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# VIRTUAL CITY FOR WATER DISTRIBUTION RESEARCH IN CRISIS MANAGEMENT

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**Abstract.** *In our society infrastructure data are crucial and research on critical infrastructures is difficult since experiments on real systems cannot be publicized. Virtual cities are one potential answer to this problem. IDEAL CITY is a virtual city of about 900000 residents fully described in GIS and other software for infrastructures modelling The city is currently under development and it will incorporate all critical infrastructures and its interdependencies, such as electric power grid, transportation, gas network and agent's networks. In this paper an example of using IDEAL CITY for simulation of an earthquake event on the water distribution network is presented. The earthquake event is characterized by a PGV of 25.04 cm/s. The city is assumed to be located on rough sandy gravel. The WDN is split in 10 districts while six pipes of different diameter made of ductile iron material has been considered in the network. Different scenarios have been selected considering the probability of failure of each pipe and a weight factor related to the diameter of the pipe itself. A method to reduce the number of scenarios analyzed that is based on the probability density function of the different events has been proposed. Finally, a resilience index has been used to compare different scenario events that is based on the number of household without service and the numerical results have been discussed. In the future, further models will be added to take into account for risk and probability of failure of critical infrastructures due to extreme events (e.g. natural and manmade hazards). The main idea is to use IDEAL CITY to develop a virtual city that will serve as a hub for the development of further research models.*


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## 1 INTRODUCTION

The world is becoming ever-more complex and unpredictable, marked by rapid urbanization, dramatic technological evolution, and climate change [1]. As a result, communities are increasingly trying to enhance their resilience against hazardous events, being aware that they cannot prevent every risk, but they must manage and adapt to risks minimizing the effects. In particular, recent earthquakes, such as the 1995 Kobe, and the 1999 Chi-Chi [2], have provoked a significant amount of damages, which have lead communities to focus their attention on the safety of critical infrastructures (i.e. gas networks, power networks, transportation systems, water distribution networks) during and after earthquakes. In the past, the main concern was the physical protection of these lifeline systems, but now attention is shifting toward the infrastructure resilience [3]. Bruneau, Chang et al. introduced the first definition of this term, without providing a detailed quantification of it, but rather a description of the community resilience characteristics [4]. Cimellaro, Reinhorn et al. expressed the first framework to quantify Resilience, considering the uncertainties in the intensity measures [5].

A resilience index *R* promoted by Cimellaro, Tinebra et al. has been adopted to measure the performance of a for a water distribution network (WDN) [3]. This index is function of the number of users with suffered water outage $n_e$, which helps planners and engineers to evaluate the WDN Functionality *F(t)*. The latter consists in delivering a certain demand of water with an acceptable level of pressure, and in its restoration process after a disaster event.

The case study deals with a Virtual City named IDEAL CITY, which is located in a seismic region. The WDN has been analyzed using EPANET 2.0 software [6] with two different approaches: Demand Driven Analysis (DDA) has been performed during normal operating conditions, and Pressure Driven Analysis (PDA) has been carried out in case of pipes failure within the system. Different scenarios have been considered, taking into account the probability of having simultaneous failures of pipes.

## 2 RESILIENCE ANALYSIS FOR WATER DISTRIBUTION NETWORKS

Cimellaro and Reinhorn [5] have provided a useful literature review of the resilience definitions and have averred that disaster resilience is “a normalized function indicating capability to sustain a level of functionality or performance for a given building, bridge, lifeline, networks or community over a period of time $T_{LC}$ (life cycle, life span, etc.) including the recovery period after damage in an extreme event” [7].

Nowadays, there is no standard procedure to quantify resilience in the context of diversified hazards or to define how communities are heading in the direction of becoming more resilient. Although past research focused mainly on the assessment of direct and indirect losses caused by hazardous events, and on the necessary actions to reduce such losses, recent studies are addressing to the search of specific measures that must be adopted before, during and after the events [4, 8].

A framework for the quantification of disaster resilience, endorsed by Cimellaro, Reinhorn et al. [5], consists in the definition of the resilience index *R*. It measures the capability to sustain a level of functionality, or performance, for a given building, an infrastructure system (transportation, water network, etc.), or a community, over a certain period of time named Control Time ($T_{LC}$), which usually corresponds to the system life cycle [3]. For its formulation, the definition of the function of functionality *F(t)* is needed. In this case, the functionality of an infrastructure consists in delivering a certain demand of water with an acceptable level of pressure, and in its restoration process after a disaster event. It is, therefore, related to the number of equivalent utilities $n_e$, that quantifies how many potential utilities have problem with the water supply. Its expression is shown below:

$$F(t) = 1 - \frac{\sum_i n_e^i}{n_{Tot}}, \quad for\, i = 1, \ldots, N \tag{1}$$

where $n_e^i$ is the equivalent number of utilities for each node that suffer insufficient pressure; $n_{Tot}$ is the total number of utilities within the distribution network; and $N$ is the total number of nodes where the utilities have been supposed to be directly connected. The number of equivalent utilities is directly proportional to the water volume lost during the earthquake event and during the successive repair operations, as follows:

$$n_e^i = n_i \frac{w_{Lost}^i}{w_i} \tag{2}$$

where $i$ is the generic node in which pressure is insufficient to ensure the water demand; $n_i$ is the total number of utilities connected to the node $i$; $W_{Lost}^i$ is the volume of water lost; and $W_i$ is the volume of water consumed by utilities under normal operating conditions. The volume of water lost has been computed as follows:

$$W_{Lost}^i = \int_{t_j}^{t_{j+1}} \left[ Q_{demand}(t) - Q_i(t) \right] dt \tag{3}$$

where $t_j, t_{j+1}$ are the generic instants after the earthquake event $(t > t_1)$; $Q_{demand}$ is the water demand at instant t; and$Q_i$ is the real water flow at time t after the failure of a pipe. The volume of water under normal operating conditions has been evaluated using the equation below:

$$W_i = \int_{t_j}^{t_{j+1}} Q_{demand}(t)\, dt \tag{4}$$

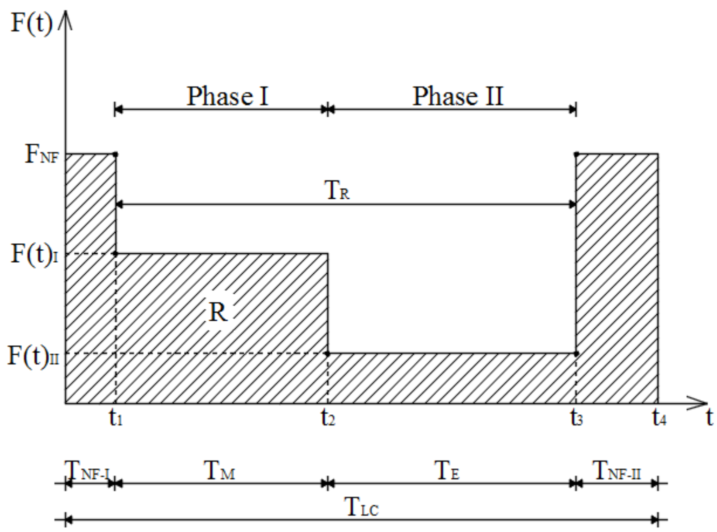


Figure 1: Functionality of Water Distribution Network (adapted from [3]).

The general form of $F(t)$ for a given extreme event is displayed in Figure 1. The Control Time $T_{LC}$ (established in 48 hours in this study) consists in four different periods: $T_{NF-I}$ and $T_{NF-II}$ are the normal operating functionality periods that occurs, respectively, before the earthquake and after the repair operations, $T_M$ is the operating period between the earthquake and the first emergency operations, and $T_E$ is the transition period for repair works. Moreover, $t_1$ is the instant when the earthquake occurs, $t_2$ is the instant when the damaged pipes are isolated, $t_3$ is the instant when the repair operations are completed and $t_4$ is a generic instant when the system works in normal conditions. The sum of the two periods $T_M$ and $T_E$ gives the recovery time $T_R$.

After the definition of the performance index *F(t)* given in Equation (1), the corresponding resilience index is defined as

$$R = \int_{t_1}^{t_1+T_{LC}} \frac{F(t)}{T_{LC}} dt \tag{5}$$

## 3 A VIRTUAL CITY FOR RESILIENCE ANALYSIS: IDEAL CITY

Focusing on past experiences can help people learn about what strategies for disaster resilience might work. The difficulty, however, lies in the low frequency of the majority of catastrophes. Gaining experience is exactly the core aim of employing a virtual city for resilience analysis.

A virtual city is a kind of virtual reality application which can be described as a real-time representation or visualization of any city and its components in an accurate and objective way [9]. It enables users to interact with objects not available in the everyday world [10]. For any virtual city, there are three fundamental concerns regarding the validity of a simulation: how much it reflects the real world environment (accuracy), how detailed is the simulated replication of the real world (reality), and what kind and amount of data can be presented through a simulation (representativeness) [11].

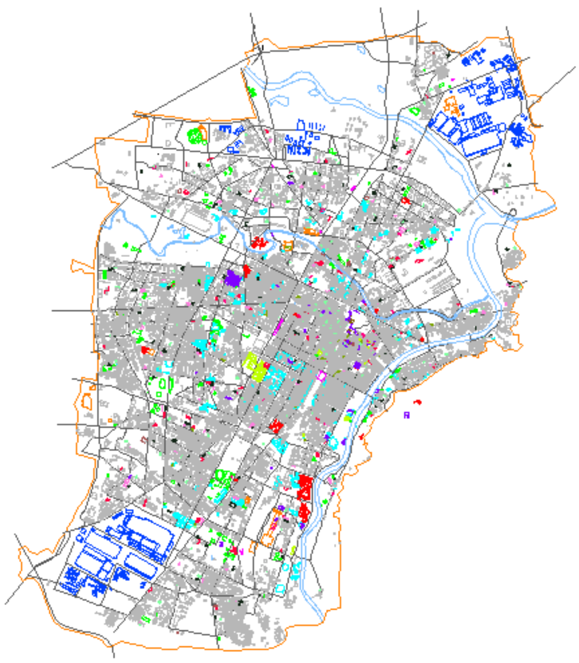

Figure 2: IDEAL CITY building and road map. Land use is indicated by color: for example, residential (grey), industrial (blue), and services (red).

