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RELIABILITY AND RESILIENCE OF WASTEWATER NETWORKS

T. Romanazzi[1] , V. Taurino[1], G.P. Cimellaro[2], M. Domaneschi[3], P. Gardoni[4]

ABSTRACT

The wastewater network is a critical infrastructure in a community and damages or disruption due to a hazard event implicate consequences in the economic security, public health and wellness of the community. Therefore, using an index to evaluate the vulnerability and the functionality of the system is essential for designers and utility managers for the design, operation and protection of wastewater network. In this paper, a functionality index for the wastewater network has been proposed that is the product of three different indices: (i) the number of users still connected to the system, (ii) the quality of sewer discharge into the water body after the treatment, in term of two pollutants, biochemical oxygen demand and total suspended solids, and (iii) the presence of leaks into the network. Seaside, a small city in Oregon, in the West cost of USA has been selected as case of study using an earthquake scenario and a restoration plan. The results show the critical elements of the networks that under the observed operating conditions would not be able to present reliable performances. Using the proposed indices in a decision support tool for governmental agencies could give guidelines for the restoration of elements that have more weight in the functionality of the system.

[1]Ms Student, Dept. of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Turin, I (email: veronica.taurino@polito.it)
[2]Associate Professor, Dept. of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Turin, I (email: gianpaolo.cimellaro@polito.it)
[3]Assistant Professor, Dept. of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Turin, I (email: marco.domaneschi@polito.it)
[4]Professor, Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana IL, USA (email: gardoni@illinois.edu)

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Reliability and Resilience of wastewater networks

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The wastewater network is a critical infrastructure in a community and damages or disruption due to a hazard event implicate consequences in the economic security, public health and wellness of the community. Therefore, using an index to evaluate the vulnerability and the functionality of the system is essential for designers and utility managers for the design, operation and protection of wastewater network. In this paper, a functionality index for the wastewater network has been proposed. It is the product of three different indices: (i) the number of users still connected to the system, (ii) the quality of sewer discharge into the water body after the treatment, in term of two pollutants, biochemical oxygen demand and total suspended solids, and (iii) the presence of leaks into the network. Seaside, a small city in Oregon, in the West cost of USA has been selected as case of study using an earthquake scenario and a restoration plan. The results show the critical elements of the networks that under the observed operating conditions would not be able to present reliable performances. Using the proposed indices in a decision support tool for governmental agencies could give guidelines for the restoration of elements that have more weight in the functionality of the system.

Introduction

The safety and the entirety of a community is constantly threatened by natural hazards like earthquakes, tsunamis, hurricanes, flooding etc. and disasters caused by the human being, such as explosions or terroristic attacks. In case of occurrence of such events, the safety of the people is in danger and the infrastructures are called to withstand to hazards and to preserve their functionality too.

Water [1] and wastewater network, transportation network [2], electric power network, communication network and information technology network [3] are among the critical infrastructure in our communities. The disruption of one of these networks may cause disruption to other networks and it may affect the wellbeing, social welfare and public health [4-5] of a community. Therefore, after the occurrence of a hazard, the functionality of these system can be compromised and a recovery process is due to reach quickly the nominal levels of functionality.

This paper deals with the reliability and resilience of a wastewater network (WWN) in seismic affected areas. Most of wastewater network components are buried under the earth and are vulnerable to the ground motion waves that induce deformations and liquefaction. The failure of the WWN can have a dramatic impact on the resilience and the public and environmental health.

In literature, Giovinazzi et al. [6] studied WWN functionality through seismic vulnerability factors for pipelines after the Canterbury earthquake sequence. A definition of wastewater functionality has been also given by Zorn and Shamseldin [7], subdividing the network in three subsystems and considering three different service levels.

A new performance index has been proposed in this study as the product of three components that allow to evaluate the functionality of the system and the restoration process in case of loss of function. Then, a case of study is considered for evaluationg the proposed methodology. It consists in Seaside, a small city of less than 7000 citizens in Oregon, in the West coast of USA.

