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An approach to measuring resilience to manage water supply systems

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Abstract: Water supply systems are exposed to events that affect the normal service provision. Water companies should follow their own policy rules to manage and overcome these types of threats. In this article, resilience is identified as the capacities of the system to delimit the impacts of hazardous event, which may be characterized by its severity and duration. The effects of disruptive events to the water service delivery are classified into water scarcity, discontinuity of water supply, discontinuity of hydraulic conditions and discontinuity of drinking water quality. The loss of service level is established by failure thresholds named as a standard level, a normative level, an accepted level and a critical level. The global model defined by the loss of service and time is used to measure resilience by means of a resilience factor. The methodology is applied to a complex real-life system, managed by Canal de Isabel II Gestión (Spain) for a drought, pipe breaks and water quality failures. Real data allow contrasting the protocols of management established by the water company. The methodology helps water utilities update their protocols for a certain hazard and provide useful information to plan their investments in order to improve the system resilience.

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1. Introduction

The concept of resilience is being used in a great range of discipline areas, such as sociology, psychology, economics, science, business, civil engineering and security, among others [1-3]. Society is concerned about the existence and the importance of this concept, though it has different understandings. Communities are exposed to disruptive events, including natural disasters (droughts, floods, earthquakes, hurricanes, tornados, tsunamis, wildfires, and winter storms), and cyber and terrorist attacks, as well as to climate change, traditional threats and manmade accidents. It is necessary to face and overcome these hazards and develop resilient systems to ensure continuous service. Some authors considers resilience as the ability to prepare for and adapt to changing conditions and withstand and recovery from disruptions [4], while others only focus on the ability of a system to bounce back from an unforeseen event [1]. In this article resilience is presented for water supply systems as the response capacity of a system in the face of a disruptive event.

Some index has been presented in order to establish a measure of Resilience. The Argonne National Laboratory Resilience Index uses a great number of variables to measure the resilience of drinking water system [5]. This index considers preparedness, mitigation measures, response capabilities and recovery mechanisms. Todoni [6] explains that, in water supply systems, failures or modified and increased demand conditions increase the internal energy dissipation, and if a surplus of energy is not available, there is a failure in the delivery. The author defines resilience as the capability of the designed system to react and overcome stress conditions, as well as describes that an increase in resilience mean a decrease of the internal energy dissipation. The resilience index of Todoni compares the amount of power dissipated in the network to satisfy the total demand and the maximum power that would be dissipated internally to satisfy constrains of demand and head. This resilience index is analysed by other authors [7] as a measure of the capability of the water distribution network to cope with failures. However, this index only considers the flux of energy.

The National Infrastructure Advisory Council defines infrastructure resilience as the ability to reduce the magnitude and/or duration of disruptive events [8]. Tierney & Bruneau [2] explain that resilience may be measured by the functionality of an infrastructure system after a disaster and also by the time it takes for a system to return to its previous level of performance. A similar interpretation is found in the literature [9-10], where resilience is represented as a combination of survivability and recoverability [11]. As may be seen, it is emphasized the importance of including time when resilience is being defined [12]. Henry and Ramirez-Marquez [11] describe a delivery function to evaluate the performance of a system at a specific time. They define resilience at time t as the ratio of recovery at this time to loss suffered by the system at a previous time. Baker et al. [13] adds the concepts of reliability, vulnerability, survivability and recoverability to the delivery function-time figure described in [1]. They also consider time to recover as a stochastic variable. Francis and Bekera [14] propose a metric to quantify resilience that incorporates resilience capacities (absorptive and adaptive capacity and recoverability). The Department of Homeland Security: Science and Technology Directorate [15] presents a resilience model ("bathtub" shape) to describe the behaviour of the system after being impacted. The total area within the resilience profile is used to compare the resilience levels, measured in performance-time units. They also include four profile types to classify the systems from high to low resilient. It should be noted that the calculation of an area in a resilience model allow comparing different systems and reaching to the conclusion that a system is resilient. Diverse interpretations of resilience lead to the need of a standard and measurable definition. In addition, system managers want to establish performance standards and resilience standards of the system.

