ResiWater deliverable report D5.2: Development of Tools for Assessing WDS Vulnerability, Resilience and Robustness and Decision Support for Design

David Ayala Cabrera, Olivier Piller, Jochen Deuerlein, Fabrizio Parisini, Fereshte Sedehizade

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RESIWATER

Deliverable Report D5.2

Written by David Ayala Cabrera &
Fabrizio Parisini

INNOVATIVE SECURE SENSOR NETWORKS AND MODEL-BASED ASSESSMENT TOOLS FOR INCREASED RESILIENCE OF WATER INFRASTRUCTURES

Deliverable 5.2

Advances in Resilience Assessment Tools

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Development of Tools for Assessing WDS Vulnerability, Resilience and Robustness and Decision Support for Design

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Contact persons:
Olivier PILLER olivier.Piller@irstea.fr
Fereshte SEDEHIZADE fereshte.Sedehizade@bwb.de

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WP 5 – Development of Tools for Assessing WDS Vulnerability, Resilience and Robustness and Decision Support for Design

D5.2 Advances in Resilience Assessment Tools

List of Deliverable 5.2 contributors:

From Irstea

Olivier Piller (olivier.piller@irstea.fr) [WP5 leader]

David Ayala Cabrera (david.ayala@irstea.fr)

From 3S Consult

Jochen Deuerlein (deuerlein@3sconsult.de)

Fabrizio Parisini (parisini@3sconsult.de)

From BWB

Fereshte Sedehizade (fereshte.sedehizade@bwb.de)

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Objectives To develop a vulnerability/resilience framework for the analysis of the WDSs behaviour under crisis conditions. In addition, to show the evolution of resilience concept through time and present new resilience indices			

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SUMMARY

The main objective of the work-package 5 is to develop a vulnerability/resilience framework for the analysis of the water distribution systems (WDSs) behavior under crisis conditions. More specifically for T5.2, it is developing technical measures for the resilience. WP 5.2 attempts to provide engineers, modelers, and managers with structured tools which allow a comprehensive analysis of crisis management to enhance the WDS resilience. In this order the mainly items of the WP 5.2 are:

1. Resilience review was further carried out, focusing at last on time dependent indicators. The results of the review serve as basis for the next resilience key performance indicators (rKPIs).
2. Three-stages of resilience through applied power\energy- based indicators.
3. Criticality analysis of water distribution networks through demand satisfaction indicators.
4. Demand compensation proposal for adaptive and restorative stages of the network resilience.

1 INTRODUCTION

Water distribution systems (WDSs) provide the cities with an essential service for life. In this sense, the main objective of a WDS is to deliver the required amount of water to the customer under a certain threshold of the desired pressure and quality (Jung, 2013), and in general to provide safety for the costumers under acceptable costs (Large et al., 2015). These networks are critical infrastructures that should face multiple and continuous changes and even abnormal events that alter their normal service provision. Water distribution systems need to be enabled to face multiple challenges. Potential hazard is mainly classified in natural disaster (e.g. earthquakes, floods, etc.), intentional attacks (terrorist attacks), and hazardous materials release. The risk environment that affects critical infrastructure (such as WDSs) is complex and uncertain in relation to threats, vulnerabilities, and consequences. In addition to the previously mentioned issues, it is worth to mentioning the currently increasing urban infrastructure and its associated communications technologies to managing critical infrastructure operations (Figure 1). So, big cities worldwide should deal nowadays with new challenges coming from attacks focused on exploiting potential cyber vulnerabilities (NIPP, 2013).

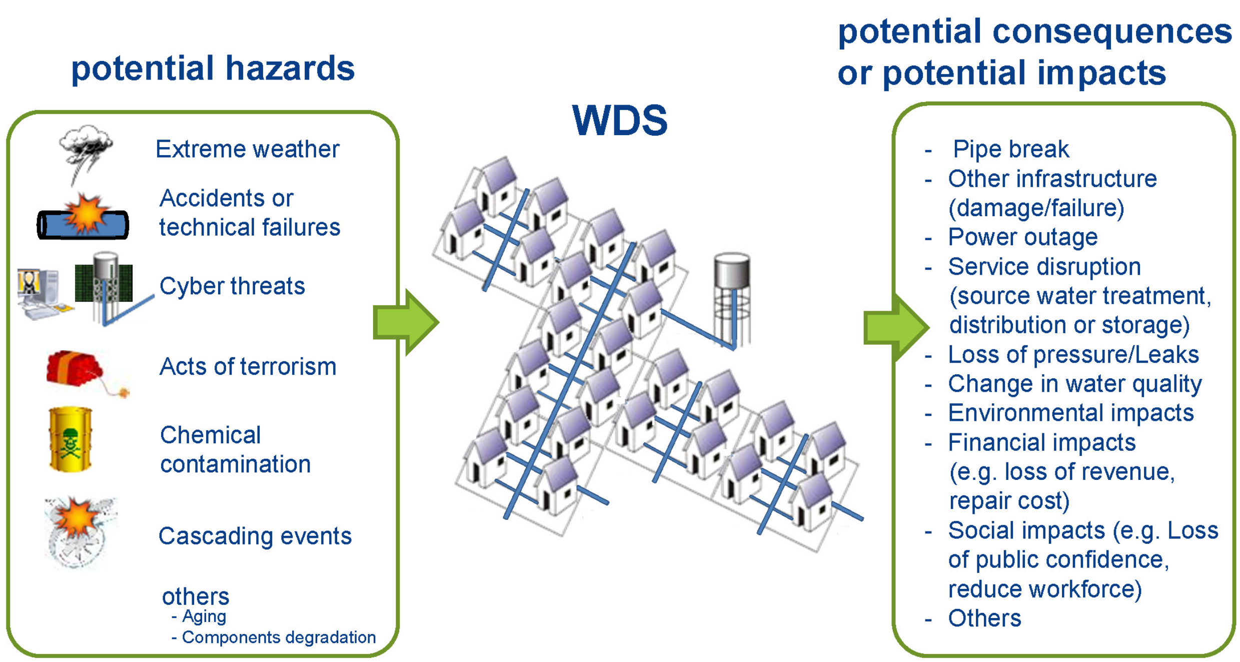


Figure 1: Evolving threats to water distribution systems.
Source: (Ayala-Cabrera et al., 2017a).

In the last years, water distribution systems have received increasing attention by the operators and research community due to their vital role they play for the modern society. They must provide a sufficient delivery of quality water to the costumers (which means, the pressure is above the minimum service value) not only during normal operation, but also in case of system failures or external accidents. There is an array of potential threats for a water distribution system, ranging from mechanical failures, adverse weather phenomena, to terrorist attacks. In this sense, the operators must focus on how their systems are resilient to these threats, in order to be able to face future disruptive events. Therefore, ensuring **resilience and safety of WDSs are big concerns for water utilities**.

WDSs 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 main 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 the drawing and treatment plants and the storage areas. In general terms the satisfaction of consumers is measured by the quality and quantity of water delivered by the WDS. 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. The **node (consumer) importance** for a WDS depends on various factors such as population sensitivities, the location in the graph, and the system performance (Ayala-Cabrera et al., 2017a). In this regard, several authors argues in their researches that the best manner to protect water quality is by maintaining positive and continuous head pressures through the networks (Ilaya-Ayza et al., 2016; Kumpel and Nelson, 2014; Robertson et al., 2003). So therefore, continuous water supply ensures security (Ilaya-Ayza et al., 2016).

The component pipes are one of the principal assets of a WDS, due to their extension through the network. The pipes that constitute the network do not have the same role in the water supply (Alonso, 2008). Thereby, some of the network pipes are more important in face of a hydraulic point of view. Recognizing the diverse and relative importance of the different pipes in a water distribution network may help in assessing their impact on the hydraulic performance of the network (Izquierdo et al., 2008). Furthermore, the **pipe importance** is related to measuring both risk of system isolation and insufficient pressures. This information, as argue Izquierdo et al. (2008) in his research, will be helpful in the different aspects of water distribution systems make-up, namely design, planning, control and management. It is for this reason that several studies such as Do Guen et al. (2014) and Berardi et al. (2014), focus their attention on the evaluation of the network's behaviour under the failure of the pipe component. WDS resilience assessment, in general, is focused on either the mechanical failure of components such as pipe or pump failure, or the hydraulic failure of the system due to degraded pipe capacities and/or uncertain nodal demand flows (Tolson et al., 2004).

In general, **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 WDS need to guarantee the availability of required quantity of water for sensitive customers, such as hospital, etc. (NIPP, 2013). The cost of risk to the health of users must also be considered (in terms of their incomes, medical treatments, etc.) as it is much greater than the cost of replacing deficient pipes (Ilaya-Ayza et al., 2016). In this context, what is the question of resilience? On the one hand, we have the infrastructural resilience that is defined as the ability to reduce the magnitude, impact, or duration of a disruption (NIAC, 2009). For the other side, resilience is the ability of the system to absorb, adapt, and / or rapidly recover from a potential disruptive event (NIAC, 2009). 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).

During time, concepts like **reliability, vulnerability, robustness**, have taken increasing place, together with resilience, to better understand how to improve WDS design and therefore help water utilities. These concepts are not independent one another, they form instead the core characteristics of a WDS; therefore, changing the characteristic of robustness for instance, could affect the resilience of the system. The focus of the ResiWater project is, as the name itself suggests, resiliency. The concept of resilience is broad and it is used not only at engineering level: a community can be resilient after an earthquake or a catastrophic event, a family after the loss of a beloved, a person struggling successfully against solitude and depression can be also resilient. For a water network system, resilience is often related as the capacity of recovery after a failure or a disruptive event. This capacity encompasses not only the "new" performance level (if reduced or the same as before the event) but also, as will be later introduced, the velocity at which the system reacts and reaches a stable performance again.

For WDS, the first (or one of the first) definition of resilience for water distribution system was given by Hashimoto et al. (1982). In his work, he proposes some criteria for describing the performance of WDS in terms of Reliability, Resiliency and Vulnerability: the reliability is defined as how often the system fails; the resilience characterizes as how quickly the system returns to a satisfactory state once a failure has occurred; and vulnerability is defined as how significant the likely consequences of a failure may be.

From a mathematical point of view, these dimensions are expressed as follows: **Reliability** is frequency or probability α that a system is in a satisfactory state

$$\alpha = Prob[X_t \epsilon \Sigma] \quad ,$$

where X_t is a random variable that describes the system output and Σ is the set of all satisfactory outputs. According to Hashimoto et al. (1982), **resiliency** (R) is defined as the inverse of the expected value of the length of time where a system output remains unsatisfactory after a failure (t_{fail}),

$$R = \frac{1}{t_{fail}} \quad .$$

About **vulnerability**, Hashimoto (1982) suggests that attention should be paid to the consequences, independently by the size of the failure. Hence, emphasis is put on not how long failure persists, but on how bad things may become.

In 2003, Bruneau et al. (2003) put a relevant contribute in defining the desirable characteristics of a system. They summarized them as **4 Rs**: Robustness, i.e. the ability of a system to avoid failure and maintain functionality over a large range of (normal and abnormal) conditions. Redundancy, which reduces the technical impact of failures; Rapidity, or the ability to recover as fast as possible from disruptive events and Resourcefulness. Lastly, Resourcefulness, the capability of the water utility to identify problems and mobilize resources and priorities. Moreover, four dimensions for the infrastructure have to be recovered: technical, organizational, social and economic. This means this is a multi-disciplinary approach and comprises technical, organizational, social and economic aspects. This is the classical approach provided by Bruneau et al. (2003). It has some lacks in terms of the notion of preparedness, covering for instance emergency plans, early detection, etc.

Some of these definitions were also recalled by Lansey (2012), with the addition of the concept of **sustainability**. The resilient sustainable interdependent infrastructure (RESIN), formulated by the US National Science Foundation definition of sustainability is: "Sustainability implies providing adequate and reliable water, energy and material resource supplies of desired quality -now and for future generations- in a manner that integrates economic well-being, environmental protection and social needs (triple bottom line)". The goal of *sustainability* is to reduce the impact of WDS. Resilience is defined by RESIN as the ability to graceful degrades and recovers from an external or internal disturbance. On the opposite, robustness is the ability of a system to avoid failure. But not always a robust system is automatically a better one. In fact, a system can be robust but not resilient (and vice versa) (Lansey, 2012).

In general terms and like as we understand in this Deliverable, resilience of water distribution systems 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. In the context of critical infrastructures, resilience can be developed by focusing on the **different stages of the performance** following a disturbance (also called resilience curve), and devising strategies and improvements which strengthen the system response (IRGC, 2016). The framework of the study (developed in this Deliverable) is based on the Franco-German ResiWater Project (see Deliverable 1.1), where the notion of resilience attempts to develop tools to prepare water utilities for crisis.

Regarding the objectives of resilience, water utility managers **require modelling tools** to be able to predict how the WDS will perform during disruptive events and understand how the system can best absorb, successfully adapt, and recover from them. Indeed, simulation and analysis tools can help WDS managers to explore how their network will respond to expected and unexpected events. Tools such as: demand-driven modelling (DDM) for sufficient pressure conditions, and pressure-driven modelling (PDM) for insufficient pressure conditions, help to simulate WDSs performance under failure event conditions. The water distribution computations are approached by a **pressure driven**

model (PDM) (Piller et al., 2017; Elhay et al., 2016), as in case of pipe failures it provides better description of the system conditions than the classical demand driven model (DDM) formulations (Creaco et al., 2016b). The assumption of fixed nodal consumptions (DDM approaches) is therefore valid only under normal conditions when the pressures can be expected to be adequate to satisfy the stipulated demand. If the operation of the system is simulated under pressure-critical conditions (due to some critical events such as mechanical and hydraulic failures or excess of demand), the relationship between pressure and outflow should, therefore, be taken into account (Moosavian and Jaefarzadeh, 2013) whether the simulations are to be realistic.

