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CRITICALITY INDEX FOR RESILIENCE ANALYSIS OF WATER DISTRIBUTION NETWORKS IN A CONTEXT OF MECHANICAL FAILURES

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Abstract *Water distribution networks (WDNs) are one of the most important urban complex infrastructures, which provide an essential resource for life. Therefore, ensuring resilience and safety for WDNs are big concerns for water utilities. WDNs are characterized by multiple components that are usually represented by a graph, i.e. a set of interconnected nodes or demand points and links or pipes. Node importance for a WDN depends on various factors such as population sensitivities, the location in the graph, and the system performance. Whilst pipe importance is related to measuring both risk of system isolation and insufficient pressures. This work attempts to explore consequences of pipe failures into the system's performance. The approach is applied in a simple benchmark network. For this network, a pipe burst event followed by two different isolation actions are analyzed. The impact on the network performance of each of the applied scenarios is assessed through a resilience criticality index specifically tailored to WDNs and also compared to normal operating conditions regarding the satisfaction rate of nodal demands. The obtained results are promising in order to quantify how resilient the system is, and supports the decision-making process to eventually reduce the occurrence of failure events and to minimize their potential consequences. The results of this study are presented, interpreted, analyzed and discussed in this paper.*

1 INTRODUCTION

Water distribution networks (WDNs) are one of the most important urban complex infrastructures, which provide an essential resource for life. Therefore, ensuring resilience and safety of WDNs are big concerns for water utilities. WDNs are characterized by multiple components that are usually represented by a graph, i.e. a set of interconnected nodes or demand points and links or pipes. Its mainly mission is the supply of water to the consumers in optimal conditions. The network topology depends on the dispersion of the consumers, the location of pickup sources and the storage areas. In general terms the satisfaction of consumers is measured by the quality and quantity of water delivered by the WDN. The vulnerability of the network to the failures occurrence depends on several factors such as the location of the pipes, the moment of the failure occurrence, the nature of the affected consumers, among others. In this sense, the node (consumer) importance for a WDN depends on various factors such as population sensitivities, the location in the graph, and the system performance. On the other side, the pipes that constitute the network do not have the same role in the water supply [1]. Thereby, some of the network pipes are more important in face of a hydraulic point of view. Furthermore, the pipe importance is related to measuring both risk of system isolation and insufficient pressures.

In general context, resilience refers to the strength of the network and its behaviour under different anomalous events [2]. The latter, in order to provide the network managers with measures that allow the implementation of actions and for supporting the decision-making process [3]. In essence, the resilience criticality indicators seek to quantify the impact on consumers as consequence of the anomaly that occurs within the WDN. The criticality of the pipe (or components) is measured through the impact due (as consequence) to the disruption (anomaly) for the supply to consumers [4]. Basically, the resilience criticality indexes allow us to evaluate the capability of the system under different abnormal operational conditions, such as emergencies, component failures, and hydraulic changes that are crucial for smooth operation of the entire system. They quantify how resilient the system is and support the decision on actions in order to reduce the occurrences and to minimize the possible consequences of failure events.

An usual method to quantify the resilience in WDN is through the use of the group of indicators based on the system power/energy, where the most popular is the resilience index by Todini [5]. The index is a ratio of the power arriving to the users, to the maximum power that can be dissipated in the network to meet the consumers' demand. In addition, it should be mentioned that the term power is the rate at which energy flows or at which energy is delivered per units of time (product of outflow and head). In order to obtain a better representation of the network reliability other authors have proposed other definitions for the Todini's resilience index such as: minimum surplus head and Network resilience index by Prasad & Park [6] and modified resilience index by Jayaram & Srinivasan [7]. Additional modifications for this index, which attempts to include different pressure-dependent modelling, are Saldarriaga et al. [8]. The most recent modification of Todini's resilience index was proposed by Creaco et al. [9]. The authors attempt to include in the indicator two different pressure-dependent modeling cases (leakage and consumption).

Hybrid approaches for assessing the hydraulic resilience together with graph theory-based measures are proposed by [4, 10], where the geodesic distance of a pipeline and the losses associated with the flow into the pipes are considered. In both of latter, the criticality of the one pipe (component) is measured through the impact due (as consequence) to the disruption (anomaly) for the supply to consumers. Other interesting work in this sense is presented by Herrera et al. [11], where the assessing of the resilience for WDNs is proposed through a topological perspective where properties such as network configuration and redundancy in connectivity are taken into account together with physical-based flow properties. Supported by graph theory, Deurlein [12] developed a generalized graph decomposition model that simplifies a network into a graph consisting of two main elements, called forests and cores, respectively. The model was subsequently applied to facilitate WDN analysis including reliability analysis [13].

In terms of the time when the disruptive event occurs and its consequence in the networks, an example of this is the work developed by Ayala-Cabrera et al. [14]. This work was developed in the framework of the Franco-German ResiWater Project [15]. This work attempted to exemplify the network resilience, considering the time when the event occurs and its developed, the sequence of the events, the type of the approach used in the hydraulic model, the system performance state and the uses of the resilience power-based indicators. As alternative to assess resilience some indicators based on graph theory have been directly related with the evaluation of resilience into the WDN; For instance, Yazdani et al. [16]. In addition, this type of indicators are used in the context of critical network interdependence in [17].

This work aims to explore consequences of pipe failures into the system's performance. There have been proposed anomalous events consisting on pipe bursts along with two subsequently isolation actions for affected pipes in the benchmark network under study. These are palliative actions that attempt to minimize potential negative effects related to pipe burst and might be classified as: 1) isolation of the affected pipe and 2) isolation of the surrounding area of the affected pipe. The impact on the network performance of each of these scenarios is assessed through a resilience criticality index specifically tailored to WDNs and also compared to normal operating conditions regarding the satisfaction rate of nodes. The water distribution computations are approached by a pressure driven model (PDM) [18, 19], as in case of pipe failures it provides better description of the system conditions than the classical demand-driven formulations (DDM) [9]. So, the overall proposal quantifies how resilient the system is and supports the decision-making process to eventually reduce the occurrence of failure events and to minimize their potential consequences. A set of further potential scenarios is also described and analysed to test the success of the method for assessing pipe criticality and network resilience.