The safety and quality of life in cities depend on the functioning of a set of critical infrastructures, also called lifelines. Their destruction or disruption, albeit partial, significantly weakens the normal functioning of cities themselves. The work of Kongar and Rossetto has led to the identification of sixteen critical infrastructures in a community, which are: electricity (power delivery), oil delivery, transportation, telecommunication, natural gas delivery, water supply, wastewater treatment, financial system, building services, business, emergency services, food supply, government, health care, education, commodities [12].

IDEAL CITY is a virtual city of about 900000 residents fully described in GIS and other software for infrastructures modelling (Figure 2). The city is currently under development and it will incorporate all critical infrastructures and its interdependencies, such as electric power grid, water distribution network, transportation, gas network and agent's networks.

In this study, IDEAL CITY is used to simulate the effects of an earthquake event on a water distribution network. The main stages of the work will be described in the next sections.

### 3.1 Model description and assumption

The water network has been simulated by using EPANET 2.0 software [6]. To create a realistically virtual environment, a real city should represent a reference model. For convenience, it was decided to take as a reference the city of Turin. The network is divided into 10 districts (Figure 3), reflecting the subdivision of the city of Turin. Each district is connected to the adjacent ones through a single pipeline, which can be closed if one or more pipes within the districts falls or needs repair; so the areas can be isolated without disrupting all areas in the network.

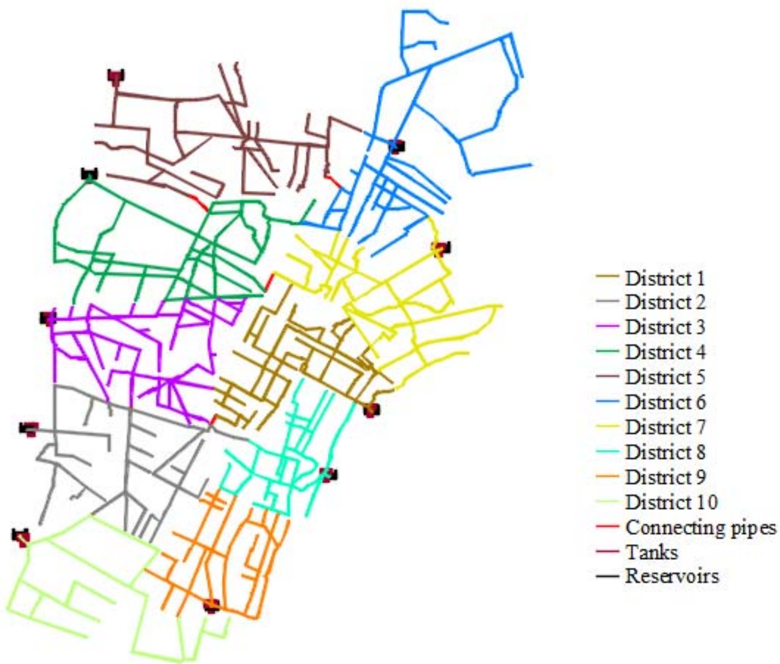


Figure 3: District view of the water network.

The number of inhabitants, equal to 891624 residents, is randomly assigned to residences. Water demand is determined by reference to the number of inhabitants and floating population (commuters and tourists). Based on similar cities, a value of daily water demand per inhabitant equal to 273.52 l/capita/day is adopted. This value is multiplied by the number of residents, commuters (20% of residents) and tourists (about 3.5 million per year) of each district in order to obtain the average water usage related to each district. The latter is used to compute the based demand at single nodes, assuming that the water collection in each node is proportional to the length of the pipes that flows to the node itself, as follows:

$$Q_n = L_n \cdot q \tag{6}$$

Where $q$ is the flow rate that has been determined as the ratio between the average water demand and the total length of the pipes; and $L_n$ is the half-sum of the length of pipes connected to the node itself. Considering that flow supplied from an aqueduct has a fluctuating trend during the year, a 24-hour time pattern for all user types is considered.

