]$, respectively, derived from the general topological matrix $\bar{\mathbf{A}}_{pn} = [\mathbf{A}_{pn} \mid \mathbf{A}_{p0}]$ of size $[n_p,n_n + n_0]$.

Afterward, a steady-state modeling for a given time interval ΔT and volume $\mathbf{V}_n$ of nodal water withdrawals, returns $\mathbf{Q}_p$ and $\mathbf{H}_n$, which depend from the assumed demands (demand-driven analysis) or from the computed demands depending on nodal heads/pressures (pressure-driven analysis) (Giustolisi & Walski 2012).

In this paper, we will focus on the system performance with respect to customer demand. Therefore, the pressure-driven analysis is mandatory in order to predict the hydraulic behavior in terms of customer unsupplied water demands with respect to the service requirements. The behavior of the customer demands is effectively modeled by Wagner's model (Wagner *et al.* 1988) allowing predicting the actual supplied water in pressure-deficient conditions (Giustolisi & Walski 2012). Furthermore, the nodal volume $\mathbf{V}_n$ contains the background leakages, which are extra demand loads, always existing in the WDN, influencing the hydraulic system capacity depending on the asset deterioration and pressures into the system. Therefore, pressure-driven analysis is also mandatory in order to model the background leakages and predict the actual capacity of the hydraulic system. Germanopoulos' model (1985) is here used to model background leakages modeling (Giustolisi *et al.* 2008).

Apulian network

We here use the Apulian network (see Giustolisi *et al.* 2008, for further details) in order to discuss the need for a post-processing of Pareto front solutions returned by the standard optimal design strategies. This case study is also used to propose, in the next section, a general strategy to obtain flexible plans (i.e. technically contiguous) from original Paretian solutions.

Without losing the generality of the methodology, in this case study we assume a deterministic variation of one endogenous element, namely the customer demand, even though it can be easily generalized by modeling the unawareness on such endogenous elements using statistics. If a statistic assumption about the demand evolution is made, the output becomes a flexible Pareto front obtained with reference to that stochastic demand. The customer demand was modelled assuming double nodal demands ($K = 2$).

Pressure-driven analysis asks for the assumption of a minimum required pressure for any service and for a correct service. Therefore, the two values (constant through the network) equal to 0 and 10 m, respectively, was assumed. The pipe level parameters of Germanopoulos' model were assumed equal to $\alpha = 1.2$ and $\beta = 1.062 \times 10^{-7}$ (constant through the network) corresponding to a leakage level equal to 25% of the maximum inflow at the pick hour.

It used a multi-objective optimization minimizing the investment cost due to pipe sizing versus the hydraulic capacity. The hydraulic capacity is measured here using the total unsupplied demand of the network, one of the many performance measures of the network:

$$UN = 1 - \frac{\sum_{i=1}^{n_n} d_i^{cust}(P_i)}{\sum_{i=1}^{n_n} d_i^{req}} \tag{2}$$

where UN is the network unsupplied demand, d_i^{cust} is the actual delivered customer demand depending on pressure P_i, d_i^{req} is the required customer demand and n_n is the number of network nodes. The definition of UN makes the optimization problem a minimization of the investment cost versus a minimization of the unsupplied water (i.e., one minus performance).

Figure 2 shows the Pareto front of the 378 optimization solutions. By analyzing the technical solutions resulting from the optimization, it is evident that the Paretian solutions are not contiguous. For the sake of clarity, let us consider a few solutions of Pareto front, such as solutions 24, 25, 26 and 27, as reported in Table 1. Even though they are four consecutive points in the diagram (Figure 2), they are 'technically non-contiguous'.

In particular, compared to solution 24, solution 25 consists of replacing pipe 23, as is also the case for solution 24. Solution 25 now uses a diameter (164 mm) which is smaller than the one of solution 24 (290 mm). Also, solution 25 provides the replacement of the pipe 24 which is not replaced in solution 24, and finally both solutions replace the pipe 34 (in both cases the diameter has been changed from 368 mm to 500 mm).

As another example, let us consider solutions 25 and 26. Solution 26 compared to solution 25 does not replace the pipes 23 and 24, while it replaces the pipe 8, and it continues to replace, as in solution 25, pipe 34 with a pipe of the same diameter provided by solution 25.

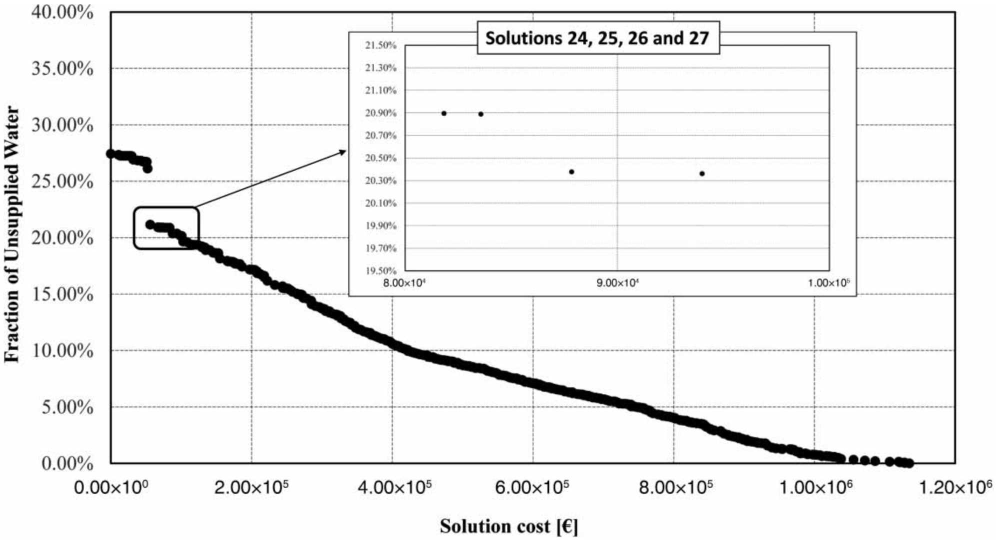

Figure 2 | Pareto front from the classic optimal pipe sizing. (The *y*-axis measures the fraction of unsupplied water that, compared to Figure 1, is 'one minus the solution's benefits/performance': this justifies the different shapes of Pareto fronts in Figure 1 and Figure 2, which are complementary.)