2 THEORETICAL FRAMEWORK TO EVALUATE THE NETWORK RESILIENCE IN WDN

The framework of the study is based on the Franco-German ResiWater Project [15], where the notion of resilience attempts to develop tools in order to prepare water utilities for crisis. In the first instance, let us define some terms that we will use in this document. For one side, we have the time of the anomalous event; t_{event} (e.g. pipe burst). Subsequently, we have the detection of the event ($t_{detection}$), and then the palliative actions are implemented. The palliative

action is represented by the measures to be implemented by the water utility in order to mitigate the anomaly effects in the network. This action is external and is implemented by the network controllers. The implementation of the palliative action demarcates a time (counted from the time of detection) that is called as $t_{palliative}$. According to the framework of the ResiWater project, the first stage (absorptive) of the network's resilience is measured since t_{event} and goes until $t_{palliative}$ (see Figure 1). During the absorptive resilience the water utility has noticed the problem after detection but not corrective actions was taken. This stage is followed by two more stages adaptive and restorative, which are demarcated by other criteria that are shown in detail through the application in an example in Ayala-Cabrera et al. [14]. In this study, we will focus on the absorptive stage of the network, where it is possible to quantify the effect of the anomalous event and the implementation of the palliative actions. In this sense, it is also possible to quantify the internal vulnerability of the system as a mirror of the absorptive capacity of the system.

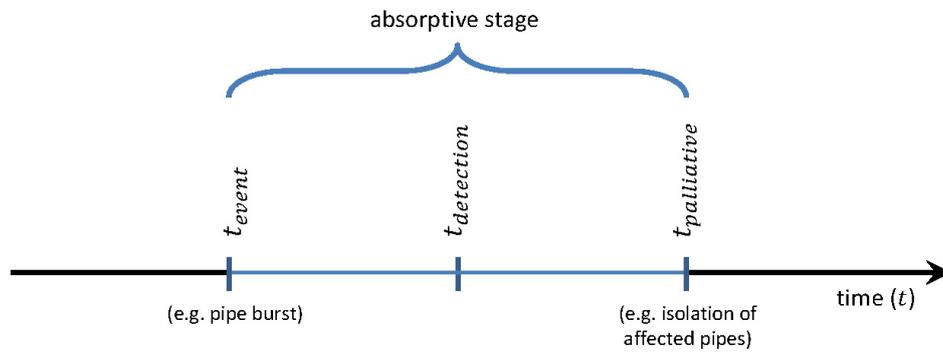


Figure 1: Disruptive events in WDN; absorptive stage - times.

2.1 Topological characteristics of the network

In hydraulic modeling the simplified topological structure of a WDN is described by a directed graph. This graph represents pipe sections as links and pipe junctions as nodes. The mathematical description of this graph is given by the incidence matrix $A_{(i,j)}^N$ (1).

$$A_{ij}^{(N)} = \begin{cases} -1; & \text{if node } i \text{ is terminal point of pipe } j \\ 0; & \text{if node } i \text{ is not connected to pipe } j \\ 1; & \text{if node } i \text{ is the initial point of pipe } j \end{cases} \quad (1)$$

Matrix A^N can be partitioned into two sub-matrices, A_f and A ; that represent nodes with fixed head (reservoirs or tanks) and nodes with unknown head (demand or junction nodes), respectively.

2.2 Hydraulic driven models

The equations that describe the steady-state of the system by the potential at the nodes (head) and the current links flows [20] are given by (2).

$$\begin{cases} Aq + d = 0; & \text{mass balance at every node} \\ \Delta h(r, q) - A^T h - A_f^T h_f = 0; & \text{energy balance at every link} \end{cases}, \quad (2)$$

where; q and h are vectors of flow rates in the links and the heads at junction nodes, respectively; d is the vector of demand; h_f is the head at fixed head nodes; r is the pipe friction coefficient; and $\Delta h(r, q)$ describes the head losses in the links.

In DDM, nodal demands are always satisfied at all nodes, independent of the available pressure head values at the corresponding demand nodes. In DDM analysis, available flow at node i , c_i (available outflow at node i) is always equal to the required design d_i (demand at node i); hence, $c_i = d_i$ [21]. In contrast, in PDM the outflow is determined by a relationship between the available pressure head and the outflow. This relation, is denoted Pressure –Outflow Relationship (POR). It contemplates three stages of satisfaction of the demand.

The PORs are generally determined by three conditions. Firstly, adequate or full –outflow; normal network operation conditions which consider that the available pressure is sufficient to satisfy the required demand of all nodes (which can represent domestic, industrial, etc.). At this point, the system will operate under a DDM when the pressure is sufficient to satisfy the demand and in the following two cases it won't. Secondly, partial or degraded –outflow; there will be a degradation in the delivery conditions, determined by the quantity that can be supplied, which is given by the current system pressure. Finally, there is a zero –flow condition; which is determined by a minimum pressure, in which case the system is unable to provide any outflow. The PORs are able to show how the system has the ability to regulate itself in terms of the available outflow and reordering the supply head pressure if it is under failure conditions. Under pressure deficient conditions only a fraction of the required demand can be delivered. Some PORs collected by Tanyimboh & Kalungi (2004) [22] are: Fujiwara & Ganesharajah (1993) [23], Gupta & Bhave (1996) [24], and Wagner et al. (1988) [25]. The Wagner formulation (3) is the most accepted POR to evaluate the networks operation under failure conditions.

$$c(h) = d \times \begin{cases} 1; & \text{if } h_s \leq h \\ \left(\frac{h-h_m}{h_s-h_m} \right)^{0.5}; & \text{if } h_m < h < h_s \\ 0; & \text{if } h \leq h_m \end{cases}, \quad (3)$$

where: h_s is the service (or reference) head necessary to fully satisfy the required demand; h_m is the head below which no water can be supplied. The latter in general is the minimum head which is defined (usually) as the nodal elevation.

