POLITECNICO DI TORINO

LAUREA MAGISTRALE IN INGEGNERIA EDILE

Reliability and Resilience of Wastewater Network

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Resume in Italian

In questo lavoro di tesi è presentato uno studio probabilistico di Reliability e Resilience relativo ad un impianto fognario. Tutte le infrastrutture infatti, sono costantemente minacciate da eventi naturali, come terremoti, tsunami, uragani, alluvioni, ma anche eventi antropologici come attacchi terroristici.

L'eventuale danneggiamento parziale o totale delle principali infrastrutture rappresenta un danno non solo economico, ma anche di salute e benessere per una comunità. L'impianto di smaltimento delle acque fognarie, come quello dell'acqua potabile, ha una importanza notevole per il benessere e la salute di una comunità, in quanto si occupa di smaltire rapidamente ed in sicurezza le acque reflue. Un eventuale danno alla rete o all'impianto di depurazione rappresenta un grande danno ambientale, considerando che la destinazione finale di queste acque è lo smaltimento in corpi ricettori idrici, nel sottosuolo e anche il riutilizzo per l'irrigazione.

Alla luce di questo aspetto, un nuovo indice di funzionalità per le reti fognarie è stato formulato in questo studio. Il nuovo indice prende in considerazion tre aspetti differenti, i punti ancora collegati alla rete dopo il terremoto, la concentrazione di sostanze inquinanti immesse nell'ambiente dopo il trattamento e la presenza di eventuali perdite nell'impianto.

Due differenti reti sono state studiate, la prima riguardante la città di Seaside, in Oregon, nella costa ovest degli Stati Uniti e la seconda relativa alla città virtuale Ideal City. Per entrambi i casi la metodologia di studio utilizzata è stata la medesima.

La prima parte del lavoro ha riguardato la creazione del modello della rete, che per Seaside è stata basata su dati reali provenienti dall' Ingegnere del "Sewer Department" della città di Seaside, i quali sono stati integrati con metodi presenti in letteratura per il calcolo di tutti i parametri geometrici necessari al corretto funzionamento di un impianto. Per Ideal City invece, i dati sono relativi alla città di Torino per quanto riguarda la popolazione, lo schema urbanistico della città e il posizionamento di elementi strategici come la centrale di trattamento delle acque reflue, mentree i dati geometrici anche in questo caso sono stati ipotizzati per la creazione di un modello il più possibile vicino alla realtà.

Le due reti sono state quindi analizzate con il software SWMM5.0 sviluppato dalla EPA (US Enviromental Protection Agency) per essere tarate e per verificarne la funzionalità nelle condizioni di esercizio.

In seguito è stato simulato un terremoto e sono stati registrati i valori di PGD, PGV e PGA a ogni elemento dell'impianto è sottoposto. La rottura di questi elementi è stata calcolata utilizzando delle curve di fragilità, in questo caso sono state adottate quelle proposte da HAZUS-MH software. Una analisi Monte Carlo è stata condotta per definire la rottura della rete da un punto di vista probabilistico, quindi 500 diversi casi possibili sono stati analizzati, ed è stata calcolata la funzionalità dell'impianto per ognuno di essi.

È stato infine calcolato il tempo di recupero delle due reti utilizzando delle curve di recupero anche in questo caso proposte da HAZUS-MH.

Dai risultati di funzionalità dei due impianti sono stati calcolati la funzionalità e la Resilienza dei due sistemi.

Abstract

The wastewater network (WWN) 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 WWN. In this paper, a functionality index (Q) for the WWN has been proposed, it is the product of three different indices: (1) the number of users still connected to the system, (2) the quality of sewer discharge into the water body after the treatment, in term of two pollutants, biochemical oxygen demand (BOD) and total suspended solids (TSS), and (3) 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.. . .

Chapter 1

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 one of these events, the safety of the people is in danger and the infrastructures are called to resist to the hazard and to preserve their functionality too.

Water and wastewater network, transportation network, electric power network, communication network and information technology network 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 of a community. Therefore, after a hazard occurs the functionality of these system is compromised and a recovery process is due to reach quickly the nominal levels of functionality.

The purpose of the thesis is studying the reliability and resilience of a wastewater network (WWN). Most of wastewater network components are buried under the earth and are vulnerable to the ground motion waves that induce deformations and liquefaction. Therefore, the failure of the network can have a dramatic impact on the resilience and the public and environmental health.

The rules to design and calibrated a wastewater network have been examined in the first part of the thesis with attention for the hydraulic of the pipes and for modeling the wastewater treatment plant.

A performance index was essential to reach the final goal of the work, so a new performance index has been proposed for our case of study. The index is defined as the product of three indices, 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(Q1), the second describes the functionality in term of quality of the discharge in the body water and the third index describes the functionality in term of leaking of the network. These indices evaluate the functionality of a wastewater system and the restoration process after the occurrence of a hazard.

Other studies about waste water network and its functionality have been conducted in the study of Liu et al., where the seismic vulnerability factors have been identified for pipelines after the Canterbury earthquake sequence. A definition of wastewater functionality is given by Conrad and Asaad (2016), they separate the network into three subsystems, i) collection, ii) treatment and iii) discharge and the overall functionality is given by the sum of the functionalities of the subsystems for three different service levels, normal, alternative and no service.

The cases of study are analyzed in the Chapter 6, a real city, Seaside and a virtual city called Ideal City. Seaside, a small city of less than 7000 citizens in Oregon, in the West coast of USA has been studied. 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 wastewater network 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 in the NIST program.

The WWN of the city of Seaside has been firstly modeled thanks to the data provided by the city engineer Geoffrey Liljenwall, that 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 and all the system is connected to the wastewater treatment plant. A GIS file has been created to contain all the information of the network, such as length, slope, inlet and outlet nodes for pipes and depth, elevation and inflow for junctions.

Ideal city is instead a virtual community developed by the research group of Politecnico di Torino, that is coordinated by professor Cimellaro.

SWMM5.0, Storm Water Management Model2004b, 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 that has been adopted is the one proposed by Guidotti et al. (2016). It isa framework to model dependent and interdependent networks and assess their resilience, for water network and electric power network.

The framework proposed by Guidotti et al. (2016) has a general approach, that is 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.Board, 2004

Chapter 2

DESIGN A WASTEWATER NETWORK

The most common form of pollution control in the U.S. consists of a system of sewers and wastewater treatment plants , which generate a wastewater network. The sewers collect municipal wastewater from the cities and deliver it to facilities for treatment before it is discharged into water bodies or land. Wastewater network is directly correlated to the storm water network, so there are two different configurations:

1. Separated sewers (Figure 2.1), 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.

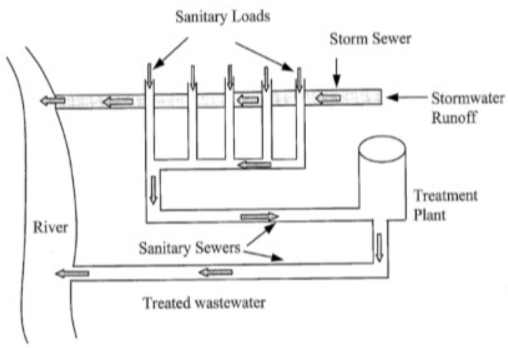


FIGURE 2.1: Separate sewer network.

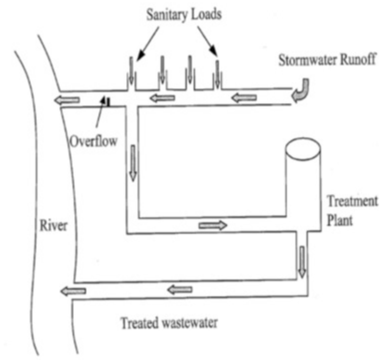


FIGURE 2.2: Combined sewer network.

2. Combined sewers (Figure 2.2), where the wastewater and storm water flow in the same pipelines. This case was 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.

2.1 Sewer

The sewer system has the purpose of carry the sewage from the buildings to the WWTP, and is made by pipelines, pump systems and tanks. The system has been designed using the kinematic method. The inputs of the method are:

- Sewer load for each point;
- Length of the pipes;
- Diameter of the pipes;
- Slope of pipes.

The diameters and the slopes of the pipes are unknown, therefore the model implements standards and indications present in literature. The minimum size for gravity sewer shall not be less than 8 inches (200 mm) in diameter and the slope shall give mean velocities, when flowing full, of not less than 2 feet per second. Slopes for pipes are usually:

- 1% for initial section, that is the connection between a house and the collection system;
- 0,5% for the halfway sections;
- 0,2-0,3% for main sewer, that connects the collection system to the WWTP.

Therefore, the method consists of guessing a diameter and a slope for a pipe and verify:

1. The velocity at least in the peak condition is larger than 2 feet per second (0,6 m/s);
2. The pipe is partially full, the hydraulic diameter is less than the 75% of the diameter;
3. The tractive force for the minimum flow should exceed the critical shear stress of 2 MPa to reach the self-cleansing condition.

The flow has been calculated using the Manning's formula, defined as:

$$Q = \frac{k}{n} \cdot R_h^{\frac{2}{3}} \cdot S^{\frac{1}{2}} \cdot A \tag{2.1}$$

where is the flow, is a conversion factor between SI and the Imperial units, is the Manning coefficient, is the hydraulic radius, is the slope and is the pipe's section.