Seaside is part of the NIST (National Institute of Standards and Technology) program for the community resilience. It is tested for Earthquake and Tsunami to better understand how a community can be prepared for these hazards, how it can adapt to changing conditions, withstand and recover rapidly from disruptions. The WWN of Seaside is modeled and studied for the first time in this work, however the water network, electric power network and transportation network are currently studied within the NIST program.

The WWN of the city of Seaside has been firstly modeled thanks to the data provided by City Engineer of Seaside. It contains the skeletonized model of the system, with all the connections of houses to the system and the location of pumps and their connections. The model has been improved adding new pipes for the parts of the city that in the system were not still connected. The wastewater treatment plant has been also implemented. A GIS file contains all the information of the network, such as length, slope, inlet and outlet nodes for pipes and depth, elevation and inflow for junctions. SWMM5.0, Storm Water Management Model, developed by EPA (US Environmental Protection Agency), is the software adopted to calibrate and evaluate the functionality parameters of the network. It is a dynamic rainfall-runoff simulation model used for the simulation of runoff quantity and quality for primarily urban areas.

The problem of functionality has been studied following a probabilistic approach and the model proposed by Guidotti et al. [8]. It is a framework to model dependent and interdependent networks and assess their resilience, for water network and electric power network. It is general and applicable to any dependent and interdependent networks subject to natural or anthropogenic. It consists in a probabilistic procedure that integrates models of damage, functionality and recovery. The procedure consists of the following six steps:

1. Generating a network model for the system.
2. Generating the hazard for the network area.
3. Assessing direct physical damage to network components.
4. Propagating the cascading effects due to dependencies to the network damage state.
5. Assessing functionality loss.
6. Predicting recovery time for network functionality.

The probabilistic aspect is present only in the damage and recovery curves of the elements, therefore, after the definition of the model and the hazard, an iterative simulation has been conducted to assess the damage, the functionality loss and to predict the recovery time.

The Monte Carlo simulation is the method used to derive the probability of failure of the network. In the end of the work are reported the functionality index of the network, the reliability and the resilience.

Types of WWN

The most common form of WWN in the U.S. consists of a system of sewers and wastewater treatment plants (WWTP). The sewers collect municipal wastewater and deliver it to facilities for treatment before it is discharged to water bodies or land. WWN is directly correlated to the storm water network, so there are two different configurations: (i) separated sewers (Fig. 1a), where the wastewater and the storm water network are separated. This configuration has the advantage that the dimension of pipes is minor than the combined system, and the WWTP is not subjected to excessive loads in case of storms. (ii) Combined sewers (Fig. 1b), where the wastewater and storm water flow in the same pipelines. This case is the most common in the US, but has an environmental issue in case of storm or flooding. If the capacity of the WWTP is exceed, part of the mix of sewage and storm water is directly load in the water body without treatment.