The DDM system (2) and its PDM counterpart can be solved efficiently by a damped Newton method [19]. Moreover, formulae exist for calculating the DDM and PDM sensitivities with respect to the demand parameter [18]. These local sensitivities bring important information about the influence of the parameter on the hydraulic state: for example, where to place sensors or confidence intervals for the hydraulic predictions.

Another pressure dependent phenomenon with big importance in the resilience studies by WDNs is the pipe burst or leakage. This interest is due to the head pressure given to water consumer demands will drop with the head pressure reduction caused by the flow through the burst [26].

Frequently, a leak is modeled by means of the well-know Torricelli equation [27]. In essence, the Torricelli formulation describes the conversion of potential pressure energy to kinetic energy under conditions of zero energy loss. In order to taken into account (for real orifices) the effective area of the orifice and frictional energy losses, a discharge coefficient C_d is introduced in the equation [28]. The Torricelli equation is written as

$$c_L = C_d A \sqrt{2g\Delta h} = C_d A \sqrt{2g} \sqrt{h - h_m}, \quad (4)$$

where c_L is the outflow rate trough the orifice; A is the orifice (leak) area; $C_d A$ represents the leak effective area; g is the gravity acceleration; and h is the head pressure at the orifice.

3 IMPACT OF A FAILURE - DEMAND SATISFACTION

As a consequence of the failure in the system a reduction in the water supplied is reflected to the users. In this sense, the satisfaction rate SR is a resilience indicator and direct measure of the reliability, for a given failure in j -th scenario and its impact at i -th consumer (node). SR is defined as the ratio of the available water delivered to the consumer and the water required for the consumers [29, 26]. Thus, SR indicates the consequences of the failure in the pipe j (or scenario) on supply at node i . This indicator for each network node is written as:

$$SR_{i,j} = \frac{c_{ij}}{d_i}. \quad (5)$$

For the other side, the impact at all nodes as consequence of the failure of the pipe j (or scenario) is given by the average satisfaction rate (SRP). This indicator assesses the overall impact of the failure in j -th pipe (or scenario) on all network consumption nodes. In general terms, SRP represents the ratio between the total volume of water delivered to the consumers under failure conditions of the component(s) j and the total volume of water required by users under normal operating conditions. The SRP for failure in pipe j is written as:

$$SRP_j = \frac{\sum_{i=1}^{n_d} c_{ij}}{\sum_{i=1}^{n_d} d_i}, \quad (6)$$

where n_d represents the number of nodes with water demands. The range of this indicator is between 0 and 1; where 0 represents a collapse situation of all network nodes and 1 represent on the contrary that all the network nodes are resilient to the failure occurred.

4 CASE STUDY

In this study, we have selected a simple benchmark network. This network is called two loop network (TNL) and was proposed by Alperovits & Shamir [30]. The network is composed by 6 demands nodes, 8 pipes and 1 reservoir. The network layout configuration is presented in Figure 2. The choice of such a simple network is motivated by the necessity of facilitating the

analysis of the results. Under this motivation several authors have used this network in studies of WDN and specifically in resilience studies. For instance we can find studies such as the optimal design which is based on resilience indicators (Todini [5], Wang et al. [31]), or in Creaco et al. [9] where pressure-dependent modeling cases such as leakage and consumption are considered for the resilience indicators, redundancy studies (Kalungi & Tanyimboh [32]), among others.

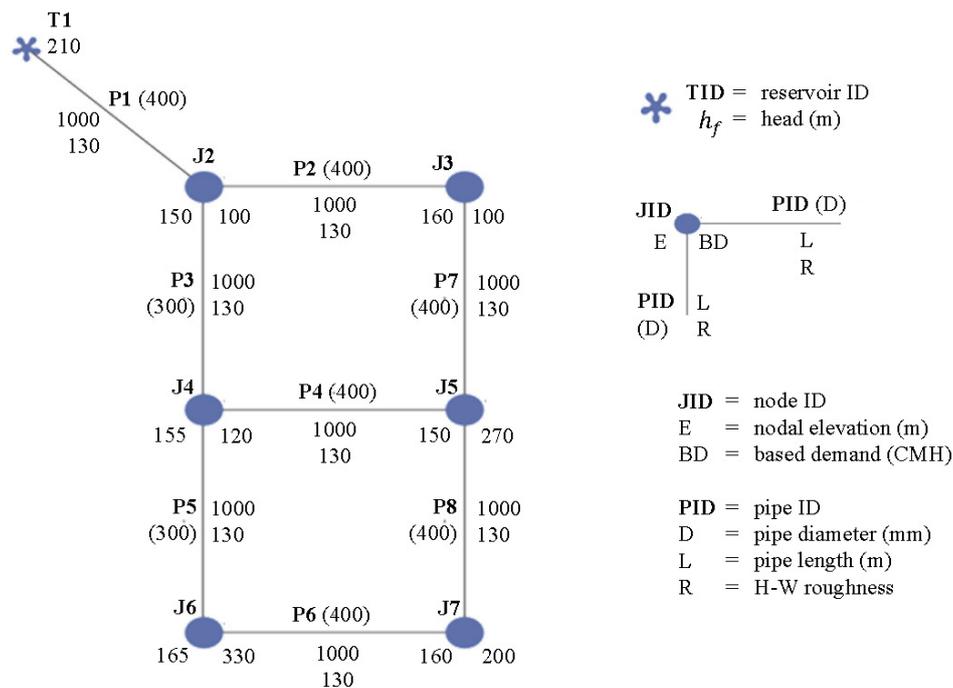


Figure 2: Network layout configuration - Case study of TNL network.