It is also important to consider the **local and background leakage** in the hydraulic model (Ayala-Cabrera et al., 2017a). The head pressure needed to deliver water consumer demands will drop with the head pressure reduction caused by the flow through the burst (Zhuang et al., 2013). Water loss via leakage constitutes a major challenge to the effective operation of municipal distribution networks since it represents not only diminished revenue for utilities, but also undetermined service quality and wasted energy resources (Moosavian and Jaefarzadeh, 2013). Concerning pressure dependant leakage model implementations, some interesting studies were already conducted. For instance, in Piller and van Zyl (2014), a method is proposed for solving the hydraulic network equations incorporating the fixed and varied area discharges (FAVAD) model. In this work, a damped Newton algorithm solves the system equations. For the other side, Bremond et al. (2009) and Jaumouillé et al. (2007) derived new hydraulic formulations from the Navier-Stokes equations that incorporate background leakage and associated inertia terms. In Bremond et al. (2009) a numerical scheme is used to solve de p-Laplacian equations for a non-uniform pressure-driven background leakage. In Jaumouillé et al. (2007) the linear background leakage was assumed uniform, which brings interesting simplification in terms of solving.

Ultimately, assessing and enhancing resilience in water infrastructures is a crucial step towards more sustainable urban water management. As a prelude to enhancing resilience, a detailed understanding is required of the inherent resilience underlying system (Diao et al., 2016). Deliverable 5.2. proposes a structured classification by means of **resilience key performance indicators** (rKPIs). It attempts to evaluate the different approaches to measure the theoretical resilience of a WDS. The classification is based on the conceptual definition proposed by the Franco-German ResiWater Project (see Deliverable 1.1), which improves the approach proposed by Francis and Bekera (2014) by inclusion of the preparedness. 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 WDS resilience. As it is usual to have limited resources in supply, 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 (Ouyang et al., 2012). From the aforementioned contributions and definitions of resilience, several proposal of parametrizing resilience were presented. In the next section the major contributions are described.

In this deliverable report, the development of the concept of resilience, applied for WDS, is presented. First, the time evolution of Resilience definition will be presented, with general assessment about the meaning of resilient system and contributions of several authors. Then, a literature review of the use of parameters expressing resiliency will be carried out. This literature review is also the basis for us to define new resilience indices which can be then implemented in the framework of the ResiWater Project.

2 LITERATURE REVIEW

As introduced in the last section, the concept of resilience in the domain of WDSs requires the development of a generic framework that allows knowing the response of the system to different disruptive events. The ultimate goal of resilience assessment is the continuity of normal system function. Normal system performance function is to be defined according to the fundamental objectives obtained in system identification. The proposed resilience paradigm might be implemented via the set of resilience capacities outlined above: absorptive capacity, adaptive capacity, and recovery and restorative capacity. The **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 or better than the initial one in a nominal way. Therefore, tools have been developed that provide representative information of the system and measures which enable the managers to adequately quantify the effects of these events. There are several studies that attempt to incorporate resilience metrics in order to ensuring the network capacity to withstand adverse or emergency operative conditions. In general, these metrics are taken into account in the design or optimization stage for WDS networks. It should be mentioned that the main focus of the implemented metrics (in the available literature) are, in essence, based on the quantity of delivered water vs expected demand. This section provides a framework applicable to WDS for assessing resilience. In addition, a compendium of the most common resilience indicators used for water utilities assessment is presented below.

2.1 Assessing resilience

The resilience concept in WDS domain remains challenge and there is an essential need to develop a generic framework to address the resilience for WDS. Resilience and specific WDS resilience is frequently measured using performance metrics. Figure 2 shows an example of a performance-based resilience curve, a “functionality curve” or “resilience triangle” (e.g. Barker et al., 2013; Henry and Ramirez-Marquez, 2012). The horizontal axis represents time and the vertical axis performance (criteria to assessing resilience) (Gay Alanis, 2013). However, metrics that reflect these principles (for the three capacities of the network) and allow knowing the network behaviour under events are required. The latter to provide support to the decision-making process (Francis and Bekera, 2014). 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) (Carpenter et al., 2001). Thereby, several studies have been proposed to quantify the resilience of water distribution networks as in Herrera et al. (2016a).

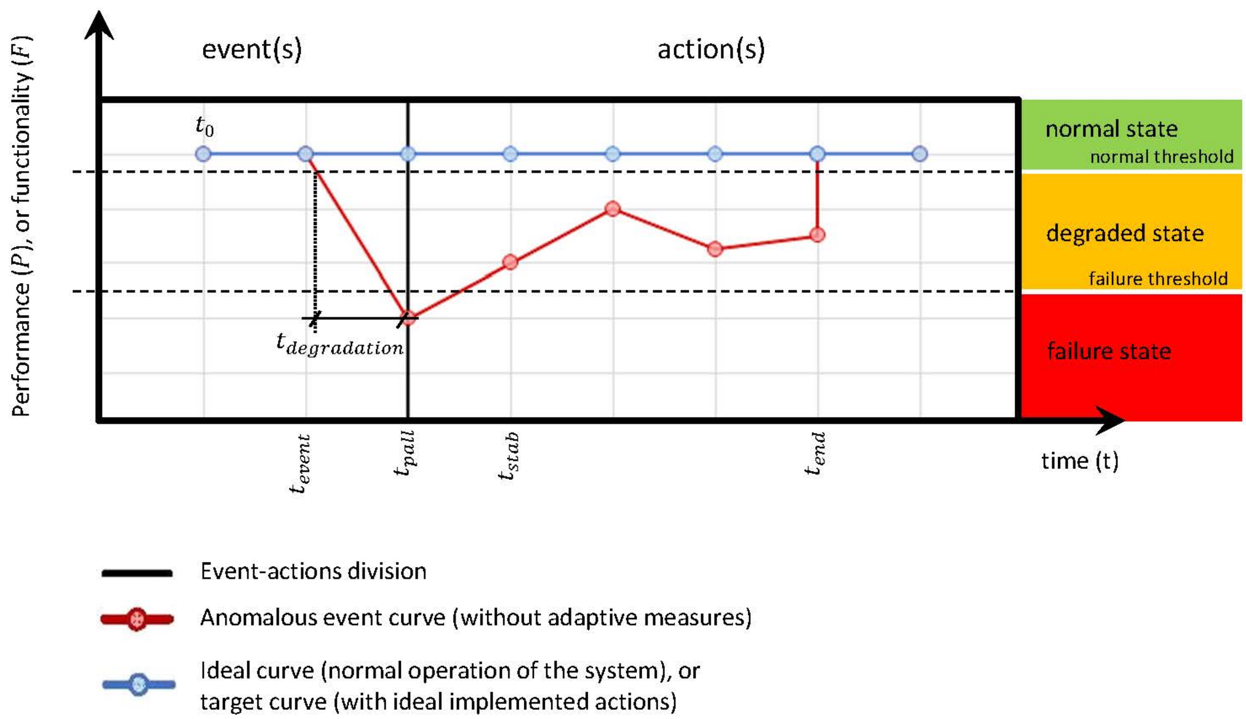


Figure 2: Resilience curve – temporal – technical dimension of the resilience.
Source: (Ayala-Cabrera et al., 2017b).

In Figure 2, the three different states of the network performance are defined for WDSs: 1) normal, 2) degraded, and 3) full failure, which ultimately evaluate the WDS performance, P. The three states for P, are determined by the two thresholds: P_{normal} and $P_{failure}$. The first one corresponds to the minimum P level for the network working in normal mode, and the second refers to the P level when the system is considered in failure mode.

Resilience curve - event(s). First division of the resilience curve is measure since the event starts (t_{event}) and goes until the water utility starts taking appropriate actions (palliative actions). There, we have the time of the anomalous event; t_{event} (e.g. pipe burst). Subsequently, we have the detection of the event (t_{det}), 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_{pall}. According to the framework of the ResiWater project (Deliverable 1.1.; ResiWater, 2017), the first stage (absorptive) of the network's resilience is measured since t_{event} and goes until t_{pall} (see Figure 2). During the absorptive resilience, the water utility has noticed the problem after detection but not corrective actions was taken. The times involved in the model (event(s) part of the resilience curve) are shown in Figure 3 ($t_{event} \rightarrow (+)\ t_{det} \rightarrow (+)\ t_{pall}$).

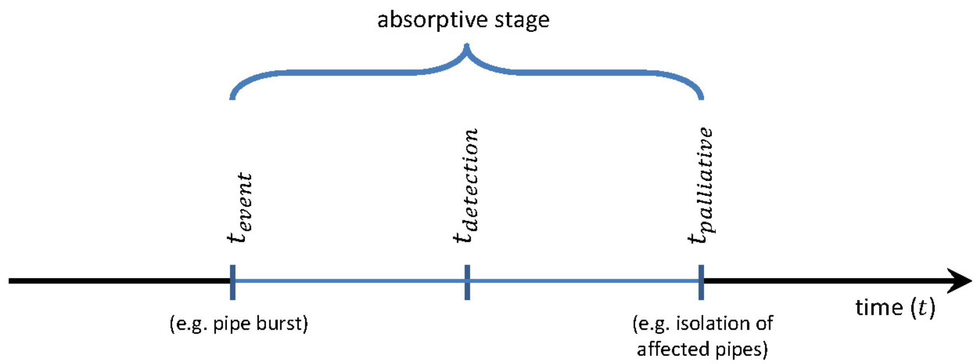


Figure 3: Disruptive events in WDS; absorptive stage - times.
Source: (Ayala-Cabrera et al., 2017a).

Quantifying resilience at absorptive stage - ResiWater approach. For quantifying resilience at this stage (R_{abs}), a discrete resilience is proposed, $R_{abs} = \{3, 2,1\}$, that corresponds to the three states of the networks´ performance at t_{pall}. The three states of the network performance in this definition are {normal, degraded, failure} (see Figure 2). In addition, the internal vulnerability of the system (V_{sys}) is defined as mirror of the absorptive capacity of the system, and is assessed as $V_{sys} = 4 - R_{abs}$ (Deliverable 1.1). t_{deg} (resp. t_{fail}) corresponds to the time at which the degradation (resp. the failure) occurs.

It is at this point of the resilience curve, where several authors focus the implementation of the resilience metrics. For instance, Deuerlein et al. (2009) with the reliability quantification through graph decomposition, or Brentan et al. (2017) with online detection of cyber-attacks through state forecasting and control by pattern recognition. The purpose of this is the quantification the system vulnerability.

Resilience curve - action(s). The absorptive 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. (2017b). The times involved in the model (action(s) part of the resilience curve) are: $\boldsymbol{t_{stab}}$ the time when all emergency measures are in place for maintaining the system performance; $\boldsymbol{t_{end}}$ the time when system performance reaches a stable level or performance; time acceptable, $\boldsymbol{t_{acc}}$ corresponds to the maximum stipulated time in which the network can be under failure. The main goal is to qualify de degree of severity that can suffer the users during the period under system is on failure mode.

Quantifying resilience at adaptive stage – ResiWater approach. For quantifying resilience at this stage (R_{adap}), the ResiWater approach is described as following:

the quantification of the resilience in this stage (R_{adap}) will depend on the state of performance at $t = \min(t_{stab}, t_{acc})$. If $t_{stab} \leq t_{acc}$ then $R_{adap} = \{3, 2, 1\}$ but if $t_{acc} < t_{stab}$ then $R_{adap} = \{2, 1, 1\}$ with the state {normal, degraded, failure}. The quantification of the resilience for this framework at this stage ends when the system performance reaches a stable level of performance equal or better than the initial one in nominal way ($P \geq P_{normal}$). Some part of this stage is overlapping with the following stage (restorative).

The purpose of the resilience quantification at this stage attempts to propose to the utility managers the adaptive actions that allow maintaining level of performance, improving the resilience, of the network in the face of the occurrence of anomalous events. Some examples of these actions are adapting pump operations (for example, turning on other pumps if available), maintaining storage tanks levels at higher levels enabling additional head Zhuang et al. (2013), adjusting control valve settings, among others.

Quantifying resilience at restorative stage – ResiWater approach.

The resilience for restorative stage (R_{rest}) will be determined whether the system succeeds in finding a new Normal state, then $R_{rest} = 3$ else it is less. As we have mentioned before, for this approach, the adaptive and restorative stages end when the system performance reaches a stable level of performance equal or better than the initial one in nominal way ($P \geq P_{normal}$).

The resilience quantification at this stage allows to provide to managers of water utilities with the suitable long-term solutions (for instance, repairing or replace affected components) and in addition provides with proper information about the vulnerability to implement adaptive actions that allow maintaining the resilience whilst the restorative actions are be implemented. Some additional actions implemented at this stage are flushing of the repaired pipe. This action seeks to operate the repaired or replaced pipe in optimal conditions, consider here cleaning of the pipe and air extraction. Flushing stirs up and removes sediments from mains and removes poor quality water from system, replacing it with fresher water from source Walski et al. (2003).

Resilience Metrics – resilience key performance indicators. As we have discussed previously, there has been considerable research conducted to develop the concept of resilience in different domains. However, resilience concept in civil engineering and specifically for WDS domain remains a challenge. There is an essential need to develop specific metrics that allows to quantify the behavior of the WDS network when it is working under failure (or unfavorable) conditions.