Table 1 | A few solutions of Pareto front showing the nominal internal diameter (D_{k1}) and the replacement cost (C_k) for solution nos 24–27 (only diameters changing among the solutions, with the related cost, are highlighted in bold)

n.	1		[2 - 23]	24		25		26		27	
link	D_{k1}	C_k	…	D_{k1}	C_k	D_{k1}	C_k	D_{k1}	C_k	D_{k1}	C_k
1	327	€ -	…	327	€ -	327	€ -	327	€ -	327	-
2	290	€ -	…	290	€ -	290	€ -	290	€ -	290	-
3	100	€ -	…	100	€ -	100	€ -	100	€ -	100	-
4	290	€ -	…	290	€ -	290	€ -	290	€ -	290	-
5	100	€ -	…	100	€ -	100	€ -	100	€ -	100	-
6	368	€ -	…	368	€ -	368	€ -	368	€ -	368	-
7	327	€ -	…	327	€ -	327	€ -	327	€ -	327	-
8	100	€ -	…	100	€ -	100	€ -	**164**	**€ 31 915**	**184**	**38 067 €**
9	100	€ -	…	100	€ -	100	€ -	100	€ -	100	-
10	184	€ -	…	184	€ -	184	€ -	184	€ -	184	-
11	100	€ -	…	100	€ -	100	€ -	100	€ -	100	-
12	184	€ -	…	184	€ -	184	€ -	184	€ -	184	-
13	100	€ -	…	100	€ -	100	€ -	100	€ -	100	-
14	100	€ -	…	100	€ -	100	€ -	100	€ -	100	-
15	164	€ -	…	164	€ -	164	€ -	164	€ -	164	-
16	290	€ -	…	290	€ -	290	€ -	290	€ -	290	-
17	290	€ -	…	290	€ -	290	€ -	290	€ -	290	-
18	164	€ -	…	164	€ -	164	€ -	164	€ -	164	-
19	229	€ -	…	229	€ -	229	€ -	229	€ -	229	-
20	100	€ -	…	100	€ -	100	€ -	100	€ -	100	-
21	100	€ -	…	100	€ -	100	€ -	100	€ -	100	-
22	258	€ -	…	258	€ -	258	€ -	258	€ -	258	-
23	100	€ -	…	**290**	**€ 25 900**	**164**	**€ 10 951**	100	€ -	100	-
24	100	€ -	…	100	€ -	**164**	**€ 16 682**	100	€ -	100	-
25	100	€ -	…	100	€ -	100	€ -	100	€ -	100	-
26	204	€ -	…	204	€ -	204	€ -	204	€ -	204	-
27	164	€ -	…	164	€ -	164	€ -	164	€ -	164	-
28	100	€ -	…	100	€ -	100	€ -	100	€ -	100	-
29	100	€ -	…	100	€ -	100	€ -	100	€ -	100	-
30	184	€ -	…	184	€ -	184	€ -	184	€ -	184	-
31	258	€ -	…	258	€ -	258	€ -	258	€ -	258	-
32	100	€ -	…	100	€ -	100	€ -	100	€ -	100	-
33	100	€ -	…	100	€ -	100	€ -	100	€ -	100	-
34	368	€ -	…	**500**	**€ 55 932**	**500**	**€ 55 932**	**500**	**€ 55 932**	**500**	**55 932 €**
	UN	Sol. Cost		UN	Sol. Cost	UN	Sol. Cost	UN	Sol. Cost	UN	Sol. Cost
	27.44%	€ -		20.90%	€ 81 832	20.89%	€ 83 566	20.38%	€ 87 847	20.36%	€ 93 999

Dk1 is the nominal internal diameter [mm]

D_{k1} is the nominal internal diameter [mm].

Finally, the solution 27 requires the increase of the pipe 8, which was already increased, i.e., replaced for the implementation of solution 26. Clearly, this is not effective from a technical standpoint.

This clearly highlights not only that solutions are non-contiguous, but also that to get the benefits associated with a given solution it is required to bring the network back to the initial conditions, making this unacceptable from both economic and technical standpoints. This confirms that the traditional Pareto front developed for deciding the one-off intervention on the network cannot be used to develop a plan.