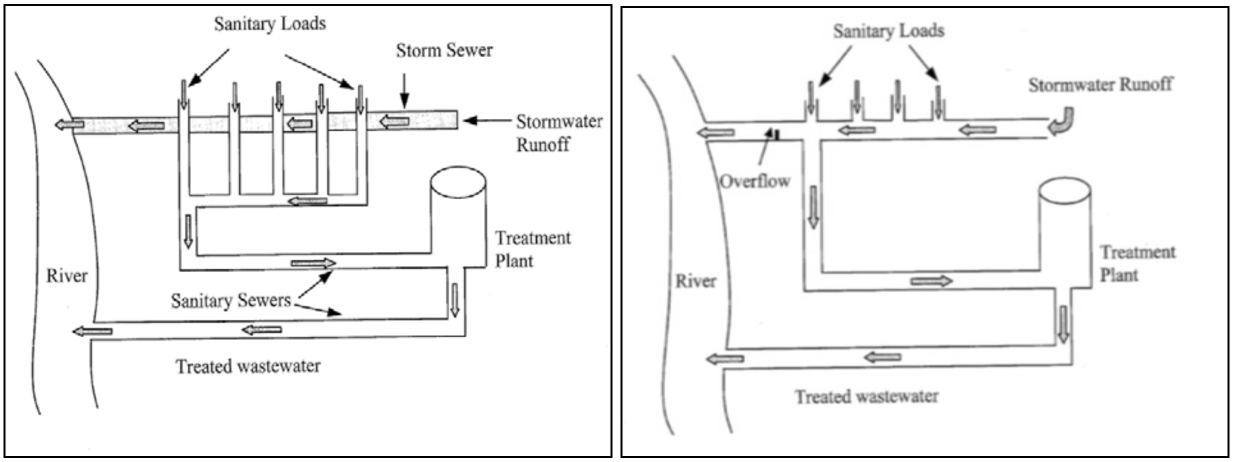


Figure 1. (a) Separated and (b) combined sewers.

Definition of a New Performance Index

The proposed index for the evaluation of functionality of a WWN is composed of three parts. The first part describes the functionality of the system as the number of demand points that are still connected to the system after the hazard:

$$Q_1 = \frac{n_{serv}}{n_{tot}} \tag{1}$$

where n_{serv} is the number of demand points still connected to the network after the earthquake; n_{tot} is the total number of demand points. It is a linear function of n_{serv}.

The second part of the index describes the functionality in term of quality of the discharge in the body water. Two different pollutant are taken into consideration, biochemical oxygen demand (BOD) and total suspended solids (TSS). The EPA thresholds for these pollutants are respectively 25 mg/l for BOD and 35mg/l for TSS. The corresponding functionality index is defined as:

$$\begin{aligned} &if\ P \le P_T \Rightarrow Q_2 = 1; \\ &if\ P > P_T \Rightarrow Q_2 = \frac{P_T}{P}; \end{aligned} \tag{2}$$

where P is the pollutant (BOD or TSS) concentration of the discharge; P_T is the pollutant threshold.

The third and last part of the index describes the functionality in term of leaking of the network:

$$Q_3 = 1 - \frac{V_{loss}}{V_{tot}} \tag{3}$$

where V_{loss} is the volume of network's leaks; V_{tot} is the load of the system, the volume of sewage drained into the network. Fig. 2 reports the components and their variation.

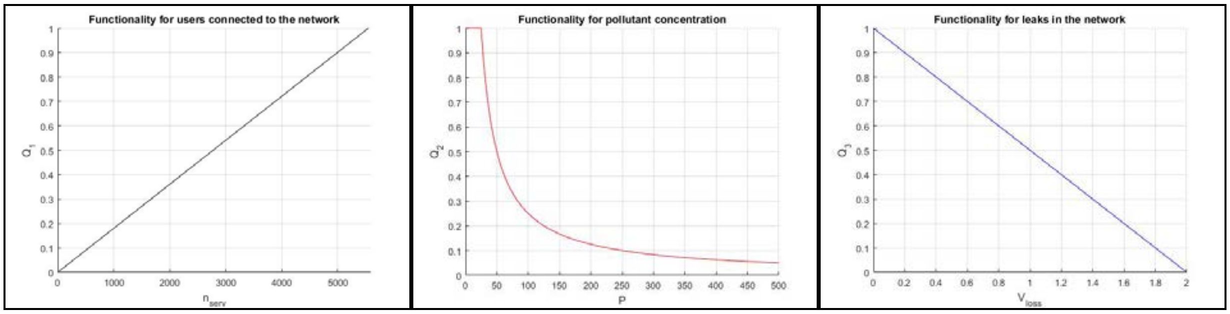


Figure 2. Components of the proposed functionality index.

