Automatic Network Response Methodology for Failure Recovery or Bursts in Drinking Water Networks

Carlos Trapiello, Ph.D.[1]; Luis Romero-Ben[2]; Jordi Meseguer, Ph.D.[3]; Vicenç Puig[4]; Gabriela Cembrano, Ph.D.[5]; Bernat Joseph-Duran, Ph.D.[6]; Miquel Sarrias[7]; David Saporta[8]; and Meritxell Minoves[9]

Abstract: This article presents a novel response methodology for the operational recovery of a drinking water network after an incident causes an interruption of service. The proposed optimization-based methodology allows computing the optimal set of interventions to be performed in order to mitigate, or even prevent, the impact of the incident on the network operation. Besides, a proof-of-concept scheme has been designed for the automatic generation of failure scenarios and the systematic implementation and validation of the proposed response methodology. Several results are presented to demonstrate the capability of the methodology to mitigate harmful incidents, as well as the performance improvements derived from the application of the obtained interventions.

Introduction

Since ancient times, the implementation and efficient management of drinking water networks (DWNs) have played a fundamental role in the development of cities. Consequently, the minimization of service interruptions in DWNs is considered a major challenge with untold beneficial social and economic consequences. The disruption of the network operation can either result from planned service suspensions or unexpected system failures like pipe bursts (Diao et al. 2016). The former is scheduled by the water utility and hence preventive actions can be performed to mitigate the associated disturbances. On the contrary, the appearance of unexpected failures is especially alarming due to its economic impact [(Liemberger and Wyatt 2019) estimated that leaks account for up to 126 million cubic meters of water worldwide every year], health repercussions (LeChevallier et al. 2003), and environmental effects (Xu et al. 2014). Accordingly, this article focuses on conceiving an adequate methodology to optimize the response of DWNs to unforeseen events, thus moving toward efficient management of the water resources in the cities.

In general, failure management plans are composed of three subsystems (Butler et al. 2017): (1) a failure detection and isolation system; (2) a real-time detection system; and (3) a response and decision support system. More specifically, in the first instance, a supervisory control and data acquisition (SCADA) software provides the system operators with valuable information regarding the damaged elements by analyzing the data collected from the network sensors. Then, after the approval of a human operator, a set of interventions are carried out with the intention of isolating the smallest possible part of the network containing the failure so that it can be repaired (Liu et al. 2017; Giustolisi 2020). However, this isolation process may result in adverse consequences for consumers who may either completely lose their water supply or suffer a pressure drop that may also cause a loss of service if the problem persists long enough to drain the network tanks. Correspondingly, the isolation of the failure should be complemented with the deployment of some corrective actions aiming at a fast service restoration. These corrective actions may include: usage of alternative water supply options (Nayak and Turnquist 2016) and redistributing flows. Nevertheless, as reported by (Mahmoud et al. 2018), even though safety aspects like failure location, vulnerability analysis, or risk assessment, among others, have been thoroughly studied in the literature, there is still a lack of efficient mechanisms for deciding which interventions must be carried out after a failure has been isolated.

On this subject, the set of interventions that are taken into consideration in the present article result from the physical redundancy of water networks in charge of conveying drinking water from the treatment plants to the different consumption points. In large cities, DWNs are typically segmented into pressure management zones (PMZs)

[1]Supervision, Safety and Automatic Control Research Center (CS2AC), Universitat Politécnica de Catalunya (UPC), Rambla Sant Nebridi, 22, Terrassa, Barcelona 08222, Spain (corresponding author). ORCID: https://orcid.org/0000-0001-7806-8679. Email: carlos.trapiello@upc.edu

[2]Dept. of Automatic Control, Institut de Robòtica i Informàtica Industrial (CSIC-UPC), Carrer Llorens Artigas, 4-6, Barcelona 08028, Spain. ORCID: https://orcid.org/0000-0002-4790-2031

[3]CETaqua, Water Technology Centre (Agbar Group), Ctra. d'Esplugues, 75, Cornella del Llobregat, Barcelona 08940, Spain. ORCID: https://orcid.org/0000-0002-0488-7556

[4]Professor, Supervision, Safety and Automatic Control Research Center (CS2AC), Universitat Politécnica de Catalunya (UPC), Rambla Sant Nebridi, 22, Terrassa, Barcelona 08222, Spain; Dept. of Automatic Control, Institut de Robòtica i Informàtica Industrial (CSIC-UPC), Carrer Llorens Artigas, 4-6, Barcelona 08028, Spain.

[5]Dept. of Automatic Control, Institut de Robòtica i Informàtica Industrial (CSIC-UPC), Carrer Llorens Artigas, 4-6, Barcelona 08028, Spain; CETaqua, Water Technology Centre (Agbar Group), Ctra. d'Esplugues, 75, Cornella del Llobregat, Barcelona 08940, Spain.

[6]CETaqua, Water Technology Centre (Agbar Group), Ctra. d'Esplugues, 75, Cornella del Llobregat, Barcelona 08940, Spain.

[7]CETaqua, Water Technology Centre (Agbar Group), Ctra. d'Esplugues, 75, Cornella del Llobregat, Barcelona 08940, Spain. ORCID: https://orcid.org/0000-0001-6721-9494

[8]Aigües de Barcelona, Carrer General Batet 1-7, Barcelona 08028, Spain.

[9]Aigües de Barcelona, Carrer General Batet 1-7, Barcelona 08028, Spain.

and district metering areas (DMAs) by means of boundary valves. Inside each PMZ, the corresponding DMAs are supplied using specific control points of the transmission network. Nonetheless, under a failure condition, there exist alternative paths that can be enabled by opening/closing the boundary valves and that may allow feeding a DMA either with water from neighboring DMAs (inside the same PMZ or from a nearby PMZ) or with water from other points of the transmission network (same PMZ or from another). In addition, the presented set of interventions (closing/opening boundary valves) can be complemented by modifying the set-points of nearby pressure-reducing valves (PRVs) and pumping stations, avoiding pressure drops while keeping the tank levels within some safety values.

At this point, it must be pointed out that the selection of the appropriate interventions must not only provide admissible water service to the consumers, but it should also be performed under some optimality criterion for the water utility company. In this sense, a natural way to proceed is to minimize the number of interventions, especially in the case of manually operated valves that may impose a limitation on the maximum number of interventions that can be carried out due to limited staff.

Literature Review

The problem of restoring the nominal service after a component failure (e.g., a pipe burst) has been widely studied in the automatic control literature through the so-called fault tolerant control (FTC) schemes [see, for example, the monographic texts Blanke et al. (2006) and Ding (2013)], which have been successfully applied in the restoration of water transmission networks (Robles et al. 2016) and sewer networks (Ocampo-Martínez and Puig 2009). Nevertheless, the above strategies focus on exploiting the analytical redundancy of the system (i.e., using a fixed set of components), whereas the selection of a subset of interventions also requires exploiting the physical redundancy of the network by bringing into play new boundary valves that are normally closed. This problem has been addressed in the context of linear systems by posing it as a mixed-integer program (MIP) in Mignone (2002) and more recently in Trapiello et al. (2021), where the MIP is combined with the information retrieved from the offline assessment of structural properties of the water network.

