

**Development of a Resilience Assessment Methodology for Networked
Infrastructure Systems using Stochastic Simulation, with Application to
Water Distribution Systems**

Leon Francisco Gay Alanis

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in
partial fulfillment of the requirements for the degree of

**Doctor of Philosophy
In
Civil Engineering**

Sunil K. Sinha, Committee Chair
Pamela M. Murray-Tuite
Annie R. Pearce
Antonio A. Trani

March 29, 2013
Blacksburg, VA

Keywords: Critical Infrastructure Systems, Asset management, Resilience, Water Distribution
Systems, Stochastic Simulation

Copyright © Leon F. Gay

Development of a Resilience Assessment Methodology for Networked Infrastructure Systems using Stochastic Simulation, with application to Water Distribution Systems

Leon Francisco Gay Alanis

ABSTRACT

Water distribution systems are critical infrastructure systems enabling the social and economic welfare of a community. While normal failures are expected and repaired quickly, low-probability and high consequence disruptive events have potential to cause severe damage to the infrastructure and significantly reduce their performance or even stop their function altogether. Resilient infrastructure is a necessary component towards achieving resilient and sustainable communities. Resilience concepts allow improved decision making in relation with risk assessment and management in water utilities. However, in order to operationalize infrastructure resilience concepts, it is fundamental to develop practical resilience assessment methods such as the methodology and tool proposed in this research, named Effective Resilience Assessment Methodology for Utilities (ERASMUS). ERASMUS utilizes a stochastic simulation model to evaluate the probability of resilient response from a water distribution system in case of disruption. This methodology utilizes a parametric concept of resilience, in which a resilient infrastructure system is defined in terms of a set of performance parameters compared with their socially acceptable values under a variety of disruptive events. The methodology is applied to two actual water distribution networks in the East and West coasts of the US.

ACKNOWLEDGEMENTS

I would like to acknowledge the continuous support and guidance provided by **Dr. Sunil Sinha** as the chairman of my advisory Committee. His advice and support made possible for me to navigate six years of graduate school at an age when many of my peers are already well established on their careers. In addition, my advisory committee was always very supportive and encouraging, and contributed definitively to this research. **Dr. Annie Pearce** was always there to help me overcome the many hurdles and doubts frequently accompanying pursue of a PhD degree. Her openness to discussion of any topic from sustainability, resilience, and life in graduate school not only sustained me, but provided me with essential advice for succeeding in this enterprise. **Dr. Pamela Murray-Tuite** was also always supportive and encouraging. Her attention to detail and valuable suggestions increased the value and rigor of this research. **Dr. Antonio Trani** was an inspiration to persist and encouraged me to always improve my work. His suggestions and challenging questions pushed me to understand my research topic much more deeply than I could have imagined. Although not in my advisory committee, the support of **Dr. Antonio Nieto**, associate professor at Pennsylvania State University, and **Lindy Cranwell** of the Civil and Environmental Engineering Department at Virginia Tech, as well as **Dr. Karen DePauw** and **Roberto Mayorga** in the Virginia Tech Graduate School was fundamental and decided.

I also want to acknowledge the friendship and support of my fellow doctoral students throughout these years. **Dr. Martha Gross, Omidreza Shoghli, Stephen Welling, Shaoqing Ge, and Thiti Angkasuwansiri** were always great friends and we all shared the challenges of graduate school. My family has a special place in my heart. I would had never being able to achieve this milestone without the decided support of my wife, **Beatriz Gay**. Her love and her support for some of my most wild projects (such as coming back to graduate school abroad after 17 years of working in the civil engineering field) always amazed me and inspired me to be worthy. My daughters **Michelle** and **Marianne** also provided me with a daily dose of love and patience, and reminded me continuously through their presence why such a wild project is worth it.

I want to acknowledge the support of the Mexican Council for Science and Technology (CONACYT) in partially funding me to fulfill this project, along with the solid support of Virginia Tech Graduate School, the SWIM Center at Virginia Tech, the U.S. Environmental Protection Agency (EPA), the Water Environment Research Foundation (WERF), and the National Science Foundation (NSF).