2.2 Wastewater Treatment Plant

The wastewater treatment plant is the other important part of a wastewater system to reach the final goal of leading into the waterbody the purified sewage. This aspect has a critical importance, because of the environmental impact of the sewage in case of issues in the purification process. Thank of it, we can use our rivers and streams for fishing, swimming and drink water. Water pollution issues now dominate public concerns about national water quality and maintaining healthy ecosystem. The main function of WWTP is to speed up the natural processes by which water purifies itself A wastewater treatment plant usually is made of two different treatment,

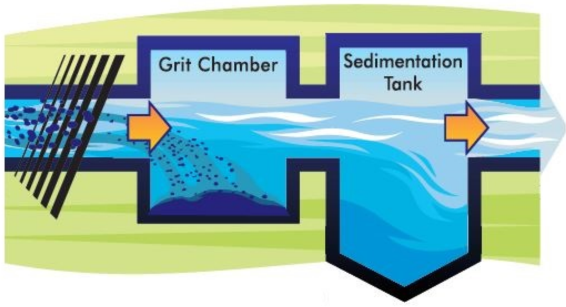


FIGURE 2.3: Primary treatment.

primary and secondary treatment. Primary treatment is the initial stage in the treatment of domestic wastewater.

- Preliminary treatment: sometimes a preliminary treatment is present before the primary and secondary treatment begins. A screen removes large floating object, such as cans, rags, bottles and sticks that may clog pumps and small pipes. The iron or steel screens vary from coarse to fine with openings of about half an inch. Sometimes plants use devices that have the double function of screen and grinder, so the pulverized matter remains in the wastewater flow to be removed in the primary treatment.

- Grit chamber: in this section sand, grit, cinders and small stones settle to the bottom. This treatment is very important in the combined sewer system, to remove the grit and gravel that washes off streets or land after storms. Copious quantities of grit and sand can cause operating problems like excessive wear of pumps, clogging of aeration devices and taking up capacity in tanks that is needed for treatment. The grit and screenings removed must be collected and trucked to a landfill for disposal or are incinerated.

- Primary sedimentation: wastewater contains suspended solids, made by minute particles of matter that can be removed with further treatment, and pollutants that are dissolved and are very fine and they are hardly removed by gravity. The wastewater enters a sedimentation tank and it slow down so the suspended solids sink to the bottom and make a mass called primary sludge.

Secondary treatment can remove up to 90 percent of the organic matter in wastewater using biological treatment. Two methods are usually used to achieve secondary

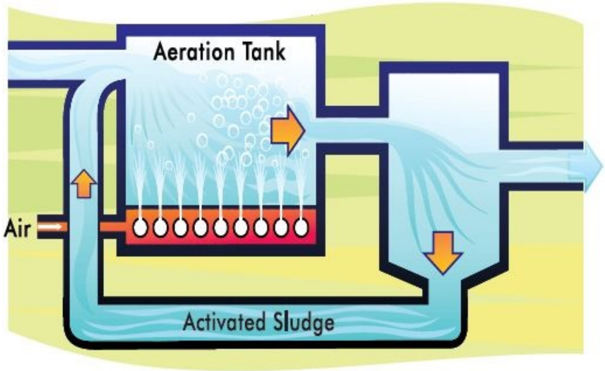


FIGURE 2.4: Secondary treatment, Suspended Growth Process

treatment:

a Attached Growth Process, where the microbial growth occurs on the surface of stone or plastic media. Wastewater passes over the media along with air to provide oxygen. This method includes bio-towers, trickling filters and rotating biological contactors.

b Suspended Growth Processes, which are designed to remove biodegradable organic material and organic nitrogen. The microbial growth is suspended in an aerated water mixture where the air is pumped in, or water is agitated to allow oxygen transfer. This method includes activated sludge, oxidation ditches and sequencing batch reactors.

Chapter 3

RESILIENCE AND RELIABILTY

Reliability and resilience are two important concepts in the analysis of the risk and in risk management.

3.1 Reliability

Probabilistic reliability analysis is a technique for identifying, characterizing, quantifying, and evaluating the probability of a pre-identified hazard. In most hydrologic, hydraulic, and environmental engineering projects, empirically developed or theoretically derived mathematical models are used to evaluate a system's performance. These models involve several uncertain parameters that are difficult to accurately quantify. An accurate reliability assessment of such models would help the designer build more reliable systems and aid the operator in making better maintenance and scheduling decisions.

The reliability of a system can be most realistically measured in terms of probability. The failure of a system can be considered as an event in which the demand, or loading L, on the system exceeds the capacity, or resistance R, of the system so that the system fails to perform satisfactorily for its intended use.[1]

The reliability analysis method used in this work is the Monte Carlo simulation.

[1] **Singh**; **2007**

3.1.1 Monte Carlo Simulation

Simulation is the process of duplicating the behavior of an existing or proposed system. It consists of designing a model of the system and conducting experiments with this model either for better understanding of the functioning of the system or for evaluating various strategies for its management. The essence of simulation is to reproduce the behavior of the system in every important aspect to learn how the system will respond to conditions that may be imposed on it or that may occur in the future.

For many systems, some or all inputs are random, system parameters are random, initial conditions may be random, and boundary condition(s) may also be random in nature. The probabilistic properties of these are known. For analysis of such systems, simulation experiments may be conducted with a set of inputs that are synthetically (artificially) generated. Each simulation experiment with a set of inputs gives an answer. When many such experiments are conducted with different sets of inputs, a set of answers is obtained. These answers are statistically analyzed to understand or predict the behavior of the system. This approach is known as Monte Carlo simulation (MCS). Sometimes, MCS is defined as any simulation that involves the use of random numbers.

The main steps in Monte Carlo simulation are:

- assembling inputs;
- preparing a model of the system;
- conducting experiments using the inputs and the model;
- analyzing the output.

The main advantages of Monte Carlo simulation are that it permits detailed description of the system, its inputs, outputs, and parameters. Following this approach, a Monte Carlo simulation has been implemented in the analysis.

It has been assumed that there is not uncertainty into the model, and there is no uncertainty into the realization of the hazard too. It is assumed that the location and the intensity of the earthquake is certain. However, the model in MatLab allows the presence of uncertainty for the hazard, but it is not the final goal of the work.

The uncertainty is only in the behavior of the components of the system, in term of fragility curve and repair rate. Therefore, the failure of an element is defined by the probability of exceeding a specific value and the probability of failure of a network is obtained after the hydraulic analysis of the damaged network.

Different versions of the damaged network are considered, and they are created removing the damaged elements. Many network realizations are necessary to have a good result of MC simulation, in this case five hundred.

3.2 Resilience

Resilience derives from the Latin word "resilio" which means to jump back and it has been used in several field such as ecology, social science, economy and engineering.

Engineering resilience is defined as the capability of a system to maintain its functionality and to degrade gracefully in the face of internal and external changes (Allenby and Fink 2005). Another important definition of resilience is given by Bruneau et al. (2003), where resilience is defined in term of four diverse types:

- Technical resilience that describes the capability of a system to perform correctly;
- Organizational resilience that describes the ability of the organization to manage the system;
- Social resilience that is the ability to cope the loss of service;
- Economic resilience that describes the capability to reduce economic losses.

A new framework to evaluate community resilience has been proposed by Cimellaro et al. (2010b), its name is PEOPLES that is the acronym for the seven major groups of the framework:

1. Population and demographics;
2. Environmental and ecosystem;
3. Organized governmental services;

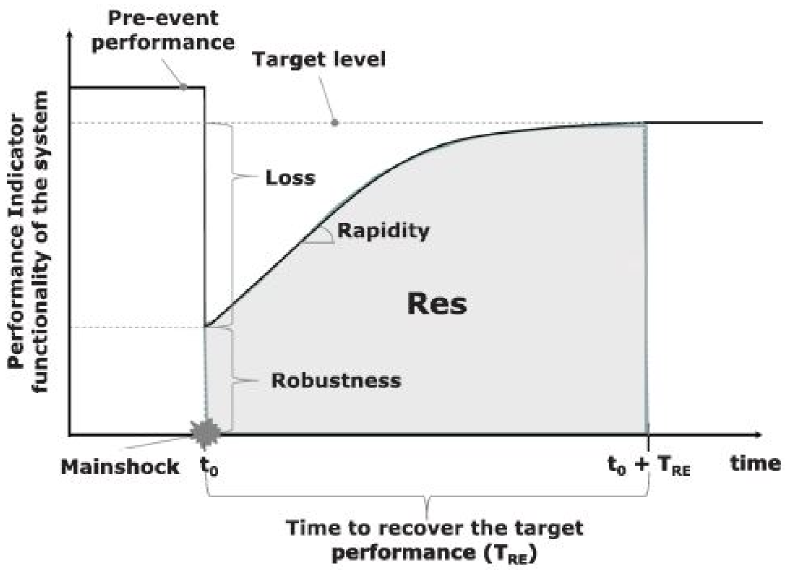


FIGURE 3.1: Functionality and Resilience

4. Physical infrastructure;
5. Lifestyle and community competence;
6. Economic development;
7. Social cultural capital.

A mathematical definition of resilience used in the thesis is the one proposed by Cimellaro et al. (2010a):

$$R(\vec{r}) = \int_{t_{OE}}^{t_{OE+}T_{LC}} \frac{Q_{TOT}(\vec{r},t)}{T_{LC}}\, dt$$

(3.1)

where Q_{TOT} is the global functionality function of the area considered, T_{LC} is the control time for the period of interest, t_O is the time instant when the event happens.