Focusing on works that address the management of interventions by using reliable DWN nonlinear models (i.e., taking into account energy and flow balances in the network nodes): in Vamvakeridou-Lyroudia et al. (2010), the authors propose a hierarchical algorithm to mitigate the effect of a single pipe burst. This algorithm relies on the offline computation of a list of interventions related to each pipe burst scenario according to historical data of flow and pressure. Besides, in Mahmoud et al. (2018), the selection of the optimal interventions among a preestablished subset is posed as a multiobjective optimization solved using a genetic algorithm that returns the Pareto optimal curve of intervention strategies. Recently, Nikoloudi et al. (2021) uses a similar approach as the core of a new interactive real-time decision-making tool for the response to failures in water distribution networks. Their tool is based on several steps covering stages like: initial impact assessment, identification of the isolation plan, identification of the response solution, and solution impact assessment. Additionally, another optimization-based methodology is presented by Zhang et al. (2020) for the resilience maximization of DWNs after large-scale disasters.

Contributions

The main contribution of this work is the proposal of a network management methodology for the selection of the optimal subset of interventions to be deployed in order to recover the nominal functioning of the DWN (after the isolation of a network pipeline due to an unforeseen event). This novel methodology is based on the formulation of the intervention selection as an optimization problem with continuous variables. Note that, unlike other approaches like Mahmoud et al. (2018), where the different interventions are modeled by means of integer variables, here the continuous-variable problem formulation allows us to solve the optimization using nonlinear programming solvers. Moreover, the proposed formulation has the same structure as model predictive controllers (MPC), which are commonly in charge of the operational control of water networks. This would facilitate a subsequent inclusion of the methodology into a real-time functional tool. Additionally, a proof-of-concept software scheme has been developed for the automatic generation of failure scenarios as well as the systematic implementation and validation of the proposed response methodology. Finally, in order to illustrate and demonstrate the operation of the proposed methodology, the proof-of-concept scheme has been used in two case studies based on real DWNs that include segments of the transmission and distribution networks.

The remainder of the paper is organized as follows: first, the problem under investigation is described in the section "Network Response after Failure," including a description of a typical DWN, the possible failure scenarios, and the different interventions. Then, section "Methodology Overview" presents the proposed methodology, outlining the optimization problem, its objectives, constraints, and the required postprocessing procedure. Later, section "Proof-of-Concept" describes the different elements of the scheme designed to assess the methodology: scenario management module, optimizer module, and simulator module. Then, section "Case Study" presents the case studies used in order to test the methodology, which are further discussed in the section "Results and Discussion." Finally, the main conclusions of the paper are drawn in the section "Conclusions."

Network Response after Failure

Any response action executed in a DWN after a failure should aim to recover the degraded water service by efficiently managing the available resources, thus minimizing the negative impact of the failure. In this regard, the advantages of an adequate response methodology are tightly connected with the benefits derived from the network usage, namely: a reduction in the recovery time of the water supply service; an improvement in the quality of the recovered services (nonsupplied demands and degraded pressure values); and a minimization of the associated operational cost (i.e., number of required interventions).

On the other hand, the set of possible response interventions that can be carried out by the system operator after a specific failure depends on many factors. In particular, for large-scale DWNs, the most restrictive factors are: the capability of the SCADA software to rapidly detect and isolate the damaged components, the network state at the detection time of the failure, the physical redundancy of the network, and the capability to actuate on redundant components.

Drinking Water Networks Structure

Generally, large-scale DWNs convey water from the treatment plants to the users/customers by means of (Mays 2011a):

- The *transmission network*, composed of trunk mains and main tanks, pumping stations, and valves, which guarantee appropriate pressure levels at different locations in the network.

- The *distribution network*, which includes sets of smaller diameter pipes, and local pressure management elements to distribute water from the main tanks to consumers.

Transmission and distribution networks have different functions and interact whenever the water is pumped from the trunk mains into the distribution network. These local structures, which include different topologies like grid systems, branch systems, or combinations of them (Mays 2011b), may be fully open or segmented into PMZs and DMAs (Charalambous 2008). The simplified general diagram of a portion of a large-scale water supply network can be found in Fig. 1, which shows the conveyance of drinking water from the treatment plant to the main drinking water storage tank(s) using trunk mains. These tanks feed the transmission network that supplies water to the distribution network. The latter is segmented into different levels:

- The PMZs encompass the DMAs that receive water at a certain pressure level.
- Inside the PMZs, the DMAs are created by means of boundary valves so that at each PMZ, the DMAs are fed with water through specific control points of the transmission network.

Response Interventions

Under nominal circumstances, water is received by the DMAs through specific inlets. However, under a failure condition, alternative paths can be enabled by opening/closing valves to feed affected DMA(s) with water from other points of the transmission network, as well as from neighboring DMAs. Depending on the DWN structure, it is even possible to use fallback alternatives that connect the affected DMA(s) with DMAs belonging to different PMZs, thus requiring the use of pressure regulation strategies. Additionally, tank filling/emptying strategies and PRVs set-points may also need to be adapted due to the failure condition.

Failure Scenarios

The anomalies that affect the nominal operation of the network are mainly produced by the deterioration of the facilities due to corrosion, materials erosion, and external pressures. These events are typically followed by the isolation of the affected network assets (pipelines and accessories) in order to proceed with their repair. Notably, the isolation strategies depend on the specific event(s) affecting the network and may cause several collateral damages, namely:

- The isolation can deteriorate the performance of a particular demand sector, partially or totally affecting its inlets, thus causing a local affectation on the water service. In this scenario, the rest of the demand zones in the water transmission remain unaffected and the performance of the tanks is minimally altered.
- The isolation of a trunk main due to an incident affecting the transmission network may also cause the partial or total closing of the inlets to one or more demand sectors (i.e., DMAs or distribution network areas). This may unbalance the water contribution of the main tanks associated with one or more demand sectors, limiting the tank autonomy and deteriorating the pressure along the affected trunk mains. Then, if the water supply autonomy of the network tanks is compromised, the water supply of the associated demand zones may also be jeopardized in the near future.

The presented situations may cause the complete or partial disruption of the water supply services, mainly due to low water pressure conditions and the deterioration of the water properties.