DEDICATION

I want to dedicate this work to all those whom through their love and patience encouraged me to always become a better person and to never give up. Particularly I want to dedicate it to my wife, **Beatriz Gay** (or **Beatriz Gonzalez de Gay**, as she would be known in Mexico) and to our daughters, **Michelle and Marianne**. They are my “solid rock” foundation.

Also to my father, **Leon Gay Guerra**, whom passed away before witnessing this moment but I believe he knows; to my mother, **Lila Alanis Armenta**, whom provided me strong love and support; and last but not least, to **Dr. Paloma Olivares** whom have been inspiring me and challenging me for the last 29 years.

TABLE OF CONTENTS

Acknowledgements	iii
Dedication	iv
List of Figures	vii
List of Tables	viii
Chapter 1. INTRODUCTION	1
1.1. Background	1
1.2. Problem Statement	2
1.3. Goal, Objectives, and Key Assumptions	3
1.4. Scope	4
1.5. Research Design	4
1.6. Contributions to the Body of Knowledge	5
1.7. Organization of Dissertation	6
1.8. References	6
Chapter 2. RESILIENCE OF CIVIL INFRASTRUCTURE SYSTEMS: LITERATURE REVIEW FOR IMPROVED ASSET MANAGEMENT	
2.1. Introduction	7
2.2. Short history of Resilience	9
2.3. Methodology	10
2.3.1. Quantitative Overview of the Literature	11
2.3.2. Qualitative Overview of the Literature	14
2.4. Discussion	17
2.5. Conclusion	22
2.6. References	23
Chapter 3. STOCHASTIC SIMULATION METHODOLOGY FOR RESILIENCE ASSESSMENT OF WATER DISTRIBUTION NETWORKS	
3.1. Introduction	31
3.2. Resilience Assessment Methodology	33
3.3. Application example	44
3.4. Conclusions	47
3.5. References	48
Chapter 4. APPLICATION OF NOVEL STOCHASTIC SIMULATION METHODOLOGY FOR RESILIENCE ASSESSMENT OF WATER DISTRIBUTION NETWORKS	
4.1. Introduction	51
4.2. Resilience Assessment Methodology: ERASMUS	52
4.3. Application of ERASMUS to Water Distribution Network One (WDN-1)	54
4.4. Discussion	63
4.5. Conclusions	64
4.6. References	65

Chapter 5. MODEL VERIFICATION AND VALIDATION	
5.1. Introduction	67
5.2. Conceptual Model Validation	69
5.3. Computerized Model Verification	69
5.4. Operational Validation	76
5.5. References	82
Chapter 6. CONCLUDING REMARKS	
6.1. Conclusions	83
6.2. Key Limitations of the Methodology and Computerized Model	85
6.3. Key Strengths of the Methodology and Computerized Model	87
6.4. Final Remarks regarding Recovery Time and Cost in this Research	88
6.5. Future work	88
6.6. Specific Observations for Future Developments on ERASMUS	90
6.7. References	91
Chapter 7. POINT OF DEPARTURE	
7.1. Current Status of ERASMUS Methodology and Computerized Model	92
7.2. Points of Departure	92
APPENDIX I. ERASMUS CODE	96

LIST OF FIGURES

Figure 2.1. Basic Performance-Based Resilience Curve	10
Figure 2.2. Two Staged Process utilized for Literature Review	11
Figure 2.3. Conducted Searches, represented as nested sets and subsets	12
Figure 2.4. Relationship among Four Selected Disciplines	14
Figure 3.1. Conceptual Model of ERASMUS	35
Figure 3.2. Failure Modes are Distributed in the Scenario Matrix following a Power Law	38
Figure 3.3. Different Types of Recovery Functions in a Functionality Curve	42
Figure 3.4. Stochastic Simulation Evaluation of System Resilience	44
Figure 3.5. Hypothetical Water Distribution Network	45
Figure 3.6. Data Points in Three Dimensions	47
Figure 4.1. WDN-1 Network Model with Elevations	55
Figure 4.2. WDN-1 Scenario Matrix Composition	56
Figure 4.3. Cloud Diagram of WDN-1 Flooding Resilience	57
Figure 4.4. Detail of the Cloud Diagram for Flooding Resilience	58
Figure 4.5. Cloud Diagram Shown Using Two Logarithmic Axes	59
Figure 4.6. Flooding Functionality Curve WDN-1	60
Figure 4.7. Effect of Number of Analyzed Scenarios on Expected System Robustness	61
Figure 4.8. Resilience Index Surface for WDN-1 Flooding	62
Figure 5.1. Simplified Modeling Process including Verification and Validation	67
Figure 5.2. Model Verification Process	70
Figure 5.3. Power Law Distribution of Failure Scenarios	72
Figure 5.4. Average Normalized Performance for Three Failure Scenario Sections	73
Figure 5.5. Average Recovery Times for Three Failure Scenario Sections	74
Figure 5.6. Average Recovery Costs for Three Failure Scenario Sections	74
Figure 5.7. Relationship between Recovery Cost and Recovery Time for WDN-2 Case	75
Figure 5.8. Resilience Index Surface for WDN-1 under Flooding	76
Figure 5.9. Operational Validation Process utilized in ERASMUS	77
Figure 5.10. The ShakeOut Scenario Flowchart	78