This was also the path we took during our literature review; here we present the most relevant contributions, from the beginnings to the time-dependent resilience definitions.

In chronological order that widely applicable to WDS for purpose of evaluate network resilience, the first work in defining resilience in WDS is by Todini (2000), where resilience is linked to the concept of **available power**. In a looped network, one would like to provide at each node more energy than required, to have sufficient surplus to be dissipated internally in case of failures. This work is inspired from the power system theory. Prasad et al. (Prasad et al., 2003; Prasad and Park, 2004) have expanded this topic using a multi-objective genetic algorithm to design a WDS. The objectives considered are the minimization of the network cost and the maximization of a reliability measure, which is called *Network Resilience* (I_{NR}). This indicator was introduced because it incorporates the effects of both surplus power and reliable loops, which can be ensured if the diameter of the pipes connected to the node do not vary widely. Tsakiris and Spiliotis (2012) utilized Todini's Resilience index definition and Failure index (also in Todini, 2000) in real scenarios. The Failure index identifies infeasibilities during the optimization process. It focuses only on the lack of power at the nodes, and expresses the degree of failure in the hydraulic network. Another improvement of Todini's resilience index came from Creaco et al. (2016a), who focused on a comparison between I_{NR} and a modified resilience index by Prasad et al. (2003). The latter considers not only the head surplus at each node of the network, but also the uniformity of the pipes connected to each network node.

Another approach for resilience is through calculating performance indicators as the **consumer demand satisfaction rate** $SR_{i,j}$. It is the ratio between the actual water flow supplied to users at the node i (c_i) and the water demand (Bremond and Berthin, 2001; Zhuang et al., 2013). In case of service disruption in some segments, the satisfaction rate can be calculated, for each scenario, associated to a generic element in the network. An "average satisfaction" SRP_j can be computed as average of the satisfaction rate relative to a failure (e.g. pipe isolation and/or pipe burst among others). This satisfaction rate will be recalled in the work carried out within the ResiWater project.

Ataoui and Ermini (2015) estimated resiliency regarding three aspects: water flow, pressure and water quality. This brought to three kinds of resiliencies, correspondingly demand, pressure and water quality resilience. In order for a system to be in a satisfactory state, these three resilience parameters must be met (given a threshold); otherwise it falls into a failure state.

A study that links resilience and vulnerability has been carried out by Soldi et al. (2015). They proposed a framework based on **complex network theory** to evaluate both resilience and vulnerability of a WDS. Hydraulic simulation is adopted in order to estimate the potential stress on the hydraulic components. While the resilience/vulnerability measures allow to estimate how the failure of a single component affects the connectivity, the hydraulic simulation permits to estimate the chances of breakage/failure of each pipe according to the current usage behavior of the WDS. The study of vulnerability/resilience was performed using graph theory.

Herrera et al. (2015a) explored a hybrid approach to bridge the gap between **graph-theoretic and hydraulic measures of resilience**. A common challenge for the actual approaches is that the combination of possible failure scenarios grows exponentially as the network becomes larger. Their work assessed the resilience of WDSs from a hybrid hydraulic-graph-theory point of view by considering energy losses associated with flow as a distance measure between two different points in a WDS. This allowed identifying nodes which require large dissipated energy for their supply. The parameters introduced are node closeness centrality, availability and capacity of the supply routes to the demand nodes.

Wright et al. (2015) presented a resilience index based on hydraulic simulations. This index is built on the reserve capacity, defined as the maximum demand multiplier that can be applied to a WDS without violating minimum service pressure levels. **The reserve capacity** shows how close a network is operating to an established threshold that represents full capacity. This index provides additional information compared to other indices, since it can successfully calculate the reduced resilience of a network that has suffered a failure, but it is still working. The reserve capacity can be used to measure the resilience of adaptive networks (when pressure reducing valves are present, for example); it is also intuitive to understand and this could help the decision makers.

With focus on time, the following works were found to be interesting for developing new **time-related rKPIs** (see Section 3.3). First, Henry and Ramirez-Marquez (2012) proposed a resilience definition that considers the evolution in time of a specific figure-of-merit. The index presented above quantifies the proportion of delivery function that has been recovered after the disruptive event, a definition that is true to the original meaning of resilience. Second, a similar framework was proposed by Baker et al. (2013), with the addition of a component **importance measure** to identify system components which are more critical than others in term of reliability of the entire system. Finally, Ayubb (2013) modelled resilience as the contribution of different system/action states (normal, failure, recovery), each of them weighted by the respective time duration and then divided by the total time duration of the event. In his work the system performance presents aging effects, in addition of an incident, so that a fully system recovery after the incident is not possible. Such representation is closer to the reality and could be considered for future work about resilience (in context of the ResiWater project). A failure and recovery profile were also added, to have a range of possible failure incident and actions taken. The value of the failure profile be a measure of robustness and redundancy, while the recovery profile curve can display the resourcefulness and the rapidity of the system to bounce back to the original state.

The indicators presented above may be split in six groups (according to their approach). The six groups of indicators (Table 1) are: 1) Power/Energy, 2) Performance, 3) Graph theory/Social Networks, 4) time, 5) sensitivities, and 6) others. Further details for the mathematical formulations of the mentioned above indicators are presented in the following sections.

Table 1: List of based indicators approaches in the available literature.

Based Indicators	**Approach**
Power/Energy	Compute the resilience in terms of power/energy delivered to the consumers.
Performance	Based in the performance obtained through mathematical model simulations. In general, PDM for hydraulic model is required to calculate the consumer demand satisfaction.
Graph theory/Social networks	Indicators based or supported by graph theory and/or social networks approaches. In general, based on three structural properties of the networks. The most used is network centrality.
Time	Although every resilience indicator is referred to a certain time of a disruptive event (begin, during, after), some are defined explicitly by factors such as start time or time duration (t_x and Δt_x). Therefore, we group them separately from the other indicators.
Sensitivities	Sensitivities are first-order estimates of change of variables (flows, heads) with respect to different kind of parameter changes Piller et al. (2017).
Other	Imported approaches from other infrastructures (e.g. transportation).

Topologic characteristics of the network. Water distribution systems may be represented as networks of nodes (e.g. reservoirs and tank) connected by links (e.g. pipes, valves, pump stations, etc.). A network can be modelled as a graph $G = G(V, E)$ in which V (vertices) is a set of nodes and E (edges or links) correspond to m links of the system (Herrera et al., 2016a; Di Nardo et al., 2013). The topological characteristics of the networks are generally represented by two matrices; the node-link incidence matrix, $A^N_{(ij)}$, and node to node adjacency matrix, $A^{AD}_{(ii)}$. The mathematical expression of $A^N_{(ij)}$ is given by the following rules:

$$A^N_{i,j} = \begin{cases} -1, & \text{if node } i \text{ is terminal point of link } j \\ \ \ 0, & \text{if node } i \text{ is not connected to link } j \\ \ \ 1, & \text{if node } i \text{ is the initial point of link } j \end{cases}$$

Matrix $A^N_{(ij)}$ is generally 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. For the other side, the adjacency matrix is a square matrix of size the number of nodes. The element $A^{AD}_{(ii)}$, noted a_{ii}, represents whether the vertices i and j are adjacent or not in the graph. The latter, is frequently used in the resilience studies through the graph\social networks-based indicators (Section 2.4). It is also possible to associate weights to the pipes (weighted graph) representing distances, costs or times, or directions (directed graph) (Di Nardo et al., 2013).

2.2 Power/Energy-based indicators

The resilience indicators in this section are split in three following classes: a) Power-based indicators, b) energy-based indicators and, c) entropy-based indicators. The collected indicators are described below.

a). Power-based measures. 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 supplied to the consumers, to the maximum power that can be dissipated in the network to meet the consumer demand. 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). Todini (2000) defines the total power (P_{tot}) supplied to the WDS, as the sum of power dissipated internally (P_{int}) and the power that is delivered to the users, (P_{ext}):

$$P_{tot} = P_{int} + P_{ext}.$$

The resilience index by Todini (2000) (I_R) is written as:

$$I_R = 1 - \left(\frac{P_{int}}{P_{max}}\right) \quad ,$$

where P_{max} is the maximum power that could be dissipated internally to satisfy the constraints in terms of demand and nodes head. The mathematical formulations for the power-based indicators are described in Table 2. This resilience indicator can also incorporate the presence of pumps by modifying P_{tot}. The optimal network design for Todini (2000) was reached using a heuristic approach, similarly to a Pareto set, where the costs versus the newly introduced I_R were plotted.

For Todini's indicator, Creaco et al. (2015) argue that under normal operating conditions, whether $h \geq h_s$ and users demands are satisfied, it holds that $P_{int} \leq P_{max}$. I_R can then only takes positive values and ranges within the interval [0, 1]: it cannot ever be strictly equal to 1 as this would imply absence of energy dissipations in the network. Saldarriaga et al (2010) argue that higher I_R value correspond to system with greater energy surplus, which have a bigger capacity of overcoming sudden failures. So, in turn, it can be deduced that by increasing the I_R of a WDS, its resilience will be improved. Also, Paez and Filion (2017) proposed in their research that this indicator have as the advantage it does not require a stochastic analysis of hydraulic or mechanical perturbations that a WDS could have, but it represents in different ways the impact and response of the network to those uncertain perturbations. I_R is consider for some authors as a measure of network robustness. For instance, Creaco et al. (2015) have used the indicator proposed by Todini (power-based indicator) for design phase and the satisfaction rate (performance based indicator, see Table 4) in the performance assessment. The author attempts with this work to prove that the I_R, also represents an effective indicator of the network robustness. The authors argue based in their results that the resilience index, represents a very good measure of network robustness as well than satisfaction rate.

Since the Todini's indicator was proposed, multiple modifications have been raised by different authors in their works. These works attempt with their variations to incorporate aspects such as topological redundancy, solving problems with the multiple sources, pressure-dependent outflows (like as leakage or/and consumption). To obtain a better representation of the network reliability, Network resilience index (Prasad et al., 2003; Prasad and Park, 2004), Network resilience by Creaco et al. (2016a) and modified resilience index by Jayaram and Srinivasan (2008) were proposed, among others. For one side, Prasad introduced a uniformity coefficient $\chi_{up,j}$, for each pipe j, which is the only difference between I_{NR} and 'Todini I_R. For the other side, Creaco et al. (2016a) introduce the definition of a loop uniformity coefficient χ_{ul}. The authors argued that the introduction of a pipe uniformity coefficient represents the network resilience better than the original formulation of Todini's index. Jayaram and Srinivasan (2008) found an inconsistency in Todini's resilience indicator if used to measure resilience when multiple sources exist in WDS. The inconsistency is due to the calculation of the resource power input term in the denominator that may results in low resilience values even if there is redundant power in the system. Indeed, some storage tanks can receive water, which will not be the case in crisis.

Additional modifications for this index tries to include different pressure-dependent modelling, as in Saldarriaga et al. (2010). The most recent modification of Todini's resilience index was proposed by Creaco et al. (2016b). The authors include in the indicator two different pressure-dependent modelling contributions (leakage and consumption). Table 2 shows a list of the main modifications of Todini's resilience index and other Power-based indicators applied by water utilities.

Table 2: Power– based indicators.

Metrics	Expression	Definition	Remarks/parameter
Power-based resilience index and modifications; based on Todini (2000)			
Resilience Index I_R (Todini, 2000).	$I_R = \frac{d^T h - d^T h_s}{h_f^T A_f q - d^T h_s} = 1 - \frac{h_f^T A_f q - d^T h}{h_f^T A_f q - d^T h_s}$	DDM model considered. Main objective, resilience-based design. -Heuristic.	Original formulation q = vector of flow rates within the pipes. h = vector of heads d = vector of water demands h_f = head at fixed nodes h_s = service head A_f = incidence matrix for nodes with fixed head $\boldsymbol{T}$ = matrix transposition.
Network resilience I_{NR} (Prasad et al. 2003; Prasad and Park, 2004).	$I_{NR} = \frac{(\chi_{up} \odot d)^T h - (\chi_{up} \odot d)^T h_s}{h_f^T A_f q - d^T h_s}$	DDM model considered. Main objective resilience based design. Based on I_R, this indicator attempts to taken into account the network topological redundancy. Heuristic	Pipe diameter uniformity coefficient is introduced. $\odot$ = Hadamard product. Attempts to taken into account topological redundancy.
	$\chi_{up,i} = \frac{\sum_{jni=1}^{npi} \emptyset_{jni}}{npi \cdot \max[\emptyset_{jni}]}$	Uniformity coefficient ($\chi_{up,i}$)	jni = pipes connected to node i. npi = number of pipes connected to node i. $\emptyset$= diameter of the pipe.
Network resilience I_{nr} (Creaco et al. 2016a).	$I_{nr} = \frac{(\chi_{ul} \odot d)^T h - (\chi_{ul} \odot d)^T h_s}{h_f^T A_f q - d^T h_s}$	Similar definition of the I_{NR} indicator.	Loop diameter uniformity coefficient χ_{ul} instead of χ_{up}. Attempts to taken into account topological redundancy.
Modified resilience Index I_{MR} (Jayaram and Srinivasan, 2008).	$I_{MR} = \frac{d^T h - d^T h_s}{d^T h_s} \times 100$	DDM model considered. Main objective resilience based design. This indicator attempts to solve the inconsistency obtained with I_R when multiple sources of water exist in WDS. This indicator is defined as the amount of surplus power available as a percentage of the sum of the minimum required power at demand nodes. -Heuristic	Attempts to fix the problem by networks with multiple sources.
Resilience Index by Saldarriaga et al. I_{RS} (Saldarriaga et al. 2010).	$I_{RS} = \frac{ct^T h - ct^T h_s}{h_f^T A_f q - ct^T h_s}$	PDM model considered (leakage). Leakage was simulated through emitters. -Heuristic	Leakage. ct = total outflow ($d + cLeak$). q and h are computed in this work through DDM. $cLeak$= leakage outflow allocated to the nodes, computed through

