ICONHIC2022
3rd International Conference on Natural Hazards & Infrastructure
5-7 July 2022, Athens, Greece

Simplified Seismic Risk Assessment for the Water Supply Network of Rhodes, Greece

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ABSTRACT

A methodology is developed for the risk assessment of the water supply network of the city of Rhodes under spatially distributed seismic loading. Graph theory is used to implement this methodology by creating in-house software in the object-oriented programming language Python. Multiple seismic events are employed that have been generated with a probabilistic approach for a 10,000 year period using the OpenQuake platform and the 2013 European Seismic Hazard Model. The intensity measure used is the peak ground velocity (PGV). Since a direct generation capability for ground motion fields with spatial correlation is not readily available for PGV, the spatial distribution of the spectral acceleration at a period of 1s was employed, which is strongly correlated with the ground velocity. Results are obtained for the length of the pipes that will break for each event. The complex topology of the network is efficiently tackled via the graph theory to track which pipes cannot supply water and which need repair. The outcomes of the analysis indicate the percentage of the customers that are left without water in each building block of the city, to assess the population that has no access to water after a destructive event. Finally, curves of the mean annual frequency of exceeding given values of the damaged pipe length and the number of pipe breaks are produced, and the average annual losses are estimated.

Keywords: Risk Assessment, Graph Theory, Seismic Hazard, Water Networks

INTRODUCTION

The water supply network is a critical lifeline infrastructure system and its undisrupted operation is vital for the prosperity of every city. The reliable supply of water is directly linked to public health and the proper function of the buildings. The water supply should be sufficient, to cover the needs of the residents and businesses and offer the appropriate quality to the consumers. However, natural hazards, such as earthquakes may severely threaten a water network. Therefore, in seismic prone countries like Greece, it is a necessity to ensure structural integrity, survival, and uninterrupted operation after a seismic event.

In the context of the EU-funded HYPERION research project, it is required to develop a method that effectively tackles the analysis, and aims to optimize and ameliorate the response of the cities after severe natural disasters. A faster response enables better preparedness to repair the affected components of the networks, minimizes the duration of the functionality loss, and therefore mitigates the consequences of the disaster in terms of economic losses and quality of life deterioration in the city. Several studies, among which one of Davis (2014), suggest that the duration of the disruption is as important as the magnitude of damage inflicted upon the city in terms of economic losses. The two fundamental approaches that have been employed to model the water supply networks are the graph theory (Pinto et al. 2010; Yannopoulos & Spiliotis, 2012; Fragiadakis et al, 2013;) and the hydraulic modeling (Esposito et al, 2015; Cavalieri, 2020; Tomar et al, 2020). The former is based on the analysis of connectivity, offering computational efficiency at the loss of some accuracy, while the latter employs the actual differential equations to compute the steady-state flow in the network, sacrificing speed for lowering bias. Herein, due to the size and complexity of urban water distribution systems, we opt for the faster graph-theoretical approach.

Another aspect that the developed methodology involves is the use of spatially correlated ground motion fields to create a more realistic model of the damages caused to the city after an earthquake event. Thus, discrete-event simulation is used to determine the losses and the functional restoration after each potential event. As an example of application, a case study for the network of the city of Rhodes, Greece is presented.

CASE STUDY MODELING

The water supply network comprises the transmission pipelines from the water sources to the city and the urban water distribution network. The transmission system brings water to the city from two separate sources: (i) a dam and (ii) an underwater aquifer tapped by a set of boreholes, as shown in Fig.1a. The distribution system consists of a dense network of pressurized pipes. For positioning the individual pipes within the city grid, it is assumed that they follow the routes of the city streets [Fig. 1(b)]. The city blocks were defined according to the Hellenic Statistical Authority data (ELSTAT 2021), including information about the demographics and the population for each. Due to the highly touristic nature of Rhodes, non-resident population will dominate several hotel-centric areas during the summer months. This seasonal change in the population composition is not accounted herein, considering only permanent residents.

To achieve an efficient risk assessment via the graph theory approach, the water supply network is separated into the transmission system and the distribution system. This separation is helpful because the transmission system is a series system, which practically means that if a single pipe fails the entire system cannot fulfill its purpose to provide the city with water. The transmission system feeds the distribution system, which is responsible to bring the water to each building and it is highly redundant by design. Therefore, the failure of an individual pipe does not completely disrupt the proper operation of the system. The distribution network is partitioned into seven areas based on the era of construction and material of the pipes (Fig. 2). For each area, the distribution of pipe material was approximately determined based on (i) the age of the network, (ii) information from the municipality, and (iii) expert opinion from local engineers on construction practices (see Table 1).