Two steps are very important in this formulation:

1. Definition of the spatial scale of the problem, in fact disasters usually produce damages into different and large spaces, that could be an individual building, a city or a state;

Functional Category	Event Occurs	0 - 24 hours	1 - 3 days	3 - 7 days	1 - 2 weeks	2- 4 weeks	1 - 3 months	3 - 6 months	6 - 12 months	1-3 years
WATER SYSTEM										
Backbone transmission facilities (pipelines, pump			R	Y	G					
Water for fire suppression at key supply points		G								
Water for fire suppression at firehydrants				R	Y		G			
Potable water at supply (WTP, wells, impoundment)			R		Y		G			
Water supply to critical facilities (hospitals, etc.)			R	Y	G					
Drinking water available at community distribution				G						
Distribution system				R	Y		G			
WASTEWATER SYSTEM										
Threats to public health and safety controlled by containing & routing raw sewage away from public			R	Y	G					
Backbone collection facilities (majortrunk lines and pump stations)			R	Y		G				
Treatment plants operating with primary treatment and disinfection			R	Y		G				
Treatment plants operating to meet regulatory requirements						R	Y		G	
Collection system						R	Y		G	

FIGURE 3.2: Example Urban/Suburban System Performance Goals for Expected Earthquake Event (Adapted from OSSPAC,2003)

where green, yellow and red represent respectively 90%, 60% and 30% of restoration.

2. Definition of the temporal scale of the problem, the control period affects particularly the resilience index.

The spatial scale of the problem is the total system of seaside, so it is a city scale for the study of the thesis.

To define the temporal scale, and in particular the control period, it has been adopted the indications of the Disaster Resilience Framework that gives guidelines for water and wastewater analysis

Therefore, following the indications of the table, the target is reaching the total functionality in about 6-12 moths for treatment plants and collection systems. The control time TLC has been assumed of 6 months for the case of study.

Chapter 4

DEFINITION OF A NEW PERFORMANCE INDEX

An index to evaluate wastewater system performance has been propesd by Zorn et al. (2016), where the wastewater is devided into three service categories:

1. Collection service, that represents wheter wastewater produced at each connection point is collected;
2. Volume, that is the colume of wastewater produced at each connection compared with pre-event volumes;
3. Treatment quality, that is the treatment and discharge of wastewater compared with pre-event standards.

Each category contains three service levels:

1. no service;
2. alternative service;
3. normal service.

The examine the overall functionality, the level of service indicators are aggregated over the service categories, so for the jth service category over time t, the fractions of the system receiving each level of service are normalized by the maximum attainable level of service to have fractions of normal service $n_{j,x}$, alternative service $n_{j,x}$ and no service.

A new performance index is proposed in this work. It 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:

$$Q_1 = \frac{n_{serv}}{n_{tot}} \tag{4.1}$$

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.

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:

$$if\ P \leq P_T \Rightarrow Q_2 = 1; \tag{4.2}$$

$$if\ P > P_T \Rightarrow Q_2 = \frac{P_T}{P}; \tag{4.3}$$

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:

$$\mathrm{Q}_3 = 1 - \tfrac{V_{loss}}{V_{tot}} \tag{4.4}$$

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.

Therefore, the total performance index is:

$$\mathrm{Q}_{Tot} = Q_1 \cdot Q_2 \cdot Q_3 \tag{4.5}$$

Chapter 5

CASE OF STUDY

5.1 Seaside

The main goal of the thesis is the study of the city of Seaside, a little 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.

Seaside is one of a group of communities that are 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.

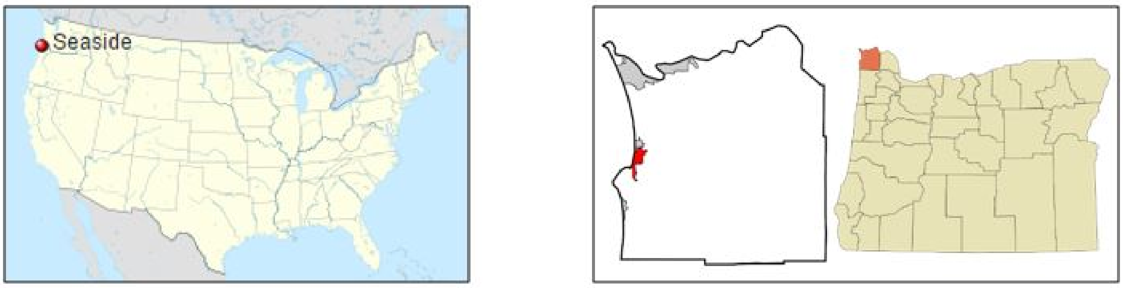


FIGURE 5.1: Location of Seaside in U.S. and in Oregon.

Residential

Location	gpcd	range
Rural Wisconsin	43	
Tampa, FL	51	26.1 - 85.2
Winnipeg, Manitoba	56	43-77
Seattle WA	57	
San Diego, CA	58	
East Bay, CA	60	
East Bay, CA	64	
Milwaukee, WI	64	
Boulder, CO	65	
Tampa FL	66	
Lompoc, CA	66	
Nationwide	66	57.3 - 73
Walnut Valley, CA	68	
Denver CO	69	
Las Virgenes, CA	70	

Residential, continued

Location	gpcd	range
Waterloo, Ontario	71	
Phoenix, AZ	71	65.9 - 76.6
Phoenix, AZ	78	
Stamford, CT	80	
Scottsdale.Tempe AZ	81	
Eugene, OR	84	
Los Angeles	90	
Morgan Hill, CA	--	79-114

Non-residential

Location	Unit flow
Stamford, CT	6-32 ged
Los Angeles, CA	30 ged
Oakland, CA	30 ged
Morgan Hill, CA	2450 gad

FIGURE 5.2: Standard sewage load in US

5.1.1 Wastewater Network

The City of Seaside has been providing wastewater treatment to the community since 1939. The average flow is one mgd (million gallons 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[1]. The system, as written into the introduction, was provided 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 was integrated:

1. The population for each tax lot, provided by Social Science studies;
2. 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 illustrated in the chapter 2.1.

[1] http://www.cityofseaside.us/departments-services/public-works/departments/sewer-department.

5.2 Ideal City

Ideal city is a virtual community developed by Politecnico di Torino, in particular by the research group of professor Cimellaro. This virtual city could be tested to studing the resilience of networks or community in case of large disaster.

The city is developed on the base of the city of Turin, (Figure 6.3) so the population is of about one milion of people. The wastewater network of Ideal City has been designed for this thesis following the criteria viewed in Chapter 2.

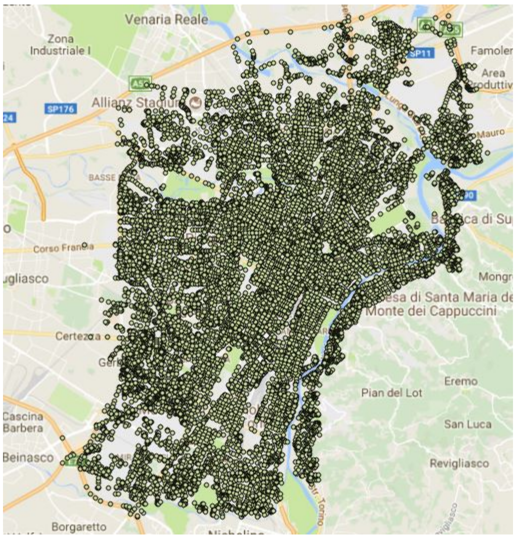


FIGURE 5.3: Ideal City

Chapter 6

SEISMIC DAMAGE MODEL FOR SEASIDE WASTEWATER NETWORK

The physical performance and functionality of the system after the hazard occurrence has been evaluate 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** Into the next subsections all the steps of the framework will be illustrate.

6.1 Generation of a network model

The two network models are generated following the kinematic method illustrated in the previous chapter. For the case study of Seaside, (Figure 7.1) the model consists of:

- 5553 junctions;
- 5530 pipes;
- 21 pumps;
- 15 storage tanks;
- 1 Wastewater treatment plant.

For Ideal City (Figure 7.2):

- 8512 junctions;

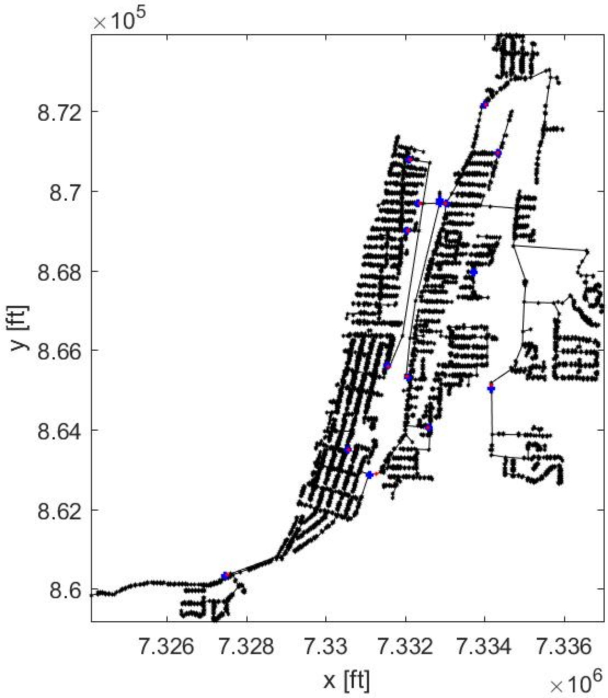


FIGURE 6.1: Wastewater network model of Seaside.

- 8368 pipes;
- 11 pumps;
- 14 storage tanks;
- 1 Wastewater treatment plant.