In the article, a resilience model for water supply systems is proposed and a metric named as resilience factor is presented. It considers loss of service and time. Resilience standards are defined from the point of view of the service disruption to the end user. Well-defined levels of service allow the establishment of failure thresholds: (1) a standard level, (2) a normative level, (3) an accepted level, and (4) a critical level. It is also considered different types of threats: (A) water scarcity, (B) water supply discontinuity, (C) discontinuity of hydraulic conditions and (D) discontinuity of drinking water quality conditions. The main objectives of this article consist of setting a definition of resilience for a whole supply and distribution system, proposing the need of rising different types of resiliencies and measuring these resiliencies. The methodology is applied to a complex real-life system, which is the water supply system of the Autonomous Region of Madrid (Spain) managed by Canal de Isabel II Gestión water utility. The study cases are a drought event, several pipe breaks and water quality failures. The obtained resilience is contrasted with real data.

2. Methodology

In water supply systems, it is possible to distinguish if the system is under normal service or in the aftermath of a disruptive event. When a hazard occurs, the system responds with its absorption and adaptation capacity. Hazards have different nature, duration and severity, and are linked to specific consequences. In this article, resilience is presented as the capacities of the system to guarantee that the consequences of a hazardous event are limited. In general, end users are satisfied if the water is continuously supplied, under satisfactory pressure conditions, with good quality and enough quantity. As a result, the following types of consequences due to disruptive events are considered, as they affect water service provision in water supply systems: A) water scarcity, (B) water supply discontinuity, (C) discontinuity of hydraulic conditions and (D) discontinuity of drinking water quality conditions. In a water supply system, threats may be assessed independently or in conjunction. In the type of threat A, a drought should be analysed as an episode. In the type of threat B, pipe breaks may be studied as a simple disruptive event or a set of them (sum of pipe breaks over a year). In this article, each threat is independently considered. In addition, episodes may have different origins: fortuitous, natural or caused.

Protocols, resources and technologies used in water supply systems help to define and satisfy different levels of service, both under normal conditions and after a hazardous event. Protocols mean the detailed sequence of actions or processes followed by the company to cope with the normal operation of the system. Protocols influence the response capability of the system. Water utilities also have their effective technology and available resources to overcome in the day-to-day operation. Therefore, harms and the set of protocols, resources and technologies are linked to each hazardous event. Consequences or harms are measured by the loss of service level. The estimation of the loss of service level is based on historical data. It is necessary to fit a set of reference thresholds of service level in order to calculate the resilience of the system. Different levels of services under anomalies correspond to the following failure thresholds: (1) a standard level that explains when a failure starts, (2) a normative level applicable to failure scenarios and defined by a law or contractual plan, (3) an accepted level allowed by end-users, and (4) a critical level under which the system is not able to be elastically recovered. These thresholds allow formulating management actions at different stages to reach the standard level of service that identifies when the systems returns to normal conditions.

Under anomalies, a quantitative metric to measure resilience is proposed. A general model is presented in Figure 1 a). The x-axis represents time and the y-axis, the service level. The service function describes the performance of the system, also over the disruption period. The model shown in Figure 1 c) has been modified in a great manner by the protocols that may be followed by the water company, as well as the resources and technologies. Resilience is measured by the integral of a product of two parameters: loss of service level and time (Figure 1 b) and d)). The general analysis procedure to calculate the resilience factor for a type of threat (for example, type A), based on Figure 1, is the following:

$$\left(R_{f_n}\right)_A = \left(R_{f_{n1}}\right)_A + \left(R_{f_{n2}}\right)_A = \int_{t_{s_1}}^{t_{n_1}} \left(F_{s_A}(t) - F_A(t)\right) \bullet dt + \int_{t_{n_2}}^{t_{s_2}} \left(F_{s_A}(t) - F_A(t)\right) \bullet dt \quad (1)$$

$$\left(R_{f_a}\right)_A = \left(R_{f_{a1}}\right)_A + \left(R_{f_{a2}}\right)_A = \int_{t_{n_1}}^{t_{a_1}} \left(F_{n_A}(t) - F_A(t)\right) \bullet dt + \int_{t_{a_2}}^{t_{n_2}} \left(F_{n_A}(t) - F_A(t)\right) \bullet dt \quad (2)$$

$$\left(R_{f_c}\right)_A = \int_{t_{a_1}}^{t_{a_2}} \left(F_{a_A}(t) - F_A(t)\right) \bullet dt \quad (3)$$