A simple network model is formed, focusing on the connectivity of end-users to the water sources via a graph-theory approach (Gibbons, 1985; Fragiadakis et al, 2013), as shown in Fig. 3. To create and study the resulting graph model, the python package NetworkX (Hagberg et al, 2008) was used. The graph of the water network consists of (i) the nodes, which represent the points of water entry (dam, boreholes), water outlets, and joints of multiple pipe branches, and (ii) the edges, which represent the pipes. In general, one needs to balance the complexity of the graph and the number/length of pipe segments. Herein, we employ edges (i.e., pipe segments) whose length is small enough to provide adequate resolution at the city block level.

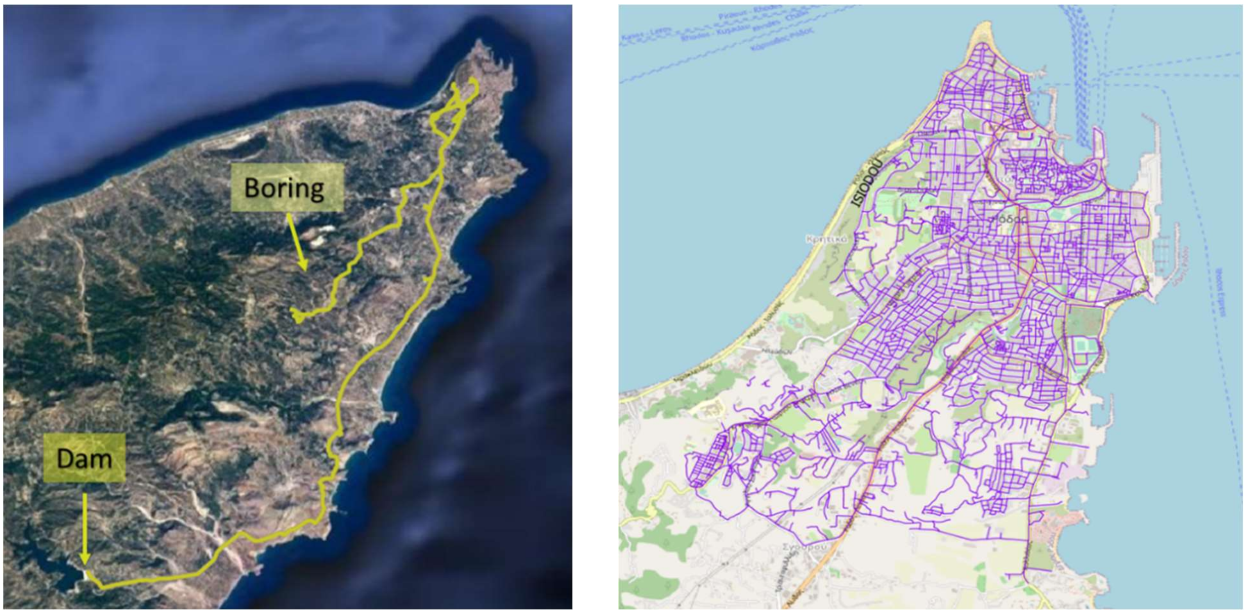

Figure 1. *The water supply system of the City of Rhodes: (a) Transmission network, (b) Distribution network.*