The EPANET hydraulic model (Figure 4) includes: 462 nodes, 525 pipes (263368.66 m total length), 9 valves, 10 pumps, 10 reservoirs, and 10 tanks. Almost all nodes are 1.2 m below the road surface. The ground elevation is between 213.99 m a.s.l and 276.93 m a.s.l. Most of the pipes are made of ductile iron. The roughness coefficient for the ductile iron is ε = 0.26 mm, using the Darcy-Weisbach formula. In keeping with the desire to develop a realistic and imperfect system, valves are not completely in line with design practices. Water sources are represented by rivers (18%) and aquifers (82%). The adduction is connected to the water tanks through pumps, each one characterized by a pump curve that depend on the difference of elevation between the source and the water tank and on the total demand flow required. The total daily demand on the IDEAL CITY WDN is 263.3 Ml/day with minimum and maximum hourly demand of 210.7 Ml/day and 342.4 Ml/day respectively.

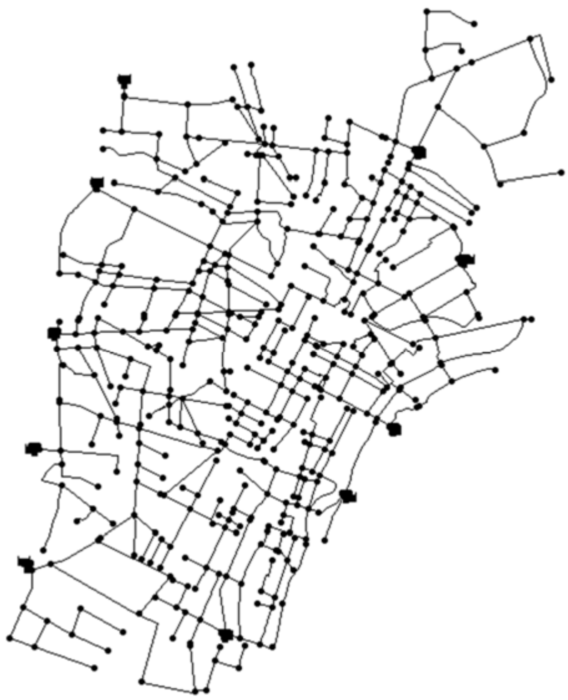

Figure 4: Hydraulic model of IDEAL CITY water distribution network.

### 3.2 Seismic hazard

Currently, the Italian evaluation of seismic hazard is based on a probabilistic approach (PSHA, Probabilistic Seismic Hazard Analysis) which considers all possible ground motions caused by earthquakes, along with their probabilities of occurrence, in order to find the level of ground motion intensity exceeded with some assigned value, within a given period of time [13]. The ground motion intensity can be expressed by the peak ground acceleration (PGA), which is not a measure of the total energy of an earthquake, but rather of how hard the earth shakes at a given site. It can be better expressed in terms of the maximum magnitude and recurrence (expected number of events in a year for each magnitude range) in order to define a seismic energy attenuation model.

The Italian National Institute of Geophysics and Volcanology (INGV) provides different interactive seismic hazard maps, including the disaggregation hazard maps. Through the disaggregation, it is possible to identify the relative contributions to seismic hazard from the different sources of the problem, the magnitude *M* and the source-to-site distance *R*. This means that for the same local soil conditions, the intensity of the ground shaking at the site depends on *M* and *R* values, even though the empirical ground motion deviates from the median value predicted, and this value is the standard deviation $\varepsilon$.

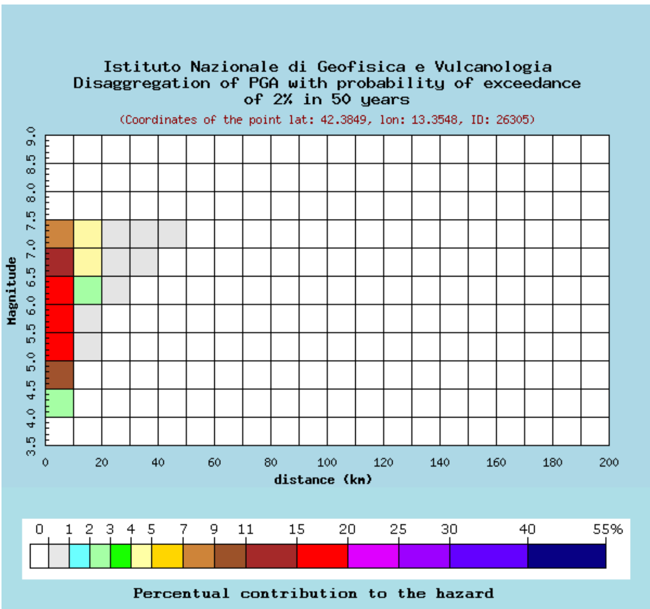


Figure 5: Disaggregation hazard map for 2% PE in 50 years (Return Period = 2475 years).

The hazard maps vary from place to place and are related to different values of the probability that a ground motion greater than the one assigned in a map occurs, in a certain time interval (usually 50 years) or to a specified return period. The disaggregation map for the analyzed virtual city is built for a return period of 2475 years with a probability of exceedance of 2% in 50 years. These maps, by design, identify *M*-*R*-$\varepsilon$ values for the mean peaks. The identified dominant seismic event has a magnitude *M* equal to 6.040 with an epicentral distance of *R* of 5.770 km (Figure 5). The Sabetta and Pugliese attenuation law [14] provides directly the *PGV* value as function *M* and *R*, modified by local soil conditions:

$$Log\,PGV = -0{,}828 + 0{,}489M - Log\sqrt{R^2 + 15{,}21} + 0{,}116 \tag{7}$$

The PVG value is 25.04 cm/s and is constant across the entire region of interest.