The main inputs for the software are:

- Geometrical properties of the system: diameter of pipes, material, slope, depth, invert elevation, pump curves and tanks' dimensions;
- Dry Weather Inflow, that represents the load for each junction, in term of sewage. All these loads have been multiplied for two time-patterns, one is a daily pattern, and the other one is an hourly pattern. In this way, the load is not constant during the day and the week;
- Pollutant inflow, two pollutants were considered:

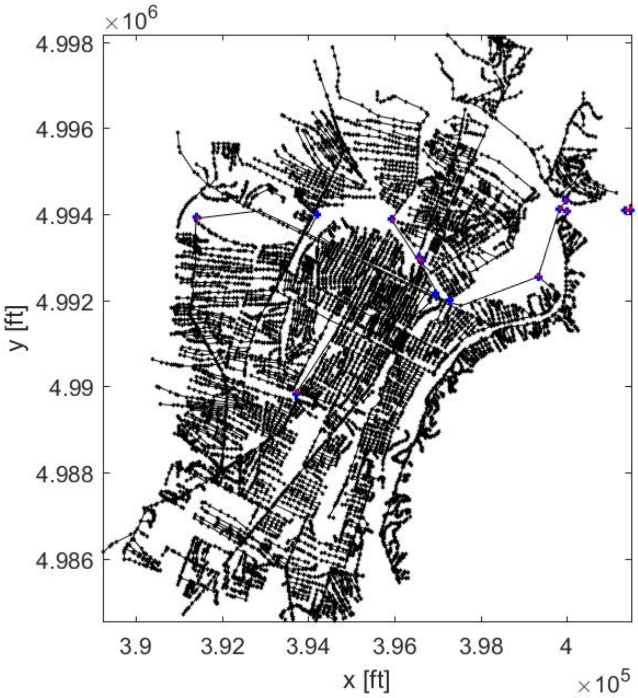


FIGURE 6.2: Wastewater network model of Ideal City.

1. BOD, Biochemical Oxygen Demand, that is the amount of dissolved oxygen needed by aerobic biological organisms to break down organic material present in each water sample;
2. TSS, Total Suspended Solids, that is the dry-weight of particles trapped by a filter.

The time patters are applied also to the pollutants inflows.

Tanks, orifices and pipes are the main element to design the wastewater treatment plant. 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. The treatment of the wastewater is reached due to the equations imposed for each tank, in fact for the primary treatment the fractional removed is the 25% an 50% respectively for BOD and TSS. For the secondary treatment, the fractional removed is 93% and 80% respectively for BOD and TSS. Pipes and orifices connect the two tanks and allow a constant flow.

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

```
**************************        Volume        Volume
Flow Routing Continuity         acre-feet      10^6 gal
**************************      ---------     ---------
Dry Weather Inflow .......          2.280         0.743
Wet Weather Inflow .......          0.000         0.000
Groundwater Inflow .......          0.000         0.000
RDII Inflow ..............          0.000         0.000
External Inflow ..........          0.000         0.000
External Outflow .........          1.359         0.443
Flooding Loss ............          0.000         0.000
Evaporation Loss .........          0.000         0.000
Exfiltration Loss ........          0.000         0.000
Initial Stored Volume ....          0.000         0.000
Final Stored Volume ......          0.955         0.311
Continuity Error (%) .....         -1.502

**************************            BOD           TSS
Quality Routing Continuity            lbs           lbs
**************************     ----------    ----------
Dry Weather Inflow .......       1983.481      2550.146
Wet Weather Inflow .......          0.000         0.000
Groundwater Inflow .......          0.000         0.000
RDII Inflow ..............          0.000         0.000
External Inflow ..........          0.000         0.000
External Outflow .........         29.813        60.285
Flooding Loss ............          0.095         0.123
Exfiltration Loss ........          0.000         0.000
Mass Reacted .............        361.140       489.533
Initial Stored Mass ......          0.000         0.000
Final Stored Mass ........        584.563       704.569
Continuity Error (%) .....         50.813        50.806
```

FIGURE 6.3: SWMM output file.

model, we have considered three parameters to check the functionality of the system:

1. No flooding in the junctions, that means that all the sewage loaded in the system reach the WWTP;
2. The number of demand points that are connected to the system;
3. 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 plant 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, (7.3).

Furthermore, the External Outflow in term of pollutant are minor than EPA standards (Figure 7.4 and Figure 7.5).

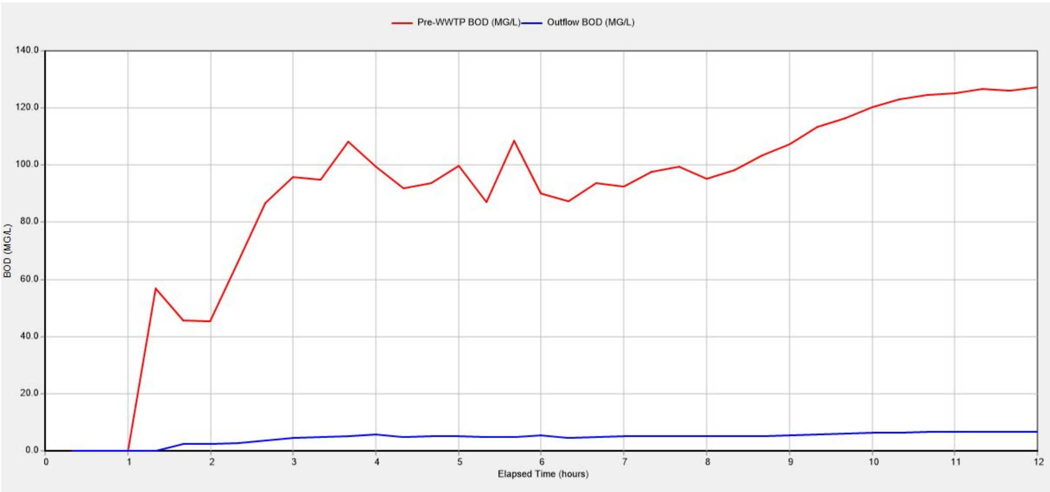


FIGURE 6.4: BOD concentration before and after the WWTP.

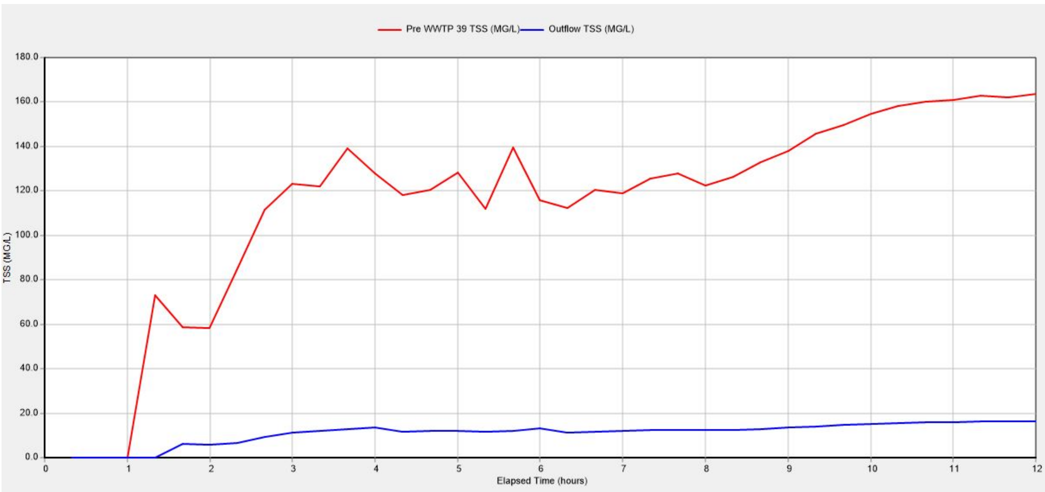


FIGURE 6.5: TSS concentration before and after the WWTP.

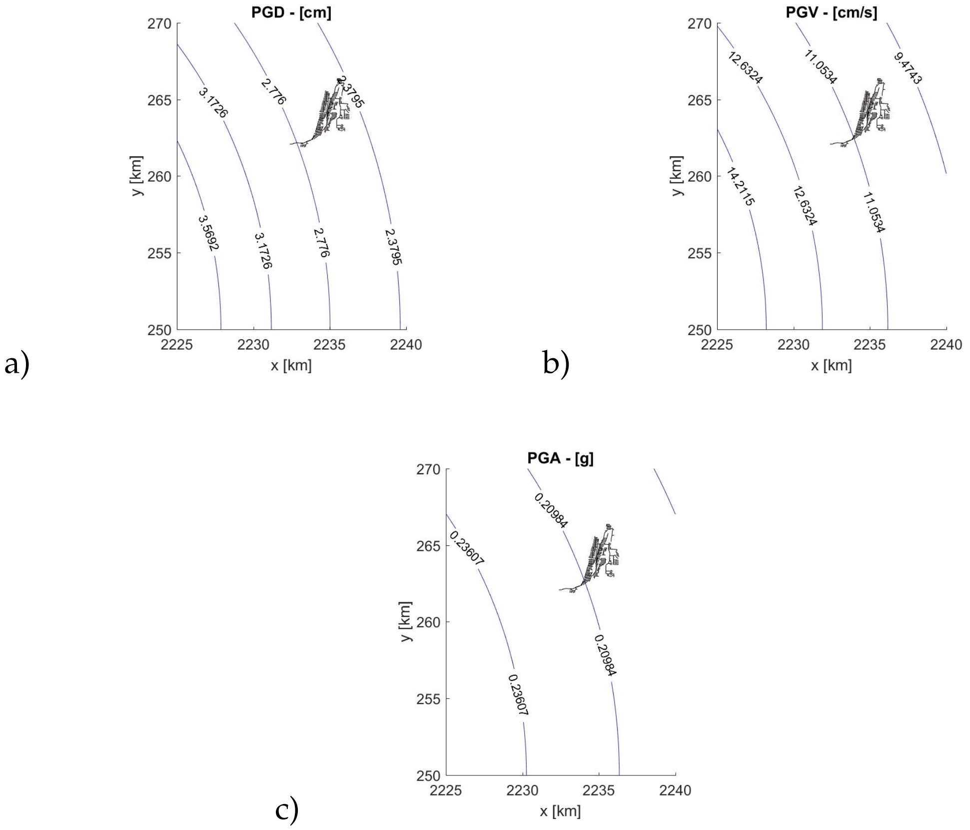


FIGURE 6.6: Ground Motion Predicted Equations for the case of study of Seaside: a) PGD; b)PGV; c)PGA

6.2 Generation of the hazard for the network area

Generate hazard for network area. We consider an earthquake of magnitude 6.5 located approximately 25 km southwest of Seaside in the Pacific Ocean. Figure 7.6 shows the maps of the PGD, PGV, and PGA. These have been obtained from the Fernandez and Rix (2006) Ground Motion Predicted Equations (GMPE). These three parameters are important to estimate the damaged state of the network.

