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Towards resilient water networks by using resilience key performance indicators

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Abstract: The main objective of a water distribution network (WDN) is to deliver the required amount of water to the customer under a certain threshold of the desired pressure and quality. These networks are critical infrastructures that should face multiple and continuous changes and even abnormal events that alter their normal service provision. Water utility managers require modelling tools to be able to predict how the WDN will perform during disruptive events and understand how the system can better absorb them. Assessing and enhancing resilience in water infrastructures is a crucial step towards more sustainable urban water management. Several resilience key performance indicators (RKPIs) have been suggested to quantify and assessing WDNs resilience. This work proposes a structured classification for measuring and understanding the supply system by means of RKPIs. The proposed classification is based on a three-stage resilience concept which includes absorptive, adaptive, and restorative stages. This classification attempts to provide engineers, modellers, and managers with structured tools which allow a comprehensive analysis of crisis management case studies in order to enhance the WDN resilience. As the resources in supply are usually limited, recovery phases have a crucial role in resilience enhancing, while under sufficient availability of resources, deploying redundancy, making critical components stronger and ensuring a rapid recovery are all effective responses of the system.

Key words: resilience, key performance indicators, water distribution networks, critical infrastructures

1. INTRODUCTION

Water distribution networks (WDNs) provide the cities with an essential service for the life. In this sense, the main objective of a WDN is to deliver the required amount of water to the customer under a certain threshold of the desired pressure and quality (Jung, 2013). These networks are critical infrastructures that should face multiple changes and eventually abnormal events that alter their normal service. Water network security refers to the water supply guarantees under safety conditions for consumers, being necessary to count on assessing all kind of potential vulnerabilities. In addition, a WDN need to guarantee the availability of required quantity of water for sensitive customers, such as hospital, etc. (NIPP, 2013). In general context, resilience refers to the strength of the network and its behaviour under different anomalous events. The latter, in order to provide the network managers with measures that allow the implementation of actions and for supporting the decision-making process (NIPP, 2013). Resilience may also be perceived as a more general concept that is relied on three-capabilities of the system: 1) absorptive, 2) adaptive, and 3) restorative and may be characterized by four properties/attributes: 1) robustness, 2) redundancy, 3) resourcefulness and 4) rapidity (Francis & Bekera, 2014).

Water network resilience refers to design maintenance, and operations of water supply infrastructure that limit the effects of disruptions and enable rapid return to normal delivery of safe water to customers. The framework of the study is based on the Franco-German ResiWater Project (ResiWater, 2017), where the notion of resilience attempts to develop tools in order to prepare water utilities for crisis. Nowadays, water utility managers require modelling tools to predict how the WDN performs during disruptive events and to understand how the system can best absorb,

successfully adapt, and recover from them. Simulation and analysis tools help WDN managers to explore how their networks respond to unexpected events. So, demand-driven modelling (DDM) for normal operating conditions, and pressure-driven modelling (PDM) for failure conditions, help to simulate WDNs performance under failure event conditions.

This paper focuses on water quantity, and for the sake of simplicity we will work with a hypothetical benchmark network. This benchmarking network allows to: derive network resilience results, use resilience indicators under two different modelling approaches (DDM and PDM), and quantify the three resilience stages. Ultimately, this work proposes a structured classification by means of resilience key performance indicators (RKPIs). The classification is based on the conceptual definition proposed by the ResiWater Project. This attempts to provide engineers, modellers, and managers with structured tools which allow a comprehensive analysis of crisis management case studies with the aim of enhancing the WDN resilience.

2. MATERIAL AND METHODS

2.1 Three resilience stages

The proposed resilience paradigm might be implemented via the set of resilience capacities outlined above: absorptive, adaptive, and restorative capacity. Where absorptive capacity refers to the capacity of the system to absorb the impact of system perturbation and to minimize consequences with little effort. Adaptive capacity is the ability of the system to adjust undesirable situations by undergoing some changes if absorptive capacity has been exceeded. Restorative capacity refers to the ability of the system to implement long-term solutions so that the system performance reaches a stable or better level than the initial.