### 3.3 Earthquake damage to water pipelines

In the common vulnerability approaches, the pipeline damage is typically expressed as the number of repairs occurring per unit length of the pipeline itself. Such method for seismic behavior of pipelines is based on studies of past earthquake scenarios and related pipelines response. The linear model adopted in the case study is fostered by the American Lifeline Alliance (ALA) in their guideline [15]. The pipe damage caused by wave propagation is related to the *PGV* value, as reported in the equation below:

$$RR = K_1 \cdot a \cdot PGV \tag{8}$$

where $RR$ is the repair ratio, that is the expected number of pipe breaks per 1000 m of pipe; $K_1$ is a coefficient depending on pipe material, pipe diameter, joint type, and soil condition, and it is equal to 0.5 for ductile iron pipes; $a$ = 0.001425 [16]; and $PGV$ is the peak ground velocity expressed in m/s. The $RR$ value corresponds to 0.00018.

The method used herein to detect the probability of failure of single pipes is similar to the procedure developed by [17]. The failure probability $P_{f,j}$ of a pipeline can be expressed by the Poisson probability distribution, as follows:

$$P_{f,j} = 1 - e^{-RR \cdot L} \tag{9}$$

where $RR$ is the repair ratio given by Equation (8); $L$ is the length of pipe; and $e^{-RR \cdot L}$ is the probability of zero breaks along the pipe. The equation is memoryless disregarding any failures that may have occurred along the pipeline in the past [16]. The average probability of failure of at least one pipe in the WDN is $P_{f,j}$ = 0.089.

Physical damages regard only the pipelines, while damage to the facilities (e.g. tanks, reservoirs, etc.) is not considered in this study. The seismic wave propagation induces axial and bending strains to pipelines due to the interaction at soil-pipe interface: if the pipe doesn't have the necessary strength, these deformations could produce damages (the bending strains are neglected). In this study the attention focuses on breaks on continuous pipelines because this type of damage produces the worst operating condition due to the total separation of the pipe.

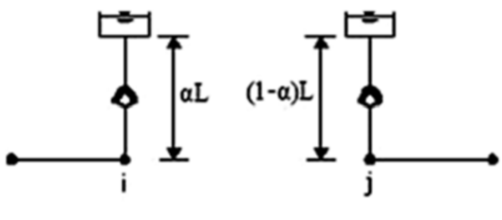


Figure 6: Pipe break simulation in EPANET 2.0 [18].

Breaks are modeled in EPANET 2.0 using the scheme shown in Figure 6: the original pipe is divided into two equal parts, because it is assumed that the break occurs in the middle point of the pipe. At the end of the two parts, two reservoirs are added in order to simulate the water flow through the break. The reservoirs have a total head equal to the elevation of the point break (this elevation is evaluated with a linear interpolation between the two nodes of the original pipe). A check valve is inserted on each new pipe such that water can only flow from breaking pipe to the reservoirs.

### 3.4 Selection of Scenarios

Resilience is an integrating concept that considers together multiple risks, shocks, stresses and their impacts on communities. The uncertainties that dominate the problem of risk management at the same time affect the resilience analysis [19]. It makes crucial the use of scenarios.

It is assumed that, in each scenario, more pipes break simultaneously, thus to identify which ones fail a computational code in MATLAB, promoted by Fragiadakis, is used. Information about pipelines are included into the platform: diameters, lengths, start and end nodes, and the failure probability $P_{f,j}$ computed with Equation (9) The importance factors linked to the pipelines relevance are also added: a value of 2 is given to the main pipeline, the pipes within the districts are set with a value of 1.5, and an importance factor equal to 1 is bestowed to the connection pipes between the districts.

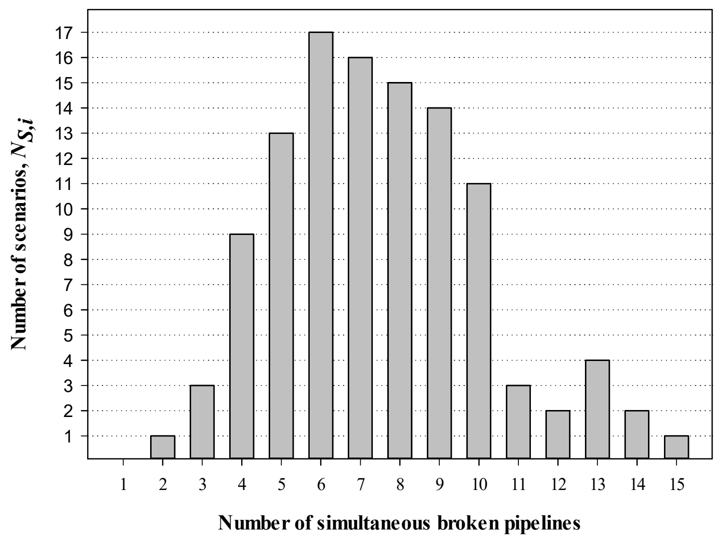


Figure 7: Distribution of scenarios evens. The total number of scenarios is 111.