INNOVATIVE STRATEGY FOR DEVELOPING INVESTMENT PLANS

This section presents the innovative strategy for developing investment plans by using a Pareto front with solutions that can be considered technically contiguous. To build contiguity, the population of Paretian solutions obtained through a multi-objective optimization procedure is post-processed according to a specific rule of contiguity. There are several ways to build contiguity among the solutions. One of these consists in introducing a rule which makes the solutions of Pareto front globally compatible among them. This means that starting from one point of Pareto front and moving forward, the next solutions of the front may be implemented by simply adding new interventions (i.e., replacing other pipes in the network) without the need for neglecting past actions. As discussed in Pellegrino *et al.* (2017), for example, a schema of contiguity may be starting with the first solution of the one-off Pareto front (i.e., the solution with lowest levels of investment and performance) and proceed with a forward pass by joining the technical solutions of the one-off Pareto front. It may happen that moving from one solution to the next one, there is a change of diameters for the same pipe, i.e., two solutions suggest the intervention on the same pipe, but by using different diameters. Assumption of a rule for making these two solutions compatible is required; for instance, using the largest pipe at the beginning. Another schema proposed by Pellegrino *et al.* (2017) assumes that the last solution of the one-off Pareto front (the one with highest investment and performance) is the target to be reached. This is the schema considered in this paper, which we named schema of 'global contiguity with backward pass development'. The new front is built by starting from this last solution (target) and prioritizing the pipes to be replaced based on their frequency of occurrence in the one-off Pareto front solutions. The basic assumption is that if an intervention is present in all, or a lot of, solutions, then it can be considered overriding compared to the less frequent interventions (Giustolisi *et al.* 2006). Looking at the resulting Pareto front shown in Figure 3, it is possible to notice that we obtain a lower number of solutions compared to the traditional front (14 solutions of the new front versus 378 solutions of the classical Pareto front), which is due to the intrinsic characteristic of the strategy determining a sequential replacement of pipes. The first and the last solution of the contiguous front (solution 1 and solution 14) are the same in one-off Pareto front (solution 1 and solution 378).

Table 2 represents the two tables related to the front in Figure 3. Each row of the Table 2 corresponds to pipes, which need to be replaced; they are 13 out of 34 for doubling the customer demand ($K = 2$). Each pipe is replaced one time while implementing the 13 solutions (the first is the starting situation). For example, pipe 34 is replaced early (solution 2) while pipe 29 is the last (solution 14). It is notable that because of the contiguity, the number of solutions (13) corresponds to the number of pipes to be replaced phasing the interventions to reach $UN = 0\%$ assuming doubling ($K = 2$), the demand. Therefore, solution 14 corresponds to the last of the original Pareto front in Figure 2, which was used to generate the flexible plan. Table 2 synthesizes the information of Table 2 by reporting the sequence of replaced pipes starting from pipe 34 and ending with pipe 29. Table 2 could be expanded adding the column of total replacement cost and *UN*.

As depicted in Table 2, the technical contiguity means that the decision maker may operatively start from any point of Figure 3, by implementing the related solution, and then move to the next one (by upgrading the intervention previously done on the WDN) without the need for neglecting the past investment or for re-optimizing the WDN, as would be the case for the one-off Pareto front.

Furthermore, the flexible Pareto front does not have any temporal dimensions. In other words, the sequence of points in the flexible Pareto front does not have any temporal meaning. It only means that the solutions are technically contiguous. The strong implication is that this flexible front can be used to develop intervention plans considering both endogenous and exogenous elements of unawareness, and may span a generic time horizon.

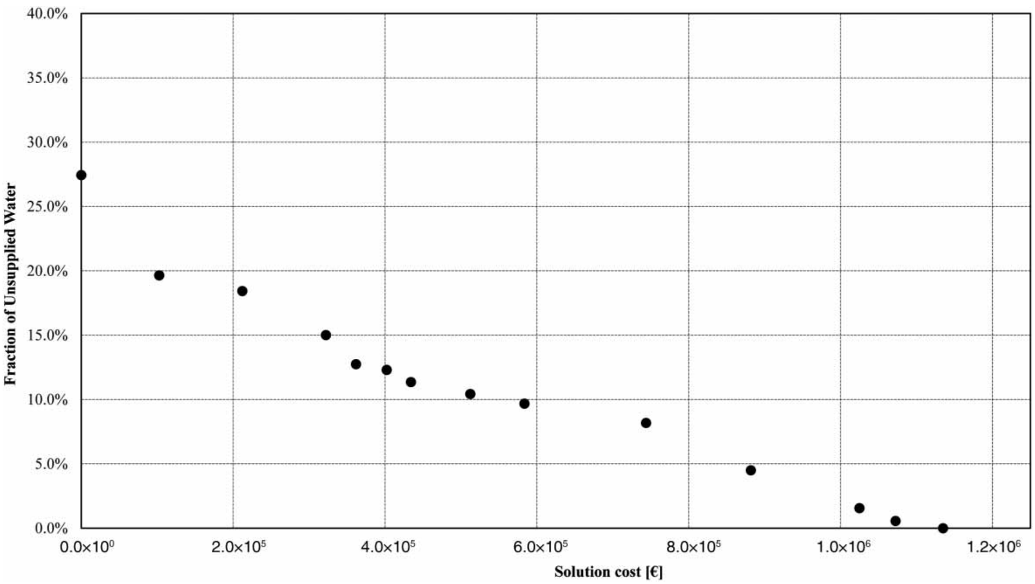

Figure 3 | Example of a Pareto front under the global contiguity scheme with backward pass development.

The endogenous elements may be considered, as is the case with most flexible design methodologies, by modeling them as statistic or deterministic changes of some variables as in the specific case study, but the strategy allows the decision maker to face for exogenous elements. For example, by using the flexible front, the decision of a water manager in order to reach the performance target established into the contract, may start to invest gradually from the first solution to the next ones following the front, thus moving toward the target performance. The actual performance associated to each action may differ, of course, from the calculated performance (the response of the WDN to the intervention is different from that expected). In this case, if, during the implementation of interventions, the performance is reached before expected, the water manager may change the plan by stopping early. On the contrary, if the performance target is not reached after having implemented the actions scheduled by the plan, the water manager may go ahead with the interventions implementing the next contiguous solution listed in the front. In the same manner, all the other exogenous elements of uncertainty may be considered, e.g., a change in the budget availability, or a change in the contract (extension, contraction or abandonment). Contrary to the existing flexible