Therefore, the total performance index is:

$$Q_{Tot} = Q_1 \cdot Q_2 \cdot Q_3 \quad (4)$$

Case Study

The city of Seaside is a small community in the west coast of U.S., located in the Clatsop County in Oregon. The city has a population of about 7000 people that becomes about 14000 people during the summer (Fig. 3).

Figure 3. Location of Seaside in US.

The City of Seaside provided wastewater treatment to the community since 1939. The average flow is one mgd (million gallons per day – about 3.8 million liters per day) and the system includes 21 pump stations to convey sewage from the collection system to the treatment plant. The treatment plant has a design capacity of 2.25 mgd and a maximum capacity of 6.75 mgd. The plant went into operation in 1986 and was updated in 2001 with the addition of a high intensity, ultraviolet light disinfection system [9].

The system by the City Engineer of Seaside in the form of AutoCAD file. This skeletonize model presented only the position of thee demand points and their connection. To assess WWN demand at each demand point two essential information has been integrated: (i) the population for each tax lot, provided by Social Science studies; (ii) data about average sewer load per person, that are provided by EPA (US Environmental Protection Agency). Once the total load of the system is known, the design of the physics properties of the system has been conducted due to the kinematic method.

Seismic Damage Model for Seaside WWN

The physical performance and functionality of the system after the hazard occurrence has been evaluated with a reliability simulation that includes the hazard modeling and the physical model of the damaged network. The probabilistic procedure followed in this paper is an application of the mentioned six-step procedure developed by Guidotti et al. [8].

The network model is generated following the kinematic method illustrated in the previous chapter. For the case study, the model consists of 5553 junctions, 5530 pipes, 21 pumps, 15 storage tanks, 1 WWTP (Fig. 4).

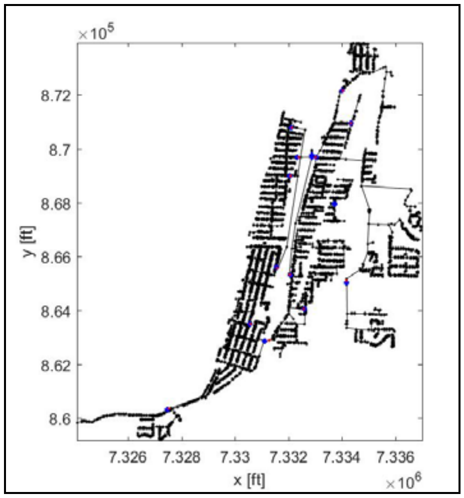


Figure 4. Network model of Seaside.

The main input for the software are the geometrical properties of the system (pipes, material, slope, depth, invert elevation, pump curves and tanks' dimensions), Dry Weather Inflow (the sewage load, Pollutant inflow (BOD and TSS). Time patters are applied to inflows.

Tanks, orifices and pipes are the main element to design the WWTP. The plant has been modeled by two tanks, one for the primary and the other one for the secondary treatment. The plant has a capacity of 1.5 mgd. Once the model of the WWN is complete, it is run the first simulation of EPASWMM to have the parameter of functionality for the pre-hazard model.

In the pre-hazard model, three parameters to check the functionality of the system have been considered: (i) no flooding in the junctions, (ii) the number of demand points that are connected to the system, (iii) the pollutant inflows in the water body. The primary and secondary treatments in the WWTP guarantee the purification of the sewage, however the outflows from the WWTP have still a concentration of BOD and TSS. EPA imposes that the thresholds are respectively 25 mg/l for BOD and 35 mg/l for TSS. The analysis of the pre-hazard model has shown that the Flooding Loss in the system is equal to zero. Furthermore, the External Outflow in term of pollutant are minor than EPA standards.

Generation of the hazard for the network

An earthquake of magnitude 6.5 located approximately 25 km southwest of Seaside in the Pacific Ocean is considered. Fig. 5 shows the maps of the PGD, PGV, and PGA. These have been obtained from the Fernandez and Rix (2006) Ground Motion Predicted Equations (GMPE).