This step has been analyzed using a MatLAB code that after reading the EPA-SWMM5.0 file, it generates the model, with all the positions, latitude and longitude, of the elements of the network. The code calculates all the intensity measures for the elements using the GMPE of Fernandez and Rix.

6.3 Assess physical damage of network components

The intensity measures are applied to the WWN and the damage state is evaluated with fragility and repair rate from HAZUS-MH software (FEMA,2003). The first step is the classification of each component:

- Lift station, that serve to raise sewage over topographical rises. Lift stations are classified in small if the capacity is less than 10 mgd, or medium/large if the capacity is greater than 10 mgd. Lift stations are also classified as having anchored or unanchored components, and in the model, there are only small lift stations with anchored components;
- Waste Water Treatment Plants, could be small if the capacity is less than 50 mgd, medium if the capacity is between 50 and 200 mgd, and large if the capacity is greater than 200 mgd. In the model, there is a small WWTP.
- Collection sewers, that are closed conduits that carry sewage (sanitary sewers, storm sewers, or combined sewers) with a partial flow. The classification parameter is the material of the pipe, that usually is clay or concrete pipes for storm water and sanitary sewers without corrosive substances.
- Tank can be elevated steel, on ground steel or concrete and both can be anchored or unanchored and buried concrete. Typical capacity is 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. In fact, for lift station and WWTP are important the values of PGA and sometimes PGD because these elements are mostly vulnerable to these two actions. Sewers are vulnerable to PGV and PGD and the damage algorithms are associated with those two ground motion parameters. Therefore, five damage states are defined for components other than sewers and interceptors :

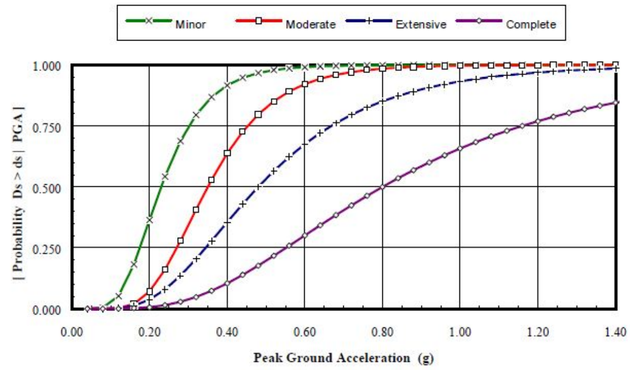
1. None (ds1);
2. Slight/minor (ds2):
    - For WWTP, it is defined by malfunction of plant for a brief time considered less than three days, due to loss of electricity;

- For pumping plants, it is defined by malfunction of plant for a short time due to loss of electric power and backup power;
- For storage tanks, it is defined by the tank suffering minor damage without loss of its contents or functionality.

3. Moderate (ds3):
   - For WWTP, it is defined by malfunction of plant for about a week due to loss of electric power and backup power if any, extensive damage to various equipment, considerable damage to sedimentation basins or considerable damage to chemical tanks. Loss of waste water quality is imminent.
   - For pumping plants, it is defined by the loss of electric power for about a week, considerable damage to mechanical and electrical equipment.
   - For storage tanks, it is defined by the tank being considerably damaged, but only minor loss of content.
4. Extensive (ds4):
   - For WWTP, it is defined by the pipes connecting the different basins and chemical units being extensively damaged and this damage will likely cause the shutdown of the plant;
   - For pumping plants, it is defined by the pumps being badly damaged beyond repair;
   - For storage tanks, it is defined by the tank being severely damaged and going out of service;
5. Complete (ds5):
   - For WWTP, it is defined by the complete failure of all pipes, or extensive damage to the filter gallery;
   - For pumping plants, it is defined by the building collapse;
   - For storage tanks, it is defined by the tank collapsing and losing of its content.

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

[a]



[b]

FIGURE 6.7: a)Damage Algorithms for Small Waste Water Treatment plant; b)Fragility Curves for Small Waste Water Treatment plant with anchored components

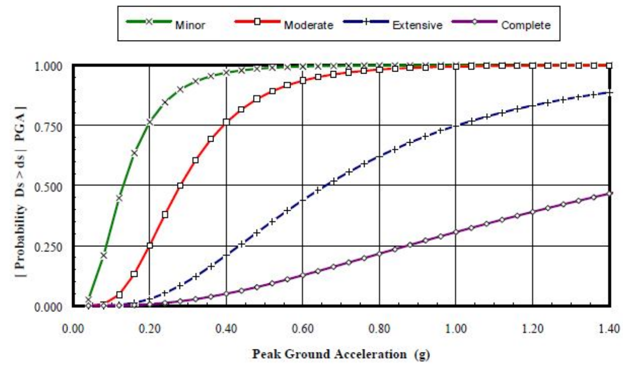
Damage functions and fragility curves are modeled as lognormally-distributed functions that give the probability of reaching or exceeding different damage states for a given level of ground motion and ground failure. Therefore, each damage state is characterized by a median value of ground motion and a dispersion factor (standard deviation), as shown in Figure 7.7 and Figure 7.8.

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

[a]

Peak Ground Acceleration			
Classification	**Damage State**	**Median (g)**	**β**
Plants with anchored subcomponents (PPP1)	slight/minor	0.15	0.70
	moderate	0.36	0.65
	extensive	0.66	0.65
	complete	1.50	0.80
Plants with unanchored subcomponents (PPP2)	slight/minor	0.13	0.60
	moderate	0.28	0.50
	extensive	0.66	0.65
	complete	1.50	0.80



[b]

FIGURE 6.8: a)Damage Algorithms for Small Pumping Stations; b)Fragility Curves for Small Pumping Stations with anchored components

crushing. It is assumed that damage due to seismic wave will consist of 80% leaks and 20% breaks, while damage due to ground failure will consist 20% of leaks and 80% of breaks. Therefore, there are two algorithms:

$$RR = K(0.0001) \cdot PGV^{2.25} \tag{6.1}$$

where is the Repair Rate, the number of pipe breaks per 1 Km of pipe, is a coefficient dependent on the pipe material, joint type, diameter and soil condition and is the peak ground velocity which has the units in cm/s.

$$RR = \Pr[liq] \cdot PGD^{0.56} \tag{6.2}$$

Where is the Repair Rate, the number of pipe breaks per 1 Km of pipe, is the probability of soil liquefaction and is the peak ground displacement which has the units of inches.

6.4 Update network damage state for dependencies

This step is not taken into analysis in this study, however the wastewater network has strong dependency with the Electric Power Network (EPN), for pumps and WWTP, the storm water network and the water network.

6.5 Assess network functionality loss

This step consists in assessing the functionality of the damaged networks. The EPA-SWMM analysis is run to evaluate the impact of the event on the network. In this step, the connectivity model may be the first assessment of system performance, however this is a not completely exact parameter, since the system, when damaged, may not satisfy prevent demands. Assessing the capacity of the system to provide the requirements, needs a 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 the thesis, this aspect is not considered, because of insufficient data about human behavior in case of hazard event. Hydraulic analysis is carry out in EPA-SWMM for all the damaged networks, therefore the output file of the MATLAB code (attached I) is used to generate a new input file to evaluate the functionality of the damaged network. The standards to evaluate the functionality have been already shown in Chapter 5.

6.6 Assess recovery time for network functionality

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:

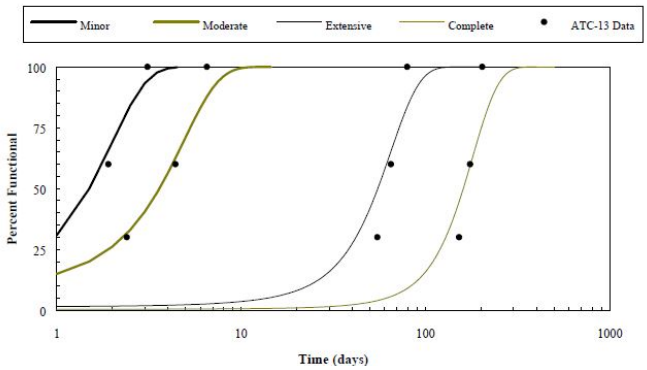
1. Time 0, right after the hazard event;
2. After 12 hours;
3. After 1 day;
4. After 1 and a half day;
5. After 2 days;
6. After 2 and a half days;
7. After 3 days;
8. After 7 days;
9. After 15 days;
10. After 30 days;
11. After 100 days.

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 the thesis in assumed a team of three workers.

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		

[a]



[b]

FIGURE 6.9: a)Restoration Functions for WWS components; b)Restoration Curves for WWTP

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 6.10: Restoration strategy and priorities

Another important concept for the restoration is the priority, in fact the WWTP, pumps and the pipes with highest diameter have a priority on the other elements. In fact, the larger pipes are the more important, because they are main collector that connect the system to the WWTP, so a damage in this part of system could mean a shutoff system.