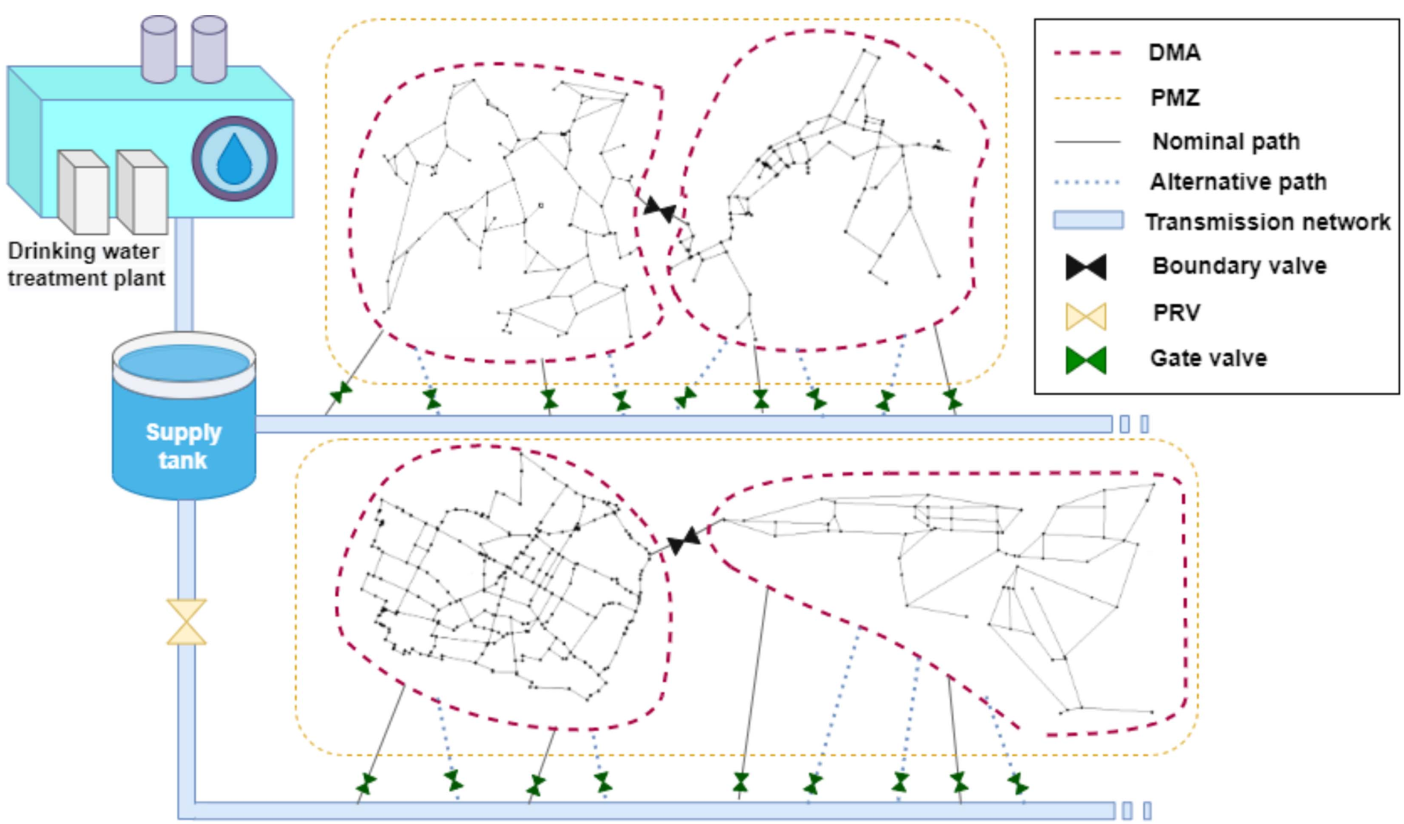

Fig. 1. Simplified scheme of a general DWN.

Methodology Overview

This section presents the proposed optimization-based methodology, describing relevant aspects related to the selection of the objectives, problem constraints, and required postprocessing procedure.

Optimization Problem

The methodology poses the selection of the optimal response interventions that yield an admissible operation of the network during a user-defined time horizon $N_f \in \mathbb{N}^+$ as an optimization problem using continuous variables. The horizon N_f must be set by the network operator considering aspects like the expected worst-case repair time (i.e., any possible failure must be guaranteed to be fixed before N_f hours) and the time horizons used in tank management strategy, which may change its operation depending on the failure (tank levels must be maintained within admissible levels that guarantee the availability of water once the nominal configuration of the network is recovered).

In order to formulate the main optimization problem used to compute the optimal set of interventions, the state of the network at failure detection time is denoted as $x_f \in \mathbb{R}^{n_x}$. Besides, the sequence $\tilde{x} = \{x(0), x(1), \ldots, x(N_f)\} \in \mathbb{R}^{n_x \times N_f + 1}$ is introduced, where $x(j)$ denotes the j-th vector of decision variables that correspond with the predicted evolution of the DWN states and inputs in a state-space formulation (the network model is presented in the section "Problem Constraints"). Notably, if the control-oriented model of a DWN is used for the response selection, the j-th decision vector $x^T(j) = [x_1^T(j), x_2^T(j), x_3^T(j), x_4^T(j), x_5^T(j), x_6^T(j)]$ (with $x_i \in \mathbb{R}^{n_i}$, for $i \in \{1, \ldots, 6\}$, and $n_x = \sum_{i=1}^{6} n_i$) is composed of the following subvectors: $x_1(j) = V(j)$ the volumes of the tanks; $x_2(j) = P_t(j)$ the pressure in the transmission network nodes; $x_3(j) = Q_p(j)$ the flow delivered by the pumps; $x_4(j) = P_{DMA}(j)$ the pressure in the DMAs; $x_5(j) = Q_{v,a}(j)$ the flow in the alternative valves (the interventions); and $x_6 = Q_{v,h}(j)$ the flow in the remaining healthy components.

Based on the notation presented, the optimal set of interventions can be obtained (after a postprocessing stage) from the optimal sequence of flows through the alternative valves $\tilde{x}_5^*$, as

$$\tilde{x}^* = \underset{\tilde{x} \in X}{\arg\min} F(x_f, N_f) \tag{1}$$

where $X \subset \mathbb{R}^{n_x}$ characterizes the admissible set; and $F{:}X \times \mathbb{N}^+ \to \mathbb{R}$ is a scalar-valued cost function that will be defined in the next section.

Optimization Objectives

Ideally, a sound response methodology should execute the optimal set of interventions that return the network to an admissible operation. On the one hand, the selected interventions should aim at recovering a close-to-nominal operation by restoring the pressure drop at the affected DMA(s). Similarly, the alternative water supply strategy must pursue minimal affectation of the nominal operation at the tanks: the water inlets may feed additional portions of the complete DWN and thus inefficient management of these assets would produce a negative impact on the water service of those areas. On the other hand, the presented objectives must be achieved using a minimum number of interventions in order to reduce the economic cost of the response strategy as well as the number of manual field interventions.

Accordingly, the trade-off between penalizing the deviations from the nominal trajectory (thus imposing a performance objective) and penalizing the number of interventions, is formulated through the design of an appropriate cost function F. This cost function is expressed as the weighted sum

$$F(x_f, N_f) = \sum_{i=1}^{7} \lambda_i F_i(x_f, N_f) \tag{2}$$

where $\lambda_i \in \mathbb{R}^+$ = user-defined weights; and F_i = i-th operational subobjective from the following set presented.

Description of the Objectives

For clarity, the different terms F_i are classified according to the level of the network operation they evaluate (transmission or distribution).

Transmission level objectives: the impact of a failure in the transmission network should be mitigated in order to minimize the affectation on other sectors of the DWN. Normally, the set of response interventions is aimed at attaining the following operational objectives:

- *Tank levels* (F_1)—The tank's water level must be maintained within certain safety values.
- *Pressure valves* (F_2)—The pressure in the transmission network must be preserved within a certain range similar to its nominal operation.
- *Pumping strategies* (F_3)—Due to their high economic and operative costs, pumping stations are normally operated following some precomputed optimal pumping strategies. However, in a failure scenario, pumping strategies may need to be slightly adapted in order to maintain the tank levels within safety values.

Distribution level objectives: greater performance degradation is accepted at the distribution level due to its local impact in comparison to the transmission level. The set of usual objectives to be accomplished by the response strategy are listed as follows:

1. *Pressure at the DMAs* (F_4)—The water pressure at the affected DMAs must be restored to its nominal value. However, some degradation in the pressure service to consumers may be acceptable, allowing a pressure drop at the demand nodes as long as its minimum value is not out of tolerance.
2. *Smooth operation* (F_5)—The smoothness in the operation of the selected alternative elements must be pursued. This is of utmost importance for manually operated elements, as changes in its operation would require the presence of a workforce.
3. *Number of interventions*—The number of applied interventions should be minimized while taking into account the prioritization of certain alternative pathways over others, e.g., the usage of transmission-network-to-DMA alternatives must be prioritized with respect to DMA-to-DMA alternatives. The minimization of the number of interventions is imposed by means of:
   - *Minimum flow through actuators* (F_6). This term is intended to minimize the water flow in the alternative elements so that water will flow through the alternative valves only when strictly necessary.
   - *Minimum pair flow* (F_7). In order to minimize the number of alternative elements to be used, F_6 is combined with an additional term that minimizes the product of the flow passing through pairs of alternative elements. Then, an equal usage of the elements is penalized, thus favoring keeping zero flow through as many elements as possible.