			emitters.
Generalized resilience Index I_{RC} (Creaco et al. 2016b).	$I_{RC} = \frac{\max[ct^T h - d^T h_s, 0]}{h_f^T A_f q - d^T h_s}$	PDM first modification of resilience Index I_R that included PDM model for consumptions and leakage. -Heuristic	Leakage and consumers (PDM). ct = total outflow ($c + cLeak$). c= users consumption; computed in this work through the Wagner et al. (1988) POR. q and h are computed in this work through PDM. $cLeak$= leakage outflow allocated to the nodes.
Others			
Unitary Power of Pipe $P_{UTP}(j)$ (Saldarriaga et al. 2010).	$P_{UTP}(j) = q_j(h_{i,ini} - h_{i,end})$	DDM. Proposed by Saldarriaga et al. (2010), the unitary power of a certain pipe j is defined as the flow within the pipe j multiplied by the difference between the piezometric head at the pipe's initial and final nodes. The designation of the nodes is done based on flow direction.	Comparison with I_R. Based on his results Saldarriaga et al. (2010) argue that I_R and P_{UTP} provide similar results (in general) as a criterion to select the most important pipes to be replaced. In addition, this author rises that the P_{UTP} indicator has an important advantage over I_R Indicator in terms of the computing time savings, which is an essential aspect to be consider when dealing with large water distribution systems.
Surplus Power Factor SPF_j	$SPF_j = \frac{P_{max\,j} - P_{avl,j}}{P_{max\,j}};\ \forall j$	Measure of the spare hydraulic capacity in a pipe. Used in Tanyimboh et al. (2016) for comparison with other surrogate measure of the reliability.	For pipe j, $P_{max\,j}$ and $P_{avl,j}$ maximum and available hydraulic power at the downstream end of the pipe, respectively.

b). Energy based measures. In the available literature, there are traditional metrics to assess resilience through the available energy at the system (see Table 3). Some examples of these are the minimum ($h_{f,s,\mathrm{min}}$) and maximum ($h_{f,s,\mathrm{max}}$) head at source s. The minimum, mean, maximum node pressure, h_{min}, h_{mean}, and h_{max}; respectively. Standard deviation of the node pressure, h_{SD}. The minimum surplus head, I_{msh}; the sum of surplus head, I_{ssh}; the energy dissipation, E_{Dis}; and the mean weighted diameter ($\emptyset_{\mathrm{Wmean}}$). The indicators mentioned above are usually computed by demand driven model (Di Nardo et al., 2017; Jalal, 2008). Energy redundancy metrics and topological redundancy metrics (see Section 2.4, graph theory/social networks- based indicators) were considered in Di Nardo et al. (2017) with a comparative study of these metrics. The comparison highlighted some network peculiarities, in terms of topology and energy, and, consequently, the possibility to define a range of similarity to build hypothetical benchmark networks. Further, the analysis highlighted that some correlations exist between topological and energy metrics although more studies are required. Topologic and energy metrics were computed, with reference to four existing networks and two hypothetical networks. The results showed the capability of these metrics to identify and measure the network similarities and differences that can be used to implement a methodology and indices to study structural vulnerability and resilience to perturbations in water networks as argue Di Nardo et al. in his work.

Table 3: Energy–based indicators.

Metrics	Expression	Definition	Remarks/parameter
Minimum source head ($h_{f,s,\min}$)	$h_{f,s,\min} = \min_{r}(h_{f,s})$	Example of used. Di Nardo et al. (2017). Comparison with based power/energy indicators. DDM.	$s = \{1, \dots, r\}$ sources. r=total number of sources in the system.
Maximum source head ($h_{f,s,\max}$)	$h_{f,s,\max} = \max_{r}(h_{f,s})$	Example of used. Di Nardo et al. (2017). Comparison with based power/energy indicators. DDM.	$s = \{1, \dots, r\}$ sources. r=total number of sources in the system.
Minimum node pressure ($h_{\min}$)	$h_{\min} = \min_{n}(h_i)$	Example of used. - Di Nardo et al. (2017). Comparison with based power/energy indicators. DDM. - Used in ResiWater Approach in order to determine the first consumer affected as consequence of the failure (quantity). Determine Resilience in absorptive stage. DDM or PDM.	n = nodes, h_i= node head pressure.
Mean node pressure (h_{mean})	$h_{\text{mean}} = \frac{1}{n}\sum_{i=1}^{n} h_i$	Example of used. Greco et al. (2012). Comparison with entropy, performance-based indicators. Di Nardo et al. (2013). Used as basis of water network sectorization. Di Nardo et al. (2017). Comparison with based power-based indicators. DDM.	n = nodes, h_i= node head pressure.
Maximum node pressure ($h_{\max}$)	$h_{\max}= \max_{n}(h_i)$	Example of used. - Di Nardo et al. (2017). Comparison with based power/energy indicators. DDM.	n = nodes, h_i= node head pressure.

Standard deviation (h_{SD})	$h_{SD} = \sqrt{\frac{\sum_{i=1}^{n}(h_i - h_{\text{mean}})^2}{n-1}}$	Example of used. - Greco et al. (2012). Comparison with entropy, performance-based indicators.	n = nodes, h_i= node head pressure.
Minimum surplus head (I_{msh})	$I_{msh} = \min(h_i - h_{\min})$	DDM metric, collected in Jalal (2008), this indicator represents how much energy can be dissipate during failure conditions.	$i = \{1, \dots, n\}$, n=nodes, h_i= node head pressure, $h_{\min}$= minimum required head pressure or design head at node with minimum head, $h_i \geq h_{\min}$ so DDM.
Sum of surplus head (I_{ssh})	$I_{ssh} = \sum_{i=1}^{n}(h_i - h_{\min})$	DDM metric, collected in Jalal (2008), this indicator represents the extent to which all consumption nodes meet pressure expectations.	$i = \{1, \dots, n\}$, n=nodes, h_i= node head pressure, $h_{\min}$= minimum required head pressure or design head at node with minimum head, $h_i \geq h_{\min}$ so DDM.
Energy dissipation (E_{Dis})	$E_{Dis} = \sum_{j=1}^{m} \Delta h(r, q)$	Example of used. Tanyimboh et al. (2016). Comparison with based power/energy indicators. DDM	j=pipes. m=total of pipes in the system. $\Delta h(r, q)$=describe the head losses in the links. q=vector of flow rates within the pipes.
Mean weighted diameter ($\emptyset_{\text{Wmean}}$)	$\emptyset_{\text{Wmean}} = \frac{\sum_{j=1}^{m} \phi_j L_j}{\sum_{j=1}^{m} L_j}$	Example of used. Di Nardo et al. (2017). Comparison with based power/energy indicators. DDM.	ϕ_j = pipe diameter, L_j=pipe length, m= pipes.

c). Entropy based measures. Several indirect indicators of reliability (also called surrogate reliability measures), such as power-based indicators (for instance, Todini, 2000; see Table 2), and entropy Tanyimboh and Templeman (2000) have been devised in recent years to limit the computational effort for network reliability assessment. Indicators such as power-based indicators, energy-based indicators, or entropy-based indicators (e.g. Tanyimboh and Templeman, 2000), are conceived in such a way as to express the redundancy of the network under normal operation conditions, argue Creaco et al. (2015). The concept of entropy of a WDS has been derived from Shannon (1948) concept of informational entropy as a measure of uncertainty. Based on Shannon (1948), Tanyimboh and Templeman (1993) introduced the statistical flow entropy indicator. The statistical flow entropy of a WDS is a measure of the relative uniformity of the pipe flow rates (Tanyimboh et al., 2016)

$$\frac{S_{ent}}{K_{ent}} = -\sum_{s=1}^{r}\left(\frac{Q_s}{T}\right)\ln\left(\frac{Q_s}{T}\right) - \frac{1}{T}\sum_{i=1}^{I} T_i\left[\left(\frac{d_i}{T_i}\right)\ln\left(\frac{d_i}{T_i}\right) + \sum_{si\in N_i}\frac{q_{si}}{T_i}\ln\left(\frac{q_{si}}{T_i}\right)\right]$$

where S_{ent} is entropy, K_{ent} is an arbitrary and positive constant (commonly taken as 1; see Gheisi and Naser, 2015), T is the total amount of water supply, T_i is the total flow reaching node i, Q_s represents the inflow at source node s, d_i represent de demand at a demand node, q_{si} is the flow rate in link si, r represent the number of source nodes, I represent the number of demand nodes, and N_i represents all the pipe flow from node i.

Authors such as Tanyimboh et al. (2011) and Greco et al. (2012) investigated which indirect index is more correlated to the network reliability, retrospectively estimated by direct performance indicators evaluation. They arrived at contrasting results: Tanyimboh et al. (2011) indicate the entropy is the best indirect reliability measure while for Greco et al. (2012) resilience should be preferred. Likewise, authors such as Gheisi and Naser (2015) and Tanyimboh et al. (2016) performed a comparison of resilience indicators for water distribution network. Both derive from their studies that **statistical flow entropy** measures better compared to the others implemented measures, for instance, the resilience index by Todini (2000) or the network resilience by Prasad et al. (2004). Moreover, both of two authors argue that the comparison among networks with similar measure of entropy is feasible.

2.3 Performance-based indicators

Because of the failure in the system, a reduction in the water supplied should be reflected to the users. The satisfaction rate SR is a resilience indicator and a direct measure of the reliability, for a given failure in the 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 (e.g., Bremond and Berthin, 2001; Zhuang et al., 2013). 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:

$$SR_{i,j,t} = \frac{c_{i,j,t}}{d_{i,t}}$$

where, t is the time that has been considered in the assessment.

A brief list of authors whose use this indicator in their works is given in Table 4.

Table 4: Performance – based indicators.

Metric	Definition	Remarks/Parameters
Focus on consumers		
$SR_{i,j,t}$	Available water delivered to the consumer and water required for consumers (Bremond and Berthin, 2001; Zhuang et al., 2013).	**Parameters** i: demand nodes, j: component(s) in failure. Most commonly used pipe\s. c: flow delivered to i-th node at time t. POR: Most commonly used Wagner et al. (1988). *Exceptions.* In Shuang et al. (2014), modification of Wagner function; inclusion the term $h_{\max,cas}$[1]. time t In Bremond and Berthin (2001), peak demand period. In Zhuang et al. (2013), along of duration of the system working under failure $\{t_{event}, \ldots\ t_{end}\}$. In Shuang et al. (2014), along of one day. **Comments** Bremond and Berthin (2001), Zhuang et al. (2013), and Shuang et al. (2014), denote this indicator as nodal reliability or nodal availability. Creaco et al. (2015) denote this indicator as a measure of network robustness. In Shuang et al. (2014), used for cascading failures and crucial pipes identification. In Creaco et al. (2015), used for comparing with power-based indicators.
Focus on system		
$SRP_{j,t}$ [2]	Average satisfaction rate for a component (is the average of $SR_{i,j,t}$ for all the nodes)	Global measure for pipe failure j, Bremond and Berthin, (2001), additional considerations by this author of this paper, **sensitivity of consumers**

[1] $h_{\max,cas}$ the acceptable maximum level of head pressure that node can bear (head capacity) (Shuang et al., 2014).
[2] Average satisfaction Rate, satisfaction rate for failure of a pipe (or a component)

$SRN_{i,t}$ [3]	Mean satisfaction rate at node i (is the pipe average of $SR_{i,j,t}$ for all the pipe bursts)	Global measure for system reliability, due to failure of component(s). In Bremond and Berthin (2001), additional considerations by this author of this paper, **probability of breaks**. In Zhuang et al. (2013), the event evaluated is the single pipe failure. In Shuang et al. (2014), the events evaluated are the multiple pipe failure, cascading failures.
$IH_{j,t}$ [4]	Hydraulic importance of a network pipe. $1 - SRP_{j,t}$; where $SRP_{j,t} = \frac{C_{total}}{D_{total}}$	D_{total}: total demand (withdrawal) of the system in normal operation case, C_{total}: maximum demand (withdrawal) for the network with component is in failure (Deuerlein et al., 2009). Indicator based on $SRP_{j,t}$, enables to quantify technical vulnerability of the system.

In works such as Creaco et al. (2015), the satisfaction rate was used as indicator of network robustness. Creaco et al. (2015) argue in their work that for complex real networks, the evaluation of these performance indicators (service reliability, whether the probabilities are involved in the final computations or not) can unfortunately be a computationally heavy task since it entails the execution of numerous pressure-driven hydraulic simulations. Some authors propose to link the robustness of a water distribution system design to its hydraulic reliability, which is classically defined as its capacity to fully satisfy users demand at each period (Hashimoto et al., 1982). For example, in research works by Zhuang et al. (2013) and Shuang et al. (2014) the reliability is defined as the ability of the system to complete the scheduled functions in a certain period under the given working state.