Three different states of WDN performance, P , are defined: normal, degraded, and failed. The three states for P , are determined by two thresholds: P_{normal} and P_{failure} corresponding to minimum P level for the network working in normal mode, and P level when the system is considered in failure mode, respectively.

The absorptive stage is measured since the event starts (t_{event}) and goes until the water utility starts taking appropriate actions, which is denoted as palliative time (t_{pall}). Additionally, two additional times, the degradation time (t_{deg}) and the failure time (t_{fail}), are defined. These correspond to the time at which the first consumer is affected by the event at different states of network performance. Thus, if the t_{deg} is greater than t_{pall} , the state for absorptive stage corresponds to the normal state. For quantifying the resilience for this stage (R_{abs}), there are proposed three values for resilience $R_{\text{abs}} = \{3, 2, 1\}$ that correspond to the three states at t_{pall} {NORMAL, DEGRADED, FAILED}. At this point, the internal vulnerability of the system (V_{sys}) is a mirror of the absorptive capacity of the system, and may be assessed as $V_{\text{sys}} = 4 - R_{\text{abs}}$.

The adaptive stage begins before the absorptive stage ends and with the anomaly detection. It is characterized by a stabilization time, t_{stab} , which is the time when all emergency measures are in place for maintaining the system performance.

To qualify the degree of severity, the acceptable time (t_{acc}) is defined that corresponds to the maximum stipulated time in which the network can be in failure conditions. The quantification of the resilience in this stage (R_{adap}) will depend on the state of performance at $t = \min(t_{\text{stab}}, t_{\text{acc}})$. If $t_{\text{stab}} \leq t_{\text{acc}}$ then $R_{\text{adap}} = \{3, 2, 1\}$ but if $t_{\text{acc}} < t_{\text{stab}}$ then $R_{\text{adap}} = \{2, 1, 1\}$ with the state {NORMAL, DEGRADED, FAILED}.

The restorative stage begins when the t_{stab} ends, and when long-term solutions begin to be implemented (for instance, repairing or replace affected component). The last two stages end when the system performance reaches a stable level of performance equal or better than the initial one in nominal way ($P \geq P_{\text{normal}}$). Finally, the resilience for restorative stage will be determined whether the system succeeds in finding a new NORMAL state, then $R_{\text{rest}} = 3$ else it is less.

2.2 Selecting suitable indicators

The selection of the appropriate measure of resilience depends on the characteristic of the system in order to provide a specific service (IRGC, 2016). In this sense, for resilience studies it is crucial to specify what system state is being considered (resilience of what) and what perturbations are of interest (resilience to what). In this sense, several studies have been proposed in order to quantify the resilience of water distribution networks (Herrera et al., 2016).

In the group of indicators based on system power, the most popular is the resilience index by Todini (2000). 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 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 (2004) and modified resilience index by Jayaram & Srinivasan (2008), among others.

Additional modifications for this index, which attempts to include different pressure-dependent modelling, are Saldarriaga et al. (2010). The most recent modification of Todini's resilience index was proposed by Creaco et al. (2016). The authors attempt to include in the indicator two different pressure-dependent modeling cases (leakage and consumption).

2.3 Model and Equations

The hydraulic conditions of the networks have generally been evaluated using DDM models as a function of demand under normal operating conditions and additional PDM implementations which have shown better response to approach WDN analysis under failure conditions. Thus, the operation of water distribution networks can be assessed by using hydraulic computer models, such as PORTEAU and EPANET. On the one hand, in the application for systems with inadequate capacity or pipe failure, the classical DDM approach is stretched to its limits (Braun et al., 2016). On the other hand, a consumption model that doesn't consider the available pressure is especially damaging in abnormal situations, such as low pressures resulting from hydraulic and mechanical failures. This is the reason why PDMs have been introduced (Piller et al., 2003).

Topological characteristics of the Network. In hydraulic modelling 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 $A_{i,j}^N$ (see, Equation 1).