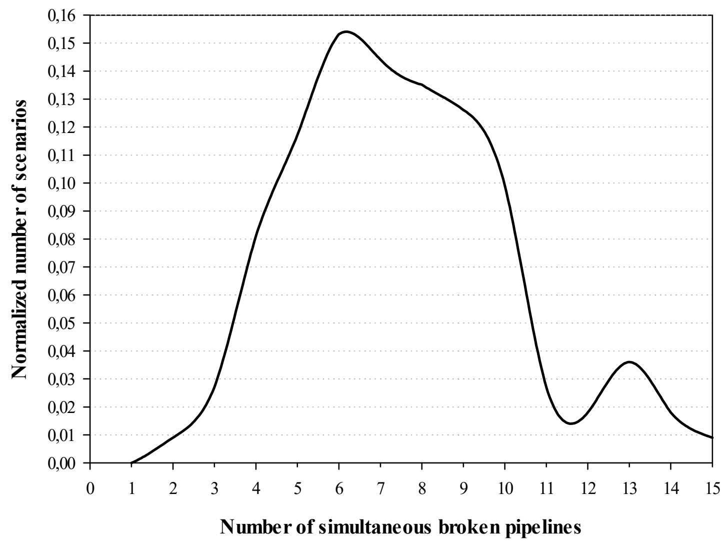


Figure 8: Normalized distribution of scenarios events.

The sufficient number of scenarios $N_S$ necessary to obtain an accurate estimation of the probability $P_{f,j}$ is computed using the relation promoted by [20] as follows:

$$N_s = \frac{1}{P_{f,j} \cdot \delta_o^2} \tag{10}$$

where $\delta_O^2$ is the required accuracy (set to 100%). The required sample size is equal to 111 scenarios. Using a script based on pipelines properties, the pipes that fail for each scenario are identified. Figure 7 shows the number of scenarios that have a certain number of broken pipes. As can be deduced from the distribution, there are no cases in which less than two pipelines break simultaneously, and this result is fully consistent with the initial assumption. Furthermore, the 17 possible scenarios characterized by 6 pipes failed represent the peak of the distribution. The maximum number of pipes that can fail simultaneously is 15. Figure 8 displays the normalized distribution of scenarios events.

### 3.5 Numerical Results of simulations

In order to obtain the previously introduced resilience index value, a particular procedure is applied. During normal operating conditions, the standard procedure to evaluate the pressure at nodes and the flow in each pipe is called Demand Driven Analysis (DDA): demand flow is fixed a priori in each node and the software provides the same value of demand flow even if the pressure is below the value necessary to satisfy that demand. The approach is correct if no problems occurs in the network.

Once the DDA is run, the values of pressures at nodes and water velocities into pipes are compared with the Italian prescriptions [21, 22]. Pressures at nodes comply with the provisions. None of the junctions suffer a pressure lower than 20m of column of water, even during low water demand. The highest flow velocities are observed at 7:00 AM and 9:00 AM. During these hours, flow velocities in few pipes reaches maximum values of 2 m/s. Some distribution pipes experience velocities less than 0.50 m/s, but more than 0.46 m/s during the lower demand conditions. Design velocity should be a maximum of 2 m/s and a minimum of 0.5 m/s.

Given that in this study the model is supposed to suffer several breaks, pressures could be insufficient at some nodes. For this reason, in case of breaks a Pressure Driven Analysis (PDA) procedure is used: firstly, with the damaged pipes in the distribution model, a DDA analysis is started; if there are some nodes with pressure below the necessary to satisfy the demand flow, these are converted in Emitter nodes [6]. An Emitter is a node in which demand flow depends on pressure according to the equation below:

$$Q_i = C_i \left( H_i - z_i \right)^{\alpha} = C_i \cdot p_i^{\alpha} \tag{11}$$

where $Q_i$ is the actual demand flow; $C_i$ is the emitter coefficient; $H_i$ is the actual total head of the $i_{th}$ node; $z_i$ is the elevation of the $i_{th}$ node; $p_i$ is the actual pressure of the node; and α is the emitter exponent (in absence of other information is equal to 0.5). To obtain the emitter coefficient is sufficient to impose the following equation:

$$C_i = \frac{Q_{demand}}{\left( H_{r,i} - z_i \right)^{\alpha}} = \frac{Q_{demand}}{p_{r,i}^{\alpha}} \tag{12}$$

where $Q_{demand}$ is the demand flow; $H_{r,i}$ is the total head necessary to satisfy $Q_{demand}$; and $p_{r,i}$ is the pressure necessary to satisfy $Q_{demand}$. Once all Emitters are inserted, the whole system is solved again.