The cascading propagation under mechanical failures was evaluated in Shuang et al. (2014) with modification of the Wagner function through the inclusion of an additional satisfaction rate indicator: $h_{\text{max,cas}}$. The $h_{\text{max,cas}}$ in their paper is the acceptable maximum level of head pressure that node can bear (head capacity). In order to obtain the $h_{\text{max,cas}}$ the expression proposed by Dueñas-Osorio and Vemuru (2009) was adapted. The expression used in Shuang et al. (2014) for h_{max} is $h_{\text{max,cas}} = (1 + \alpha c)h_s$; where αc is a variable to calibrate and allows a systematic evaluation of aggregated performance of the components of WDS during cascading propagation. This work assumes that when a pipe of the WDS is closed as consequence of the failure (pipe isolation) then it triggers the network flow to be redistributed among all nodes. If the nodal pressure head exceeds its capacity, this node fails to provide water. The failure triggers the reduction of its downstream pipes. The pressure of one node change leads to other node pressure changes to varying degrees. In this situation, a new round of load redistributed occurs and leads to cascading failures. The iterative process continues until there are no failure nodes or pipes produced, which implies the cascading can be considered stopped.

[3] Mean satisfaction rate at nodes, satisfaction rate at each node.
[4] Hydraulic importance.

2.4 Graph theory/Social Networks-based indicators

The resilience assessment of water distribution networks has been carried out for decades by a priori evaluating the network topology, under the assumption that a densely network layout allows overcoming of local pipe failures and peaks in the water demand spatial and temporal pattern. A considerable number of metrics based on purely structural characteristic of the network and its connectivity, have extended uses in the available literature. In this concern, we can found **centrality indicators** that, in essence, attempt to know the structural (topological) capacity of the network to tackle the problems (to face up to the problems) (Freeman, 1978). These metrics can be classified in three groups in relation with the attribute that are based on. These three groups are:

- **based on the degree of nodes.** These are metrics of the communication activity of the network.
- **based on intermediation (betweenness).** These are metrics of the potential to control of the communication within network.
- **based on proximity (closeness).** These are indicators of independence or efficiencies for the network.

Di Nardo et al. (2017) consider indicators like as structural or topological redundancy metrics. Another point of view of this kind of measures is those social networks, whose are focused on the capacity of the network members (nodes) to cope the problems through the three basic and structural properties of the networks (Freeman, 1978). A brief list of graph theory/Social networks- based indicators is presented in Table 5.

Table 5: Graph theory/Social networks – based indicators.

Metric	Expression	Definition	Remarks/parameters
Average Degree (I_{AD})	$I_{AD} = \frac{2m}{n}$	Example of used. (Yazdani et al., 2011). Comparison with other graph theory-based indicators. (Di Nardo et al., 2017). Comparison with based power/energy-based indicators.	m = total pipes in the system, n= total number of nodes in the system.
Density (I_{Den})	$I_{Den} = \frac{2m}{n(n-1)}$	Example of used. (Yazdani et al., 2011). Comparison with other graph theory-based indicators. (Di Nardo et al., 2017). Comparison with based power/energy-based indicators	
Clustering coefficient (I_{CC})	$I_{CC} = \frac{3N\Delta}{N_3}$	Example of used. (Soldi et al., 2015). Comparison with other graph theory-based indicators. (Di Nardo et al., 2017). Comparison with based power/energy-base indicators	$N\Delta$= network triangles, N_3= network connected triples.
Meshedness coefficient (I_{MC})	$I_{MC} = \frac{m-n+1}{2n-5}$	Example of used. (Herrera et al., 2016a). Comparison with K-shortest-path I_{GT}, and power/energy-based indicators. (Di Nardo et al., 2017). Comparison with based power/energy-based indicators	Valid for one-single connected component, and one single tank.
Average Path length (I_{APL})	$I_{APL} = \frac{\sum_{\forall i_s \neq i_t} \sigma(i_s, i_t)}{\frac{1}{2} n \cdot (n-1)}$	Example of used. (Di Nardo et al., 2017). Comparison with based power/energy-based indicators	$\sigma(i_s, i_t)$ = shortest path from i_s to i_t.
K-shortest paths Index ($I_{GT}(i)$)	$I_{GT}(i) = \sum_{s=1}^{r} \left(\frac{1}{K} \sum_{k=1}^{K} \frac{1}{res(k,s)} \right)$	Example of used. Herrera et al. (2016a). Comparison with power-based power/energy indicators, graph theory indicators by other authors, and entropy indicators. 20 random experiments for each scenario. 3 scenarios: 1) normal operating conditions, 2) and 3), failure of 2.5% and 5.0% of randomly selected pipes; respectively.	r= total number of sources in the system $s = \{1, \ldots, r\}$. K = shortest routes. $r(k,s)$ = (adaptation of shortest path); surrogate measure of energy loss (the resistance to water transport, associated with k-th path to source

	$res(k) = \sum_{j=1}^{m} f(j) \frac{L}{\emptyset_j}$ (Herrera et al., 2016a)	Measure of energy loss.	$f(j)$ = estimates the friction factor by pipe age and material for the j-th pipe. L= length of the pipe. $\emptyset$= diameter of the pipe.
Betweenness Centrality (I_{BC})	Frequency with which a node is located "between" two other nodes. $I_{BC} = \frac{\sum_{i_s}^{n} \sum_{i_t}^{n} \frac{g_{i_s i_m i_t}}{g_{i_s i_t}}}{(n^2 - 3n + 2)/2}$	Example of used. (Yoo et al., 2015) by sensitivity of flow direction. Subject: water quality and sensor location. In this study the shortest path is determined based on the final adjacency matrix. This study have compared of "Betweenness centrality method" and multi-objective genetic algorithm (development of travel, determination of minimize number of sensor, location and detection time.	$g_{i_s i_t}$= denotes the number of shortest paths between nodes i_s and i_t. $g_{i_s i_m i_t}$= represents the number of shortest path on which node i_m is positioned.

In specific, some metrics were computed starting from the network graph and adjacent matrix, some of this are compiled in the Table 5: the **Average degree** Costa et al. (2007) average value of node degree distribution, provides immediate information on the organization of the network, representing the total number of "connections" that the network has on average; the **Density** (Jamakovic and Uhlig, 2007) measures how many edges are in the set E compared to the maximum possible number of edges between vertices in set V, it provides information about the general level of connection between the nodes of a graph in terms of "inclusivity"; the **Clustering coefficient** (Wasserman and Faust, 1994) measures the average probability that two neighbors of a vertex are themselves neighbors, in other terms, it provides the presence of a high number of triangles and the relative number of transitive triples, i.e. the fraction of connected triples of nodes which also form triangles measuring the fraction between the total triangles and the total connected triples; the **Meshedness coefficient** (Buhl et al., 2004) is the fraction between the total and the maximum number of independent loops in planar graphs for a single connected component; for WDNs; paths between tanks and resource nodes should be considered as well (pseudo-loops). Finally, the **Average Path Length** (Costa et al., 2007), starting from the distance between two any nodes i_s and i_t, defined as the number of edges along the shortest path connecting them, measures the mean distance between two nodes, averaged over all pairs of nodes.

These types of indicators have been intensely used like as indicators of the networks resilience. In this sense, Yazdani et al. (2011) have explored a suite of WDS expansion strategies (branched, looped, extra-lopped and perfect-mesh) and the effects of these expansions in the resilience of the evaluated networks. Oversimplification of WDS in abstract graph models is extremely useful but is far from sufficient for a comprehensive assessment of system resilience, as conclude (Yazdani et al., 2011) in his work. There are some other studies that include these kinds of indicators for interdependences of critical networks (for instance, Pinnaka et al., 2015). Several authors argue in their works that the graph-based indicators approach cannot satisfy a network redundancy analysis and some other complementary metrics (e.g. energy-based metrics) are needed (Di Nardo et al., 2017). Thereby, some types of resilience metrics such as hybrid approaches have emerged (for instance, Herrera et al., 2015b). Hybrid approaches for assessing the hydraulic resilience together with graph theory-based measures are proposed by Herrera et al. (2016b) and Herrera et al. (2015b), 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. (2016a), where the assessing of the resilience for WDSs is proposed through a topological perspective where properties such as network configuration and redundancy in connectivity are considered together with physical-based flow properties.

Supported by graph theory, Deuerlein (2008) 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 WDS analysis including reliability analysis (Deuerlein et al., 2009).

2.5 Time-based indicators

As the ResiWater Project moved on, and the knowledge about the concept of resilience – it was clear that such a broad theme had to be confined with focus on a characteristic; this characteristic was time. In ResiWater project, following the definitions of the Deliverable 1.1, resilience was immediately defined as a dimension strongly connected with time.

Obviously, each indicator can be placed in a certain time step of the disruptive event, for example an indicator could describe the system performance before, or after an incident takes place; the contribution in section 2.1 are explicitly linked with the different times that occur throughout the whole event, so that they can provide a better overview of the different factor that come in play (for example the severity of the incident and the resilience actions). Compared to this time-dependent approach, we could almost say that the other indicators describe the system resilience "statically".

Table 6: Time – based indicators.

Metric	**Formula**	**Definition**	**Remarks/parameters**
Resilience (Henry and Ramirez-Marquez, 2012)	$R_F(t_r\|e_j) = \dfrac{F(t_r\|e_j) - F(t_{deg}\|e_j)}{F(t_0) - F(t_{deg}\|e_j)}$ $\forall\ e_j \in \Sigma_e$	Index true to original meaning of resilience Key parameters: disruptive events, component restoration, overall resilience strategy	$R_F(t_r\|e_j)$ = portion of delivery function that has been recovered from the disruptive event; $F(t_r\|e_j)$ = functionality during the disruptive event; $F(t_{deg}\|e_j)$ = functionality at degradation time. $F(t_0)$ = functionality at the normal operating conditions; t_0 = starting time of the observation; $t_r \in (t_{deg,}t_{end})$ = time during the disruptive event; Σ_e = set of disruptive events.
Resilience (Ayubb, 2013)	$R_e = \dfrac{T_i + F\Delta T_f + R\Delta T_r}{T_i + \Delta T_f + \Delta T_r}$ $F = \dfrac{\int_{t_i}^{t_f} f dt}{\int_{t_i}^{t_f} P dt}$ $R = \dfrac{\int_{t_f}^{t_r} r dt}{\int_{t_f}^{t_r} P dt}$	Strongly connected with risk management Methods for valuation and benefit-cost analysis are provided	Failure and recovery profiles introduced; R_e = resilience; t_{event} = time to incident, F = failure event, ΔT_f = duration of the failure event, ΔT_r = duration of the recovery event R = Recovery event ΔT_r = Duration of the recovery event P = system performance, t_f = time at which the failure event ends; t_r = time when the recovery ends, r , f = recovery and failure profiles.

2.6 Sensitivities-based indicators

Another interesting point of view for resilience assessment is the exploration through different network sensitivity matrices that characterize the structural system properties (for instance, adjacency matrix, incidence matrix and loops matrices). Sensitivity coefficients give additional information of how much decision variables, such as pressures and flow rates, will vary locally to changes in the boundary conditions. They come back making affine approximations of the system behavior. They may be explicitly worked out (see, Piller et al., 2017) from one network model hydraulic simulation. As it is a simpler way than using the full model, some theory graph-based and sensitivity resilience indicators were used in this type of exploration. In this regard, the parameters vary systematically by statistical, spectral or another criterion (e.g. normal distributions). Subsequently, the networks resilience is quantify and tailored in ranges (maximum and minimum ranges). Some examples of this kind of resilience quantification are compiled in Table 7.

Table 7: Sensitivities – based indicators.

Metric	**Reference**	**Seeks**	**Parameter of performance/Stage performance**
SATS[5]	(Deuerlein et al., 2017)	Obtained the sensitivities of the supernodes of a network graph, which are crossroad critical nodes in the core.	Quantity (absorptive stage).
SAARI[6]	(Izquierdo et al., 2008)	Relative importance of pipes. Contemplated uncertainty of the data. Mathematical model, steady state. Results a fuzzy estimated state of the network.	Quantity (absorptive stage)
Sensitivity of flow direction	(Yoo et al., 2015)	Different water demands in the nodes and the corresponding changes in-pipe flow directions are considered in this study. Uses of graph theory/social networks (betweenness centrality), random nodal demand generation (normal distribution).	Quality (general)

[5] SATS: Sensitivity analysis of topological subgraphs.
[6] SAARI: Sensitivity analysis to assess the relative importance of pipes.

2.7 Other indicators

Finally, a brief list of other resilience indicators that might be useful in the resilience studies is presented in Table 8.

Table 8: Others resilience indicators.

Metric	Reference	Seeks	Remarks
Reserve capacity	Indicator based on reserve capacity. (Wright et al., 2015)	- Indicators adapted from transport networks.	- Critical link analysis (absorptive) quantity. - Consideration of multi-feed (multi-source) systems. - Hydraulic model approach: DDM.
Expansion rate	Indicator based on network capacity. (Ilaya-Ayza et al., 2016).	- Indicator, used to explore the process of the network capacity by replacing pipes.	- (restorative), quantity. - Theoretical maxflow indicator (Q_{maxt}) is determined by the intersection of the setting curve and the supply curve. - Include: cost of replacing a pipe j, component pipes. Diameter and length are considered as well.

3 DEVELOPING METRICS FOR WDS RESILIENCE

Resilience is a topic of interest for the urban cities, as they consider the complex risk from natural disasters, terrorism, aging infrastructure, and climate change faced by the transmission, storage, and distribution systems for WDSs. If WDS infrastructure is to become more resilient, better use of metrics will be crucial to guiding planning and evaluating progress.