Mathematical Formulation of the Objectives

Here, the mathematical formulation of the objectives introduced is discussed.

- Objectives F_i, with $i \in \{1, \ldots, 4\}$, can be posed as weighted quadratic terms that penalize the deviation of the variables of interest with respect to some reference values

$$F_i(x_f, N_f) = \sum_{j=0}^{N_f} (x_i(j) - \bar{x}_i(j))^T W_i (x_i(j) - \bar{x}_i(j)) \quad (3)$$

where $\{\bar{x}_i(0), \ldots, \bar{x}_i(N_f)\}$ = sequence of reference values that account for: the mean safety tank volume obtained from the safety bounds of the tanks ($i = 1$), nominal pressure values ($i = 2$), flow pumping curves ($i = 3$), and set-point pressure at the DMAs ($i = 4$).

- The smooth operation of the alternative elements is posed as

$$F_5(x_f, N_f) = \sum_{j=1}^{N_f} (x_5(j) - x_5(j-1))^T W_5 (x_5(j) - x_5(j-1)) \quad (4)$$

- The subobjectives in charge of minimizing the number of interventions are

$$F_6(x_f, N_f) = \sum_{j=0}^{N_f} x_5(j)^T W_6 x_5(j) \quad (5)$$

$$F_7(x_f, N_f) = \sum_{j=0}^{N_f} \left(\sum_{i=1}^{n_5 - 1} \sum_{k=i+1}^{n_5} x_5^i(j) x_5^k(j) \right) = \frac{1}{2} \sum_{k=0}^{N_f} \left[\sum_{i=1}^{n_5 - 1} \sum_{k=i+1}^{n_5} [(x_5^i(j) + x_5^k(j))^2 - x_5^i(j)^2 - x_5^k(j)^2] \right] \quad (6)$$

where $x_5^i(j) = i$-th element of vector $x_5(j)$. Eq. (6) penalizes the flow passing through the possible pair combinations of alternative elements.

Finally, W_i, with $i \in \{1, \ldots, 6\}$, denote diagonal weight matrices of appropriate dimensions that reflect the relative importance of the variables within the same subobjective.

Problem Constraints

Hereafter, a control-oriented model of the network assuming direct control of the flow through the different actuators is used. This is a typical assumption when addressing high-level control of complex networks (Cembrano et al. 2000), considering that lower-level regulators are in charge of steering the system toward the imposed flow set-points. Notably, the system evolution is subject to the following constraints related to the flow and energy conservation of the network, tank dynamics, and limit on the physical values [see Wang et al. (2017) for an extended description of the proposed formulation]:

$$\sum_{i \in in(m)} Q_i(j) - \sum_{i \in out(m)} Q_i(j) = 0, \quad \forall\ m \in M \quad (7)$$

$$K_l Q_l^{\alpha}(j) = P_u(j) - P_d(j), \quad \forall\ l \in L \quad (8)$$

$$V_t(j+1) = V_t(j) + \Delta t \left(\sum_{s \in in(r)} Q_s(j) - \sum_{s \in out(r)} Q_s(j) \right), \quad \forall\ r \in R \quad (9)$$

$$\underline{V} \le V(j) \le \bar{V}, \qquad \underline{P} \le P(j) \le \bar{P}, \qquad \underline{Q} \le Q(j) \le \bar{Q} \quad (10)$$

$$x(0) = x_f \quad (11)$$

where $V(j) = x_1(j)$; $Q(j) = [x_3^T(j), x_5^T(j), x_6^T(j)]^T$; and $P(j) = [x_2^T(j), x_4^T(j)]^T$. Besides, $Q_l(j)$ is the flow rate in link l; $in(m)$ and $out(m)$ are the set of pipes that are supplying flow to and delivering flow from node m at time instant t; M is the set of nodes; L is the set of network links; R is the set of the network reservoirs; in(r) and $out(r)$ are the set of pipes that are supplying flow to and delivering flow from reservoir r at time instant t; $K_l \in \mathbb{R}$ is the friction loss coefficient at the link l, $\alpha = 1.852$ is the Hazen–Williams coefficient and $P_u(j)$ and $P_d(j)$ are the hydraulic heads at the ends of link l. Note that the flow passing through link l matches the flow passing through one of the actuators in $Q(j) = [x_3^T(j), x_5^T(j), x_6^T(j)]^T$. Additionally, Eqs. (7) and (8) represent mass conservation and energy conservation equations for the network, whereas Eq. (9) represents the dynamics of the reservoir. Finally, the constraints in Eq. (10) characterize the limits on the tank volumes, head pressures, and handling flows, whereas Eq. (11) sets the initial conditions on the problem variables.

Postprocessing

The continuous formulation of the optimization problem requires processing the obtained solution in order to retrieve the final optimal set of interventions. To this end, given the optimum sequence $\tilde{x}_5^* = \{x_5^*(0), \ldots, x_5^*(N_f)\}$, obtained from solving (1), the following postprocessing rule is applied: the i-th intervention is executed at failure detection time if $x_5^{i*}(j) > \varepsilon_i$ for any $j \in \{0, \ldots, N_f\}$, where ε_i is a user-defined threshold that accounts for the minimum flow to consider the activation of the i-th element.

Proof-of-Concept

This section presents an operational software scheme that allows the implementation and testing of the methodology presented. On this subject, Fig. 2 shows a general diagram of the software scheme and its modules. The different blocks depicted in the figure and how they interact are described in the following sections.

Scenario Management Module

The scenario management module is in charge of handling the different elements required for running the optimizer and hydraulic simulator (HS) modules. To that end, in order to test a specific scenario, Step (I) requires that the user defines the following set of parameters related to the scenario description and objective prioritization:

(a) Damaged elements and failure time.
(b) Pipes that have been isolated (in order to repair the anomaly) and isolation time.
(c) Available alternative elements that can be brought into play.
(d) Repair time horizon.
(e) Priority of objectives (tuning parameters).

In Step (II), the model is automatically generated by considering the (new) network topology (connections among the different elements) and by taking into account energy and mass balances detailed in the network hydraulic model that is integrated into the HS module. Besides, the information retrieved from Step (I.b) and Step (I.c) is used to generate the set of equations that make up a network model containing the isolated network elements (e.g., pipelines and accessories) plus the possible alternative elements. This new model is used by the optimizer module.

In Step (III), the failure information provided in Step (I.a) is used to run a simulation of the faulty system in the HS module. Then, the state of the network variables (node pressures, flows,

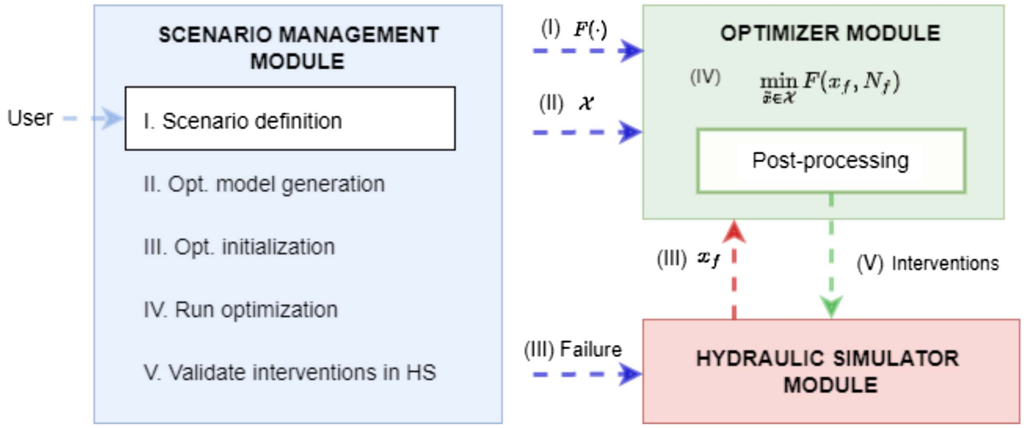

Fig. 2. General scheme of the response methodology.

and reservoir volumes) can be estimated at the isolation time. These initial conditions are supplied to the optimizer module.