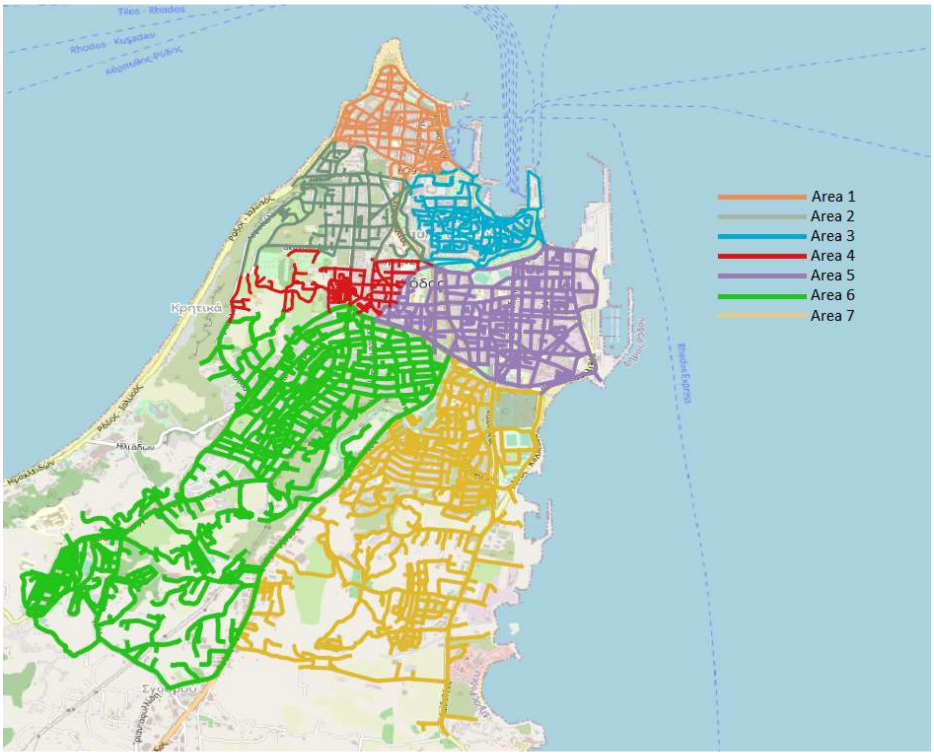

Figure 2. *Partitioning of the water distribution system on the city of Rhodes, Greece into seven areas based on the age and the material of the pipes.*

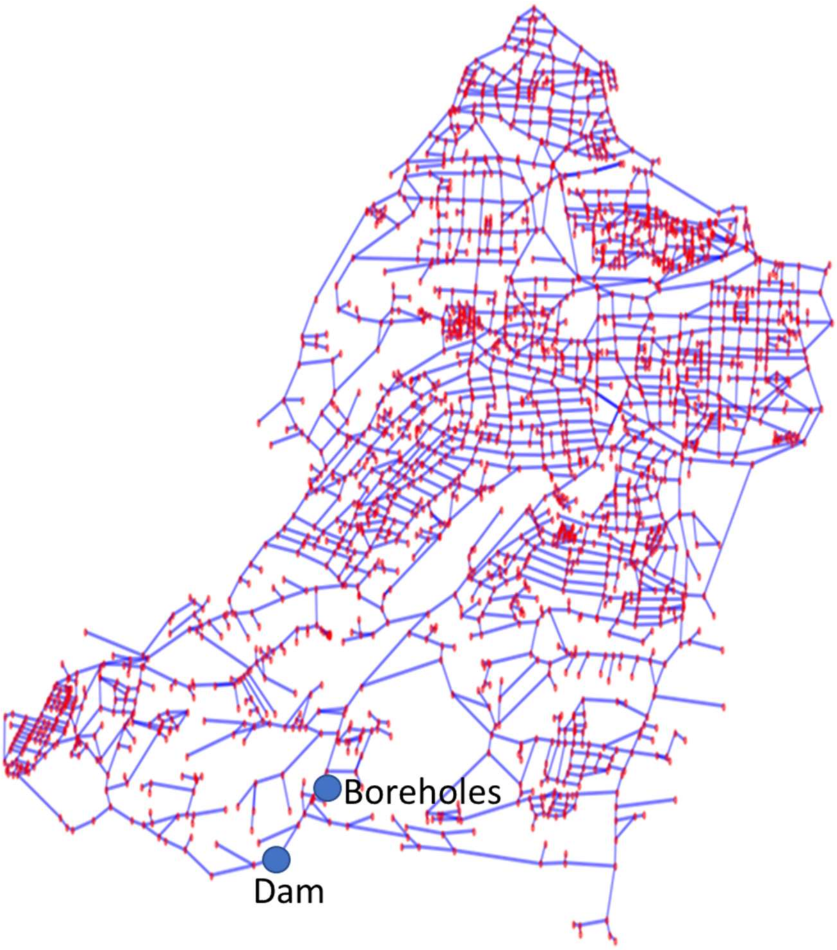

Figure 3. *Visualization of the graph theory approach (red: nodes, blue: pipes, dots: points-of-entry, connecting the transmission to the distribution network).*