We have considered three different scenarios for this study. These three scenarios are normally presented in the WDN management. In the first instance, the anomalous event is given in the network (in this case pipe burst) and later we will evaluate 2 palliative actions implemented in order to mitigate the impact of the anomaly. So, the first one (scenario 1), is the pipe burst at a single pipe. The first of the palliative actions (scenario 2) corresponds to the well-known and studied isolation of the pipe by means of two valves located at the ends of the pipe, which allow to close exclusively the affected pipe. This scenario is an action that is normally used to represent the rupture of pipes in WDN. This type of simulation serves to quantify the system's resilience by means of indicators, and in this way to make preventive actions, such as twinning of the most critical pipes, establishing schemes and prioritizing maintenance or rehabilitation actions, etc. The second of the palliative actions (scenario 3) corresponds to the isolation of a surrounding to the affected broken pipe. This scenario can occur in the network due to the isolation valves' configuration, where the exact location of the isolation valves is often unknown, or it is simply necessary to close more than one affected pipe. The latter is not an exclusive palliative action of this type of event (pipe burst) and its application may be related to other

criteria for resilience quantification (e.g. quality). On the other side, for events such as network contamination (intentional or unintended) the closure of surrounding area nearby to the sensors that have detected the event, is applied in order to implement the corrective actions such as flushing. This action is applied to renew the water and extract the contaminant substance of the affected pipes and additionally to avoid the diffusion of the contaminant into the network. It is at this point where it is more effective to look at the impact that is generated in the application of this palliative action.

4.1 Impact at system and nodes as consequence of burst position in the affected pipe

At this point, we will evaluate the effects of placing the leak at three different points of the affected pipe. The three selected pipe burst location are: 1) at initial point of the pipe, 2) at middle point of the pipe, and 3) at terminal point of the pipe. These three location options have been labeled in this work as {Pos0, Pos50, Pos100}; respectively. The burst position is referred to the flow direction within the pipes (see Figure 3). The flow directions have been obtained through the simulation of the network under normal operating conditions.

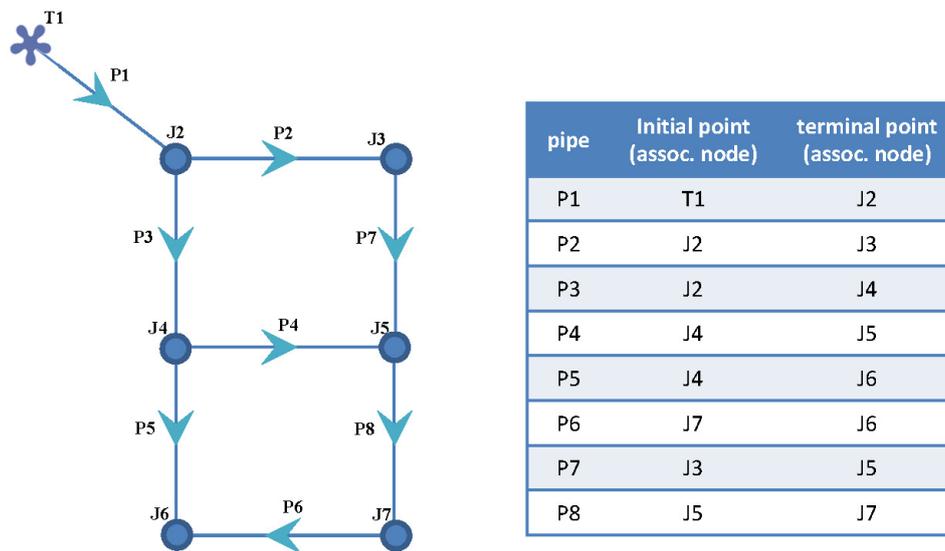


Figure 3: Burst position - Flow direction under normal operating conditions.

The results obtained by applying the above described resilience indicator (SRP) for the three proposed positions of the leak are shown in Figure 4.

Figure 4 shows that the maximum impact on the network under study is obtained when the leak is located at the ends of the affected pipe. This observed condition is preserved in the resilience results of the minimum impact. Except for the pipe 3, where the minimum network impact is given by Pos50. The maximum and minimum impact on the network are evaluated at this point as $maxImp_j = \min(SRP_{j,Pos})$ and $minImp_j = \max(SRP_{j,Pos})$. In addition, the figure shows a difference in the impact for each pipe ($minImp_j - maxImp_j$), where it can be seen that the maximum difference in the impact is given for the initial position (Pos0) and final position