Chapter 7

RESULTS

The results of hydraulic simulations of the systems are the data to evaluate the three functionality indices, so how it is described in the previous chapter we have defined the indices.

7.1 Seaside

The first index shows a recovery time of about thirty days, this because this one considers the points that are disconnected to the system. (Figure 8.1)

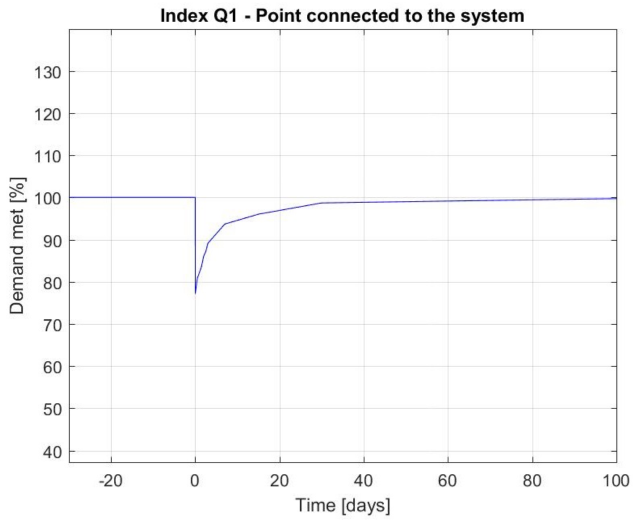
For the recovery strategy of the network the elements that have priority for the restoration are pumps and the main pipes, so the pipes with the largest diameter that represents the primary branches of the network. In addition, the location of the pipes, that are buried into the ground, makes difficult the research of broken elements. Therefore, the recovery time for this index of functionality needs more time than the other two indices.

The second index needs a recovery time of less than ten days (Figure 8.2). This index is totally dependent form the wastewater treatment plant, so a damage in pumps or treatment tanks compromises the functionality. This implicates that the recovery time is quite fast, because the wastewater treatment plant has the highest priority for all the system.

The third index has a recovery time of about 8 days (Figure 8.3). 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

Time [days]	Index Q_1
0	0.772
0.5	0.809
1	0.822
1.5	0.837
2	0.861
2.5	0.872
3	0.891
7	0.937
15	0.96
30	0.987
100	0.997

a)

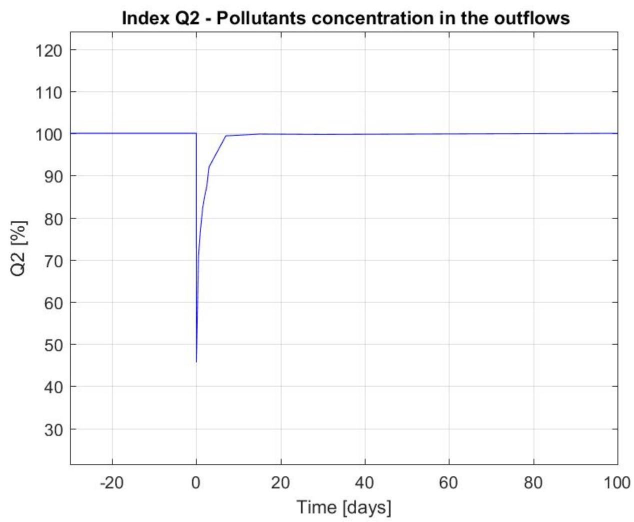


b)

FIGURE 7.1: a, Table of functionality term Q_1. b, Functionality term Q_1.

Time [days]	Index Q_2
0	0.457
0.5	0.707
1	0.774
1.5	0.823
2	0.852
2.5	0.875
3	0.92
7	0.994
15	0.998
30	0.997
100	1

a)



b)

FIGURE 7.2: a, Table of functionality term Q_2. b,Functionality term Q_2.

a)

Time [days]	Index Q_3
0	0.892
0.5	0.909
1	0.924
1.5	0.948
2	0.964
2.5	0.972
3	0.984
7	0.991
15	0.995
30	0.998
100	1

b)

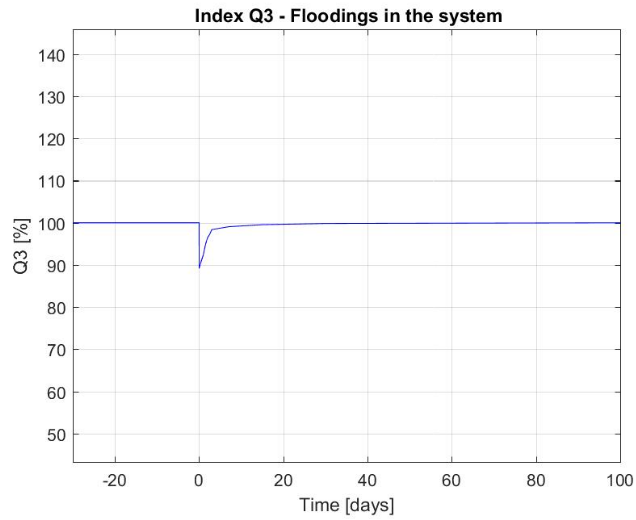


FIGURE 7.3: a, Table of functionality term Q_3. b, Functionality term Q_3.

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 total functionality recovery time, (Figure 8.4) in strongly dependent to the first index that has a larger recovery time, in fact for the total functionality the recovery time is about thirty days.

The mean values of the total functionality index are reported in the Figure 8.4, these values represent the mean of the Monte Carlo simulation. The first value of performance represents the reliability of the system, the value of functionality at time zero right after the hazard event.

7.1.1 Scenario

In this subsection, a single run of the Monte Carlo simulation is analyzed to better understand what happens to the network in case of an earthquake. This scenario example has been randomly selected among the five hundred different realizations of the simulation.

At the time T_0, right after the earthquake, ten pipes are destroyed and some pipes show leaking, five storage tanks are damaged, two important pumps are totally destroyed and two big branches of the system are disconnected to the network. The

a)

Time	Index
[days]	Q
0	0.32
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	1
100	1

b)

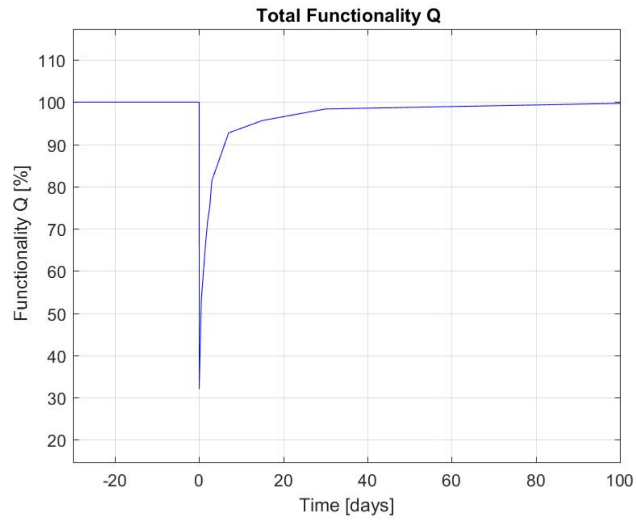


FIGURE 7.4: a, Table of total functionality Q. b, Total functionality Q.

wastewater treatment plant has no damage. (Figure 8.5) The network presents a flooding loss of about 0.08 mgd and the 14% of the points are disconnected from the network. The functionality index Q_1 is 0.86, the index Q_2 is 0.89 and Q_3 is 1 beacause the treatment plant has no damages. The total functionality of the system is 0.76.

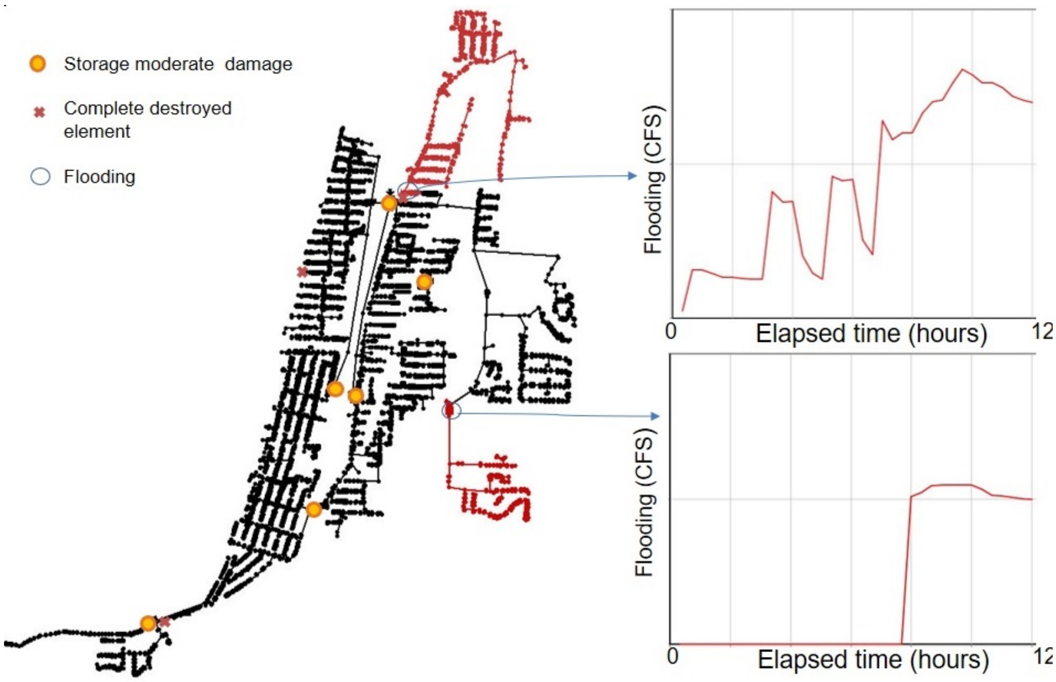


FIGURE 7.5: Total functionality Q

Analyzing the recovery process, in about 3 days the functionality of the system reaches the pre-hazard functionality. In this case the major damage was in the two pumps that have the highest priority for the and this allow the quickly recovery of the system.