Table 1. *Probability of occurrence of different pipe material types per sub-area.*

	Cast Iron (%)	**Asbestos (%)**	**PVC (%)**
Area 1	60	30	10
Area 2	60	30	10
Area 3	60	30	10
Area 4	10	30	60
Area 5	10	30	60
Area 6	0	50	50
Area 7	0	0	100

PIPE VULNERABILITY

Beyond aging, earthquakes constitute the main natural hazard for piping. Pressurized pipes are really vulnerable, and of the highest concern for seismic damage. The methodology used for the seismic assessment of the water distribution (pipe) network is based on the American Lifelines Alliance (ALA, 2001) guidelines. The procedures proposed by the ALA guidelines aim to evaluate the probability of damage from earthquake hazards to individual components of the system. To accomplish that, observations from past disruptive earthquakes are used to form empirical vulnerability functions related to the peak ground velocity (PGV), relevant to the damage of the buried pipes due to ground shaking caused by wave propagation (O'Rourke & Liu, 2012).

The vulnerability is presented in terms of the repair rate per unit length (RR) of pipe for given PGV:

$$RR = 0.01425 \cdot PGV \text{ per 100 meters of pipe length} \tag{1}$$

Eq. (1) represents the performance for a generic "average" pipe. Modification factors are employed to further distinguish different pipe materials. So, the pipe vulnerability function becomes:

$$RR = K_1 \cdot 0.01425 \cdot PGV \text{ per 100 m of pipe length} \tag{2}$$

where K_1 is provided in Table 2 and was decided based on the per pipe material, joint type, soil, and pipe diameter. The probability of failure (P_f) for an individual pipeline and a given value of PGV is calculated as:

$$P_f = 1 - e^{-RR \cdot L} \tag{3}$$

where L is the length of the pipe. According to HAZUS-MH (FEMA, 2003), as well as ALA, not all of the failures are breakages; per HAZUS-MH, 20% of such failures are breakages and 80% are leakages. Only the breakages require immediate repair and can stop a pipe from providing at least some water to the residents of the city.

Table 2. *Material modification factors for pipe fragility curves per ALA (2001).*

	K_1
Cast Iron	1.00
Asbestos	1.00
PVC	0.50
Steel	0.15

SEISMIC HAZARD

Engineers are, typically, used to the point-wise representation of seismic intensity via design spectra. However, this is inadequate for determining the concurrent damage of a widely distributed system, such as the water supply network. To this end, event-specific spatially-correlated fields of ground motion intensity are employed to represent the local maxima of ground motion intensity of any given earthquake. The PGV values were calculated via event-based probabilistic seismic hazard analysis (PSHA) using the open-source OpenQuake engine (GEM, 2021) with a single ground motion prediction equation by Cauzzi et al. (2014). This analysis generates a stochastic event set (SES) for a given investigation time that accounts for the potential realizations of seismicity based on the known seismic sources. Since spatial correlation functions are not widely available for the PGV, the fields produced by OpenQuake are essentially uncorrelated in space, leading to potential bias in the estimation of damage and loss. To remedy the situation, the spatial correlation of the spectral acceleration at a period of 1s, $Sa(1s)$, was employed (Fig. 4), for which appropriate models are readily available (Jayaram and Baker, 2009). Sa(1s) is strongly correlated with PGV, having a positive correlation around 0.8 (Bradley, 2012). Thus, spatially correlated fields of Sa(1s) were generated for the same stochastic event catalog considered for the PGV. Per each field, the PGV values were reordered to correspond to the ordering of Sa(1s) values over the grid of points considered. Thus, for example, the maximum PGV value observed anywhere in the point grid was placed at the point where the maximum Sa(1s) value appeared, and similarly for the second largest, the third, and so on. In Fig. 4 an example of an event is presented to showcase the procedure for reordering the PGV fields to inject spatial correlation.

In essence, one needs to determine "all" potential earthquake scenarios by assuming a long enough investigation time period, herein 10,000 years, and assess the individual components per ALA for each case. Having data from past earthquakes would have served as a useful validation example, unfortunately, such data is not available. Since thousands of smaller magnitude events will tend to appear in these 10,000 alternative realizations of a single year, the majority of which cannot damage the water pipes, only events (or fields) having a minimum PGV value of 5 cm/sec are considered. This reasonable engineering assumption significantly reduces the computational cost of the analysis, thus reducing the total number of events considered from 130,000 in the initial SES to about 2,800 in the final one, without any loss of accuracy.