Where R_{f_n} is the normative resilience factor (sum of $R_{f_{n_1}}$ and $R_{f_{n_2}}$ in Figure 1), R_{f_a} is the accepted resilience factor ($R_{f_{a_1}}$ plus $R_{f_{a_2}}$ in Figure 1) and R_{f_c} is the critical resilience factor. F is the service function; F_s, the standard level; F_n, the normative level and F_a, the accepted level of service. The subscript A is referred to the type of threat A. This formulation is applicable to other cases. It is possible that a threat remains in the first level of severity. In this case, the normative resilience is the unique resilience factor that has to be calculated. It should be noted in Figure 1 that the service function in the original state when the threat occurs may be above the standard level (level 0 of severity). That is the reason why the service function may reach the standard level some time after the occurrence of the disruptive event. The instant of time where these two functions intersect (the service function and the standard level) may be defined by the variable t_{s_1}. In the same way, after recovery measures are taken, the service function intersects with the standard level at t_{s_2}. The recovery function represents how the service is being gradually recovered to reach at least the standard level of service. It should be mentioned that if the normal operation conditions when the hazard occurs were the conditions of the standard level, the time t_{s_1} would be the same point as the occurrence of the event, t_e. Similarly, if the normal operation conditions in the recovered state were coincident with the ones related to the standard level, the time t_{s_2} would be the same point as the final recovery time, t_f. The service function intersects with the normative level at t_{n_1} and t_{n_2}, and with the accepted level at t_{a_1} and t_{a_2}. The resilience factor for the type of threat A is obtained with the normative, accepted and critical resilience factor:

$$(R_f)_A = W_{n_A} \bullet (R_{f_n})_A + W_{a_A} \bullet (R_{f_a})_A + W_{c_A} \bullet (R_{f_c})_A \qquad (4)$$

Where W_{n_A}, W_{a_A} and W_{c_A} are specific weights for the type of threat A that multiply each partial resilience factor, which are calculated within a level of severity (level 1, 2 and 3, respectively). The specific weights have to be analysed in each case study, due to the fact that the measures that should be taken in each level of severity to recover the system have different impact on the end-user. The system resilience is the result of the sum of the resilience factors calculated for each type of threat that occurs at the same time in the water supply system. Specific weights (W) should be considered in order to aggregate the resilience factors. More research is needed in order to define quantitatively these specific weights. If four types of threats (A to D) occurred at the same time in the system, the resilience factor of the system would be:

$$R_f = (R_f)_A \cdot W_A + (R_f)_B \cdot W_B + (R_f)_C \cdot W_C + (R_f)_D \cdot W_D \qquad (5)$$

The global resilience factor, R_f, should integrate similar levels of severity in order to represent the society´s perception of failures. Thus, different weights should be used for each type of threat. Water utilities may use the resilience factor in order to know how they are prepared for certain hazardous events. When a water company contrast its system resilience (established by its protocols, technologies and resources) with real data related to a specific threat (defined by the loss of service level and time), managers may plan and focus their investments on investigation, planning, regulation, water quality monitoring, repairing, renewal, replacement, vigilance, security, civil infrastructure, construction of dams, enhancement and enlargement of reservoirs, etc. The lower the resilience factor is, the more resilient a system is considered. The comparison between different water companies is also possible, as long as the same levels of service are defined.