LIST OF TABLES

Table 2.1. Top Ten Keywords for Each Search Level, and Number of Occurrences	13
Table 3.1. Probability of Failure Groups	37
Table 3.2. Asset Grouping	45
Table 4.1. System Resilience according with Societal/Utility Expectations	62
Table 5.1. Boundary Scenarios Parameters	71
Table 5.2. Key Parameters in the ShakeOut Scenario	79
Table 5.3. ERASMUS Scenarios Equivalent to ShakeOut	80
Table 5.4. ERASMUS Scenarios Equivalent to Loma Prieta 1989	81

CHAPTER 1

Introduction

1.1. Background

Water is essential for life. Since early times in human history, the location of water sources is a significant factor in deciding where to settle. After centuries, people realized that other considerations need to be taken into account in addition to the available water quantity in a given place, such as water quality. Available water has to be both abundant enough and safe for consumption.

Water infrastructure was developed as a response to these human needs, water quantity and quality. The earliest water distribution systems utilized open channel conveyance systems, but water borne disease was common and the need for safe water produced closed piping systems and the gradual separation of infrastructures dealing with either drinking water or wastewater.

Today, water infrastructure belongs in a bigger meta-system composed of civil infrastructure systems such as road networks, airports, water distribution systems, sewerage, telecommunication, and power generation systems. The infrastructure meta-system enables our current social well-being, public health, and economic development. Furthermore, the quantity and quality of available infrastructure services at any time in human history can be related to the degree of civilization achieved in different places (Petroski 2010).

The role of infrastructure systems is becoming even more significant in contemporary societies due to the current urbanization trend of the world population (U.N. 2012). More people live currently in urban centers than ever before, and the trend is expected to continue toward increased urbanization. Since urban centers are essentially concentrations of interlinked infrastructure systems, these infrastructure systems have to perform continuously to support the quality of urban life.

The U.S. Department of Homeland Security (DHS) has a list of Critical Infrastructures and Key Resources (CI/KR) which are essential for the continuous operation of the U.S. economy. Water infrastructure is one of the critical infrastructure systems, but the continued operation of water infrastructure systems face significant challenges including financial constraints, natural hazards, and man-made hazards.

Due to the extended geographical distribution of critical infrastructure networks such as water distribution systems, it is impractical to protect every single asset. Instead, an approach is required for increasing the system's ability to preserve performance and expedite recovery in case a disruptive events occurs. Such an approach is provided by implementing the concept of infrastructure resilience.

Resilience is not a new concept, but its application to management of infrastructure systems is recent. Resilience is a concept that integrates other better known concepts including emergency

preparedness, survivability, and adaptability. Resilience is related to system reliability and vulnerability, although these three concepts have different meanings.

“Infrastructure resilience” is still mostly an academic term, since its application to daily system operation is limited. However, resilience-based methodologies and tools for risk management on infrastructure systems is a promising area of research. The academic study of infrastructure resilience is beginning to percolate into daily infrastructure operations and planning. Holistic Infrastructure Asset Management frameworks are under development that consider the three key performance management, sustainability management, and resiliency management pillars.