For this study, 20 m of water column is the pressure necessary to satisfy demand flow in each nodes. The PDA is applied during Phase I and Phase II (Figure 1), and, ought to the variable demand flow is steady within the time step selected, this procedure is adopted for the different time steps included in these phases: for example, for the Phase I, which lasts two hours, the PDA procedure is applied two times with two different values of demand flow corresponding to these time steps.

For the computation of $F(t)$ for the entire system, the global equivalent utilities $n_e$ that suffer the lack of water are considered equal to the sum of the equivalent utilities $n_e$ of the districts affected by the failures of the pipelines. The Recovery Time, in this case, is assumed constant for all the simulations: after the earthquake, according to this paper, the first emergency operations, that is the isolation of the zones where the damaged pipes occur, are realized within 2 hours, while for the repair operations, if the diameter is less than 600 mm, it takes about 12 hours. Further 24 hours must be added, that is the time necessary to inform previously the population of the repair operations. Hence, the Recovery Time has been assumed equal to 38 hours. Finally, the $R$ for each scenario is computed. Table 1 summarizes the resilience index values according to Equation (5) for the different scenarios selected.

| Scenario | R | Scenario | R | Scenario | R | Scenario | R |
|---|---|---|---|---|---|---|---|
| 1 | 1.00 | 29 | 0.93 | 57 | 0,97 | 85 | 0,71 |
| 2 | 0.98 | 30 | 0.96 | 58 | 0,99 | 86 | 0,95 |
| 3 | 0.90 | 31 | 0.92 | 59 | 0,91 | 87 | 0,94 |
| 4 | 0.99 | 32 | 0.94 | 60 | 0,90 | 88 | 0,87 |
| 5 | 0.94 | 33 | 0.94 | 61 | 0,90 | 89 | 0,97 |
| 6 | 0.99 | 34 | 0.99 | 62 | 0,88 | 90 | 0,96 |
| 7 | 0.89 | 35 | 0.81 | 63 | 0,97 | 91 | 0,91 |
| 8 | 0.99 | 36 | 0,92 | 64 | 0,85 | 92 | 0,74 |
| 9 | 0.94 | 37 | 0,93 | 65 | 0,98 | 93 | 0,75 |
| 10 | 0.83 | 38 | 0,83 | 66 | 0,94 | 94 | 0,91 |
| 11 | 0.91 | 39 | 0,86 | 67 | 0,91 | 95 | 0,95 |
| 12 | 0.84 | 40 | 0,84 | 68 | 0,95 | 96 | 0,81 |
| 13 | 0.98 | 41 | 0,95 | 69 | 0,91 | 97 | 0,76 |
| 14 | 0.87 | 42 | 0,95 | 70 | 0,88 | 98 | 0,94 |
| 15 | 0.78 | 43 | 0,92 | 71 | 0,91 | 99 | 0,95 |
| 16 | 0.99 | 44 | 0,91 | 72 | 0,93 | 100 | 0,81 |
| 17 | 0.99 | 45 | 0,90 | 73 | 0,87 | 101 | 0,93 |
| 18 | 0.97 | 46 | 0,90 | 74 | 0,89 | 102 | 0,93 |
| 19 | 0.78 | 47 | 0,93 | 75 | 0,91 | 103 | 0,91 |
| 20 | 0.88 | 48 | 0,89 | 76 | 0,98 | 104 | 0,79 |
| 21 | 0.85 | 49 | 0,87 | 77 | 0,94 | 105 | 0,85 |
| 22 | 0.91 | 50 | 0,82 | 78 | 0,90 | 106 | 0,85 |
| 23 | 0.96 | 51 | 0,91 | 79 | 0,92 | 107 | 0,72 |
| 24 | 0.95 | 52 | 0,89 | 80 | 0,96 | 108 | 0,68 |
| 25 | 0.86 | 53 | 0,76 | 81 | 0,92 | 109 | 0,90 |
| 26 | 0.98 | 54 | 0,95 | 82 | 0,81 | 110 | 0,88 |
| 27 | 0.92 | 55 | 0,81 | 83 | 0,73 | 111 | 0,85 |
| 28 | 0.95 | 56 | 0,95 | 84 | 0,97 | | |

Table 1: Resilience Index Summary for Different Scenario Events.

Some observations can be immediately done: first of all, in every district exists a zone that, in case of damage, produces the worst consequences and, selecting an event rather than another one within this zone, it will cause the same effects; secondly, the peripheral areas have a minor influence within the district in case of pipe failure.

As expected, the lowest value of *R* index is obtained with Scenario 108 (Figure 9), which corresponds to failure of 13 pipelines, whose characteristics are listed in Table 2. In this case, the seven districts supplied by the main pipelines remain without water until the pipeline is repaired. This generates a drop of the function *F(t)* and therefore of *R*.