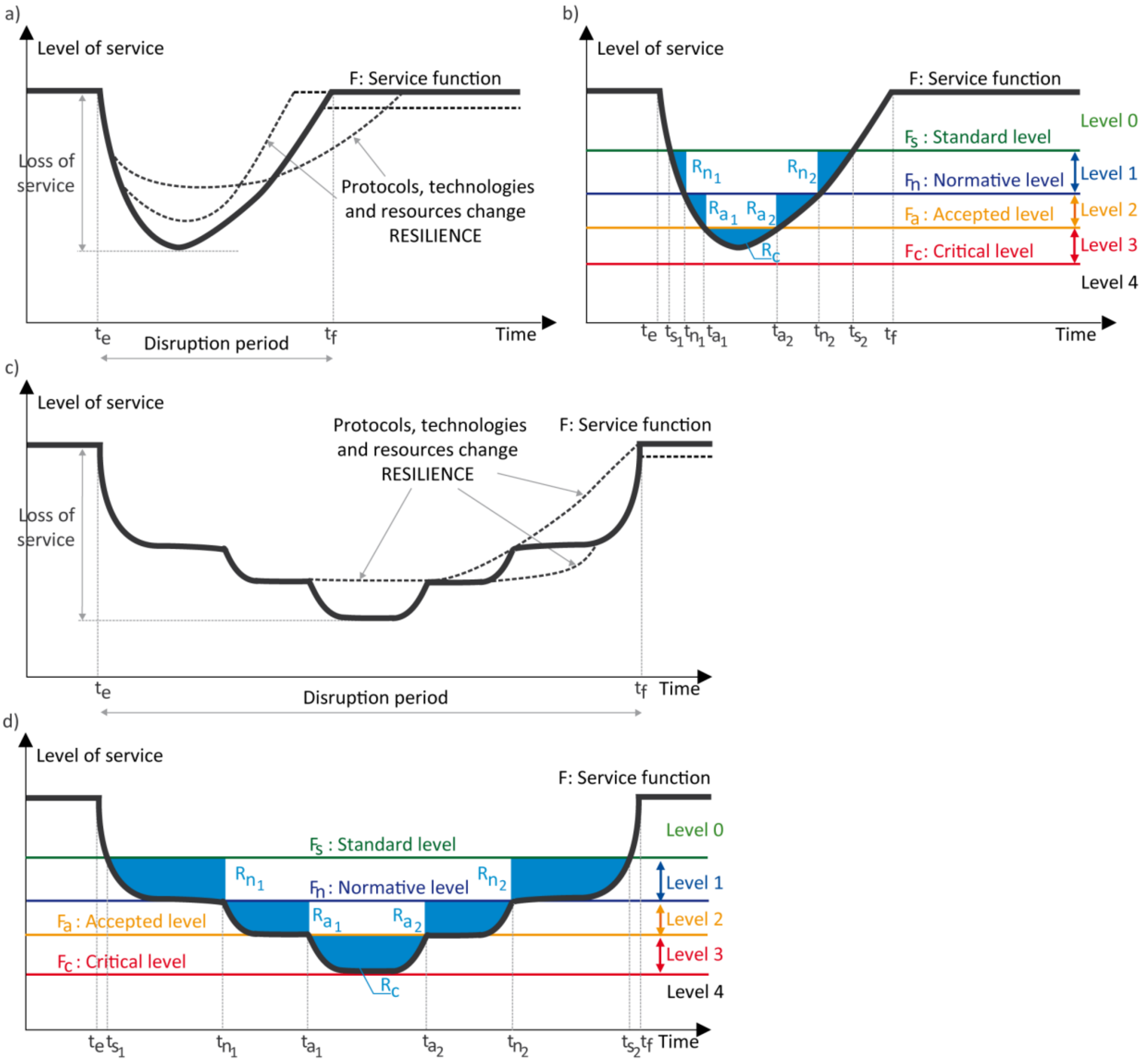

Figure 1. a) and c) Resilience models: levels of service and disruption time. b) and d) Calculation of the resilience factor. The level of service (standard level, normative level, accepted level and critical level) and the levels of severity (level 0, level 1, level 2, level 3 and level 4) are shown.

3. Case study

The characteristics of the water supply system of the Madrid Community (Spain) are presented in Figure 2. Canal the Isabel II Gestión is the water utility that supplies water to more than six million people in this region. The managed water supply system has more than 17,000 kilometres of main pipes, 321 water tanks, and about 760,000 service connections as well as 235,000 operational and control elements.

Several case studies are presented: a drought, pipe break and water quality failure. The water supply system of Madrid faced a drought between 2005 and 2006 that required specific actions to restrict the total expected demand. It was a drought of first degree of severity. The Spanish Decree 97/2005 was enacted the 29th September 2005 in order to establish exceptional measures to manage water supply in the region of Madrid, because a drought had been declared. Prior to this decree, in

July 2005, Canal Isabel II Gestión had founded a Drought Committee in May 2005, and had launched a campaign called "The challenge of water" addressed to end users, for the purpose of saving water. Another campaign with the same objective was launched in April 2006, and its name was "Madrid needs more water". Finally, the Decree 46/2006 of the 30th November 2006 repealed the exceptional measures to manage water supply in the Autonomous Community of Madrid. In this article, the system resilience is assessed for the explained episode.

The other case studies are pipe breaks and water quality failures. In the case of pipe breaks, the occurrence time starts when the water service provision is shut off, and the final recovery time is defined based on when the water service is restored. As for water quality failures, once it is confirmed that the drinking water quality conditions are not adequate, the time of occurrence is linked to the first complaint of an end-user. The final recovery time is coincident with the resolution time of the disruptive event.