Table 2 | Decision support tables related to Pareto set of solutions in Figure 3 (diameters that change are highlighted in bold)

(a)

ID/Sol.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
6	368	368	368	368	368	368	368	368	368	368	368	**500**	**500**	**500**
7	327	327	327	327	327	327	327	327	327	327	**500**	**500**	**500**	**500**
8	100	100	100	100	100	100	**164**	**164**	**164**	**164**	**164**	**164**	**164**	**164**
11	100	100	100	100	100	**184**	**184**	**184**	**184**	**184**	**184**	**184**	**184**	**184**
14	100	100	100	100	100	100	100	100	100	**290**	**290**	**290**	**290**	**290**
15	164	164	164	164	164	164	164	164	**290**	**290**	**290**	**290**	**290**	**290**
17	290	290	290	290	290	290	290	**500**	**500**	**500**	**500**	**500**	**500**	**500**
18	164	164	**327**	**327**	**327**	**327**	**327**	**327**	**327**	**327**	**327**	**327**	**327**	**327**
21	100	100	100	100	100	100	100	100	100	100	100	100	**164**	**164**
28	100	100	100	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**
29	100	100	100	100	100	100	100	100	100	100	100	100	100	**184**
32	100	100	100	100	**204**	**204**	**204**	**204**	**204**	**204**	**204**	**204**	**204**	**204**
34	368	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**
UN	27.44%	19.65%	18.43%	15.02%	12.74%	12.30%	11.35%	10.43%	9.68%	8.17%	4.50%	1.55%	0.56%	0.00%

(b)

	K = 2	
Pipe ID	Diam	New Diam
34	368	750
18	164	327
28	100	258
32	100	204
11	100	184
8	100	164
17	290	500
15	164	290
14	100	290
7	327	500
6	368	500
21	100	164
29	100	184

design methodologies embedding the temporal dimension (for example, when assuming that the demand will increase or decrease at a specific point of time), in the proposed innovative strategy the evolution of both endogenous and exogenous elements is not constrained to follow a predefined temporal course (e.g., increase or decrease each 20 years).

Considering also the final sequence of all the pipes that have to be replaced in order to increase the demand of the desired value (K = 2) by having also at the same time the maximum WDN performance (UN = 0%), it is evident that the technically contiguous solutions of the new fronts are still robust from a technical standpoint. In fact, looking at Table 2, the first three pipes to be replaced (i.e., nos 34, 18 and 28) correspond to a specific flow path that has to be strengthened in terms of hydraulic conductivity. Such pipes are, in fact, the most common in the 378 solutions of the original Pareto set. This highlights an important characteristic of the proposed strategy. It does not invent new solutions, and it is not built on a specific future scenario. It post-processes the solutions obtained through any optimization procedure (such as genetic algorithm, GA) and makes them technically contiguous in order to allow for the development of plans. This implies that the proposed strategy is still able to maintain all the information provided by the optimization procedure and continue exploiting it during WDN planning. In other words, we proposed a post-processing of the information contained in the Pareto set of solutions in order to make it effective for WDN planning. This is a general idea which, beyond the specific methods here reported, contributes to create a bridge between classic optimal design and flexible investment planning. As a further step in this direction, once a possible schema of contiguity has been selected, it might be directly included into the multi-objective framework by constraining the optimization to provide optimal contiguous solutions. This could be a worthwhile field of investigation. It would allow water managers to continue using a multi-objective optimization framework with the contiguity constraint in order to develop investment plans on WDNs under the increasing unawareness in medium–long term planning.

Finally, we discuss here the optimality of the 'flexible' Pareto set with respect to the original one. In overlapping and comparing the two fronts (Figure 4), some interesting insights can be drawn.

First, the 'flexible' front shows a loss of optimality compared with the one-off Pareto front. The points of the flexible front are, on average, above the classical front's points. This means that given a level of investment (on *x*-axis), the benefits delivered by the technical solution drawn from the classical front (calculated as '1 – *y*', with *y*-coordinate being the fraction of unsupplied water) are higher than

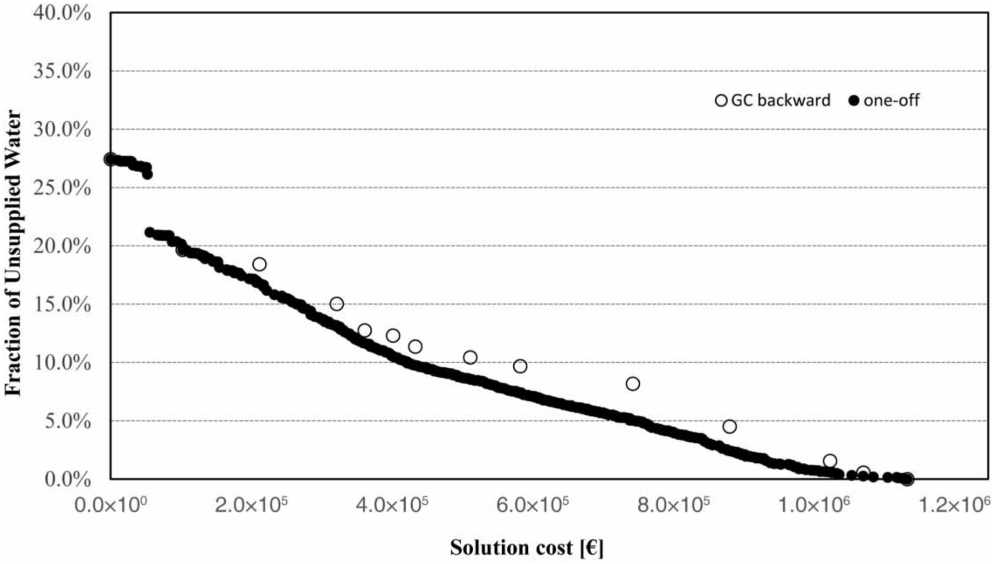

Figure 4 | Comparison of traditional Pareto front and the Pareto front under the global contiguity scheme with backward pass development.