The indicators proposed in this document in order to assess the networks resilience are based on the ResiWater project framework. These indicators are based in the first instance on the quantity of water supplied to the consumer by system. The main objective of the proposed indicators is to provide to the WDS managers with comprehensive assessment of the network´s behavior and in addition to prepare the utilities to cope the emergency cases.

The indicators proposed in this Deliverable suggest three recommendations that could improve the metrics available in the literature review to support the water distribution management.

To do this, the following three propositions have been made: 1) analysis of the three stages of resilience in WDSs, 2) critical analysis for networks of the WDS, and 3) demand peak compensation. These three proposals are detailed below.

3.1 Three resilience stages analysis and power based indicators

The first indicator proposed in this document was developed in terms of the time when the disruptive event occurs and its consequence in the networks. This indicator attempts to assess the network resilience, considering the time when the event occurs and the sequence of the events, the type of hydraulic model, the system performance state and the use of the resilience power-based indicators. In general terms and like as we understand in this proposal (and in general in Deliverable 5.2), resilience of water distribution systems 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. In the context of critical infrastructures, resilience can be developed by focusing on the different stages of the performance following a disturbance (also called resilience curve), and devising strategies and improvements which strength in the system response. The framework of this proposal is based on the Franco-German ResiWater Project, where the notion of resilience attempts to develop tools in order to prepare water utilities for crisis (Deliverable 1). The theoretical framework to assess resilience by proposal 1 is presented in Figure 4.

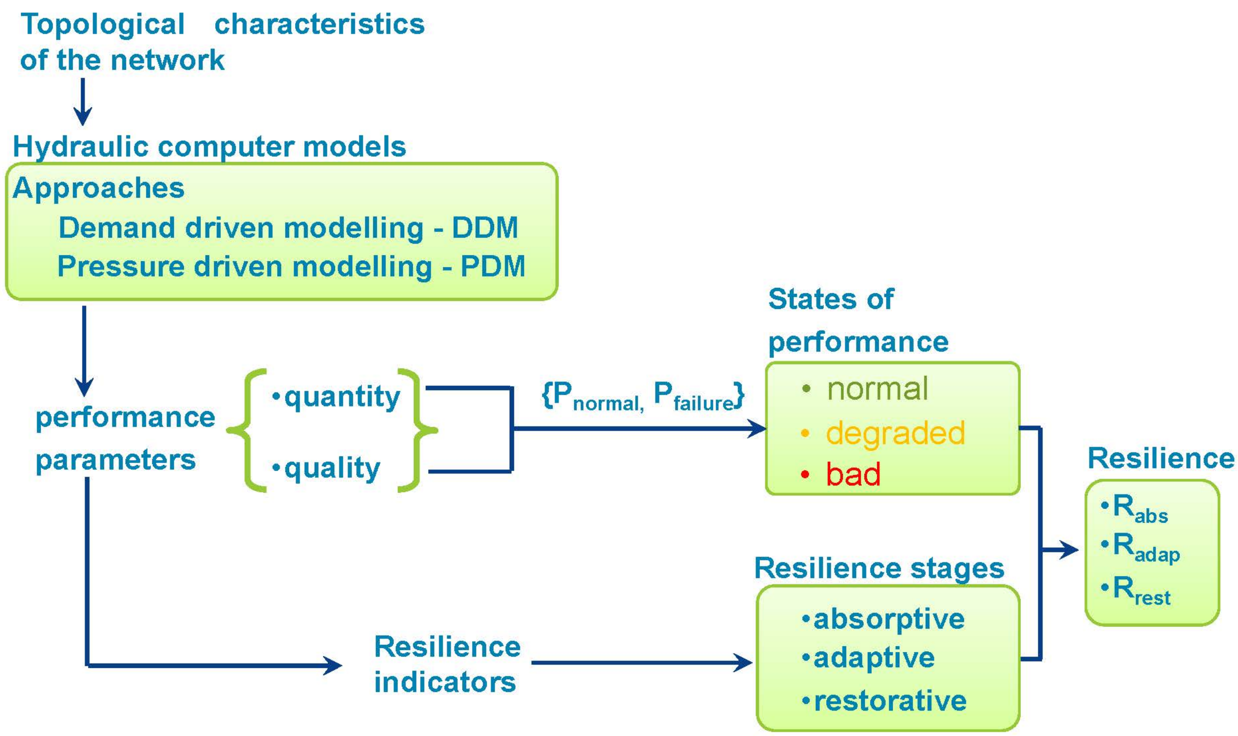


Figure 4: Theoretical framework to assess resilience – Quantity; proposal 1.
Source: (Ayala-Cabrera et al., 2017b)

We have mentioned that a preliminary version of this approach was presented in the congress 10th World Congress of EWRA - On Water Resources and Environment, "Panta Rhei", Athens (Greece). Then, another extension of the approach will be publishing in Special Issue of the "Water Utility Journal". The abstract and conclusion, of this approach are presented as follow.

- **Abstract.** The main objective of a water distribution system (WDS) 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 WDS 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 WDSs 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, modelers, and managers with structured tools, which allow a comprehensive analysis of crisis management case studies in order to enhance the WDS 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.

- **Case study, results and discussion.** The study of the resilience that is applied in this proposal is based on the three stages of resilience. For demonstration, a hypothetical benchmark network was used. The network is composed of two reservoirs, twenty-five water demand nodes and forty pipes (Figure 5.a). The Figure 5.b shows for all tested periods how the head pressure at each node is increased 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 the same way, we can observe (graphically) that in both cases, the obtained curve presents a strong correlation with the inverse of the demand patterns for each node (Figure 5.c).
  In Figure 5.b, it can be observed that the maximum effect of failure at any individual system component, namely pipe (isolation) or tank (minimum level), is in the absorptive stage. The situation is worse for periods of high demand (periods 7 and 8). Similarly, Figure 5.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.

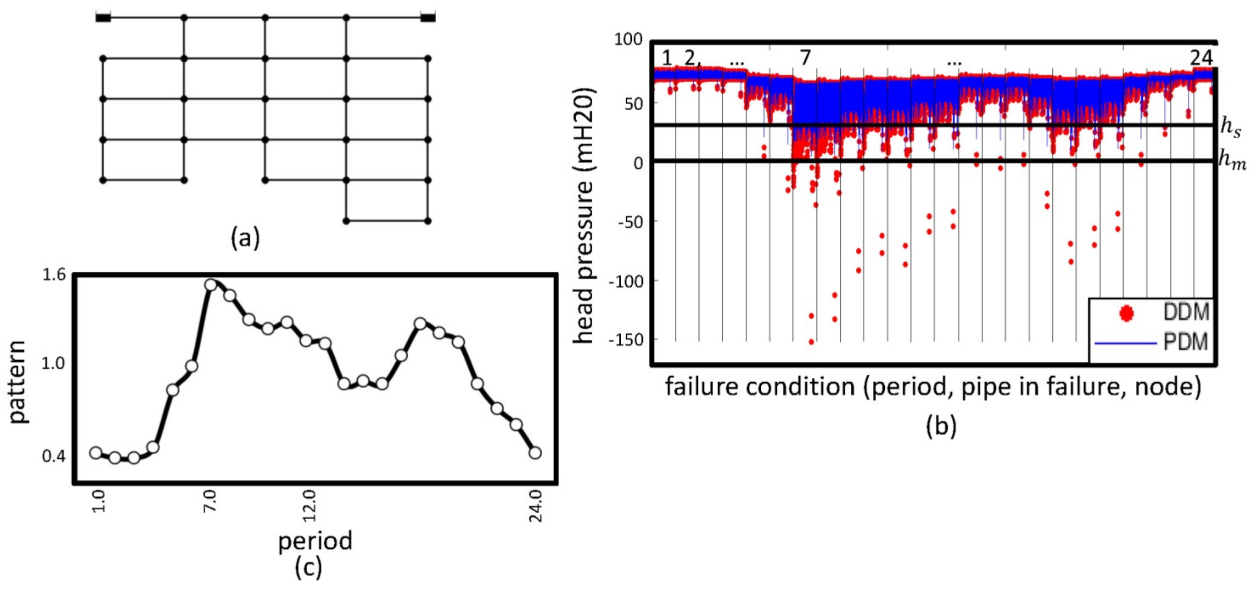


Figure 5: Pipe characteristics and head pressure results. – Proposal 1.
(a) Network layout; (b) single pipe failure condition for all periods; and (c) demand pattern.
Source: (Ayala-Cabrera et al., 2017b)

In this proposal, we applied the resilience index (I_r) by Todini (2000) and its generalization (I_{RC}), by Creaco et al. (2016b) (see Table 2). The interest of the application of these two indicators in this proposal (and in general for the Deliverable 5.2.) 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.

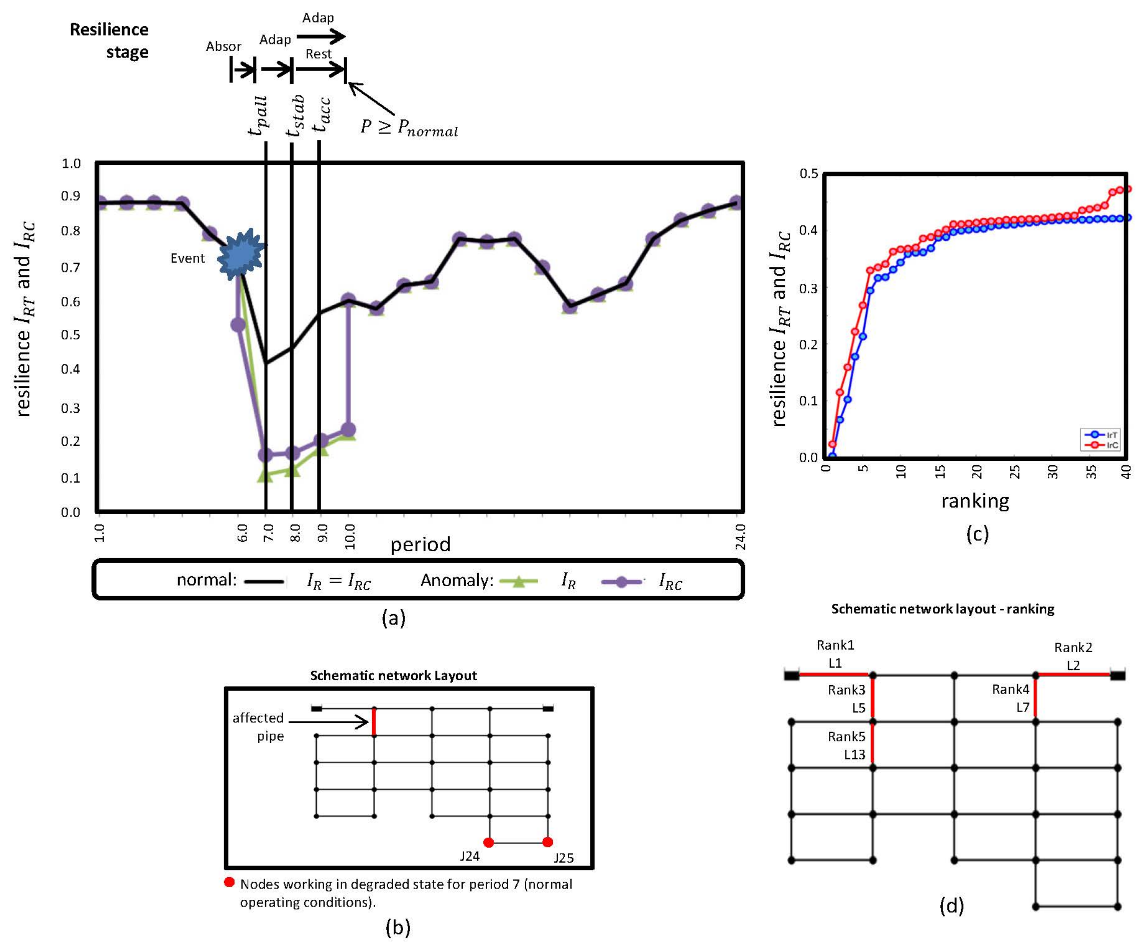


Figure 6: Analysis through resilience indicators. – Proposal 1.
(a) Resilience stages; (b) network layout – stages; (c) ranking of pipe – peak demand period; and (d) network layout – ranking. Source: (Ayala-Cabrera et al., 2017b)

Figure 6.a shows how the internal system vulnerability at the absorptive stage evolves within the adaptive time. The resilience indicators become more relevant by ranking the system vulnerability for each component of interest (Figure 6.c). These rankings allow to subsequently implementing actions enhancing system resilience. The aim of the three-stage resilience is to catch both of the applied indicators in this case. This allows evaluating the sequence of events and effects of any possible action implemented (at each stage). The

assessment also depends on the simulation model, as it can be seen at I_{RC} indicator, as the system has self-regulation ability.

- **Conclusions.** Some resilience key performance indicators on power/energy nature were applied on a case study from the literature. The results have shown the importance of applying different measures for the three resilience stages that enable to quantify network changes under stress conditions. The study highlights using tools that allows better understanding of the network performance facing different disruptive events. This is the case of the application of hydraulic models under the PDM approach, in comparison with the DDM approach. Providing this information to WDS managers allow them to implement actions to prevent catastrophic effects on water networks.

This work attempted to exemplify the network resilience, the proposed approach is based on event-driven approach and here are considering the time when the event occurs and its developed, the sequence of the events, the type of the approach (PDM or DDM) used in the hydraulic model, the system performance state and the uses of new resilience power-based indicators. The results are promising so that detailed information for the WDS managers can be provided in order to implement actions in face to prevent catastrophic effects on the network. Since other performance characteristics such as quality, their impact can be studied and quantified under disruptive events under the approach presented in this document. Although the indicators applied (power-based indicators) have shown good results, it is of main interest to analyze other indicators such as those based on mixing graph theory and hydraulic parameters (Herrera et al., 2016a) to then expand the current proposal to deal with even more aspects of the water network.