After 12 hours, (Figure 8.6 c), the 95% of the demand points are connected to the system, thanks to the recovery of one of the pumps.There is still a flooding loss of about 0.015 mgd. The index Q_1 is 0.95, the index Q_2 is 0.98 and the total functionality of the system is 0.93.

After 36 hours (Figure 8.6 c), all the pipes and storages are fixed, there is onlu one pump still damaged and the functionality is of 96,4% with a flooding loss of 0.014 mgd. Q_1 is 0.96, the index Q_2 is 0.98 and the total functionality of the system is 0.94.

After 3 days, (Figure 8.6 d) all the system is fixed and the functionality reaches the pre-hazard one.

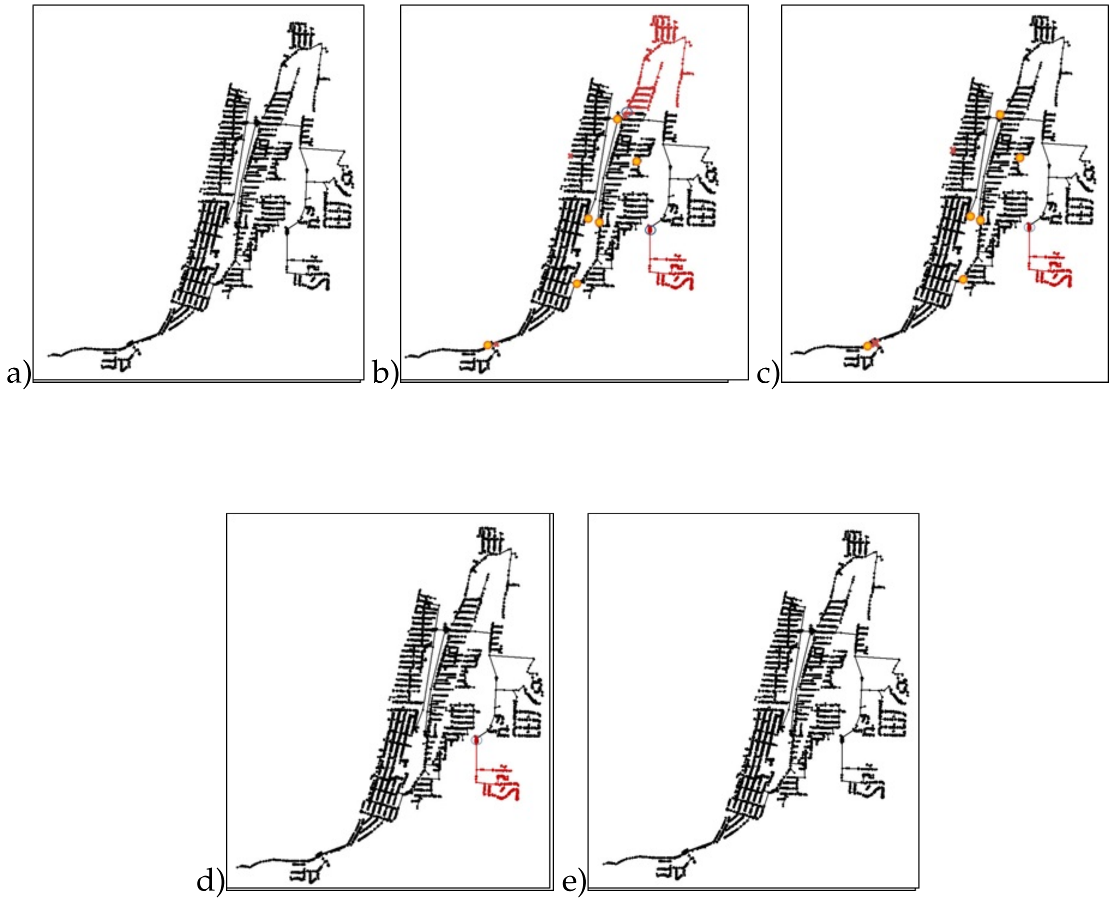


FIGURE 7.6: Seaside Scenario. a)Time 0-:Pre-hazard; b)Time 0+: Post hazard; c)Time 1: After 12 hours; d)Time 3: after 36 hours; e)Time 6: after 72 hours

7.1.2 Resilience

The resilience index has been calculated following those values of functionality, as seen in Chapter 3 it is the normalized area of the functionality index. Therefore, the resilience index R is given by the area of each rectangles made by the value of functionality and the time that it occurs. The total area has been normalized by the time control T_{LC} of 3 months. Therefore, the resilience index R is 0,9620. (Figure 8.7).

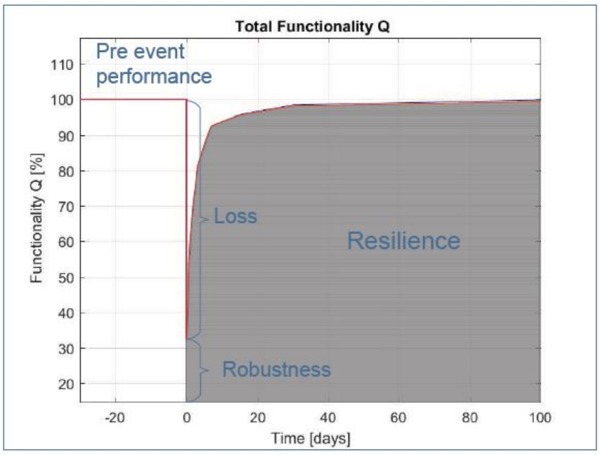


FIGURE 7.7: Resilience of Seaside

7.2 Ideal City

In the case of Ideal city, the first index Q_1 shows that the 85 per cent of the demand points are connected to the system after 7 days and the total funtionality is reached after fourty days. (Figure 8.8)

a)

Time [days]	Index Q_1
0	0
0.5	0.305
1	0.403
1.5	0.453
2	0.65
2.5	0.693
3	0.76
7	0.857
15	0.922
30	0.989
100	1,000

b)

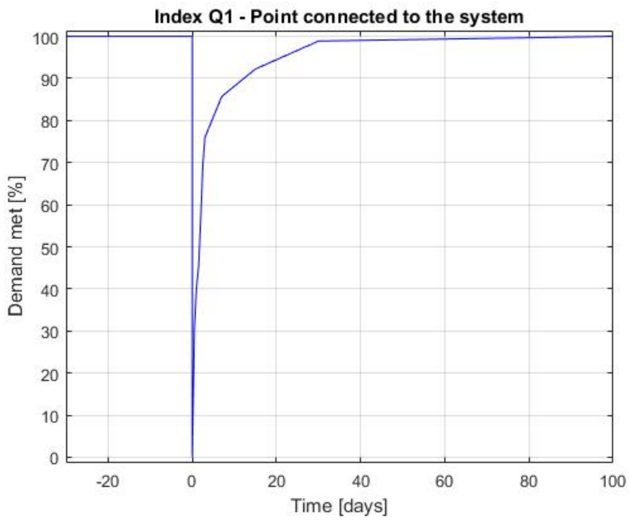


FIGURE 7.8: a, Table of functionality term Q_1 for Ideal City. b, Functionality term Q_1 for Ideal City.

The second functionality index Q_2, (Figure 8.9) has a recovery time of thirty days and it reaches the fifty per cent of functionality after about seven days.

a)

Time [days]	Index Q_2
0	0.041
0.5	0.107
1	0.16
1.5	0.19
2	0.249
2.5	0.306
3	0.334
7	0.599
15	0.934
30	1
100	1

b)

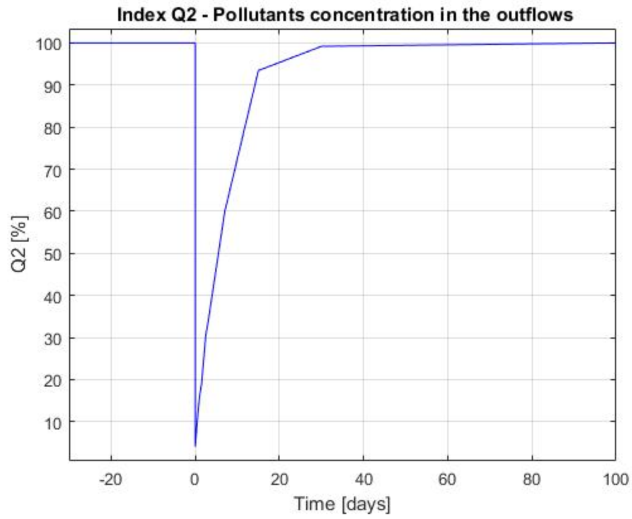


FIGURE 7.9: a, Table of functionality term Q_2 for Ideal City. b,Functionality term Q_2 for Ideal city.

The third functionality index Q_3, (Figure 8.10) reaches the total functionality after one week.

The total functionality index Q, (Figure 8.11) has a recovery time of three months.

7.2.1 Resilience

The resilience index has been calculated in the same way of the previous case, it is given by the area of each rectangles made by the value of functionality and the time that it occurs. The total area has been normalized by the time control T_{LC} of 3 months. Therefore, the resilience index R is 0,9310.