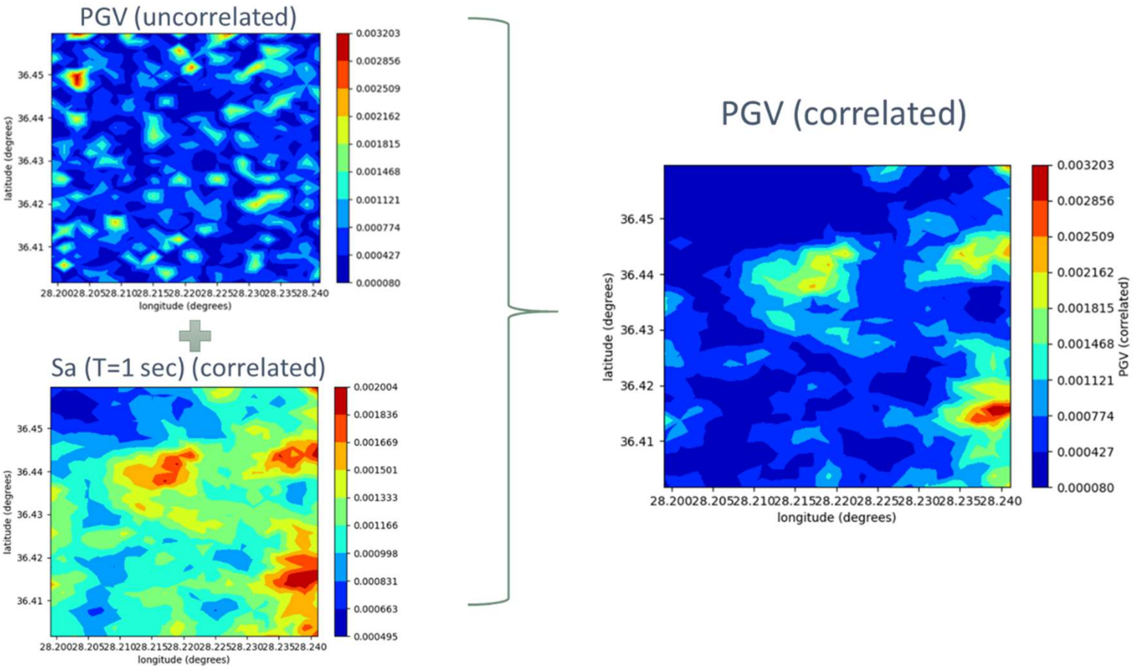

Figure 4. *Creation of spatially correlated ground motion fields for PGV by imposing the correlation structure of* $Sa(1s)$.

RISK ASSESSMENT METHODOLOGY

The overall network system reliability is assessed via the statistics of the considered scenarios, forming in effect a large-scale Monte Carlo simulation. Firstly, per each seismic event in the SES, the failure of individual pipes is assessed. Specifically, for the given material of each pipe, the probability of having different numbers of failures (breakages and leakages combined) within its length is calculated based on a Poisson probability. Given this probability mass function, a sample of 100 realizations of the number of pipe failures is created. All in all, per each seismic event in the reduced SES, 100 realizations of the condition of the entire water supply system are generated.

Then, for each such realization, we need to determine the areas of the city that are left without water after the failed pipes have been removed. Equivalently, given thenetwork geometry and our modeling approach, we want to find those city blocks that are not connected through any path to the water sources. To do so efficiently, we turn to the separation of the system into transmission and distribution.