4. Results and discussion

Protocols of the water company that manages the water supply system of the Autonomous Region of Madrid (Spain), considers different failure thresholds for a drought event according to the severity of the disruptive event: (1) in the standard level, the water company supplies water to the 100% of end-users; (2) in the normative level, the water supply should be reduced by 9.4% over a year; (3) in the accepted level, the water supply should be decreased in 26% over two years, and (4) in the critical level, the water supply should be reduced by 51.4% over a year [16]. In some way, the normative level is defined, so the normative resilience factor may be defined as:

$$\left(R_f\right)_{normative} = 9.4\% \bullet 12\, months = 112.8\% \bullet month = 9.4\% \bullet 1\, year = 9.4\% \bullet year \quad (6)$$

The normative resilience factor is represented in Figure 2, since the the day when the Decree 97/2005 was enacted to establish exceptional measures to manage water supply in Madrid, that is the 29th September 2005. The occurrence time of the disruption is equal to the initial intersection time, presented in Figure 1, $t_e = t_{i_1}$ (29 September 2005). In the first level of severity, the resilience factor is, in reality, less than the normative resilience factor. However, the company took actions to reach a water supply reduction of 9.4% over 12 months. The main actions consisted of changes in habits of end users related to water use.

The water supply over the disruption period has been compared to the water supply under normal conditions in order to contrast the management protocols of contingencies. In that way, it is possible to know if the water supply reached the established terms. Figure 2 shows the water supply both in case of disruption and in normal conditions. The normal water supply values in normal conditions are determined with data of previous years without failures, adapted to the real climatic conditions and prediction models. The water supply in normal conditions represents the standard level of service. The deviation from this level allows the assessment of the effectiveness of protocols. Specifically, the percentage of service reduction is calculated as follows:

$$\%Reducction = \frac{Watersupply\ in\ normal\ conditions - Watersupply\ under\ failure\ conditions}{Watersupply\ in\ normal\ conditions} \bullet 100 \quad (7)$$

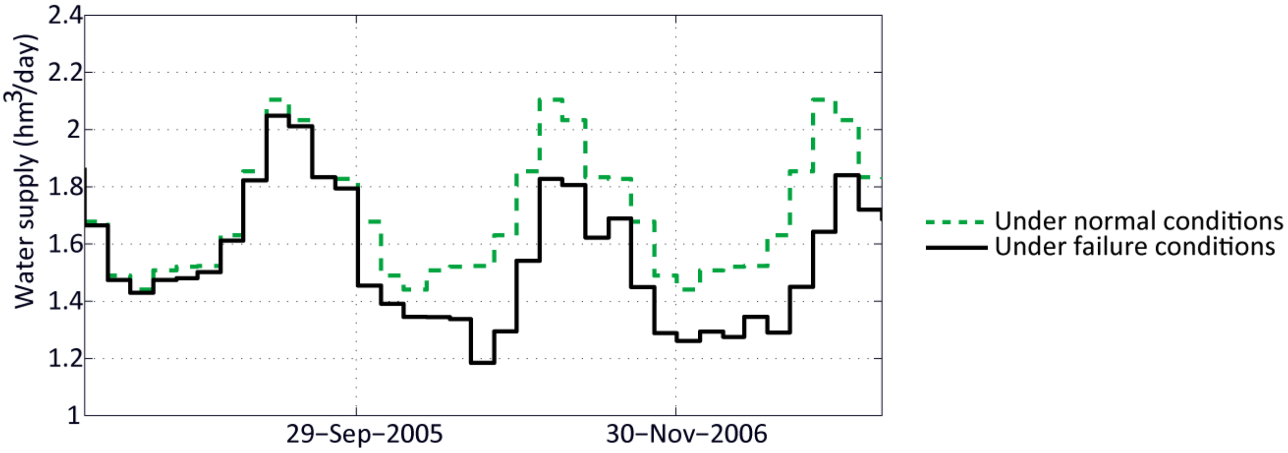

Figure 2. Water supply (hm3/day).