Which cannot be measured, cannot be improved. Although resilience is the result of a complex interaction of many diverse factors and not only a system attribute, it can be assessed and enhanced, and thus a variety of resilience assessment methodologies for infrastructure have been developed recently. Their approaches vary considerably, including graph theory, theory of evidence, Bayesian probability, system dynamics, and others. Despite such developments, most of those methodologies lack practical applicability as decision support tools for system management.

1.2. Problem Statement

Frameworks and models for assessing and managing the resilience of critical infrastructure have been developed. However, these frameworks and models are mostly academic exercises without immediate application to informing and supporting current managerial decision making.

One of the most successful developments of a practical resilience measure is RAMCAP (Risk Analysis and Management for Critical Asset Protection). The American Society of Mechanical Engineers (ASME) and the American Water Works Association (AWWA) developed a framework called RAMCAP Plus as a risk management tool that includes assessing the resilience of water utilities. RAMCAP is constituted by a seven-step process for risk and resilience analysis and management, and it was designated by the American National Standards Institute (ANSI) as the J-100 Standard. Although successful in terms of its implementation, the RAMCAP approach for resilience assessment can be significantly improved.

Summarizing, current frameworks, methodologies, and tools for assessing and managing critical infrastructure resilience can be significantly enhanced by developing innovative methodologies and tools addressing the following issues:

1. Practical applicability
2. Capacity for consideration of multiple hazards
3. Capacity for consideration of the hazardous effects of slow-onset, potentially disruptive processes, such as ageing; as well as the more traditional sudden onset disruptive events.
4. Capacity for consideration of the consequences of asset management decisions on the overall system resilience.

1.3. Goal, Objectives, and Key Assumptions

This research is intended to address some of the most significant issues and shortcomings identified in previous attempts to establish a practical methodology for assessing infrastructure resilience.

The main research question is “How can the resilience of any water distribution network can be measured a priori, enabling a multi hazard approach capable of including slow-onset disruption and utilizing concepts from infrastructure asset management familiar to water utilities’ staff?”

Although the present research is intended to answer the main question, there are other related questions which are addressed through this research:

- a. How can it be decided whether a water distribution system is resilient or not?
- b. What is the impact of immediate/delayed maintenance and investment decisions on system resilience?
- c. What budget is required by a given water utility to significantly increase the probability of having an efficient response to an unforeseen disruptive event?

The goal of this research is to “**Develop a resilience assessment methodology for water distribution systems that relates to infrastructure asset management and is flexible, simple, and expandable**”. Such a methodology may benefit from the utilization of concepts and tools from current Infrastructure Asset Management frameworks applied in the water sector, such as condition ratings, probability of failure, business risk exposure, criticality, and others.

In order to achieve the research goal, the specific objectives of this research are to:

1. Identify features that allow deciding whether a system is resilient,
2. Identify aspects of resilience useful for water distribution systems,
3. Identify attributes of water distribution systems relevant for resilience assessment,
4. Identify Asset Management tools relevant to resilience assessment and management

Key Assumptions of this research are:

1. Resilience is not a system attribute (Hollnagel et al. 2006), thus resilience results from a combination of factors internal and external to the system under consideration, and is impacted by daily management decisions.
2. In any networked infrastructure system, resilience can be measured utilizing a set of n parameters that describe system performance and recovery values.
3. Infrastructure resilience is the result of a stochastic process. As a consequence, stochastic simulation can be utilized as basis for a robust methodology for forecasting the likely resilience level of any given water distribution system under a variety of hazards. Stochastic simulation converts an unknown probability (whether the system is resilient) into a *posterior probability* estimated from the result of a series of mathematical

experiments. Stochastic simulation allows the existence of significant uncertainties in the model input parameters and processes, since it does not require the detailed explanation of every single step involved in the process.