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

DDM. Matrix A^N can be partitioned into two submatrices, A_f and A ; that represent nodes with fixed head (reservoirs or tanks) and nodes with unknown head (demand or junction nodes), respectively. The equations that describe the steady-state of the system by the potential at the nodes (head) and the current links flows (Piller et al., 2003) are given by Equation 2.

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

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.

PDM. 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, $c_i = d_i$ (Sivakumar & Prasad, 2014). 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). 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. In this way, it can be supplied a remainder of delivered flow. Wagner et al. (1988) formulation (Equation 3) is the most accepted POR to evaluate 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 head necessary to fully satisfy the required demand; h_m is the head below which no water can be supplied. The latter is the minimum head which is usually defined as nodal elevation.

The DDM system (Equation 2) and its PDM counterpart can be solved efficiently by a damped Newton method (Elhay et al., 2015). Moreover, explicit formulae exist for calculating the DDM and PDM sensitivities with respect to the demand parameter (Piller et al., 2017). 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.

3. RESULTS AND COMMENTS

3.1 Definition of the network and performance analysis

The study of the resilience that is applied in this section is based on the three stages of resilience. For demonstration, a hypothetical network, originally proposed by Islam et al. (2011) is used. The network is composed of two reservoirs, twenty-five water demand nodes and forty pipes (Figure 1.a). The total length of all pipes is 19.5 km. The water is supplied by gravity from the elevated reservoirs with the total heads of 90 m and 85 m, respectively. Pipe length varies from 100 m to 680 m and the diameters vary from 200 mm to 700 mm. The basic demand is in the range of 33.33 L/s to 133.33 L/s and the demand pattern is defined for 24 hours (Figure 1.c).

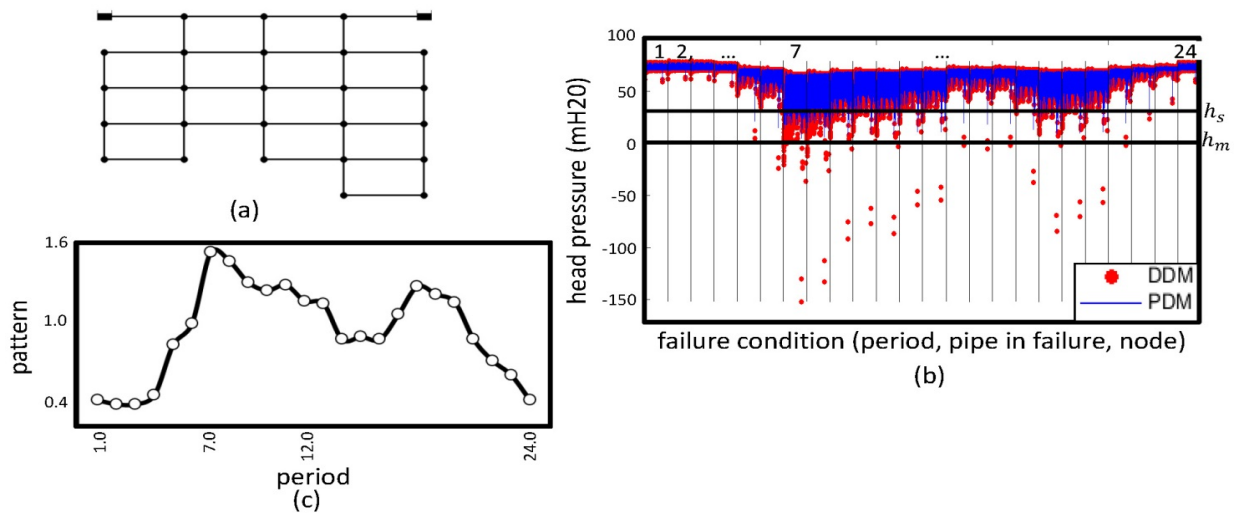


Figure 1. Pipe characteristics and pressure results. (a) Network layout; (b) single pipe failure condition for all periods; (c) demand pattern.