those associated to the solutions provided by the new front. The loss of optimality is measured by the vertical distance (*y*-axis) between two points belonging to the two fronts, fixed the level of investment (*x*-coordinate). This is particularly evident in the central part of the diagram, rather than at the extremes. The first solution, in fact, represents the starting point of both diagrams, while the last solutions are those when the target in terms of network performance (here unsupplied water) has been reached. This fact means that the adaptability comes at a cost: if the water manager decides to intervene gradually on WDNs following the flexible Pareto front, the technical solution corresponding to the stopping point (generally identified by a level of investment cost corresponding to the available budget and/or a level of performance corresponding to the fixed target) is generally less convenient than the corresponding point on the classical Pareto front. In other words, it is possible to find a one-off solution (on the classical Pareto front) characterized by similar performance with a lower level of investment cost, or by the similar level of investment with a higher level of performance. The post-processing of Paretian solutions will result in a loss of optimality with respect to the classic multi-objective optimization, the loss of optimality being partly the price of adaptability. The quantification of the cost of the flexibility and its trade-off with the benefits of flexible and informative plans considering the uncertainties in medium–long term planning could be the object of further research.

Second, the strategy has the new perspective of integrating different plans (i.e., on-spot optimization plans) based on different assumptions. To this purpose, the next section reports the same flexible plans assuming that the customer demand will increase by four and six times.

A FURTHER PERSPECTIVE OF THE METHODOLOGY

We perform here the analysis by using different values of the increased demand, namely, we set its value at four and six times the initial value.

Table 3 reports, similar to Table 2, the flexible plan derived by post-processing the one-off front obtained by the standard multi-objective optimization with $K = 4$ and $K = 6$, respectively.

Table 4 reports for the three considered scenarios ($K = 2$, $K = 4$ and $K = 6$) the sequences of pipes that should be gradually replaced in order to bring the network from the status quo to the status with maximum hydraulic performance ($UN = 0\%$).

Clearly, the number of pipes to be replaced according to flexible plans (13 for $K = 2$ as in Table 4) increase to 18 and 19 for $K = 4$ and $K = 6$, respectively, as reported in Table 4. In fact, by increasing the final customer demand, both the number of pipes and the diameter of the specific replaced pipe increase because it is necessary to increase the hydraulic system capacity. Table 4 shows that pipe 34 is always present, but requires a larger diameter. It is replaced with a pipe of diameter 750 mm for $K = 2$ and 100 mm for $K = 4$ and $K = 6$; while pipe 23 is only present for $K = 2$ and $K = 4$.

Table 4, together with the network layout (Figure 5), considering that the single reservoir also feeds the hydraulic system, shows a rationale in the sequence of pipes, namely that when K increases the final sequence of pipes to be replaced does not completely change. For instance, the first two pipes are the same for all three scenarios (although with an increased diameter which is technically consistent with the increased K), while some other pipes vary the priority position when K changes. It is possible to correct the fact that pipe 6 should be replaced before pipe 7 considering the flow paths from the single reservoir.

This discussion opens further research perspectives in WDN planning. In fact, varying K or any other hydraulic boundary condition and attributing to each scenario resulting from the flexible optimization a probability of occurrence pose the foundation for the integration of the resulting ‘flexible’ plans and allow the decision to be made once the unawareness about future conditions is solved. In other words, synthesizing the information resulting from different optimizations, each obtained with different uncertain hydraulic variables, could allow for integrating different plans. Each plan is characterized by different boundary conditions and probability of occurrence, while maintaining the flexibility of the original scheme and the robustness with respect to exogenous unpredictable events during the planning horizon. This is an open research direction, which is out of the focus of the present paper, although it represents the natural perspective of the proposed strategy.

Table 3 | Results of analysis with K = 4 (a) and K = 6 (b) (the diameters changing among the solutions are highlighted in bold)

(a)

ID/Sol.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
3	100	100	100	100	100	100	100	100	100	100	**290**	**290**	**290**	**290**	**290**	**290**	**290**	**290**	**290**
6	368	368	368	368	368	368	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**
7	327	327	327	327	327	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**
8	100	100	100	100	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**
13	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	**258**	**258**	**258**
14	100	100	100	100	100	100	100	100	100	100	100	100	100	100	**368**	**368**	**368**	**368**	**368**
15	164	164	164	164	164	164	164	164	164	164	164	164	**500**	**500**	**500**	**500**	**500**	**500**	**500**
16	290	290	290	290	290	290	290	290	290	290	290	290	290	**500**	**500**	**500**	**500**	**500**	**500**
17	290	290	290	290	290	290	290	290	290	290	290	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**
18	164	164	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**
20	100	100	100	100	100	100	100	**164**	**164**	**164**	**164**	**164**	**164**	**164**	**164**	**164**	**164**	**164**	**164**
22	258	258	258	258	258	258	258	258	258	258	258	258	258	258	258	258	258	258	**500**
23	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	**164**	**164**	**164**	**164**
24	100	100	100	100	100	100	100	100	100	**184**	**184**	**184**	**184**	**184**	**184**	**184**	**184**	**184**	**184**
28	100	100	100	**290**	**290**	**290**	**290**	**290**	**290**	**290**	**290**	**290**	**290**	**290**	**290**	**290**	**290**	**290**	**290**
30	184	184	184	184	184	184	184	184	184	184	184	184	184	184	184	184	184	**258**	**258**
32	100	100	100	100	100	100	100	100	**290**	**290**	**290**	**290**	**290**	**290**	**290**	**290**	**290**	**290**	**290**
34	368	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**
UN	55.08%	45.97%	43.09%	39.28%	38.30%	34.56%	27.11%	24.95%	20.78%	20.71%	16.36%	14.32%	13.02%	12.33%	0.05049	4.34%	3.29%	2.89%	0.00%