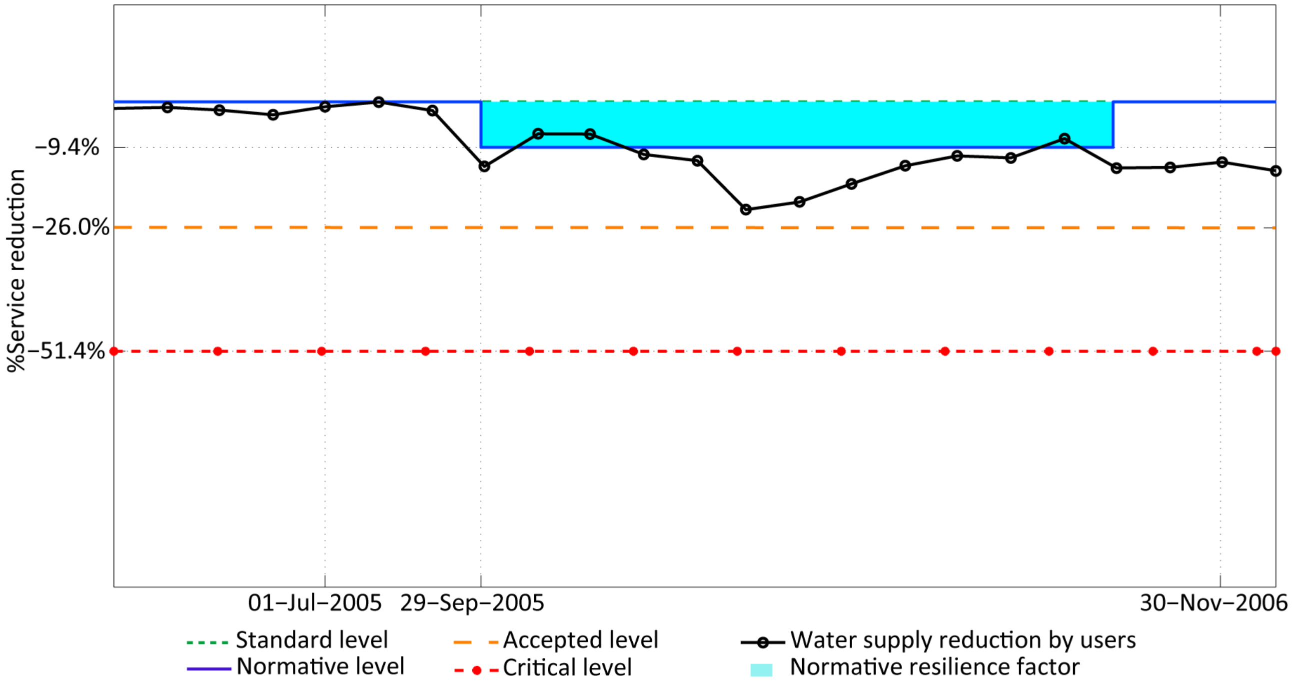

Figure 3. Normative resilience factor and evolution of water supply reduction.

Figure 2 shows the water supply both in case of disruption and in normal conditions. The normal water supply values in normal conditions are determined with data of previous years without failures, adapted to the real climatic conditions and prediction models. The water supply in normal conditions represents the standard level represented in Figure 3. The percentage of water supply reduction is also shown over the disruption period, that is between the Decree 97/2005 was enacted to establish exceptional measures to manage water supply in Madrid, the 29th September 2005, and the day these exceptional measures were repealed, the 30th November 2006. The period of time before and after the drought is also presented. The obtained results allow contrasting the effectiveness of protocols followed by the company in the first level of severity due to water scarcity. It may be observed that the voluntary reduction of water is higher than the one expected by the protocols, which is represented with the resilience factor. Thus, it may be conclude that protocols in case of contingencies are effective. In Figure 3, it is also represented the date of July 2005, because the water company launched a campaign called "The challenge of water" addressed to end users to save water. In addition, when the Decree 107/2006 repealed the exceptional measures, the 30th November

2006, the water supply was under the normal conditions. The main reason was that the end-users were accustomed to use less water than they used to.

If the water reserves overcome the second level of severity, the protocols of the company establish a water supply reduction of 26.0% over 24 months. In the same way, if the third level of severity is reached, water supply should be decreased in 51.4% over 12 months. The time since the drought is declared until the accepted and critical levels are reached has to be considered in order to calculate resilience. In the study case, the drought was always in the first level of severity, so no additional actions had to be taken.

In the case of pipe breaks that cause water supply discontinuity or water quality failures that produces water drinking discontinuity, the resilience factor is measured by means of the number of affected properties downstream of the break over the disruption period. Therefore, the resilience factor for each type of threat calculated as follows:

$$\left(R_f\right)_B = Number\ of\ affectedproperties \bullet disruption\ time \tag{8}$$

Figure 4 and 5 show two examples of how different pipe breaks and water quality failures affect the water service provision. It is presented the calculated resilience factor.