Since the transmission system comprises two separated series systems, one per each water source (dam or boreholes), these are the first to be assessed. Per each of the two transmission subsystems, the failure of one of the pipes leads to an inability of the subsystem to provide water for distribution. Thus, the first step requires checking whether, in the realization at hand, water can reach the distribution system. To that effect, four alternative scenarios/conditions for the water supply to the city are considered:

1. From both the dam and the boreholes

2. Only from the boreholes

3. Only from the dam

4. None of the sources

In the last scanerio ("4. None of the sources"), there is a complete lack of water supply to the city. If any of the two sources can provide water to the system, the distribution system is assessed. The two transmission subsystems provide the distribution system with water at two different points-of-entry. These points-of-entry are considered as direct points of water supply for the city distribution system, assuming the relevant transmission line has not failed. Therefore, after having removed the pipes that have failed (represented as edges for the graph theory), subgraphs of the nodes that are connected through a path to each point-of-entry are formed. The rest of the nodes that are not included in the subgraphs have no access to water and consequently can't offer supply. These nodes are removed from the graph with all their adjacent edges. It is assumed that even having one of the sources available is adequate to at least provide some supply of water for the entire city, which in reality may not be enough for some uses and may require rationing.

After removing all the parts of the graph that cannot distribute water, the impact to the city itself can be defined by assessing how many residents have no access to water. To do so, per each block we estimate the percentage of its population that have access to water by assuming that it is equal to the percentage of individual pipes surrounding the block in question that can still supply water. This procedure is repeated for all the possible realizations for the system.

RESULTS

The performance of the water transmission system for all the realizations and seismic events is presented in Table 3. Indicative results for one of the considered realizations are illustrated in Fig. 5 in terms of the percentage of population that have access to water per block. These realizations provide the result for the entire system based on whether the pipe fails or not, and how many times, for each one of them. As far as the entire system for all potential seismic scenarios is concerned, the mean annual frequency (MAF) of exceedance is calculated for different impact metrics of interest such as (i) the damaged length [Fig. 6(a)], (ii) the number of breaks and leaks [Fig. 6(b)], and (iii) the percentage of people that do not have access to water (Fig. 7). Such data can be used to identify the most influential part of a network, i.e., the one that most contributes to lowering accessibility to water, this becoming a likely target for rehabilitation/replacement actions.

Table 3. *Performance of the water transmission system.*

Available water source	Realizations	Percentage
Both sources	231 k	81%
Only boreholes	26 k	9%
Only dam	6 k	2%
No source	22 k	8%
Total	285 k	100%

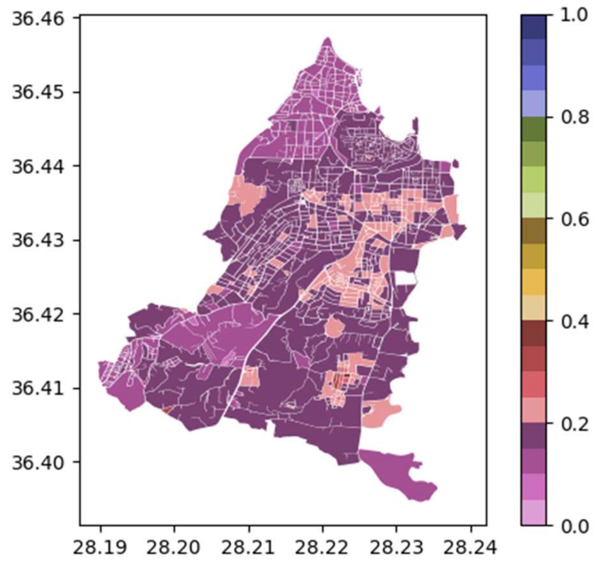

Figure 5. *An example of the estimated percentage of pipes still supplying water to city blocks after a severe event (purple: lowest percentage, blue: highest percentage).*