3.2 Criticality indicator for resilience analysis through demand satisfaction indicator

The second proposed indicator attempts to explore consequences of pipe failures into the system performance. The anomalous events consists of pipe bursts followed by two subsequently isolation actions for affected pipes in the network. 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 WDSs and also compared to normal operating conditions regarding the satisfaction rate of nodal demands.

The schematic proposed configuration in order to assess criticality by WDSs networks in the second proposal is presented in Figure 7.

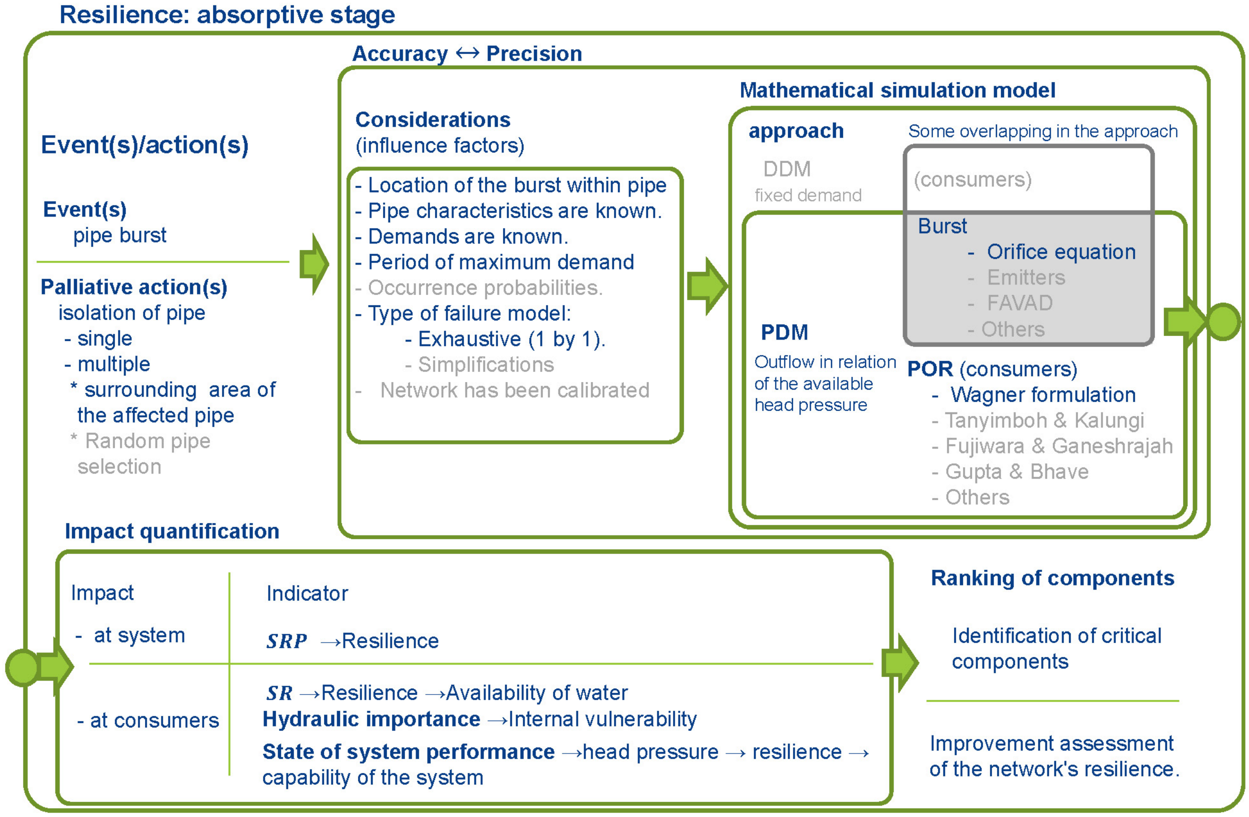
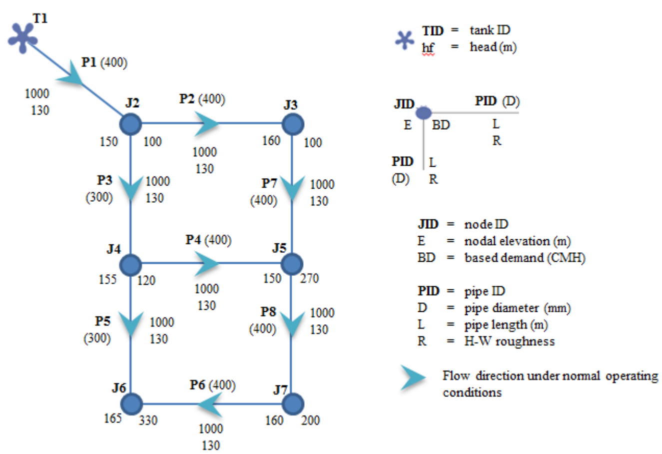


Figure 7: Theoretical framework to assess criticality – Quantity; proposal 2.
Source: (Ayala-Cabrera et al., 2017a)

We have mentioned that a preliminary version of this approach was presented in the congress on Numerical Methods in Engineering - CMN2017, Valencia (Spain). The abstract and conclusion, of this approach are presented as follow.

- **Abstract.** Water distribution systems (WDSs) are one of the most important urban complex infrastructures, which provide an essential resource for life. Therefore, ensuring resilience and safety for WDSs are big concerns for water utilities. WDSs 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 WDS 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 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 WDSs and also compared to normal operating conditions regarding the satisfaction rate of nodal demands. The obtained results are promising in order to 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. The results of this study are presented, interpreted, analyzed and discussed in this paper.

- **Case study, results and discussion.** For this proposal, we have selected a simple benchmark network. The network is composed by 6 demands nodes, 8 pipes and 1 reservoir. The network layout configuration and the flow direction obtained through the simulations of the network under normal operating conditions are presented in Figure 8.



pipe	Initial point (assoc. node)	terminal point (assoc. node)
P1	T1	J2
P2	J2	J3
P3	J2	J4
P4	J4	J5
P5	J4	J6
P6	J7	J6
P7	J3	J5
P8	J5	J7

Figure 8: Case study – Proposal 2.
(a) Network layout; and (b) Burst position – List of flow direction.
Source: (Ayala-Cabrera et al., 2017a)

The mainly results obtained with this proposal are presented in Figure 9 and Figure 10.

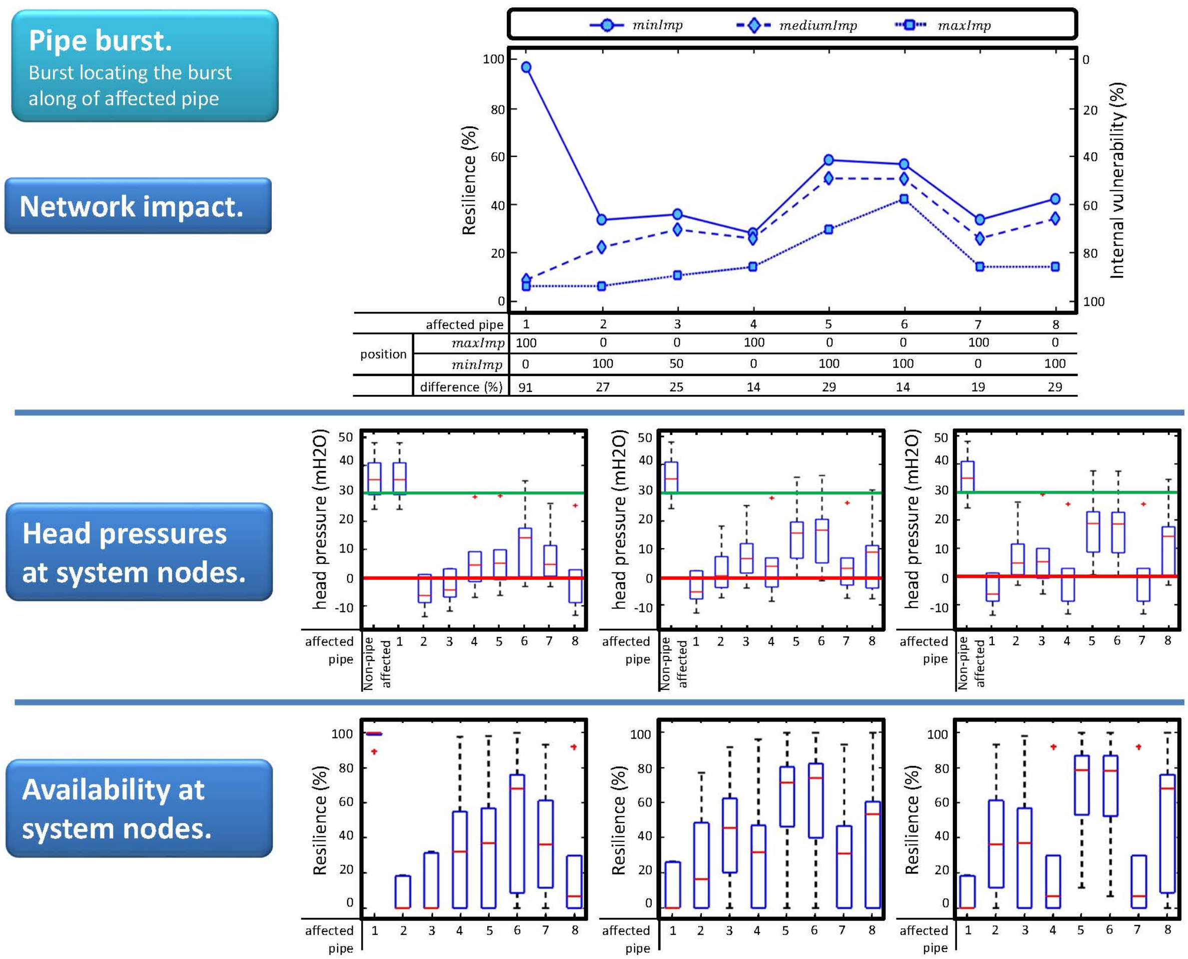


Figure 9: Pipe burst; Results – Proposal 2.
Source: (Ayala-Cabrera et al., 2017a)

Figure 9 reveals the importance of considering the location of the burst-event along the pipe in resilience assesses. Figure 9 shows a considerable difference in the impact (at entire system) for each pipe, due to location of the burst-event (along the pipe). As consequence of the pipe burst, a considerable decreasing in the state of the system performance is observed in Figure 9. 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.

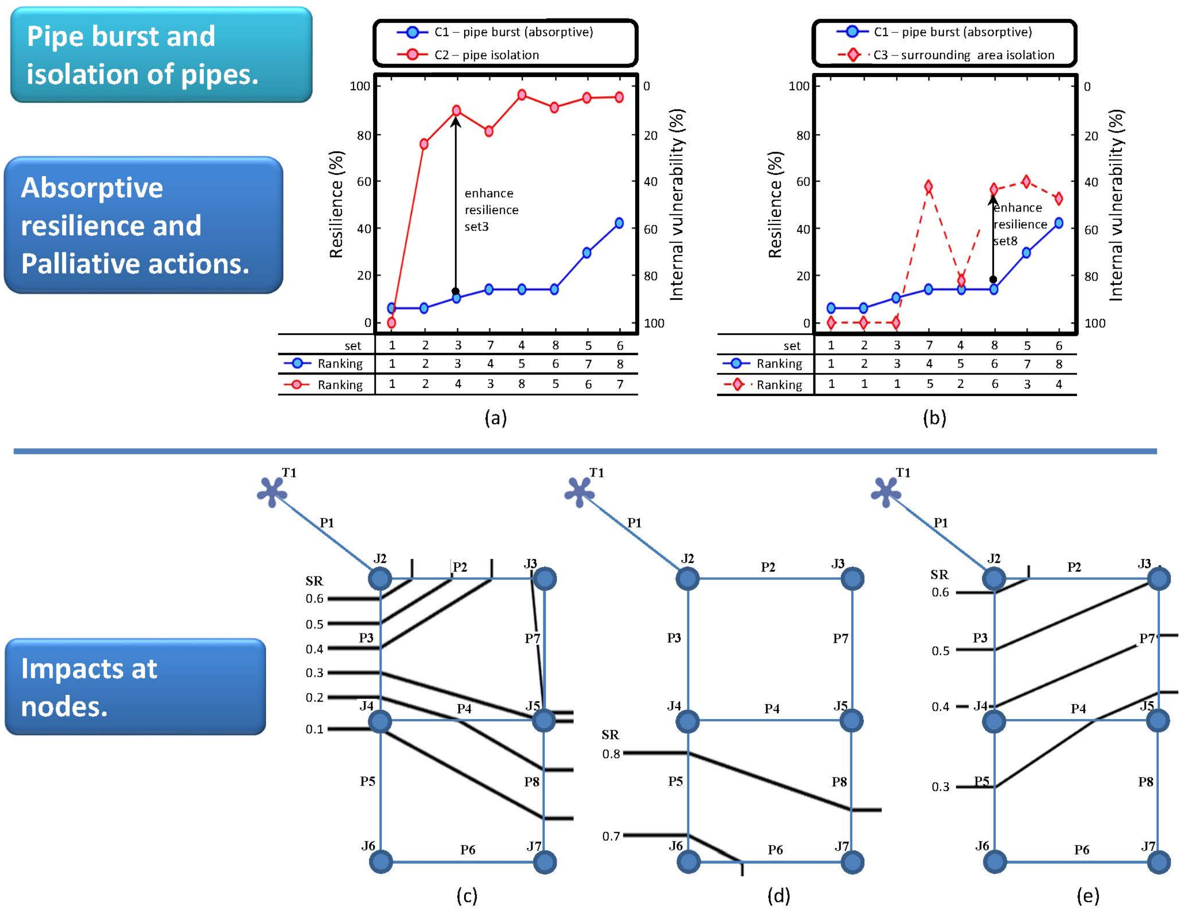


Figure 10: Pipe burst and isolation of the affected pipe – Proposal 2.
(a) and (b) Impact of the failure (hydraulic importance); (a) pipe burst and single isolation; and (b) pipe burst and isolation of surrounding affected area. (c), (d) and (e) SR isoclines; (c) pipe burst, (d) pipe isolation, and (e) isolation of surrounding affected area. Source: (Ayala-Cabrera et al., 2017b)

As we can observe in Figure 10, 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 each pipe. The indicator applied in Figure 10, 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 10 shows 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).