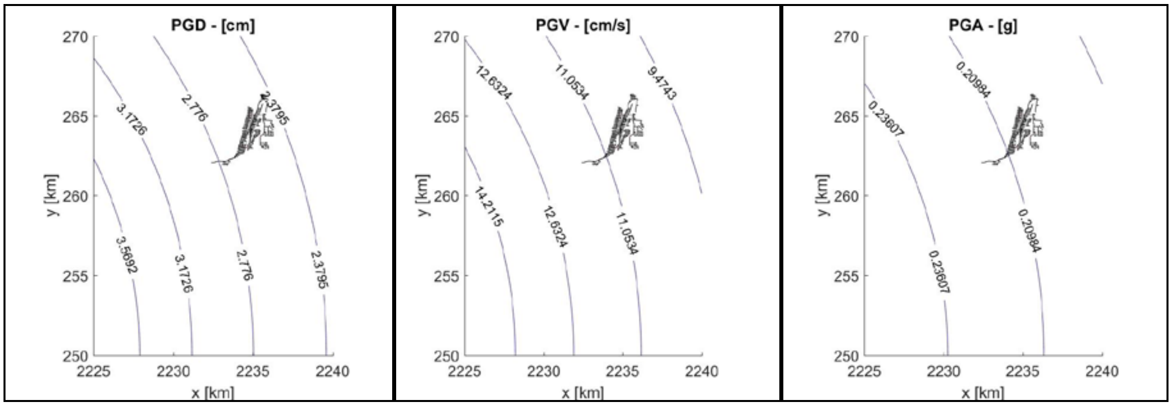


Figure 5. Ground motion prediction for the case study.

The intensity measures are applied to the WWN and the damage state is evaluated with fragility and repair rate from HAZUS-MH software [10].

The first step is the classification of each component: Lift station, Waste Water Treatment Plants small with capacity less than 50 mgd, Collection sewers (closed conduits that carry sewage - sanitary sewers, storm sewers, or combined sewers), Tank (capacity in the range of 0,5 mgd to 2 mgd).

The second step is the definition of the damage state of each component, and each component has different criteria to evaluate it. Indeed, for lift station and WWTP the critical values are those ones of PGA and sometimes PGD. Sewers are vulnerable to PGV and PGD. Five damage states are defined for components other than sewers and interceptors: None (ds1), Slight/minor (ds2), Moderate (ds3), Extensive (ds4), Complete (ds5). They have different definitions for each component of the system.

Damage functions and fragility curves are modeled as lognormally-distributed functions that give the probability of reaching or exceeding different damage states for a given level of ground motion and ground failure. Therefore, each damage state is characterized by a median value of ground motion and a dispersion factor (standard deviation). Fig. 6 shows the case of small WWTP.

For the damage state of pipes, empirical relations are provided. Those relations give the expected repair rates due to ground motion or ground failure. The concept of repair rate assumes a strong importance, and it is the number of pipe breaks per 1 Km of pipe. To reach a better quality of simulation each pipe has been divided into ten segments and the intensity measures have been determined at the end of each segment, so the repair rate of the pipe is the average value.

For sewers and interceptors are considered two damage states, leaks and breaks. Typically, a ground failure produces a break, while a ground motion produces a crushing.

Updating network damage state for dependencies is not taken into analysis in this study: e.g. the WWN has strong dependency with the Electric Power Network (EPN), for pumps and WWTP.