(b)

ID/Sol.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
3	100	100	100	100	100	100	100	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**	**368**
6	368	368	368	368	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**
7	327	327	327	327	327	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**	**750**
8	100	100	100	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**
12	184	184	184	184	184	184	184	184	184	184	184	184	184	184	184	184	184	184	**500**	**500**
13	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	**229**	**229**	**229**	**229**
14	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	**500**	**500**	**500**	**500**	**500**
15	164	164	164	164	164	164	164	164	164	164	164	164	164	**500**	**500**	**500**	**500**	**500**	**500**	**500**
16	290	290	290	290	290	290	290	290	290	290	290	290	290	290	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**
17	290	290	290	290	290	290	290	290	290	290	290	290	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**
18	164	164	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**
20	100	100	100	100	100	100	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**
22	258	258	258	258	258	258	258	258	258	258	258	258	258	258	258	258	258	258	258	**327**
23	100	100	100	100	100	100	100	100	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**
25	100	100	100	100	100	100	100	100	100	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**	**258**
28	100	100	100	100	100	100	100	100	100	100	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**
29	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	**290**	**290**	**290**
32	100	100	100	100	100	100	100	100	100	100	100	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**	**500**
34	368	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**
UN	66.75%	58.56%	54.89%	54.21%	47.54%	40.96%	36.52%	30.62%	30.61%	29.91%	26.13%	21.21%	18.98%	17.04%	0.15544	7.79%	6.03%	2.02%	0.86%	0.00%

CONCLUSIONS

This paper presents an innovative strategy which aims at supporting water managers in the formulation of flexible investment plans allowing for adaptive management under the increasing unawareness in medium–long term planning. The key idea of the proposed strategy to the adaptive planning is to develop investment plans by post-processing a Pareto front obtained by a standard multi-objective optimization technique in order to obtain sequential actions. This means retrieval of a set of 'technically contiguous' actions from the Paretian solutions, i.e., by imposing that each action upgrades the previous one. Several ways to build contiguity among the solutions are possible. This paper discusses some of them, and uses the most effective for pipe sizing and applies it to the Apulian network.

The contribution of our research is twofold. First, we contribute to the technical literature, which extensively addresses the issue of WDN adaptive design. While it considers the unawareness about elements endogenous to the system through statistic or deterministic assumptions, it lacks studies focusing on the general planning of WDNs (i.e., development of plan of interventions) considering also the unawareness about exogenous elements to the system (such as budget change, contract change, different answers of hydraulic systems to new interventions). Second, we contribute to the practice by offering a useful instrument that can support water company managers in developing long term plans on WDNs under the increasing unawareness on both exogenous and endogenous elements.

This innovative strategy is then shown and demonstrated using a case study related to the increase of hydraulic capacity. The findings and their discussion suggest the following interesting insights.

First, the traditional Pareto front developed to decide the one-off intervention on the network cannot be adopted

Table 4 | Final sequences of pipes replaced in the scenarios K = 2 (a), K = 4 (b) and K = 6 (c)

(a) K = 2

Pipe ID	Diam	New Diam
34	368	750
18	164	327
28	100	258
32	100	204
11	100	184
8	100	164
17	290	500
15	164	290
14	100	290
7	327	500
6	368	500
21	100	164
29	100	184

(b) K = 4

Pipe ID	Diam	New Diam
34	368	1000
18	164	368
28	100	290
8	100	368
7	327	750
6	368	750
20	100	164
32	100	290
24	100	184
3	100	290
17	290	750
15	164	500
16	290	500
14	100	368
23	100	164
13	100	258
32	100	258
22	258	500

(c) K = 6

Pipe ID	Diam	New Diam
34	368	1000
18	164	500
8	100	500
6	368	750
7	327	750
20	100	258
3	100	368
23	100	258
25	100	327
28	100	500
32	100	500
17	290	1000
15	164	500
16	290	1000
14	100	500
13	100	229
29	100	290
12	184	500
22	258	327