Finally, in Step (IV), the optimization problem in charge of selecting the optimal subset of interventions is launched, whereas in Step (V), the obtained solution is validated in the HS module by simulating the system evolution during the repair horizon specified in Step (I.d).

Hydraulic Simulator Module

The HS module plays a fundamental role in the presented workflow. It simulates the behavior of the drinking water network in a sufficiently detailed and precise way. This module implements the hydraulic model of the transmission network including a surrogate representation of DMAs and all the existing alternative water supply options (alternative interconnections) that can be used in failure scenarios to recover the water service. In these models, a DMA is represented by a node whose demand is equal to the total demand within the DMA and connected to the transmission network using as many equivalent pipes as associated control points. In general, existing alternative paths connecting the same entities (i.e., two DMAs or a DMA and a transmission pipe) are represented using one equivalent pipe.

The HS module may also include variations in the affected DMA(s) flow consumption, characterizing possible reductions in consumer demands as a response to a pressure drop caused by the failure. Note that the optimizer module provides a set of response interventions that guarantee certain admissible operations for the worst-case scenario in which the consumers do not change their consumption patterns. Thus, the new network configuration should be able to cope with reductions in the DMA(s) flow demand while keeping the performance admissible.

Optimizer Module

The optimizer module constitutes the key block of the scheme since it is in charge of solving the network response problem. To that end, an optimization-based software tool is required in order to solve the nonlinear problem. As previously mentioned, the objectives and the faulty network model are provided from the scenario management module, whereas the initial conditions are derived from the HS module (cf. Fig. 2). In addition, the nonlinear equations and constraints that are implemented in the optimizer module should be checked to be consistent with the model implemented by the HS module in terms of hydraulic emulation.

Case Study

In order to assess the suitability of the methodology, the proof-of-concept operational scheme shown in Fig. 2 has been implemented by means of the following set of software elements:

1. The failure scenario under investigation is defined (including damaged elements, isolated pipes, and available alternatives) and implemented in the HS module. A commercial network simulator has been used to generate, configure, and run the corresponding hydraulic models. In addition, as part of the project that includes this work, the selected emulation tool has been assessed to replicate the behavior of the hydraulic model that is used by the real water utility.
2. An automatic equation-generation module has been developed in order to retrieve the network information from the HS and generate the network model required by the optimizer module. Then, each network element in the simulator is represented by a set of equations, as follows:
   - Each pipe of the simulator model is represented by its Hazen–Williams equation [Eq. (8)], which establishes the head at the network nodes. Besides, their connectivity is translated from the simulator by taking into account the mass conservation in the nodes [Eq. (7)].
   - The tanks of the simulator model are converted and simplified by means of Eq. (9) so that the tank volume only depends on its previous state and the net input/output tank flow.
   - Physical limits of the simulator network elements are included in the Optimizer module [Eq. (10)].
   - The cost functions [Eqs. (3)–(6)] are automatically derived from the list of network elements retrieved from the simulator, linking the required hydraulic variables to the associated objectives.
   - This optimization-oriented model is generated to be compatible with the algebraic modeling language GAMS (Rosenthal 2007), which is at the core of the optimizer module. The GAMS model is discretized considering a sampling time of 1h.
3. A hydraulic simulation with the corresponding failure scenario is run in order to compute the initial conditions required by the optimizer module [provided through Eq. (11)].
4. The Optimizer module runs the GAMS optimizations, and the obtained solutions are postprocessed in order to obtain a final list of the optimal subset of interventions.
5. The final set of interventions are reflected in the HS in order to assess the performance of the network after the response.

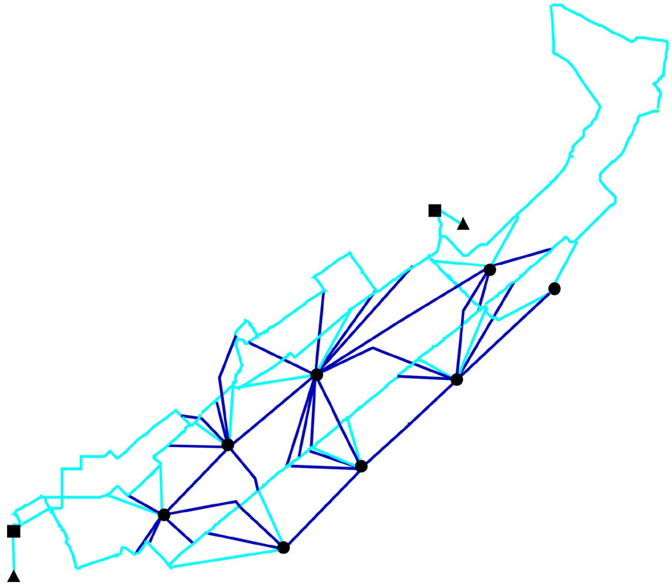

Fig. 3. Case study 1: transmission network (light line); available alternatives (dark line); and existing DMAs (circles), tanks (squares), and pumping stations (triangles).

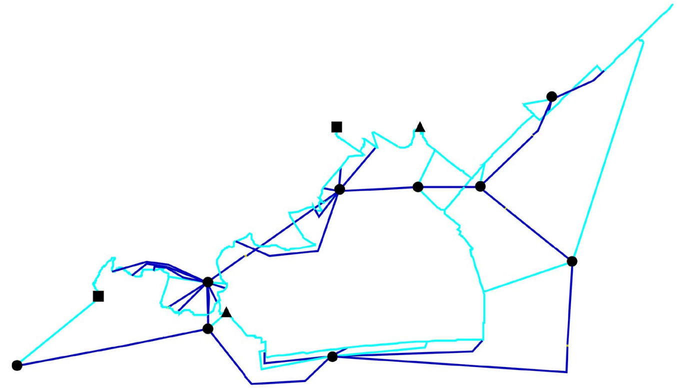

Fig. 4. Case study 2: transmission network (light line); available alternatives (dark line); and existing DMAs (circles), tanks (squares), and pumping stations (triangles).

Description of the Scenarios: Two different sets of failure scenarios have been taken into consideration in order to faithfully capture the different incidents that may arise in DWNs, namely:

- *Local scenarios* that have a local impact on the distribution network but not on the transmission network. These scenarios emulate the case in which certain pipelines of the transmission network are isolated, affecting only the water supply of one or a few DMAs, which may suffer a total interruption of the service. This isolation has a negligible impact on the assets of the transmission network (i.e., tanks, pumping stations, and remotely controlled valves) and on the water availability to supply the distribution network. Therefore, for these *local scenarios*, the proposed methodology must compute the minimal alternative interconnections to be enabled in order to maximize the quality of the water supply service in the affected DMA(s).

  The reality-inspired network that has been used to test the *local scenarios* is shown in Fig. 3. This grid-topology network is composed of two PMZs and eight DMAs (characterized as demand nodes), two tanks, and two pumping stations. Besides, there are 32 alternative water supply options (alternative interconnections) that can be used to minimize the impact of failure affecting the water supply service.
- *Global scenarios* that have a negative impact on both the transmission and distribution networks. These scenarios consider that the shutdown of certain pipelines of the transmission network isolates key infrastructures like water tanks or pumping stations, preventing them from fulfilling their expected operation. Thus, in the *global scenarios*, the proposed methodology must compute the best tank management strategy in order to recover the existing water autonomy of the system while also selecting the alternative interconnections required to recover the water supply service in the affected DMA(s) (since there is also a local impact).