Peak Ground Acceleration			
Classification	Damage State	Median (g)	β
Plants with anchored components (WWT1)	slight/minor	0.23	0.40
	moderate	0.35	0.40
	extensive	0.48	0.50
	complete	0.80	0.55
Plants with unanchored components (WWT2)	slight/minor	0.16	0.40
	moderate	0.26	0.40
	extensive	0.48	0.50
	complete	0.80	0.55

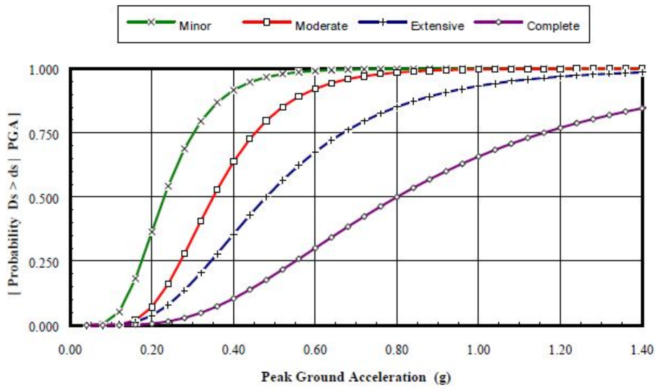


Figure 6. Damage Algorithms for Small Waste Water Treatment plant. Fragility Curves for Small Waste Water Treatment plant with anchored components.

Assess network functionality loss

The EPA-SWMM analysis is run to evaluate the impact of the event on the network. The connectivity model may be the first assessment of system performance, however the system, when damaged, may not satisfy prevent demands. Assessing the capacity of the system to provide the requirements, needs both the quantification of the capacity of the network and of the demand on the network. Therefore, the prediction of the post event demand is the most challenging aspect for the designer, because of the uncertainty in the human behaviors after the hazard. In this work, this aspect is not considered, because of insufficient data about human behavior in case of hazard event.

Class	Diameter from: [in]	Diameter to: [in]	# Fixed Breaks per Day per Worker	# Fixed Leaks per Day per Worker	# Available Workers	Priority
a	60	300	0.33	0.66	User-specified	1 (Highest)
b	36	60	0.33	0.66	User-specified	2
c	20	36	0.33	0.66	User-specified	3
d	12	20	0.50	1.0	User-specified	4
e	8	12	0.50	1.0	User-specified	5 (Lowest)
u	Unknown diameter	or for Default Data Analysis	0.50	1.0	User-specified	6 (lowest)

Figure 7. Restoration functions for WWS and curves for WWTP. Restoration strategy.

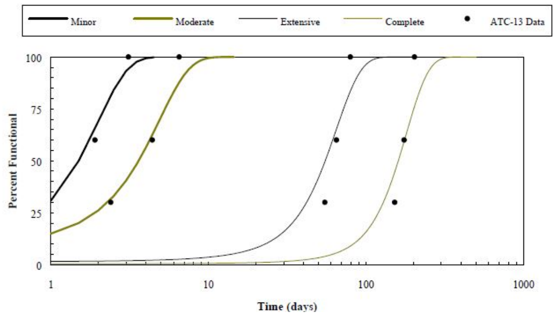
The network damage and functionality is update according to the restoration curves provided by HAZUS-MH software. In this study, ten time-steps have been considered: Time 0, right after the hazard event; 12 hours; 1 day; 1.5 day; 2; 2.5; 3; 7; 15; 30; 100 days.

The restoration curves for Waste Water system are based on ATC-13 expert data, and are given in form of dispersions of the restoration functions.

The restoration functions for pipelines are expressed in term of number of days needed to fix the damage, leak or break. In the table given by HAZUS the information is in term of break or leak fixed per day per worker, so the number of workers can be decided by the designer. In this work, a team of three workers is assumed.

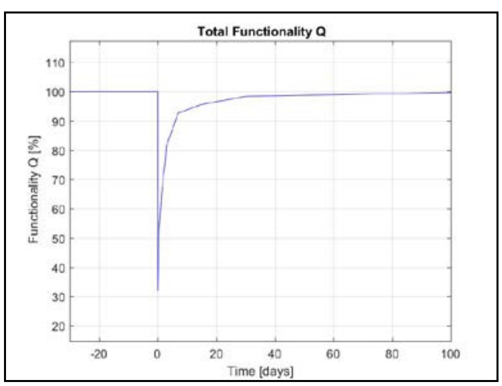
Another important concept for the restoration is the priority. Indeed, the WWTP, pumps and the pipes with highest diameter have a priority on the other elements (shutoff system).