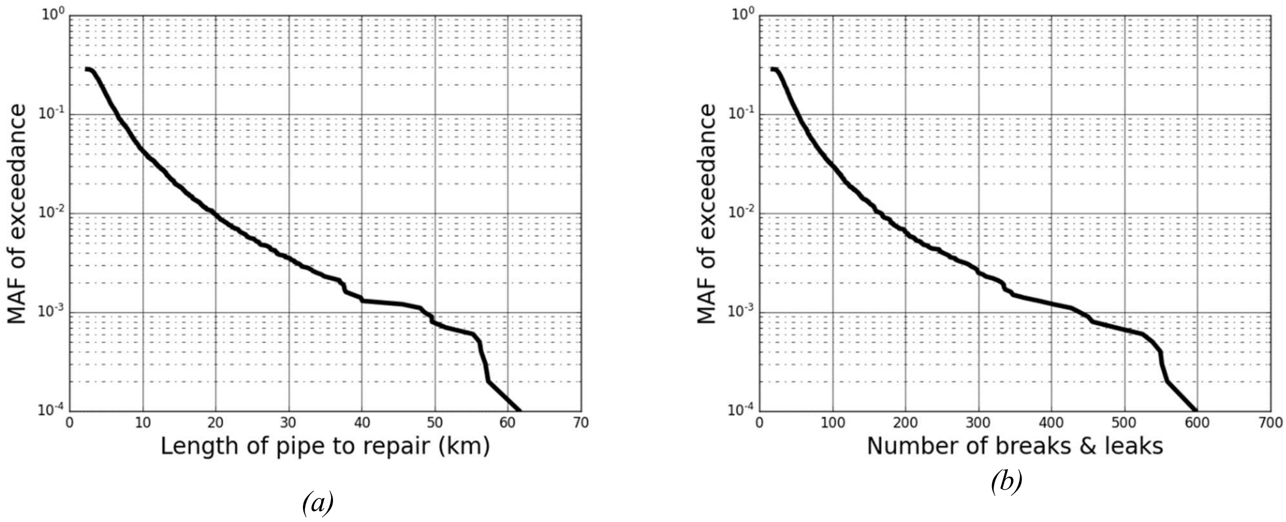

Figure 6. *Mean annual frequency of exceeding (a) given damaged length of pipes, (b) given number of breaks and leaks.*

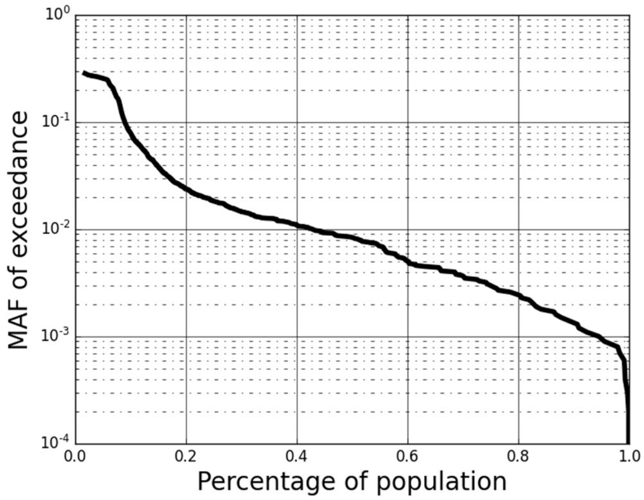

Figure 7. *Mean annual frequency of exceeding given percentages of the population without water supply.*

The results for the average annual loss of the water supply network are:

- Damaged length: 2.04 km of which 1.63 km are leaking pipes, and 0.41 km are broken pipes requiring immediate replacement.
- Number of failures: 17 of which 13 are leakages and 4 are breakages.
- Population percentage without water: 3.2% corresponding to around 1,600 residents. If it is assumed that only 20% of the pipes will have a breakage, this is brought down to 320 residents with no access to water.

As far as the design earthquake scenario is concerned, having a probability of exceedance 10% in 50 years (equivalent to a return period of 475 years), the results are much worse:

- Damaged length: 37 km of which 29.6 km are leaking and 7.4 km are broken pipes.
- Number of failures: 330 of which 264 are leakages and 66 are breakages.
- Population percentage without water: 82% corresponding to around 41,000 residents. If it is assumed that only 20% of the pipes will have a breakage, this is brought down to 8,000 residents with no access to water.

CONCLUSIONS

The methodology developed in this study is an efficient way to assess the risk for a water supply network that accounts for both the topology of the system as well as the spatially correlated seismic intensities. The ALA guidelines are efficiently combined with graph theory and Monte Carlo simulation to provide results for the expected failures that will affect the water supply. While simple in comparison with more elaborate approaches that employ hydraulic network simulators, the adopted method can take advantage of publicly available data to provide cost-effective modeling and fast computations. It gives information about the extent of the failures for the entire system, and therefore the city, as well as localized information per city block that could be translated into useful results for the number of people that will be affected by a catastrophic seismic event.

ACKNOWLEGMENTS

Financial support has been provided by the European Framework Programme for Research and Innovation (Horizon 2020) under the "HYPERION" project with Grant Agreement number 821054. Special thanks are also extended to the municipality of Rhodes, the Hellenic Statistical Authority, and the Municipal Water Supply Company of the Municipality of Rhodes (DEYAR) for supplying the data required to build the water supply network model.

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