- **Conclusions.** The consumer demand satisfaction was applied on a simple example. By virtue of the hydraulic model used (PDM approach), the resilience indicator accounts for both the structure of the network and also the energy 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 link 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 the leakage in the affected link. 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.

This work attempted to evaluate the network resilience when it is working under critical operative conditions due to pipe burst-event. The proposed approach is based on event-driven approach and here are considering the relevance of the burst location along the pipe, the effectiveness of the palliative actions, the absorptive stage of the network (absorptive resilience), the approach used in the hydraulic model (PDM), the system performance state and the uses of classical resilience performance-based indicators.

3.3 Time-dependent indices and demand peak compensation

From the results of the literature review and in particular from the concept of time-dependent resilience and the performance indicators presented in sections 2.3 and 2.5, some indices are now proposed.
An important contribution for the creation of these indices comes from the PDM (pressure dependent modelling/method) theory that was presented and implemented within the ResiWater Project (Deliverable 4.1).
In particular, a system to identify the number of fully- and under-supplied demand nodes, using different indicators (I_U, I_A, I_L) was presented (Deliverable 4.1, section 4.2.3 Algorithm).

The first index SI (Supply Index) describes the ratio between the fully supplied nodes over the total number of the demand nodes, for a certain time step in case of non-stationary scenarios:

$$SI(t) = \frac{I_U^T I_U}{\text{n}^\circ}(t) \in [0;1]$$

With:
n° = total number of demand nodes;
I_U = Index vector of fully supplied nodes;
t = time step.

Although $SI(t)$ gives an immediate feeling of the system performance in terms of satisfied consumers, one should take into account that not all the customers, considered as singular demand nodes, can be treated as equal (for example, an under-supplied hospital is more vulnerable than an under-supplied single house). Therefore another more consistent and interesting index is introduced.

This index $SR(t)$(Supply Ratio) is the ratio between the resulting, reduced demand (due to PDM approach) D_{res} and the desired demand D_{des}, calculated again for a given time step:

$$SR(t) = \frac{D_{res}(t)}{D_{des}(t)} \in [0;1]$$

In this case, a more homogenous and weighted representation of the missing water to the customers is represented.

The index is similar to $SRP_{j,t}$ defined in Table 4. The difference is that is not exclusively related to pipe failures but calculated as a global performance indicator for all kind of scenarios. Since it is calculated for every time step in transient calculations it is a time dependent value. It can be applied also to fast transient calculations (water hammer). It has been shown in test calculations that the kind of modeling technique used can have an impact on the index. For example, water hammer events can lead to low pressure waves with the consequence that withdrawal is not possible or reduced at the side of the customers for a short period in time. However, this short time is a minor issue in contrast to other problem such as pollution due to low pressure. Therefore, the usage of the index is especially proposed for slow transient analysis

Although, $SI(t)$ and $SR(t)$ are time dependent indices, they still represent transient points of view of the system performance that does not consider the cumulative aspects of deficiencies
Nonetheless, from the suggested indices we were able to formulate an active resilience action: how can we meet the expected daily demand for each customer, for example, when PDM conditions arise?

We called this resilience action "**Demand Peak Compensation**" or "Deficit Function".
The idea behind is that, if for peak demand hours not all customers can be fully supplied during disruptive events, the deficit that builds up is shifted to later hours, thus, guaranteeing the delivery of the full daily demand, however, not to the usually desired time. This approach can be related to intermittent WDS that are in use for example in the developing countries.

The proposed method provides the deficit demand at successive time steps, when the network conditions allow to fulfill the desired demand (and the "missed" demand of the precedent times).
In the following, a pseudo-code is presented to better explain the computational steps that we developed:

$\boldsymbol{for}\ timestep = \mathbf{1}{:}\boldsymbol{T}$
$\quad D_{des} = Q_0 * LF(timestep);$
$\quad D_{new} = D_{des} + Dfct;$
$\quad PDM\ Solver(D_{new}) \rightarrow\ D_{res};$
$\quad Dfct = Dfct + (D_{des} - D_{res});$
$\boldsymbol{end}$

With:
Q_0 = base demand;
LF = load factor;
D_{des}= desired demand;
$Dfct$ = deficit demand;
D_{res}= resulting demand from PDM.

Given a network and a pre-defined daily demand pattern, the expected result is a curve, which is eventually flattened, compared to the starting one. The peaks are “cut down”. The missing water delivery is compensated during low demand hours.

Study case – simple Network.
The aforementioned resilience action was tested on a small network, the same used for the implementation of the PDM algorithm by 3S Consult (see Deliverable 4.1, paragraph 4.2.4).
As a recall, the network consists of a reservoir, 8 nodes and 10 pipes. To this network, a default daily demand curve was assigned (Figure 11).

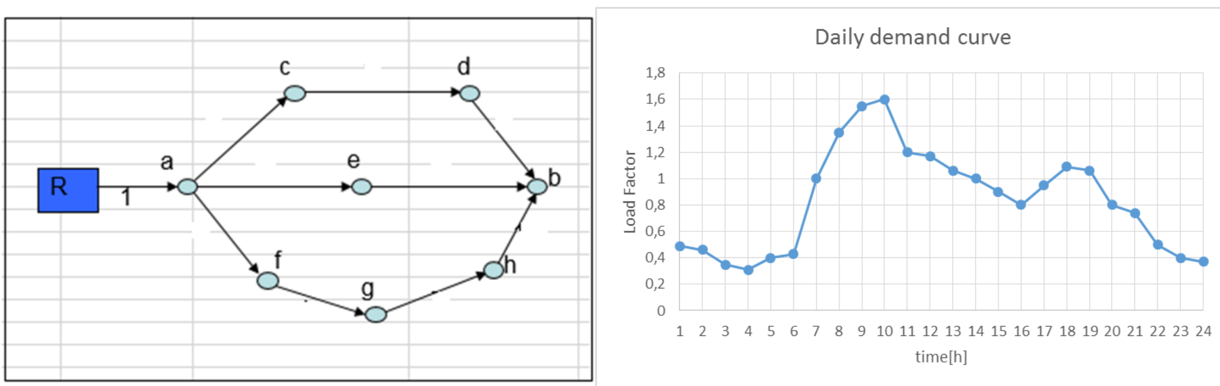


Figure 11: Test network (left) and daily demand curve (right).

Results and discussion
The results were significant for the nodes b, g and h, due to their base demand value and position in the network. In the Figure 12, the curves of desired demand (blue) and the calculated demand curve resulting from the demand peak compensation (red) are shown:

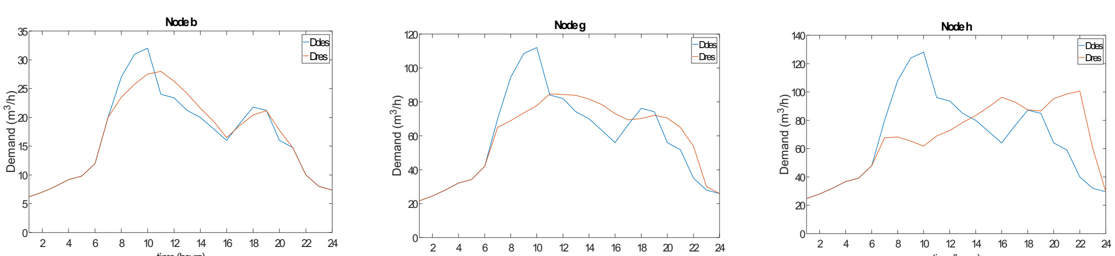


Figure 12: Desired demand vs. resulting demand for Node b, g and h.

Alongside the new demands curves, also the deficit function for the three nodes was plotted, both as a cumulative function (blue) and in dependency of time (red).

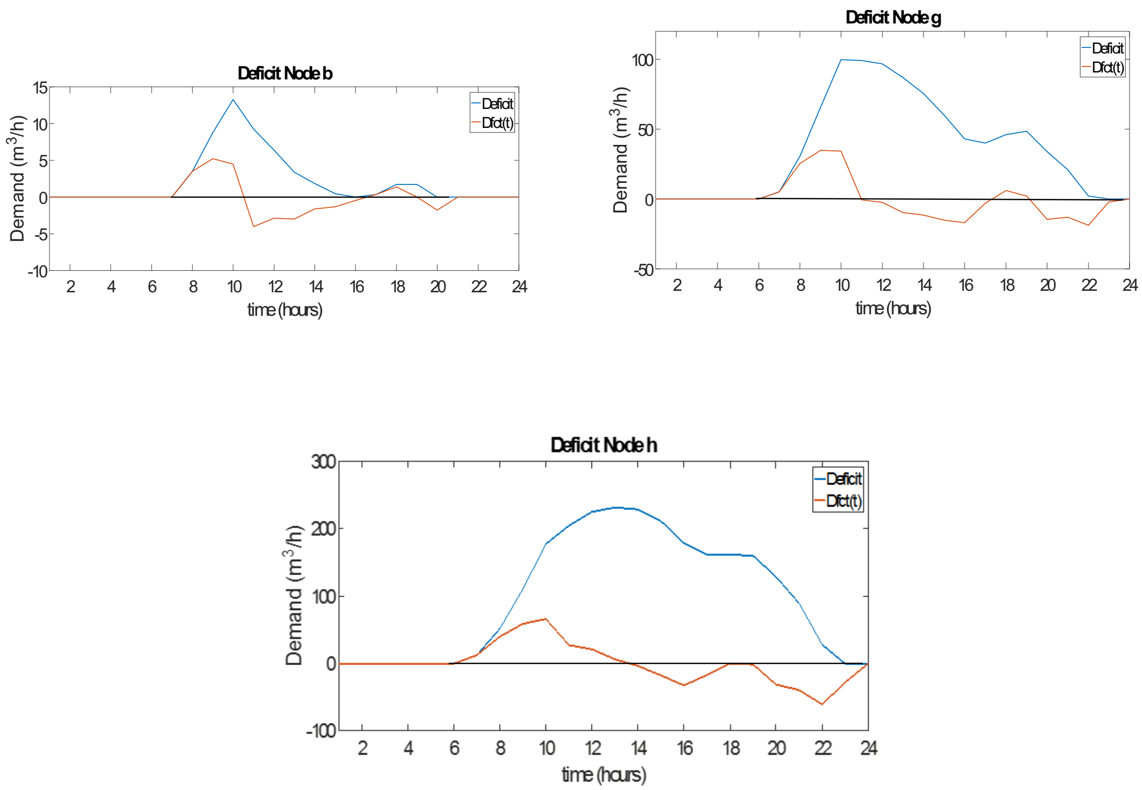


Figure 13: Deficit functions for Node b, g and h.

From the results of the cumulative deficit function, a further resilience index $DPCR$ (Demand Peak Compensation Resilience) could be defined, as the inverse of the time duration of insufficient supply:

$$DPCR = \frac{1}{\Delta t} \in [0; \infty)$$

Where Δt is the time interval from start of insufficient supply until demand deficit is zero. In contrast to the performance indices SI and SR the DPCR index can be understood as a resilience index since it refers to the ability of a system to recover from extreme situations and takes into account the time dependent nature of resilience. Similar to SR and SI it is not tailored for particular events such as pipe failures. In contrast, all three indices are suited for testing the performance of the system for different scenarios.

4 CONCLUSIONS AND NEXT STEPS

As far as WDS resilience is concerned, during this period a literature review of indicators was done. Several resilience indicators have been suggested to quantify connectivity, reliability, robustness, redundancy, and security for assessing WDSs resilience. Then using the indicators that have been collected in the literature review, we have generated a database of the given indicators to quantify the resilience of the WDSs under failure conditions. It should be mentioned that the database of the collected resilience indicators (provided by the literature review), is in continuous updating throughout the duration of the ResiWater project. The implementation of the mentioned indicators within the proposed model has been carried out in gradual manner because this procedure has been done as the network resilience approach has been extended. A first classification based on the ResiWater project approach for assessing the network resilience has been made.

This work attempted to exemplify the network resilience, considering the time when the event occurs and the sequence of the events, the type of the approach (PDM or DDM) used in the hydraulic model, the system performance state and the uses of new resilience power-based indicators. A second work attempts to quantify the importance of the WDS components and the impact on the consumers that its failures can generate (this through the uses of resilience indicators).

Finally the third proposition is linked with the time concept, in complement to event-driven, both in a static and dynamic ways. A set of three resilience indices has been presented, with included an active resilient action, which eventually, will be further implemented/improved.

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