  The reality-inspired network that has been used to test the *global scenarios* is shown in Fig. 4. This network is organized into three PMZs that include nine DMAs, two water tanks, two pumping stations, and 27 alternative interconnections. Notice that the network has a branch topology with only one water inlet in the right-upper part of the network and two water tanks (with their associated pumping stations) in the main transmission pipeline. This particular topology ends up causing the shutdown of one of the pumping stations in most of the simulated incidents and thus the operational strategy of the other pumping station needs to be adapted in order to recover the water supply and pressure levels in the DMAs.

Results and Discussion

Case Study 1—Local Scenario

In this case, an incident in the transmission network trunk with a reference hydraulic head (pressure plus elevation) of 130 m of water column (mWC) causes the shutdown of some pipelines affecting the inlets **ENT1** and **ENT2** of **DMA6** (cf. Fig. 5). This DMA has 11 alternative water supply options (alternative interconnections) that

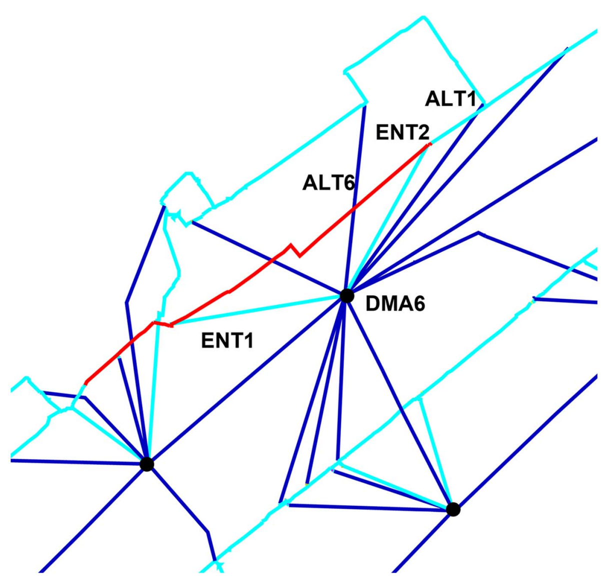

Fig. 5. Case of Study 1: incident in the transmission network closing the inlets of **DMA6** (**ENT1**, **ENT2**); alternative water supply options proposed by the methodology (**ALT1**, **ALT6**) to recover head in DMA6.

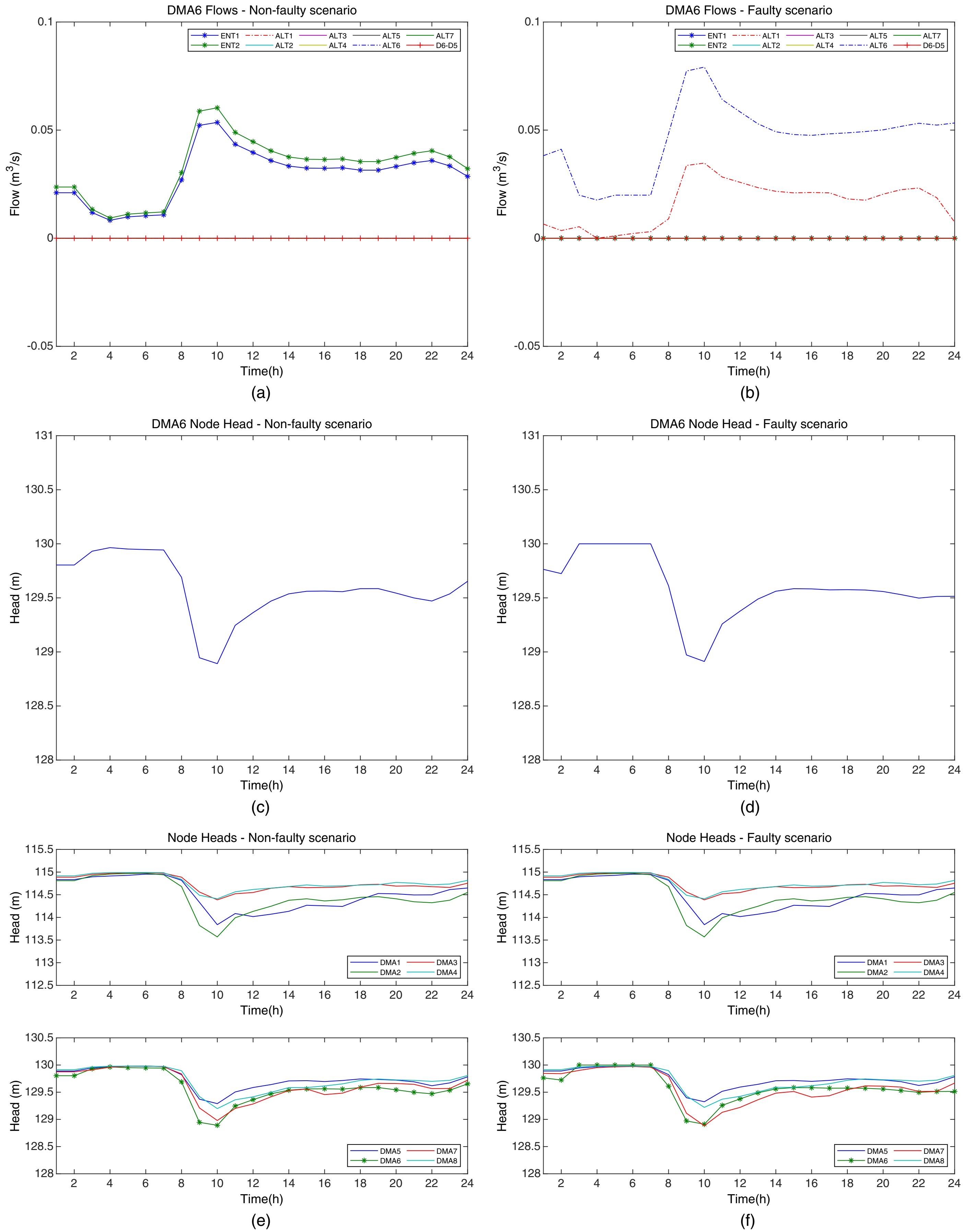

Fig. 6. Case of Study 1: (a and b) flow supplying **DMA6** in the healthy/after-response scenario; (c and d) hydraulic head in **DMA6** in the healthy/after-response scenario; and (e and f) hydraulic head in all DMAs in healthy/after-response scenario.

could be enabled in order to recover the water supply service: seven interconnections with other pipelines of the same PMZ (**ALT1**, … , **ALT7**), two interconnections with DMAs of the same PMZ (**D6-D5**, **D6-D7**), and two interconnections with a DMA of a different PMZ (**D6-D3**, **D6-D2**).

Regarding the priorities, the alternative interconnections of the same PMZ (**ALT**1, … , **ALT**7) are given the highest priority in order to avoid the need for manual pressure regulation; then, the interconnections (**D6-D5**, **D6-D7**) that connect the affected DMA with other pipelines of the transmission network are given an intermediate priority; finally, the interconnections (**D6-D3**, **D6-D2**) are given the lower priority since they connect the affected DMA with other DMAs having lower reference heads (115 mWC). Besides, the time horizon has been set to $N_f = 24$ h, considering the requirements of the local water utility regarding the failure repair time and the tank management time horizon.