The analysis was developed for all the periods under study, and consists in isolating one by one every pipe of the system in each period and analysing the performance response at every node. The following analysis will be carried out based on the differences obtained by comparing the failure conditions using a DDM and PDM approach. We have analysed the available pressures at the nodes for each proposed period (Figure 1.b). The Figure 1.b shows for all tested periods how the head pressure at each node is increases under PDM (blue area), in opposite to DDM approach. This shows that the system regulates itself because of the failure, and this self-regulation is not reflected in the DDM approach.

In Figure 1.b shows that the maximum effect of failure at any individual system component, namely pipe (isolation) or tank (minimum level), is in the absorptive stage. The issue increase its impact for periods of high demand (periods 7 and 8). Similarly, Figure 1.b shows that, under PDM, the network can self-regulate its pressures by supplying the system with additional energy enough to provide user's demands.

3.2 Example of application

In this study, we applied the resilience index (IrT , Equation 4) by Todini (2000) and its generalization (IrC , Equation 5) by Creaco et al. (2016). The interest of the application of these two indicators in this study is due to the fact that the first one operates under a DDM and the second one under a PDM. And both let us to quantify the resilience in terms of the available power of the system.

$$IrT = \frac{\max[d^T h - d^T h_s, 0]}{h_f^T A_f q - d^T h_s} \quad (4)$$

$$IrC = \frac{\max[c^T h - d^T h_s, 0]}{h_f^T A_f q - d^T h_s} \quad (5)$$

As example of application, the three-stage resilience study was applied to a random pipe (Figure 2.b) of the network. The sequence of the scenario is: pipe burst, isolation of the pipes, repairing then flushing.

Pipe Burst Leak. It is assumed in this study that a leak starts at the beginning of the period 6, and ends at the end of this period (once the leaky pipe is isolated). Duration 1 hour. Simulated using the orifice equation.

Isolation of the pipe/repairing. Starts at the beginning of period 7 and ends at the end of the period 9. Duration 3 hours.

Flushing of the isolated pipe. This action seeks to operate the repaired or replaced pipe in optimal conditions, consider here cleaning of the pipe and air extraction (not simulated in this work).

An initial analysis of the pressures for the systems for the stipulated performance conditions $P_{normal} = h_s = 30$ mH2O and $P_{failure} = h_m = 0$, shows that under no mechanical failure in the network, this network is already deficient in pressure head, at hour 7 (demand peak). Although the selection of the period, in case of the pipe isolation, was analyzed in the period 7. So, it operates in degraded state at nodes (J24, J25), see Figure 2.b, with a head pressure of (29.31, 29.58) and (29.51, 29.76) mH2O in DDM and PDM predictions, respectively. In this sense, the network already starts with hydraulic failure given its inability to supply water under requirements for these consumers.

Based on this information, $t_{event}=6$ period (pipe burst leak); the event is assumed detected within this period; $t_{pall}=7$ period (isolation of the affected pipe); $t_{stab}=8$ period (repairing actions). In addition, we assumed that $t_{acc}=3$ hours, criteria: time that the street can be closed, so $t_{acc}=9$ period.