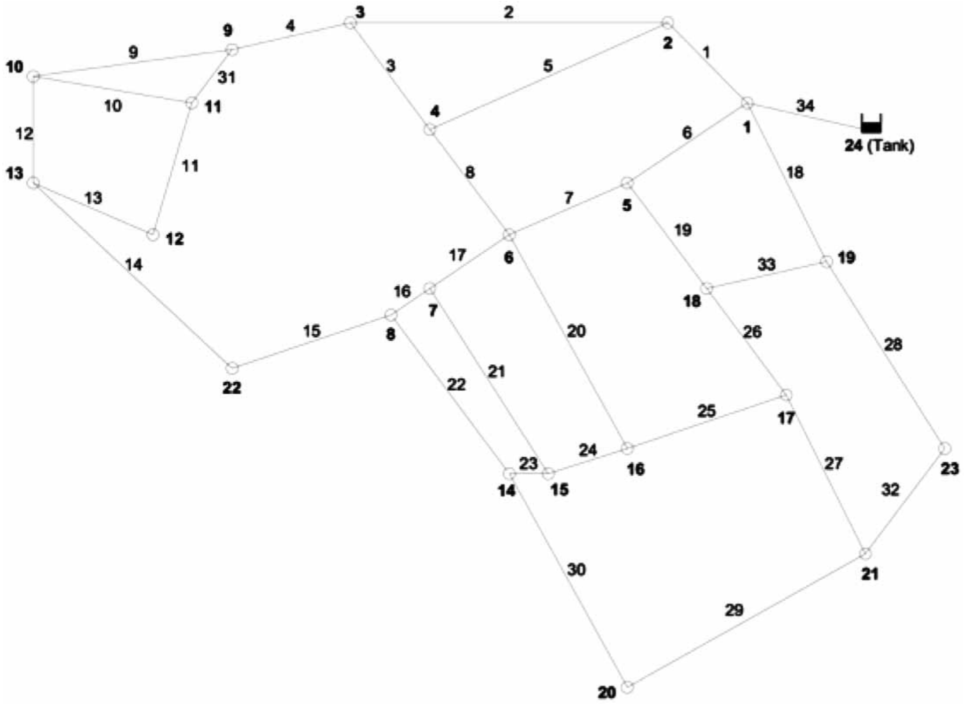

Figure 5 | Apulian network layout.

for developing a plan. In fact, once a solution has been implemented, to get the benefits associated to another optimal solution in the front, it is needed to bring the network back to the initial conditions, making this unacceptable from both economic and technical standpoints. Contrarily, the new Pareto front developed with technically contiguous solutions may support the adaptive management of WDNs, since each solution, once implemented, may be further upgraded, without the need of demolishing past interventions.

Second, while the contiguity allows for adaptive WDN planning, it is not free since it produces a loss of optimality compared with the classical front. Such a loss of optimality is represented by the vertical distance (on the y-axis) between the two fronts. This result suggests that the loss of optimality created by the technical contiguity may be one of the criteria to select the optimal schema of contiguity. Thus, the issue of quantifying the cost of flexibility and its trade-off with the gains provided by the proposed strategy could be object of future studies.

Third, the solutions sequenced in the flexible Pareto front can be used to develop plans of interventions considering both endogenous and exogenous elements of uncertainty, and may span a generic time horizon. The endogenous elements may be considered, as usually done by the flexible design methodologies, by modeling them as statistic or deterministic assumptions, while the exogenous elements are accounted by the inner feature of the strategy, which is not constrained to a predefined scenario of uncertainty. Water managers may develop a plan that starts from one generic point of the Pareto front (characterized by a certain level of investment and performance) and go forward gradually with further investments until reaching the performance target assumed for the multi-objective optimization. The water manager may decide to change the plan, and, for example, continue investing on the network once the targeted performance has been reached (due to availability of more budget, or extension of the contact, etc.) without the need to neglect past interventions. In the same way, the water manager may decide to stop investing earlier than the scheduled (because the performance has been reached before the scheduled end, or the budget has been reduced, or the contract has been shortened, etc.). Furthermore, the flexible Pareto front does not have any temporal dimensions. In other words, the sequence of points in the flexible Pareto front does not have any temporal meaning, but it means only that the solutions are technically contiguous.

Forth, the flexible fronts are robust from a technical standpoint. In fact, those pipes that are replaced in all the one-off Pareto front solutions given their strategic importance for the network continue to be replaced in the flexible front (the diameter depends on the specific rule for building contiguity). This demonstrates that contiguous solutions are close to the optimal ones from a technical perspective (unless some minor differences due to the specific schema of contiguity adopted, such as the difference in diameters), but differ for costs and benefits.

Fifth, the 'rules' for searching the contiguity among the optimal solutions of the one-off Pareto front may be easily changed according to the objectives of the planning managers, intervention costs, uncertainty, etc. For the sake of generalization of the developed strategy, further research will also be oriented to investigate other possible rules for searching the contiguity among the optimal solutions of the one-off Pareto front and compare the performance of all these new fronts.

Sixth, contrary to existing flexible design methodologies, that assume an a priori scenario of uncertainty evolution (formulated ex-ante as a decision tree), the proposed innovative strategy for adaptive planning adopts a flexible Pareto front which is built by post-processing the classical Pareto front (obtained from standard multi-objective optimization techniques) with any kind of contiguity schema. This implies that the proposed strategy is still able to maintain all the information provided by the optimization procedure and exploit it during the planning of WDNs. Including the selected schema of contiguity directly into the multi-objective framework will allow water managers to continue to still use the multi-objective optimization framework with the contiguity constraint in order to develop investment plans on WDNs under the increasing unawareness in medium–long term planning. This is not a trivial task since the contiguity constraint is a global constraint. Further research could be devoted to address this issue.

Finally, considering different scenarios of unawareness about the demand (more in general, on endogenous elements), we found that the final sequence of pipes to be replaced is not completely changed. This opens a new research perspectives in the WDN planning: varying K or any other hydraulic boundary condition and attributing to each scenario a probability of occurrence poses the foundation for the integration of the resulting flexible plans. This, in turn, allows for making decisions on pipe replacement once the unawareness about (boundary) conditions is solved. In other words, developing plans which synthetize the information resulting from optimizations under different boundary conditions, each with a different probability of occurrence, will enable the decision maker to intervene on the network in an informed way. At the same time, the flexibility of the original scheme and the robustness with respect to exogenous unpredictable events during the planning horizon is also guaranteed. The issue of how integrating flexible fronts related to different K-values represents an open planning perspective would be an excellent object of future research.

REFERENCES

Babayan, A. V., Kapelan, Z., Savic, D. A. & Walters, G. A. 2005 Least cost design of robust water distribution networks under demand uncertainty. *J. Water Resour. Plan. Manage.* **131**, 375–382.

Basupi, I. & Kapelan, Z. 2015 Flexible water distribution system design under future demand uncertainty. *J. Water Resour. Plan. Manage.* **141**, 1–14.