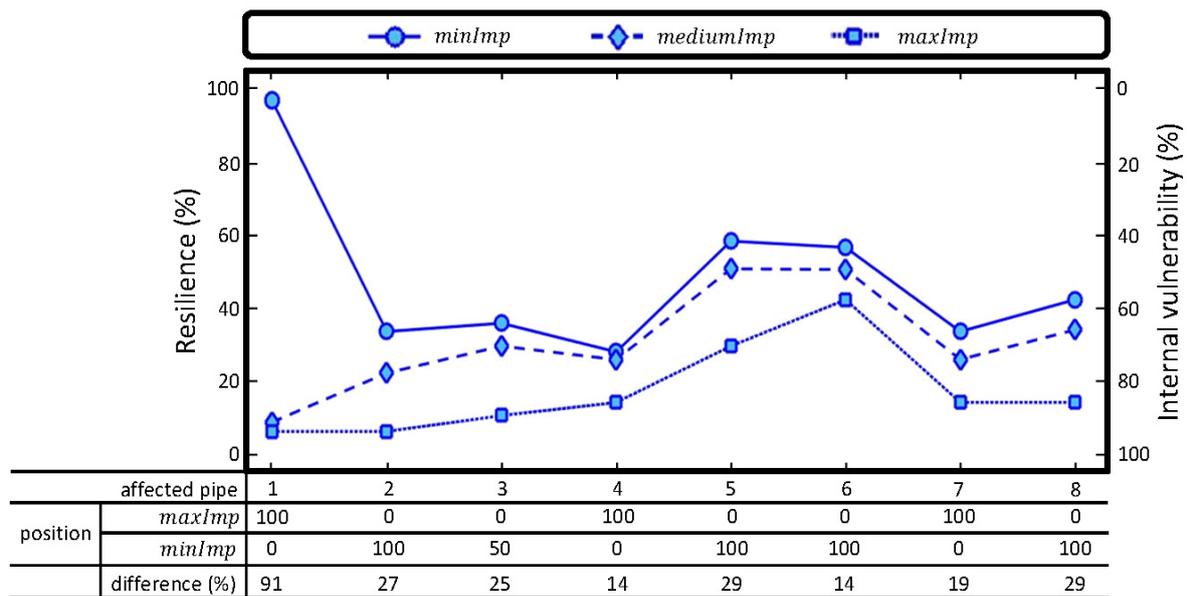


Figure 4: Network impact after locating the burst along of the affected pipe.

(Pos100) for the pipe 1, around 91% in terms of the resilience for availability.

For more exhaustive analyzes it is proposed (for future works) the uses of another resilience indicators that allow to complete the one that is proposed. The obtained results for the maximum impact in the network as consequence of the pipe burst, is the most critical that will be used below to compare with the palliative measures to be implemented.

Therefore, we are going to analyze the head pressures for each node of system for the three selected points (along the affected pipe - Figure 5). As consequence of the pipe burst, a considerable decreasing in the state of the system performance is observed in Figure 5. Thus, the network's performance state obtained (for the network under study) as a result of burst of each of its pipes (one by one) is in general terms of failure state. Nevertheless, as in this case the network nodes are operating in degraded state. This can be observed especially when the pipe leakage is placed at the ends of the pipes (Pos0 and Pos100). The state of the performance for the system in failure (in the stage of resilience absorptive) is considered when the first consumer is affected by a pressure lower than the service pressure ($h \leq h_s$; in this example $h_s = 30\text{mH}_2\text{O}$ - line green). For other side, the nodes performance state are determined for two conditions; $h_m < h < h_s$ (with $h_m = 0\text{mH}_2\text{O}$ in this example - line red) and $h \leq h_m$; for degraded and failed state, respectively.

In Figure 6, the results obtained by applying the resilience indicator (satisfaction rate) are presented.

4.2 Pipe burst and isolation of the affected pipe

The results of the system resilience which are shown in Figure 7 for the three cases considered in this paper and their respective rankings of the hydraulic importance of the affected component

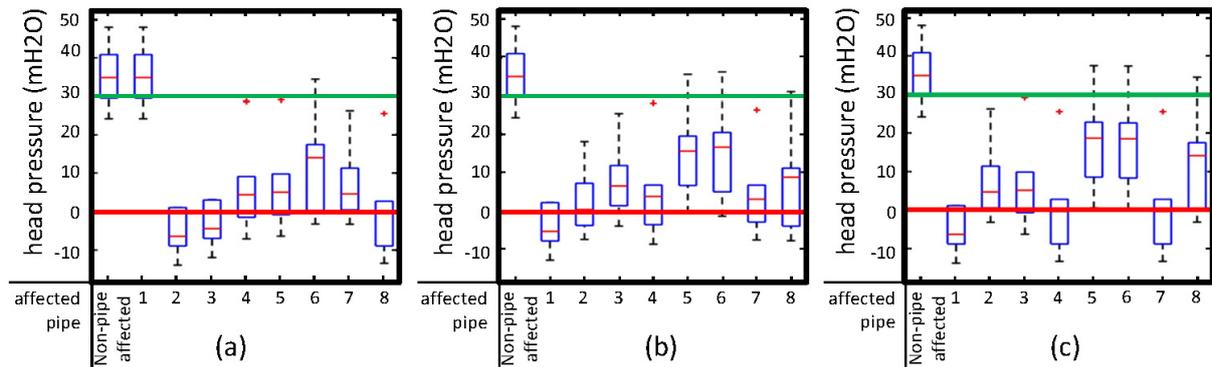


Figure 5: Head pressures at system nodes - Pipe burst. (a-c) Position of leak along of affected pipe, (a) Pos0, (b) Pos50, and (c) Pos100.

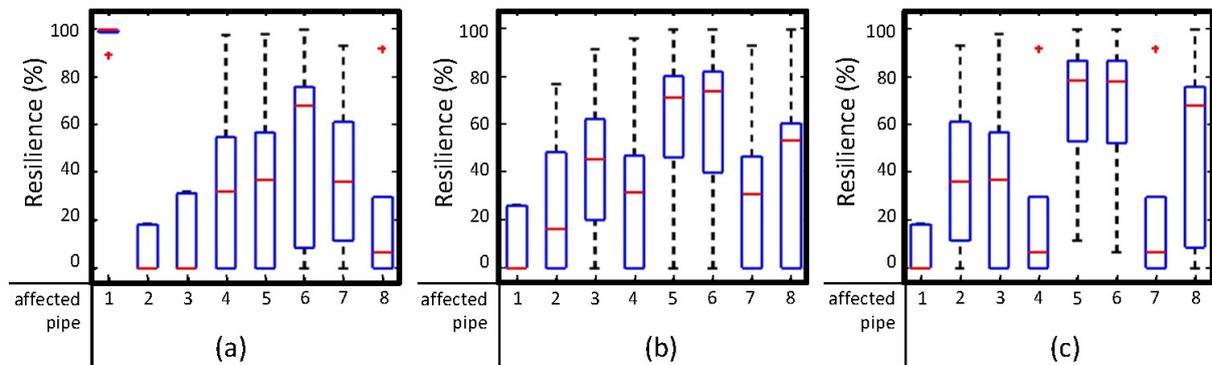


Figure 6: Availability at system nodes - Pipe burst. (a-c) Position of leak along of affected pipe, (a) Pos0, (b) Pos50, and (c) Pos100.