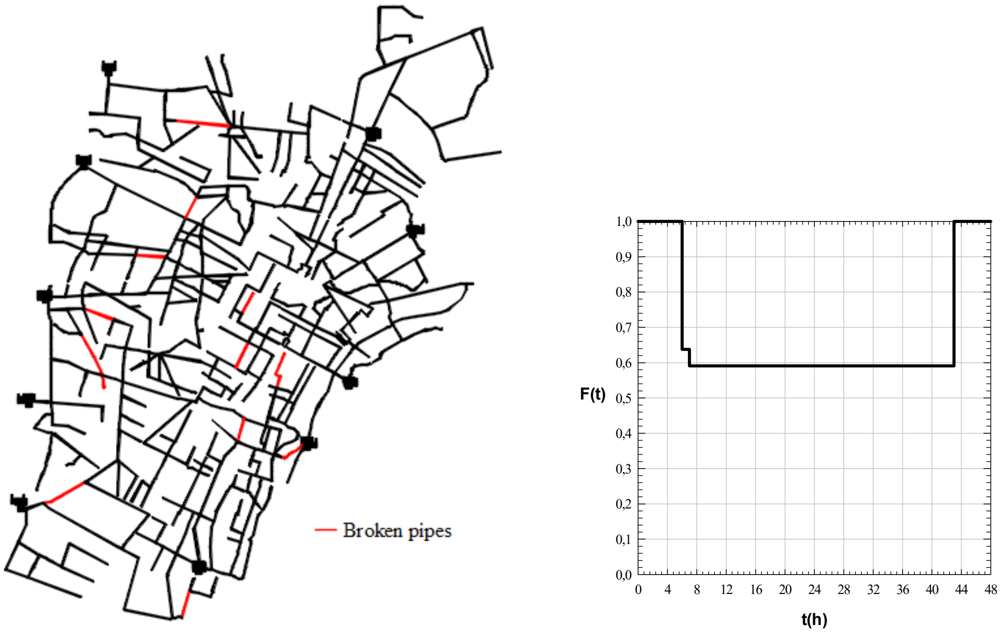


Figure 9: Scenario 108 - 4 broken pipelines. R = 0.68

| Pipe | District location | D (mm) | Average flow loss (l/s) |
|---|---|---|---|
| p52 | 1 | 300 | 161.26 |
| p77 | 1 | 100 | 17.03 |
| p89 | 2 | 400 | 536.08 |
| p135 | 3 | 125 | 37.38 |
| p151 | 3 | 400 | 1012.16 |
| p247 | 4 | 300 | 441.41 |
| p255 | 4 | 100 | 21.01 |
| p308 | 5 | 400 | 564.47 |
| p417 | 8 | 100 | 58.84 |
| p418 | 8 | 500 | 2132.55 |
| p448 | 8 | 100 | 149.75 |
| p510 | 10 | 200 | 220.81 |
| p516 | 10 | 150 | 34.17 |

Table 2: Characteristics of the broken pipelines in scenario 108.

## 4 CONCLUDING REMARKS

- In this study, the attention is focused on WDNs following the occurrence of extreme natural events such as earthquakes. In particular, the case study of the IDEAL CITY WDS is considered. After collecting and assuming all the useful information to describe the system structure and the seismic risk of the area, the index resilience *R* is identified. Its definition and the identification of its quantitative and qualitative dimensions have demonstrated that it is not just an intrinsic characteristic of the WDN but it also depends on the conditions in which the subject operates. Indeed, for its formulation, the definition of the function of functionality $F(t)$ and the recovery time $T_R$ are needed. This latter quantity is characterized by a high uncertainty. The main subject necessary to define the function of functionality $F(t)$ is the number of users that may have problems with the water supply (defined in this study equivalent utilities). The recovery time on utilities is assumed based on comparable situations. The global resilience index *R* of the distribution system is expressed taking under consideration the utilities numbers of all districts affected by all the simultaneous pipes failure.
- Through a vulnerability analysis of buried pipelines, different hypotheses are formulated about the main types of pipes failure, and breakages have been chosen because they produce the worst results in terms of pressure and flow rate lost.
- Different scenarios are selected using MATLAB, highlighting, through engineering considerations, the worst events within the distribution system. Analysis is performed with the use of the software EPANET 2.0 using the Pressure Driven Analysis (PDA) in which the flow rates delivered to the utilities are functions of pressures. At the end of the analysis, the results have been compared.
- The work is a starting point to design of different restoration plans in order to improve the resilience of the network. In the future, the method used to solve this network could be extended to a larger and more detailed one. Performing an analysis using a larger network could reveal more advantages and disadvantages. Furthermore, models will be added to take into account for risk and probability of failure of critical infrastructures due to extreme events (e.g. natural and manmade hazards). The main idea is to use IDEAL CITY to develop a virtual city that will serve as a hub for the development of further research models.

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