Restoration Functions (All Normal Distributions)			
Classification	**Damage State**	**Mean (Days)**	**σ**
Lift Stations	slight/minor	1.3	0.7
	moderate	3.0	1.5
	extensive	21.0	12.0
	complete	65.0	25.0
Waste Water Treatment Plants	slight/minor	1.5	1.0
	moderate	3.6	2.5
	extensive	55.0	25.0
	complete	160.0	60.0
Sewers/Interceptors	See Section 8.1.7		



Results

The three functionality indices are evaluated through the numerical simulations. The first component Q_1 shows a recovery time of about thirty days, this because this one considers the points that are disconnected to the system. For the recovery strategy of the network the elements that have priority for the restoration are pumps and the main pipes, so the pipes with the largest diameter that represents the primary branches of the network. In addition, the location of the pipes, that are buried into the ground, makes difficult the research of broken elements. Therefore, the recovery time for this index of functionality needs more time than the next two indices. The second component Q_2 needs a recovery time of less than ten days. This index is totally dependent form the wastewater treatment plant. The third index Q_3 has a recovery time of about 8 days. The main leaking in the system are in the point where either a pump or a tank is damaged, so these kinds of element have priority in the restoration plan. Those are the points with the major values of flooding because the positions of pumps and tanks are exactly at the bottom of branch of pipes, so they collect great quantity of sewage and in case of damage higher is the quantity of sewage, higher is the flood. The recovery time is shown in Fig. 8 (about 30 days, accordingly with index component Q_1). In the same figure, the mean values of the total functionality index are reported. They represent the mean of the Monte Carlo simulation. The first value of performance is the system reliability, i.e. the functionality at time zero right after the event.



Time	Index
[days]	Q
0	0,320
0,5	0,532
1	0,597
1,5	0,663
2	0,718
2,5	0,751
3	0,814
7	0,927
15	0,956
30	0,978
100	1,000

Figure 8. Total functionality Q and Monte Carlo simulation outcomes (the mean values of the total functionality index).

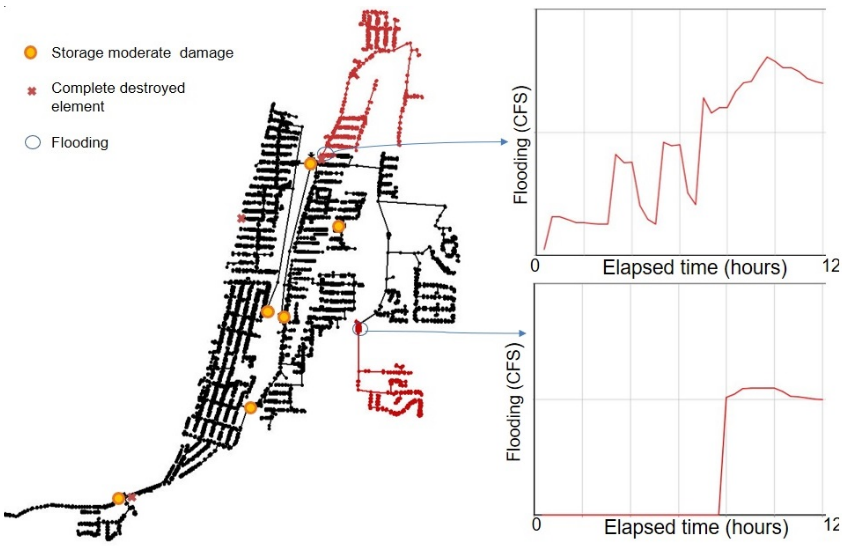


Figure 9. Single run of Monte Carlo simulation.