(in this case pipes) are shown in Figure 7. The sets of the three proposed scenarios were labeled for scenario 1 and 2 in correspondence with the affected pipe. In other words, for the set of pipes $P\{P_1, \dots, P_j\}$ we have $set\{1, \dots, j\}$. For scenario 3 the sets were labeled in the same way as for the other two cases; associating the set label to the affected pipe. However, in this scenario each set will be confirmed by the pipes adjacent to the affected pipe, so we will have for the studies case that $set1\{P_1, P_2, P_3\}$, $set2\{P_2, P_1, P_3, P_7\}$, $set3\{P_3, P_1, P_2, P_4, P_5\}$, $set4\{P_4, P_3, P_5, P_7, P_8\}$, $set5\{P_5, P_3, P_4, P_6\}$, $set6\{P_6, P_5, P_8\}$, $set7\{P_7, P_2, P_4, P_8\}$, and $set8\{P_8, P_6, P_4, P_7\}$.

Figure 7 includes the previous time of the pipe isolation (burst - absorptive resilience) to be repaired through isolation valves, and the closure of the affected pipe or surrounding area as a palliative measure to mitigate the impact of the pipe burst. Subsequent measures to be implemented (to be applied after palliative actions) such as auxiliary pumping (if the system has thereof) [26] at the adaptive resilience stage or the implementation of long-term actions such as repair or replacement of the affected pipe, are not contemplated in the current study. In this sense, we are going to order the results of the resilience obtained previously for the maximum impact of the first event (pipe burst) in order of the mayor to minor losses of the resilience

obtained for the model with the failure of affected pipe (Figure 7a, blue line). Preserving the obtained order obtained with the ranking of the results for the first case, in Figure 7, we have placed the results of the resilience for the palliative measures to be implemented (scenario 2 and scenario 3) in the same order for the ranking obtained with the scenario 1; Figure 7a with red continuous line for isolation of affected pipe, and Figure 7b with red dashed line for isolation of surrounding area.

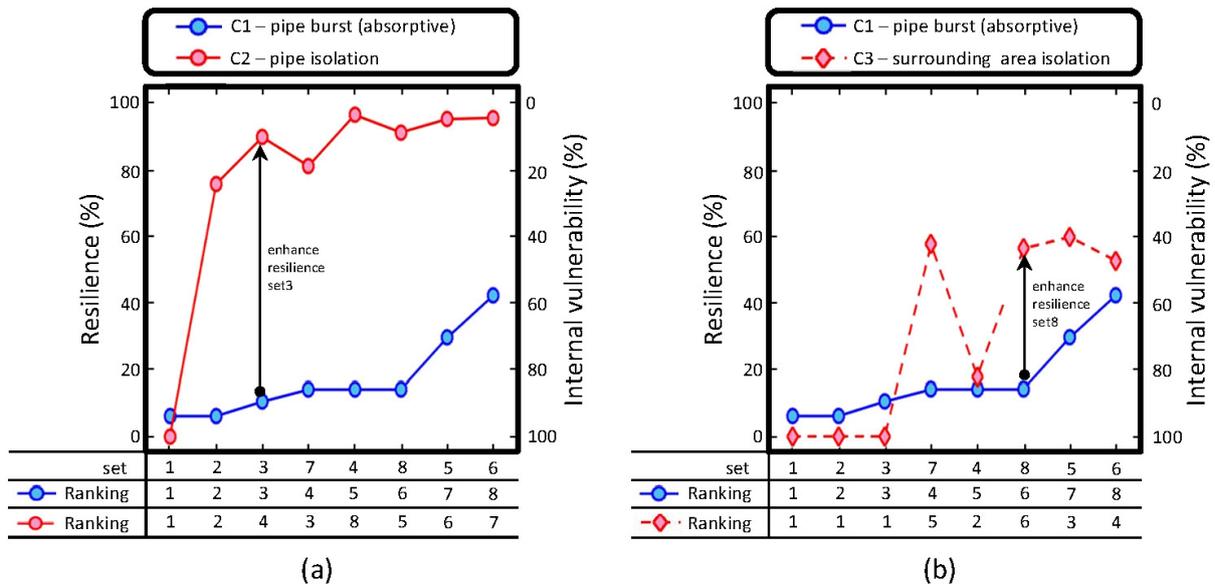


Figure 7: Absorptive resilience and palliative measures - Impact of the failure (hydraulic importance). (a) Pipe burst and single isolation; and (b) Pipe burst and isolation of surrounding affected area - maximum adjacency pipes isolated.

As we can observe in Figure 7a, the variation of the hydraulic importance of the pipes is considerably between the rupture time and the moment of the pipe isolation. In this sense, it should be considered that the pipe isolation of the affected area is determined by the consideration that each pipe break can be closed by valves of isolation located at the ends of the each pipe.

The indicator apply in Figure 7b, indicate the links that have reduced the overall operating quantity of the network when the burst occurs (absorptive resilience) and when the isolation of affected pipe is applied (palliative actions). Figure 7b shows an enhance of the system resilience after the implementation of the palliative action (isolation of simple pipe). The average value of the improvement in the resilience value was in order to 55% for all the pipes, except when the removal set corresponds to pipe P1 (set 1).

In Figure 8 the general impact at the system nodes generated as a consequence of the three proposed scenarios is presented. These results are presented (in this figure) in form of the resilience isoclines in order to facilitate the interpretation of thereof.