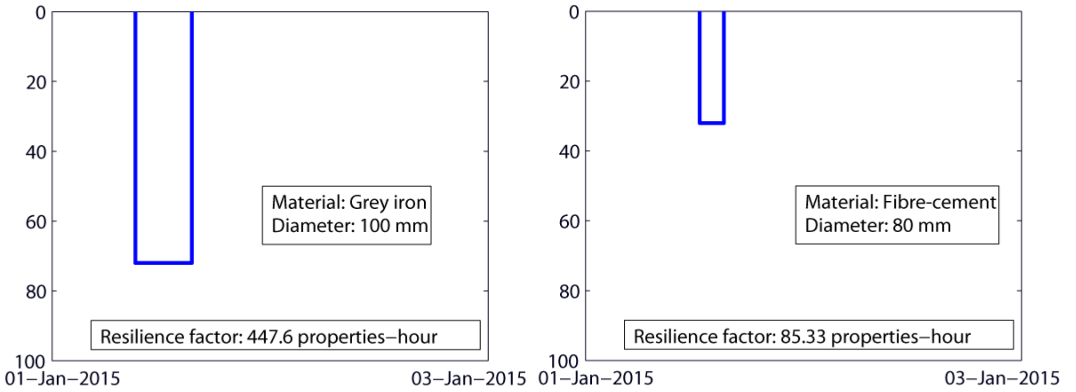

Figure 4. Resilience factor for different pipe breaks.

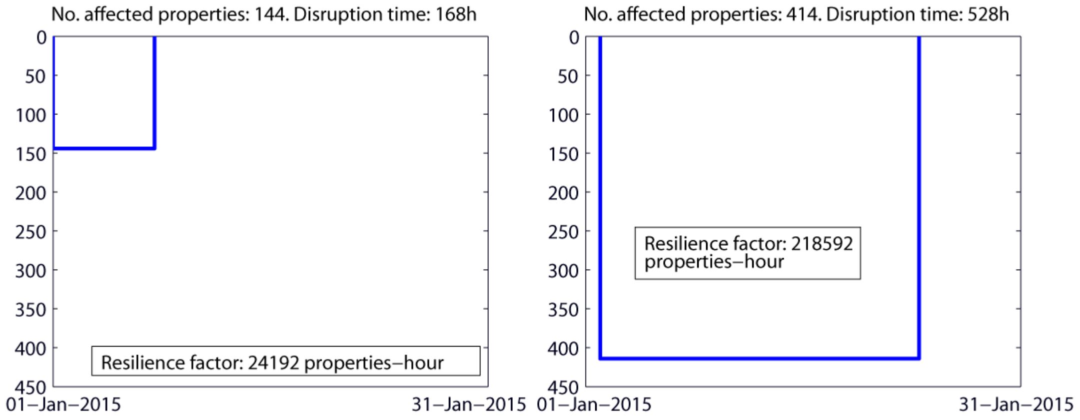

Figure 5. Resilience factor for different water quality failures.

The system resilience factor should be calculated in future analysis with all types of threats that generate disturbance in the system at the same time. It should be mentioned that the W_A would have a substantially higher value than the other weights (W_B, W_C and/or W_D), as this drought had the most relevant impact on end-users. The resilience factor of every type of threat has to have the same units, referred to the percentage of loss of service or number of affected properties per time. In addition, more research is needed to define the failure thresholds (standard, normative, accepted and critical level of service) for pipe breaks and water quality failures. Water companies should analyse their protocols, resources and technologies to know how their water supply system is going to performance under anomalies and fix their failure thresholds. It is recommended to establish global levels of service to allow comparison between different companies and know how the society reacts to threats. Furthermore, these thresholds classify the level of severity produced by a threat and are necessary to know what type of measures should be taken to recover the system to normal conditions. They constitute reference values to operate and plan investments to improve the system resilience. The resilience factor may be also used to update the protocols followed by a water company in the aftermath of a disruptive event.