Before the incident occurs, **DMA6** is supplied using its inlets (**ENT1**, **ENT2**), which yields a head around 130 mWC. Regarding this healthy scenario, Fig. 6(a) shows the flows used to supply **DMA6**, while Figs. 6(c and e) depict the node head in **DMA6** and in all the remaining DMAs respectively. On the other hand, if no response interventions were carried out, the fault would cause total disruption of the water service of **DMA6**. Accordingly, making use of the response methodology, the obtained solution proposes the supply of **DMA6** through the activation of two alternative interconnections of the same PMZ, namely, **ALT1** and **ALT6** [Fig. 6(b) show the flow through the alternative components after response]. By means of these response interventions, the **DMA6** head follows a profile similar to the healthy scenario [cf. Fig. 6(d)] without causing a major impact on the remaining DMAs [see Fig. 6(f)]. Consequently, the pressure in all the network nodes lies within the accepted tolerance set by the water utility for these types of abnormal situations (8%).

Case Study 2—Global Scenario

In this case, an incident in the transmission network (reference hydraulic head of 70 mWC) causes the shutdown of some pipelines affecting the inlet **ENT1** of **DMA5** as well as the suction pipeline of the pumping station (**PS1**) in charge of filling the main water tank of the network (**T1**). This tank plays a critical role in maintaining network pressure levels and the existing water autonomy to supply DMA demands (Fig. 7). Thus, in this scenario, the affected DMA can still be supplied using the remaining available inlet (**ENT2**).

Regarding the pressure levels, this incident would cause the hydraulic head during the peak demand to drop from 73 mWC in the nonfaulty scenario to 67 mWC if no response interventions are carried out. Note that this could be regarded as acceptable given the reference head value for **DMA5** (70 mWC) and the accepted tolerance (8%). Nonetheless, the nonavailability of **PS1**, which is responsible for keeping water levels in the **T1** within certain safety levels, is critical due to the vital role of this tank: unless it is completely full when the incident occurs, the water level will drop below safety levels, compromising the pressure and, consequently, the water supply of existing DMA demands. Again, N_f is set to 24h to meet the requirements of daily operation at the water utility.

Accordingly, in this type of scenario, the network operation needs to be adapted in order to mitigate the impact of the loss of key infrastructures like pumping stations or water tanks, assigning the highest priority to solve this task and using alternative interconnections to recover the water supply services in the affected DMAs only if any negative impact persists. Particularly, in the case study, there is an extra water tank (**T2**) pumping station (**PS2**) group with a secondary role that has enough hydraulic power to fill **T1** in the case that **PS1** is not available.

On the one hand, the solution provided by the response methodology demands to increase the pumping flow of **PS2** in order to counterbalance the workload associated with the faulty **PS1** [cf. Figs. 8(a and b)], keeping **T1** and **T2** within their safety volume levels [see Figs. 8(c and d)]. On the other hand, the affected DMA can be supplied with water just through **ENT2** [cf. Figs. 9(a and b)], keeping its head within the accepted tolerance [see Figs. 9(c and d)]. The rest of the DMAs would remain unaffected, hence providing a satisfactory water service [cf. Figs. 9(e and f)].

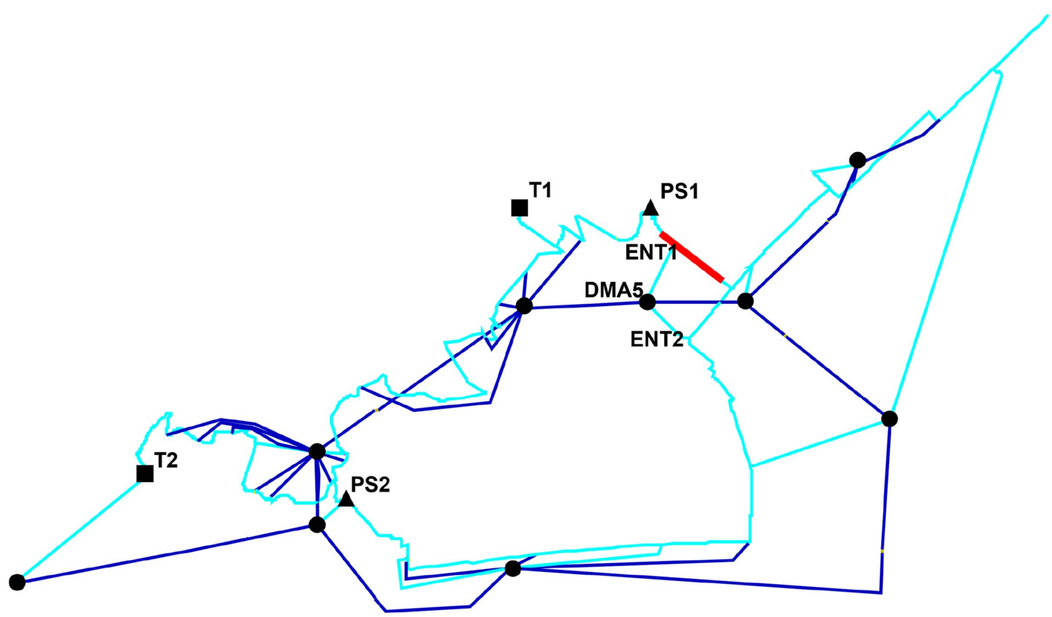

Fig. 7. Case of Study 2: incident in the transmission network affecting one DMA inlet (**ENT1**) and the suction pipeline of the pumping station **PS1**, compromising the water level at tank **T1**.