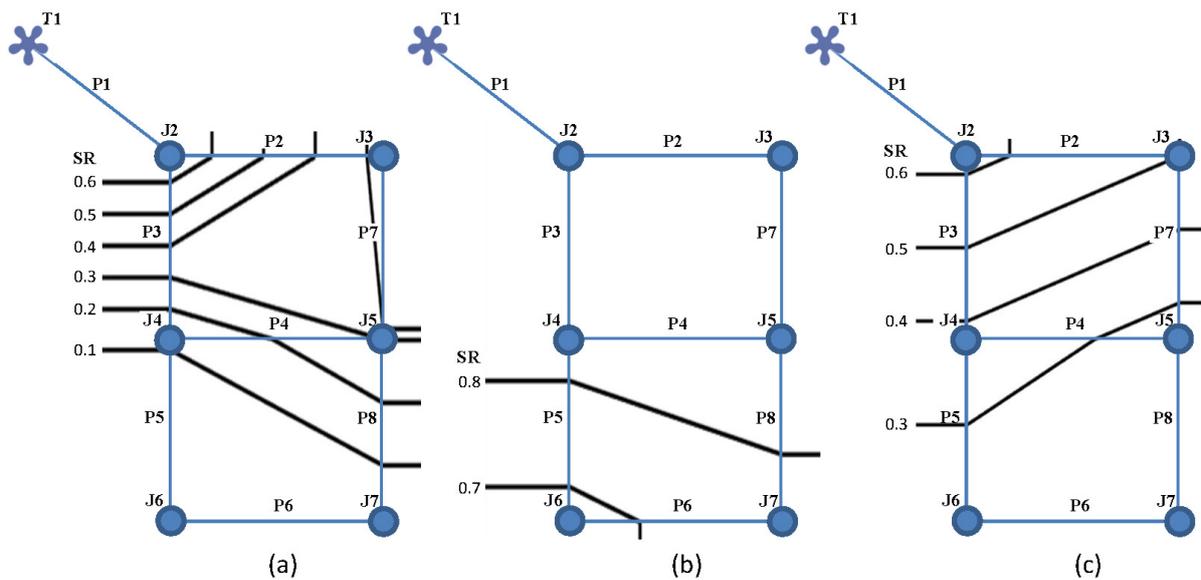


Figure 8: Impact at nodes - *SR* isoclines. (a) Pipe burst, (b) pipe isolation; and (c) isolation of surrounding affected area - maximum adjacency pipes isolated.

5 CONCLUSIONS

In this paper we have evaluated some of the most critical conditions for a simple benchmark network. In this sense, we have applied a well-known resilience indicator as it is the satisfaction of demand. By virtue of the hydraulic model used (PDM approach), the resilience indicator accounts for both the structure of the network and also the energy's level availability that influences water deliveries. In the first instance, this indicator has been implemented for simulating a pipe burst event (as an anomalous event). In addition, in this study, we take into account two scenarios of isolation of the affected pipe which are considered as palliative measures of mitigation of the anomalous event. The first one is obtained by the exclusive isolation of the affected pipe, and the second one, considers the isolation of a surrounding area of the affected pipe.

For the first scenario the resilience was evaluated in dependence of the position along the pipe where the event is placed. The results showed that the consideration of the location of this type of the event for the simulation presents a great importance as we can see in the results of the theoretical resilience obtained. Thereby, the evaluation of the most important components (pipes in this case) and the generated impact at consumer's (nodes), for this type of event, varies considerably according to the location of it in the affected pipe. Thus, the rankings that allow prioritizing preventive actions for this type of events are highly dependent on the applied considerations in the simulation models. The results of the study have showed that the maximum impact (in the case study) for this anomalous event occurs when the position of it at the limits of the affected pipe.

In this regard, the contrast of the first event with the palliative actions showed that:

- The exclusive isolation of the affected pipe (scenario 2) is the ideal case of the isolation as palliative action in comparison with the scenario 3 as it shows an enhance in the network resilience of 71%. In contrary, the scenario of isolation of the surrounding area of the affected pipe (scenario 3) shows respectively the network resilience of 26%. However, the exclusive isolation of the affected pipe is not always possible, due to the configuration of isolation valves in the networks, network contamination events, among others. Therefore, as the results showed, if it was necessary to isolate an area the configurations which would not collapse the network (for the study case) are the set4 to set8.
- Finally, for the configuration of the network under study, the most critical impact on the nodes (as consequence of the failure cases evaluated in here) was presented in the furthest nodes (nodes J6 and J7) from the source (T1). However, the results showed that although the farthest node from the source (J7), it was not precisely the most critical node in the three scenarios evaluated. That in the case of the network under study the most critical node was the node J6. On the other side, the palliative action of the exclusive isolation of the affected pipe showed that only the closure of the pipe that is directly connected with the source (as it is evident) is capable to collapse the functioning of the network.

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REFERENCES

- [1] C.D. Alonso, *Programación óptima de la renovación de tuberías en un sistema de abastecimiento urbano: Análisis de los factores de influencia*, Master Thesis, Universitat Politècnica de València, Valencia, Spain, (2008).
- [2] NIAC, 2009. Critical infrastructure resilience, final report and recommendations. Available online URL http://www.dhs.gov/xlibrary/assets/niac/niac_critical_infrastructure_resilience.pdf, (last accessed in Aug. 2016).
- [3] NIPP, 2013. Partnering for critical infrastructure security and resilience. Available online URL <https://www.dhs.gov/sites/default/files/publications/National-Infrastructure-Protection-Plan-2013-508.pdf>, (last accessed in Aug. 2016).
- [4] M. Herrera, R. Wright, E. Abraham, J. Izquierdo, R. and Pérez-García, “Condiciones hidráulicas sobre medidas de centralidad en grafos para la evaluación de la resiliencia de redes de distribución de agua”, *Acta Universitaria*, Vol. **26**, pp. 82-90, (2016).
- [5] E. Todini, “Looped water distribution networks design using a resilience index based heuristic approach”, *Urban Water*, Vol. **2**, pp. 115-122, (2000).