5. Conclusions

This article presented a new methodology that aims at measuring resilience for water supply systems. Resilience is presented as the capacity of the systems to overcome threats and be able to delimit the impacts. Therefore, resilience may be measured by the magnitude of failures, characterized by their duration and severity. A classification of types of threats is presented, in consideration of water service disruption: (A) water scarcity, (B) supply discontinuity, (C) Discontinuity of hydraulic conditions and (D) discontinuity of water quality conditions. A set of failure thresholds are also shown: (1) standard level, (2) normative level, (3) accepted level and (4) critical level. When these thresholds are exceeded, the system is in the level of severity 1, 2, 3 and 3, respectively. A resilience model that allows calculating a resilience factor is proposed. It measures the loss of service function from the standard level and also considers the disruption period.

The methodology was applied to the complex real-life water supply system of the Autonomous Region of Madrid (Spain), managed by the water company Canal Isabel II Gestión. For the study case of a drought of first level of severity, the failure thresholds are exposed. Results show that the normative resilience factor is $9.4\% \bullet year$. The effectiveness of protocols is contrasted with real data of water supply over the disruption period. It has been demonstrated that the voluntary water supply was even greater than the required by the protocols. Therefore, protocols in case of first level of severity were adequate that type of threat. It has been verified that the end users were accustomed to use less water than they usually need, once the drought had finished. Furthermore, the resilience factor for different pipe breaks and water quality failures are presented. More research is needed to establish failure thresholds for these types of events and define the specific weights to aggregate the resiliencies factors. The methodology allows measuring resilience of the systems, assessing protocols, technologies and resources used in the company, as well as planning in order to improve the system resilience.

References

1. Author 1, A.B. Title of Thesis. Level of Thesis, Degree-Granting University, Location of University, Date of Completion.
2. Title of Site. Available online: URL (accessed on Day Month Year).

1. Henry, D.; Ramirez-Marquez, J.E. Generic metrics and quantitative approaches for system resilience as a function of time. *Reliability Engineering and System Safety* **2012**, *99*(1), 114–22.
2. Tierney, K.; Bruneau, M. (2007) Conceptualizing and Measuring Resilience: A Key to Disaster Loss Reduction. TR News, National Academies, Transportation Research Board, May-June 2007.
3. Prior, T.; Hagmann, J. Measuring resilience: methodological and political challenges of a trend security concept. *Journal of Risk Research* **2014**, *17*(3), 281-98.
4. White House. Presidential Policy Directive - Critical Infrastructure Security and Resilience, PPD-21. 2013, Washington, DC;

https://www.whitehouse.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resi Accessed August, 10, 2015.

5. Petit FD, Bassett GW, Black R, Buehring WA, Collins MJ, Dickinson DC et al.. Resilience measurement index: as indicator of critical infrastructure resilience. Decision and information sciences division. Argonne National Laboratory, 2013.
6. Todini, E. (2000). Looped water distribution networks design using a resilience index based heuristic approach. Urban Water **2** (3): 115122.
7. Tsakiris, G.; Spiliotis, M. Applying resilience indices for assessing the reliability of water distribution systems. *Water Utility journal* **2012,** 19-27.
8. National Infrastructure Advisory Council (NIAC). Critical Infrastructure Resilience, Final Report and Recommendations, U.S., 2009.
9. Castet, J-F.; Saleh, J.H. On the concept of survivability, with application to spacecraft and space-based networks. *Reliability Engineering and System Safety* **2012**, *99*, 123-138.
10. Ayyub, B. M. Systems Resilience for Multihazard Environments: Definition, Metrics, and Valuation for Decision Making, *Risk Analysis* **2014**, *34*, 340–355.
11. Uday, P.; Marais, K.B. Resilience-based system importance measures for system of systems. *Procedia Computer Science* **2014**, *28*, 257-264.
12. Haimes, Y. Y. On the Definition of Vulnerabilities in Measuring Risks to Infrastructures. *Risk Analysis* **2006** *26* (2), 293–296.
13. Barker K., Ramirez-Marquez J.E.; Rocco, C.M. Resilience-based network component importance measures. *Reliability Engineering and System Safety* **2013** *117*, 89–97.
14. Francis R.; Bekera B. A metric and frameworks for resilience analysis of engineered and infrastructure systems. *Reliability Engineering and System Safety* **2013**, *121*, 90-103.
15. Department of Homeland Security: Science and Technology Directorate. Risk and Resilience: Exploring the Relationship. National Infrastructure Advisory Council: Homeland Security Studies & Analysis Institute, Washington, 2010.
16. Cubillo, F.; Ibánez, J.C. Manual de Abastecimiento del Canal de Isabel II, 2003. ISBN: 84-932364-5-4. Canal de Isabel II, Madrid, España.