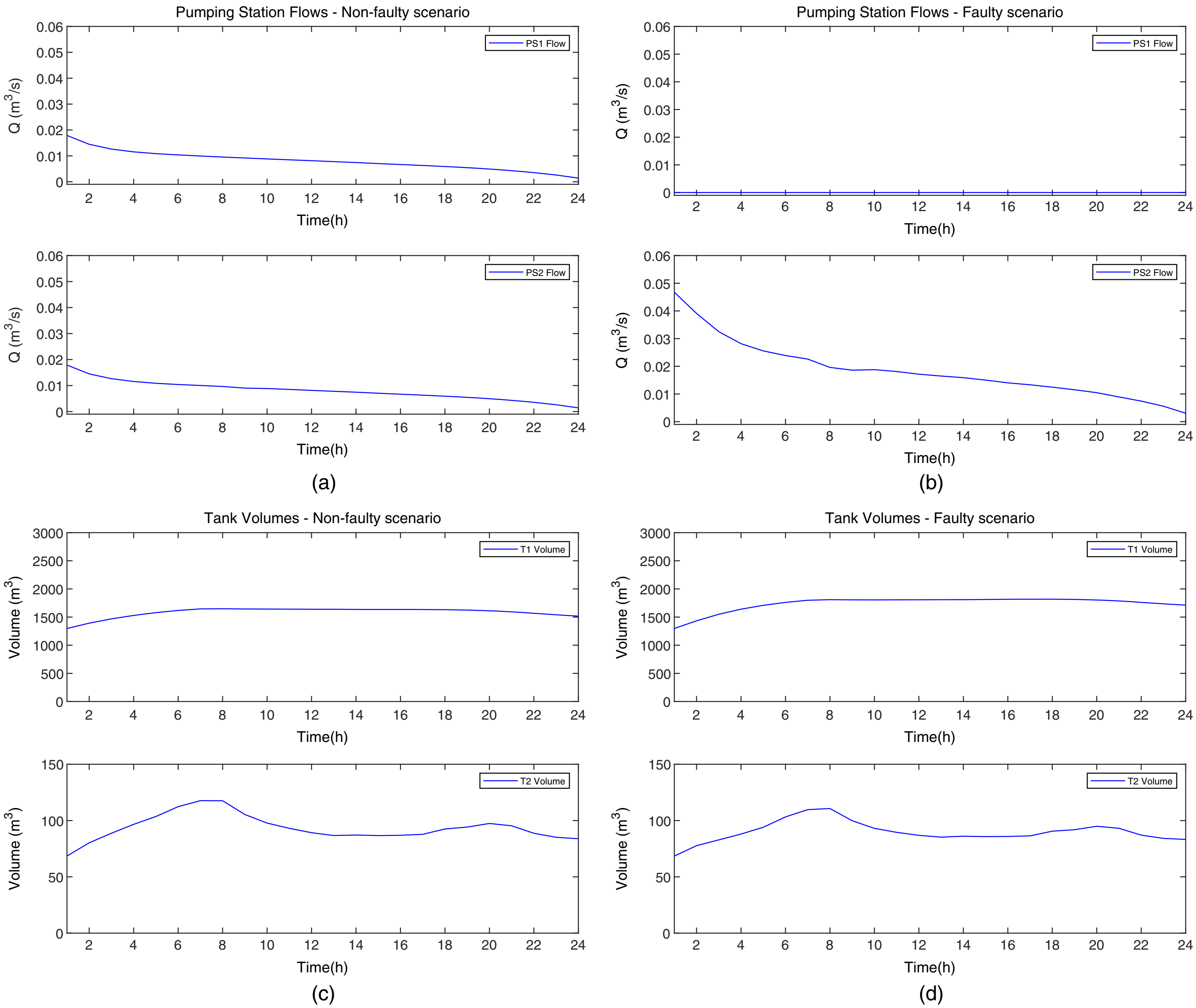

Fig. 8. Case of Study 2: (a and b) flow evolution in the pumping stations (**PS1**, **PS2**) in the healthy/after-response scenario; and (c and d) Tanks (**T1**, **T2**) volume in the healthy/after-response scenario.

Conclusions

This article proposes a methodology for the computation of the optimal subset of interventions to be executed after an incident degrades the water supply service. The methodology poses the intervention selection as an optimization problem with continuous variables that returns the optimal set of interventions using an optimization-oriented model of the network.

A proof-of-concept software scheme has been designed to implement the methodology and assess its performance. This scheme is based on the coordinated execution of three main modules: the scenario management module, which is used to settle and configure the scenarios under study; the HS module, which uses a hydraulic simulator to retrieve detailed information about the incident effect; and the optimizer module, which implements the proposed methodology, returning the optimal set of interventions.

In addition, two case studies have been used to assess the suitability of the methodology, emulating the different types of incidents that may appear in a real network. For both of them, the achieved results have shown the capability of the method to generate a set of interventions that cause proper recovery of the water service and suitable management of the key resources of the network, if necessary, taking into account operational constraints and priorities.

Future research directions should take into account a more detailed model of the network, considering, for example, low-level interventions within the DMAs; while analyzing the induced computational complexity. In addition, a hierarchical response scheme that solves an ordered set of optimization problems addressing the response at different levels of the network (e.g., transmission, distribution, and DMAs), could be investigated as a means to provide scalable response methods. Similarly, the software scheme created for methodology validation might be evolved into a training tool for water utility operators. Finally, it would be of great interest to carry out further studies on segmentation techniques that allow only meaningful alternative interventions to be considered in the optimization problem.

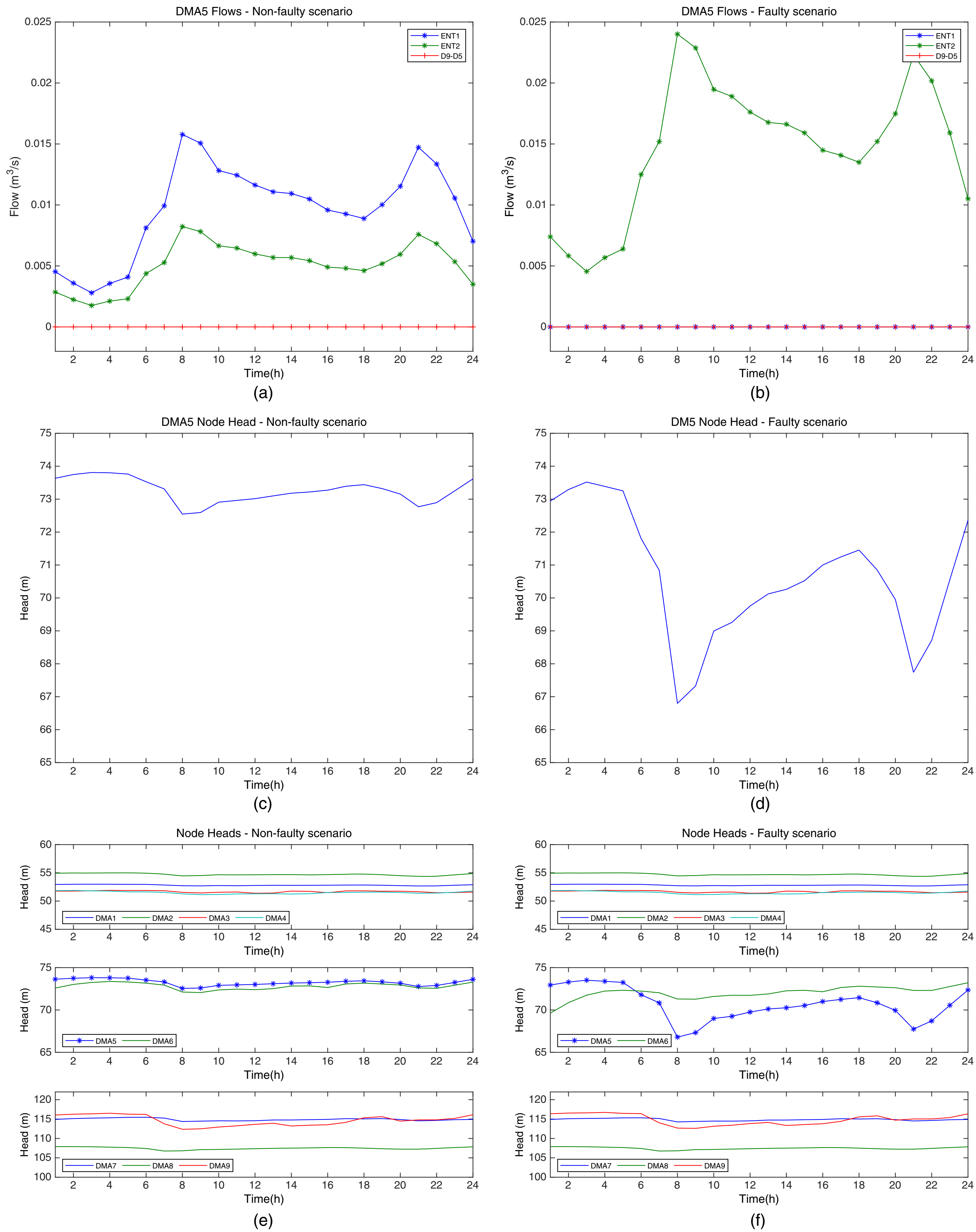

Fig. 9. Case of Study 2: (a and b) flow supplying **DMA5** in the healthy/after-response scenario; (c and d) hydraulic head in **DMA5** in the healthy/after-response scenario; and (e and f) hydraulic head in all DMAs in healthy/after-response scenario.

Data Availability Statement

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions, namely, the network information, optimization codes, and scenario management scripts.

Acknowledgments

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