-
- [6] T.D. Prasad, and N.S. Park, “Multiobjective genetic algorithms for design of water distribution networks”, *J. Water Resour. Plann. Manage.*, Vol. **130**, pp. 73-82, (2004).
- [7] N. Jayaram, and K. Srinivasan, “Performance-based optimal design and rehabilitation of water distribution networks using life cycle costing”, *Water Resour. Res.*, Vol. **44**, pp. 1-15, (2008).
- [8] J.G. Saldarriaga, S. Ochoa, M.E. Moreno, N. Romero, and O.J. Cortés, “Prioritised rehabilitation of water distribution networks using dissipated power concept to reduce non-revenue water”, *Water Resour. Res.*, Vol. **7**, pp. 121-140, (2010).
- [9] E. Creaco, M. Franchini, and E. Todini, “Generalized resilience and failure indices for use with pressure-driven modeling and leakage”, *J. Water Resour. Plann. Manage.*, Vol. **142**, pp. 1-12, (2015).
- [10] M. Herrera, E. Abraham, R. Wright, J. Izquierdo, and R. Pérez-García, *Medidas híbridas para el análisis de la resiliencia de redes de distribución de agua. XIV Seminario Iberoamericano de Redes de Agua y Drenaje - SEREA, 2015*, Guanajuato, México (2009), pp. 1-11.
- [11] M. Herrera, E. Abraham, and I. Stoianov, “A graph-theoretic framework for assessing the resilience of sectorised water distribution networks”, *Water Resour. Manag.*, Vol. **30**, pp. 1685-1699, (2016).
- [12] J. Deurlein, “Decomposition model of a general water supply network graph”, *J. Hydraul. Eng.*, Vol. **134**, pp. 822-832, (2008).
- [13] J. Deurlein, A. Wolters, D. Roetsch, and A. Simpson, *Reliability analysis of water distribution systems using graph decomposition. World Environmental and Water Resources Congress, 2009*, Kansas, Missouri, United states (2009), pp. 1-11.
- [14] D. Ayala-Cabrera, O. Piller, J. Deurlein, and M., Herrera, *Towards resilient water networks by using resilience key performance indicators. 10th World Congress of EWRA - On Water Resources and Environment, “Panthai Rhei”, 2017*, Athens, Greece (2017), (Submitted full paper).
- [15] ResiWater, 2017. Available online URL <http://www.resiwater.eu/>, (last accessed in March. 2017).
- [16] A. Yazdani, R.A. Otoo, and P. Jeffrey, “Resilience enhancing expansion strategies for water distribution systems: A network theory approach”, *Environ. Modell. Softw.*, Vol. **26**, pp. 1574-1582, (2011).

- [17] S. Pinnaka, R. Yarlagadda, and E.K. Cetinkaya, *Modelling robustness of critical infrastructure networks. 11th International Conference on the Design of Reliable Communication Networks - DRCN, 2015*, Kansas, Missouri, United States (2015), pp. 95-98.
- [18] O. Piller, S. Elhay, J. Deurlein, and A. Simpson, “Local sensitivity of pressure-driven modeling and demand-driven modeling steady-state to variations in parameters”, *J. Water Resour. Plann. Manage.*, Vol. **143**, pp. 1-12, (2017).
- [19] S. Elhay, O. Piller, J. Deurlein, and A. Simpson, “A robust, rapidly convergent method that solves the water distribution equations for pressure-dependent models”, *J. Water Resour. Plann. Manage.*, Vol. **142**, pp. 1-12, (2015).
- [20] O. Piller, B. Bremond, and M. Poulton, *Least action principles appropriate to pressure driven models of pipe networks. Conference on World Water and Environmental Resources Congress, 2003*, Philadelphia, Pennsylvania, United states (2003), pp. 1-15.
- [21] P. Sivakumar, and R.K. Prasad, “Simulation of water distribution network under pressure-deficient condition”, *Water Resour. Manag.*, Vol. **28**, pp. 3271-3290, (2014).
- [22] T. Tanyimboh, and P. Kalungi, “Reply to comments on ‘Redundancy model for water distribution systems’ ”, *Reliab. Eng. Syst. Safe.*, Vol. **86**, pp. 335-337, (2004).
- [23] O. Fujiwara, and T. Ganesharajah, “Reliability assessment of water supply systems with storage and distribution networks”, *Water Resour. Res.*, Vol. **29**, pp. 2917-2924, (1993).
- [24] R. Gupta, and P.R. Bhave, “Comparison of methods for predicting deficient-network performance”, *J. Water Resour. Plann. Manage.*, Vol. **122**, pp. 214-217, (1996).
- [25] J.M. Wagner, U. Shamir, and D.H. Marks, “Water distribution reliability: simulation methods”, *J. Water Resour. Plann. Manage.*, Vol. **114**, pp. 276-294, (1988).
- [26] B. Zhuang, K. Lansley, and D. Kang, “Resilience/availability analysis of municipal water distribution system incorporating adaptive pump operation”, *J. Hydraul. Eng.*, Vol. **139**, pp. 527-537, (2013).
- [27] M. De Marchis, C.M. Fontanazza, G. Freni, V. Notaro, and V. Puleo, “Experimental evidence of leaks in elastic pipes”, *Water Resour. Manag.*, Vol. **30**, pp. 2005-2019, (2016).
- [28] J.E. van Zyl, and A.M. Cassa, “Modeling elastically deforming leaks in water distribution pipes”, *J. Hydraul. Eng.*, Vol. **140**, pp. 182-189, (2014).
- [29] B. Brémond, and S. Berthin, *Reliability of a drinking water supply system. IWA Specialised Conference Management of Productivity at Water Utilities, 2001*, Brno, Czech Republic (2001), pp. 167-174.

- [30] E. Alperovits, and U. Shamir, "Design of optimal water distribution systems", *Water Resour. Res.*, Vol. **136**, pp. 3271-3290, (1977).
- [31] Q. Wang, M. Guidolin, D. Savic, and Z. Kapelan, "Two-objective design of benchmark problems of a water distribution system via MOEAs: Towards the best-known approximation of the true Pareto front", *J. Water Resour. Plann. Manage.*, Vol. **141**, pp. 1-14, (2015).
- [32] P. Kalungi, and T. Tanyimboh, "Redundancy model for water distribution systems", *Reliab. Eng. Syst. Safe.*, Vol. **82**, pp. 275-286, (2003).