7.2.2 Scenario

This scenario example for Ideal City has been randomly selected among the five hundred different realizations of the simulation.

At the time T_0, right after the earthquake, sixteen pipes are destroyed and some pipes show leaking, only one storage tank is partially dagmaged, three pumps are seriously damaged and one is totally destroyed and and the secondary treatment of the wastewater treatment plant is compromised. (Figure 8.12 b). The network

a)

Time [days]	Index Q_3
0	0.717
0.5	0.726
1	0.757
1.5	0.781
2	0.836
2.5	0.895
3	0.927
7	0.949
15	0.956
30	1
100	1

b)

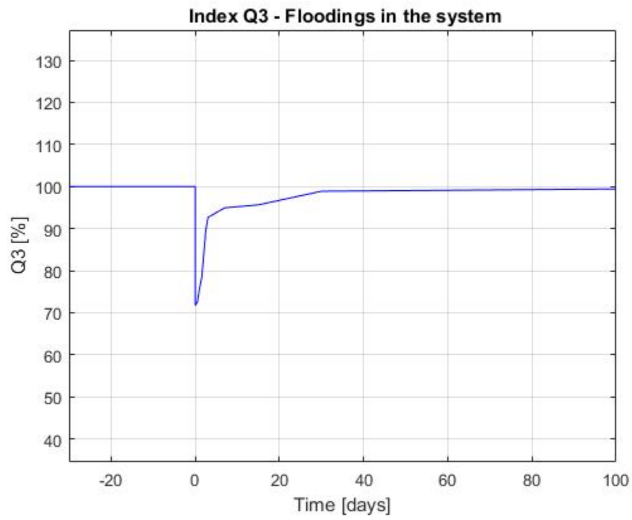


FIGURE 7.10: a, Table of functionality term Q_3 for Ideal City. b, Functionality term Q_3 for Ideal City.

a)

Time [days]	Index Q
0	0.067
0.5	0.119
1	0.15
1.5	0.208
2	0.268
2.5	0.298
3	0.571
7	0.913
15	0.982
30	1
100	1

b)

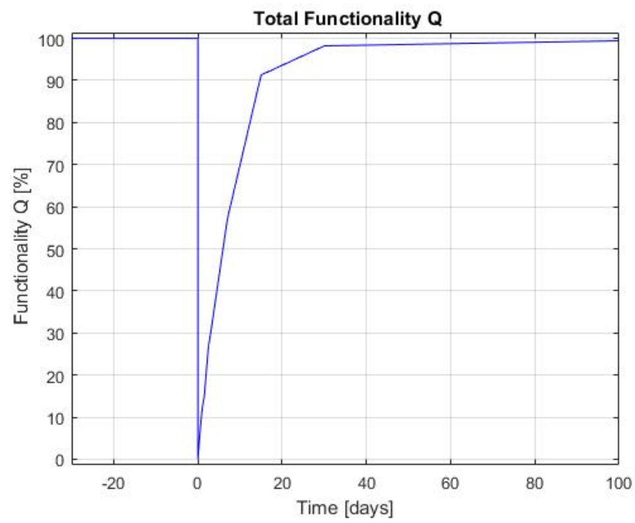


FIGURE 7.11: a, Table of total functionality Q for Ideal City. b, Total functionality Q for Ideal City.

presents a flooding loss of about 5 mgd, and Q_1 is 0,1, Q_2 is 0.05, Q_3 is 0.82. The total functionality is and The total functionality of the system is 0,004.

The firts improvement of the system is at the time T_2, after 24 hours because the wastewater treatment plant is normally working, the storage is fixed and only three pumps and thirteen pipes are damaged. The network has a flooding loss of about 3 mgd, and Q_1 is 0.7, Q_2 is 0.39, Q_3 is 0.89. The total functionality is and 0.26.

After 2.5 days the functionality is 0.67, all the system is working except ten pipes and one pump. There is still a flooding loss of 0.2 mgd, Q_1 is 0.98, Q_2 is 0.72, Q_3 is 0.95. The total functionality is and 0.26.

The system reaches the pre-hazard functionality at the time T_8, after one week.

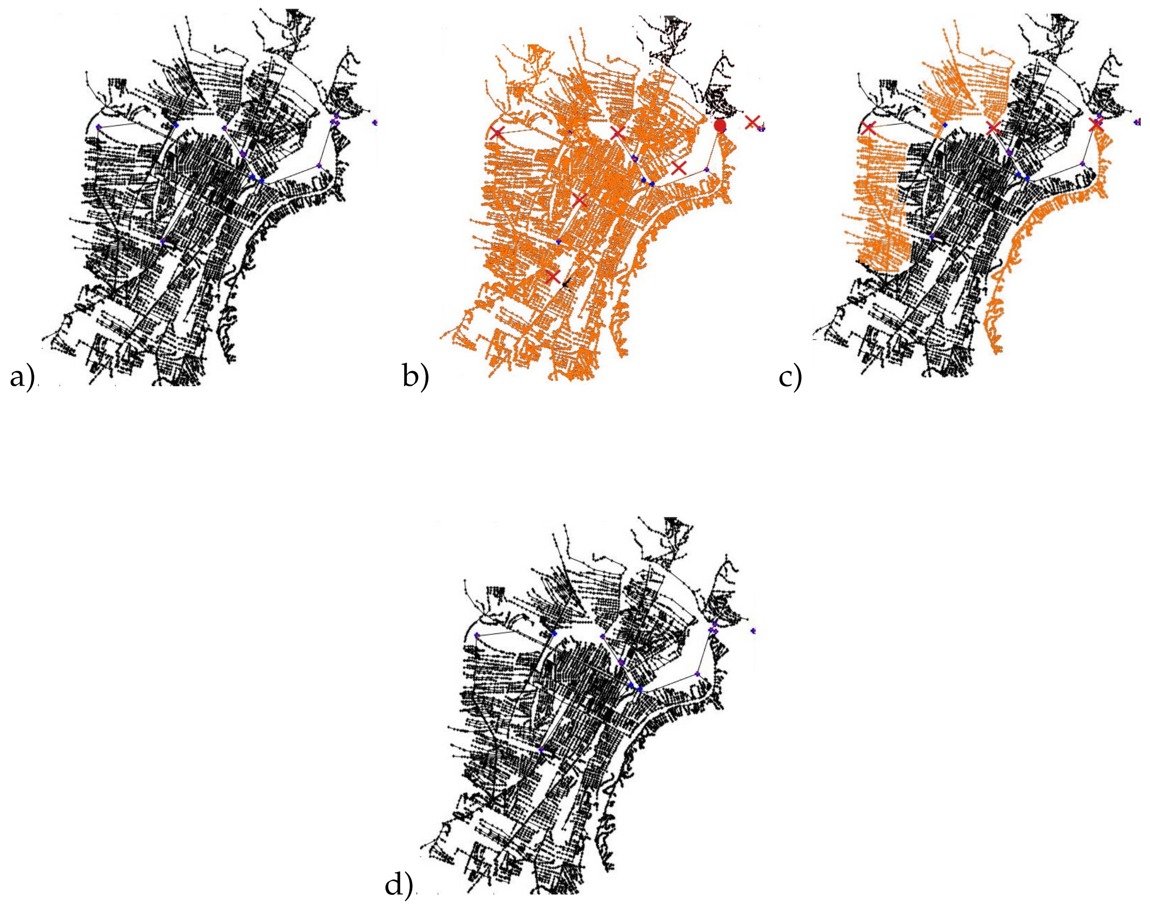


FIGURE 7.12: Ideal City Scenario. a)Time 0-:Pre-hazard; b)Time 0+: Post hazard; c)Time 2: After 48 hours; d)Time 6: after 72 hours

Chapter 8

CONCLUSIONS

The thesis presents a probabilistic approach to analyzing network resilience, and the prediction of recovery time includes physical damage and network functionality.

The first part of the work presents the model design of the wastewater of the two cities. The system of Seaside is in part the real one, because the design is started by the real data provided by the city engineer, and in part has been modeled following the indication of normal design of a wastewater network. The system of Ideal city has been designed in this work for the first time and the only data based on a real situation are the population and the transportation network. No uncertainty is considered in the two models.

A new performance index has been proposed, to evaluate the functionality of the wastewater network. This index, Q, in made of other three indexes. Q_1 represents the number of point connected to the system, Q_2 represents the quality of the inflow in the water body after the treatment, and Q_3 represents the presence of floods in the system.

The procedure proposed by Guidotti has been applied to the two cases of study, and the results demonstrate that the recovery time to meet the functionality Q_1 is about 30 days for Seaside and 40 days for Ideal City. The quality of the outflow from the wastewater treatment plant presents a recovery time of about one week for the two networks, this parameter is faster than the previous one because Q_2 is only depending on the wastewater treatment plant, that has a priority on the recovery strategy.

The index Q_3 has a recovery time of 8 days for Seaside and 7 days for Ideal City, and this is explained, as for the second index, for the priority strategy of pumps, that present the main values of floods in the system.

Both of the networks show a longer recovery time for the first index than the other two, this can be explaned for the recovery strategy that has a higher priority for pumps, treatment plant and the main pipes. Another aspect is the position of pipes that are buried into the ground and this demands more time for the reconnaissance of damaded pipes.

Results show that the total index in mainly affects by the first index, and presents a recovery time of about 1 month for Seaside and three months for Ideal City.

This study in 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. Fragility and recovery strategies can be replaced with more specific curves and strategies to reach better results.

Another aspect that can be considered is the dependencies of the wastewater network with the others network, like potable water network, electric power network, transportation network and social science, to study the behavior of people after a hazard occurrence.

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