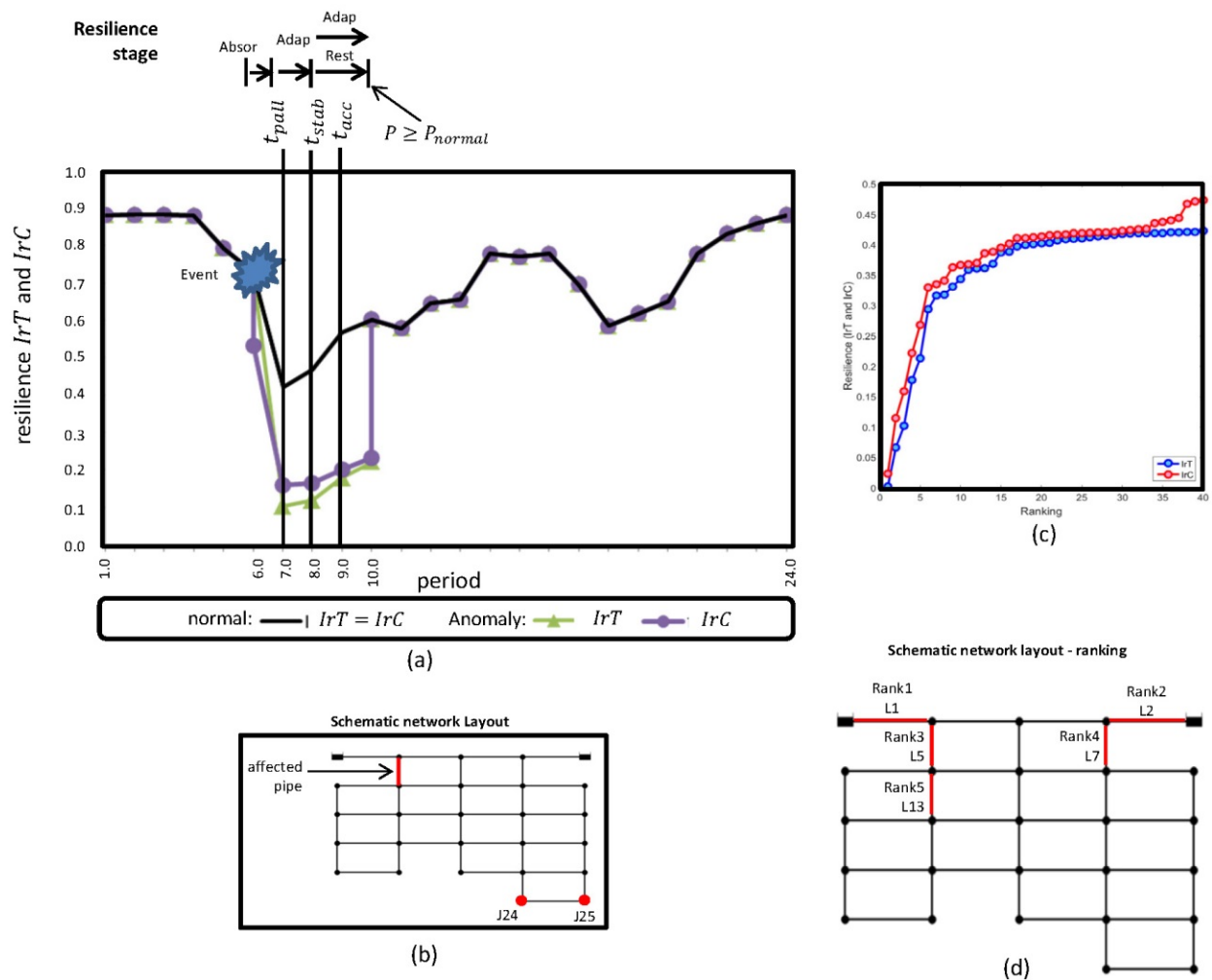


Figure 2. Resilience indicators. (a) Resilience stages; (b) network layout – stages; (c) ranking of pipe – peak demand period; (d) network layout.

In both cases, we can observe a favourable enhancement of the value of the index for IrC in comparison with IrT . Those are the consequences of the performance results used for the index IrC , which provide more realistic condition of the behaviour of the system under the failure condition evaluated. The a priori analysis performed for the system based on the resilience metrics, allows us to know the ranking of the relative importance of the components. Thus, this allows us to observe the plausible maximum impact in the network (event placed on maximum demand peak). This shows that any damage in pipes connected with the reservoirs can have a high unfavourable impact on the network operation conditions. Likewise, this shows that any change in the tank levels, where the levels of the tanks are below to the minimum level (for the maximum peak demand), can provide to the system with a high unfavourable effect on the system resilience.

4. CONCLUSIONS

This paper presents an application example of the resilience key performance indicators, based on three system capacities and its application into the three stages of the event. The results have shown the importance of applying different measures that enable to quantify network changes under stress conditions. The study highlights using tools that allows better understanding of the network's performance facing different disruptive events. This is the case of the application of hydraulic models under PDM approaches, in comparison with DDM approaches. Providing this information to WDN managers allow them to implement actions to prevent catastrophic effects on water networks.

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