Creaco, E., Franchini, M. & Walski, T. 2014 Accounting for phasing of construction within the design of water distribution networks. *J. Water Resour. Plan. Manage.* **140**, 598–606.

Farmani, R., Walters, G. A. & Savic, D. A. 2005 Trade-off between total cost and reliability for any-town water distribution network. *J. Water Res. Plan. Manage.* **131**, 161–171.

Filion, Y. R. & Jung, B. S. 2010 Least-cost design of water distribution networks including fire damages. *J. Water Res. Plan. Manage.* **133**, 658–668.

Filion, Y. R., Adams, B. J. & Karney, B. W. 2007 Stochastic design of water distribution systems with expected annual damages. *J. Water Res. Plan. Manage.* **133**, 244–252.

Germanopoulos, G. 1985 A technical note on the inclusion of pressure dependent demand and leakage terms in water supply network models. *Civil Eng. Syst.* **2**, 171–179.

Giustolisi, O. & Walski, T. M. 2012 Demand components in water distribution network analysis. *J. Water Res. Plan. Manage.* **138**, 356–367.

Giustolisi, O., Laucelli, D. & Savic, D. A. 2006 Development of rehabilitation plans for water mains replacement considering risk and cost-benefit assessment. *Civil Engineering and Environmental Systems* **23**, 175–190.

Giustolisi, O., Savic, D. A. & Kapelan, Z. 2008 Pressure-driven demand and leakage simulation for water distribution networks. *J. Hydr. Eng.* **134**, 626–635.

Giustolisi, O., Laucelli, D. & Colombo, A. F. 2009 Deterministic vs. stochastic design of water distribution networks. *J. Water Res. Plan. Manage.* **135**, 117–127.

Giustolisi, O., Berardi, L. & Laucelli, D. 2014 Optimal water distribution network design accounting for valve shutdowns. *J. Water Res. Plan. Manage.* **140**, 327–338.

Haimes, Y. Y. 1998 Sustainable operation of threatened infrastructures. *J. Infrastruct. Syst.* **4**, 1–4.

Huang, D., Vairavamoorthy, K. & Tsegaye, S. 2010 Flexible design of urban water distribution networks. In: *World Environmental and Water Resources Congress*, 16–20 May, Providence, Rhode Island, USA, pp. 4225–4236.

Ivetić, D., Vasilić, Ž., Stanić, M. & Prodanović, D. 2016 Speeding up the water distribution network design optimization using the ΔQ method. *Journal of Hydroinformatics* **18**, 33–48.

Kapelan, Z. S., Savic, D. A. & Walters, G. A. 2005 Multi-objective design of water distribution systems under uncertainty. *Water Resour. Res.* **41**, W11407-1–W11407-15.

Marques, J. C. R., Cunha, M. C. & Savić, D. A. 2014 Using real options in the optimal design of water distribution networks. *J. Water Resour. Plan. Manage.* **141**, 1–10.

Marques, J. C. R., Cunha, M. C. & Savić, D. A. 2015a Using real options for an eco-friendly design of water distribution systems. *Journal of Hydroinformatics* **17**, 20–35.

Marques, J. C. R., Cunha, M. C. & Savić, D. A. 2015b Multi-objective optimization of water distribution systems based on a real options approach. *Environmental Modeling & Software* **63**, 1–13.

Marques, J., Cunha, M., Savić, D. & Giustolisi, O. 2017 Water network design using a multiobjective real options framework. *Journal of Optimization*. https://doi.org/10.1155/2017/4373952.

Pellegrino, R., Costantino, N. & Giustolisi, O. 2017 An innovative approach to support planning of investments on water distribution network. In: *Lesam 2017*, 20–22 June, Trondheim, Norway.

Prasad, T. D. & Park, N. S. 2004 Multiobjective genetic algorithms for design of water distribution networks. *J. Water Resour. Plan. Manage.* **130**, 73–82.

Savic, D. A. & Walters, G. A. 1997 Genetic algorithms for the least-cost design of water distribution networks. *J. Water Resour. Plan. Manage.* **123**, 67–77.

Setiadi, Y., Tanyimboh, T. T. & Templeman, A. B. 2005 Modeling errors, entropy and hydraulic reliability of water distribution systems. *Adv. Eng. Soft.* **36**, 780–788.

Simpson, A., Dandy, G. & Murphy, L. 1994 Genetic algorithms compared to other techniques for pipe optimization. *J. Water Resour. Plan. Manage.* **120**, 423–443.

Tolson, B. A., Maier, H. R., Simpson, A. R. & Lence, B. J. 2004 Genetic algorithms for reliability-based optimization of water distribution systems. *J. Water Resour. Plan. Manage.* **130**, 63–72.

Torii, A. J. & Lopez, R. H. 2012 Reliability analysis of water distribution networks using the adaptive response surface approach. *J. Hydr. Eng.* **137**, 227–236.

Wagner, J. M., Shamir, U. & Marks, D. H. 1988 Water distribution systems reliability: simulation methods. *J. Water Res. Plan. Manage.* **114**, 276–294.

Walski, T. M. 2001 The wrong paradigm: why water distribution optimization doesn't work? *J. Water Resour. Plan. Manage.* **127**, 203–205.

Zhang, S. X. & Babovic, V. 2012 A real options approach to the design and architecture of water supply systems using innovative water technologies under uncertainty. *J. Hydroinform.* **14**, 13–29.

Zhou, Y. & Hu, T. 2009 Flexible design of delivery capacity in urban water distribution system. In: *Int. Conf. on Management and Service Science, 2009, MASS '09*, IEEE, Wuhan, China.

First received 6 February 2017; accepted in revised form 5 August 2017. Available online 9 October 2017