In Fig. 9 a single run of Monte Carlo simulation is reported. It has been randomly selected among 500 realizations. After the earthquake 10 pipes are destroyed, some show leaking, 5 tanks are damaged, 2 pumps are destroyed and 2 big branches of the system are disconnected to the network. WWTP has no damage. The functionality components $Q_{1\text{-}3}$ are: 0.86, 0.89, 1 respectively and Q = 0.76. In about 3 days the system recover its pre-event functionality (Fig. 10).

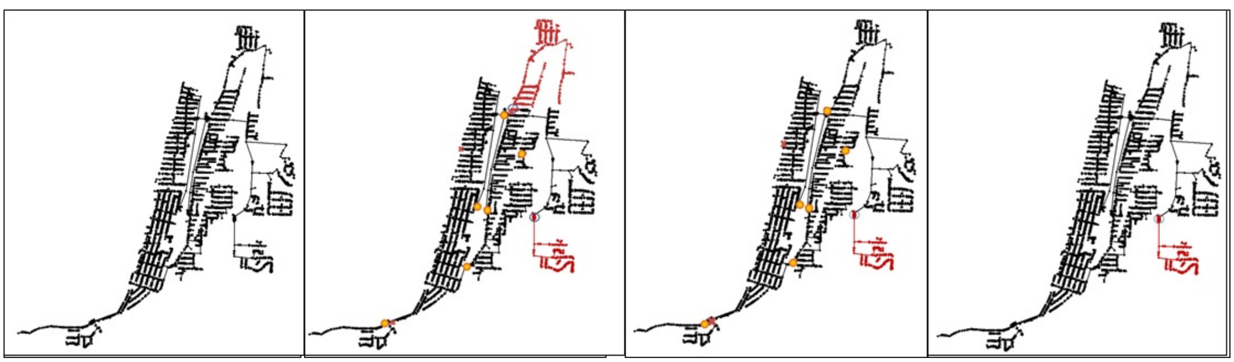


Figure 10. Pre-hazard, hazard time, after 12 and 36 hours. Total recovery at 72 hours.

The resilience index has been computed following the functionality evaluations. The total area has been normalized by the control time T_{LC} . Therefore, R=0.962 results (Fig. 11).

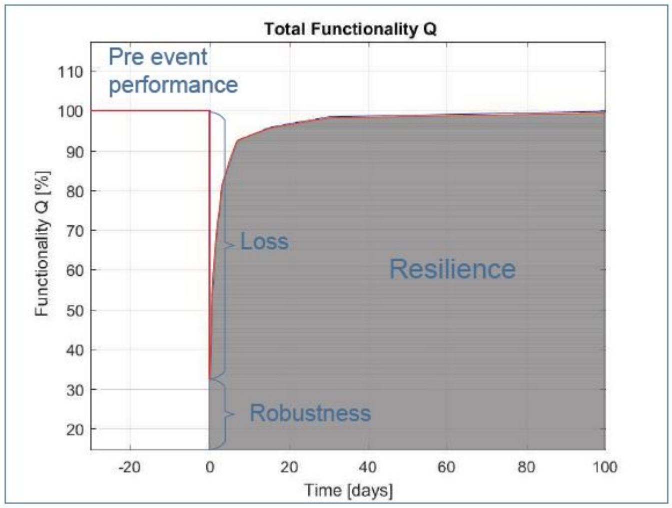


Figure 11. Resilience of Seaside.

Conclusions

The paper presents a probabilistic approach to analyze wastewater network resilience and the prediction of recovery time that includes physical damage and network functionality. A new performance index has been proposed, to evaluate the functionality of the wastewater network. The methodology has been applied to a case study of the Seaside city in Oregon.

This study is greatly influenced by the recovery strategy and fragility curves proposed by HAZUS-MH software. The main issue of these curves is that they have an elevated level of uncertainty, because they are based upon expert opinion.

Further studies will focus on considering the interdependencies of the wastewater network with the others network, such as water distribution network, electric power network, transportation network and socio-technical networks, to study the behavior of people after a hazard occurrence.

Acknowledgments

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