1.4. Scope

The research scope has to be narrowed down from the strategic infrastructure resilience challenge in order to address a tractable problem. First of all, the methodology and tool developed in this research is intended only for water distribution networks, particularly physical assets. Second, although achieving infrastructure resilience requires a multidisciplinary perspective, this research is focused only on the technical aspects. The research scope has the following boundaries:

1. Since resilience after a disruptive event results from a complex interplay of a multitude of factors, this research considers system resilience as the result of an eminently stochastic process that includes only the technical aspects of physical assets performance.
2. The resilience assessment is based on a limited definition of system performance. This methodology considers the quantity of water delivered to demand nodes as the key performance metric, although other metrics may be integrated in the future.
3. An estimation of recovery costs associated with different system failure modes is included as part of the resilience assessment. These costs include direct and indirect costs of asset repair. The costs do not include the occurrence of other community disruptions or resources such as road closures or the availability and cost of alternate sources of water.
4. An estimation of recovery times associated with different system failure modes is also performed as part of the analysis. The recovery times are estimated in a one-asset-at-a-time repair basis. Utility capacity to respond to different asset failures simultaneously is not assumed.
5. Recovery times and costs are estimated utilizing information from the RS Means' Heavy Construction Cost Data 2011 due to a lack of utility-specific information. As the quantity and quality of data increases in the future, the quality of the model output is expected to increase as well.

1.5. Research Design

The research is designed for generating data that can be analyzed utilizing statistical techniques. Stochastic simulation provides a promising approach for the development of this resilience assessment methodology for the following reasons:

- a. It does not require a detailed modeling of every process related to infrastructure system resilience before, during, and after a disruptive event occurs. The need for such modeling would be a major barrier in developing an achievable and practical mathematical resilience model for utilities, given the many factors involved, complex interactions, and feedback

loops that may need to be considered, as well as the interdependencies with other infrastructure systems.

- b. All the processes involved in system loss of performance and recovery from a disruptive event compose a complex problem. Therefore, considering them the result of a stochastic process is an achievable approach, very likely without significant loss of generality.
- c. Stochastic simulation does not require the ability of imagining all possible what-if scenarios by the analyst. Failure modes are randomly generated, which eliminates possible analysis bias towards those failure scenarios that seem more likely or are easier to imagine at the time of the analysis. Random failure scenarios provide analytic results independently of the scenario plausibility.

The stochastic simulation is combined with deterministic system performance analyses to reduce uncertainty from statistical variance. Although failure scenarios are randomly generated, the hydraulic analysis of the network for each scenario is deterministic.

The research includes the development of a tool for resilience assessment in water utilities. The stochastic simulation tool is coded in MATLAB, and integrated with the free hydraulic analysis engine EPANET 2.0. The integrated MATLAB-EPANET simulation tool allows a straightforward resilience assessment of the considered water utility under a specific type of disruptive event.

1.6. Contributions to the Body of Knowledge

This research contributes to the current Body of Knowledge in engineering resilience of infrastructure systems as follows:

1. Providing a unique conceptualization of infrastructure system resilience in terms of the interaction of system response (Performance) and societal expectations (Acceptable System Performance). This is consistent with previous observation by other authors regarding the fact that Resilience is not a system attribute (Hollnagel et al. 2006, 2008).
2. Conceptualizing infrastructure system resilience in terms of a set of n parameters, which can be represented in a resilient response region of a n -dimensional space: A foundation of parametric resilience can be expanded in the future. Although for this research only three parameters are utilized, in theory system resilience can be defined in terms of n parameters.
3. A methodology and computerized tool called “Effective Resilience Assessment Methodology for Water Utilities” (ERASMUS) for conducting assessments of networked infrastructure system resilience utilizing stochastic simulation, based on utility-provided information and asset management terminology.
4. The methodology can be generalized and expanded to accommodate future advances, as well as analyze other types of networked infrastructure systems. Since the methodology is based on the analysis of a network model, the network can be expanded in the future to include not only physical assets but functional relationships as well. In addition, further

system performance metrics can be used; for example, water quantity or water quality, and relate them with the system Level of Service. The methodology can be linked in the future to other management tools such as Geographical Information Systems (GIS).

5. The Biased Sampling methodology utilized for assembling the set of failure scenarios to analyze with ERASMUS was originally utilized for understanding selective predation in biology (Chesson 1976; Fog 2008a; b), which produced the Multivariate Wallenius' Non-Central Hypergeometric probability distribution. This research represents the first application of a probability distribution from the evolutionary theory of biological organisms to the resilience assessment of critical infrastructure, which sets a foundation for future developments.

1.7. Organization of Dissertation

This dissertation was assembled utilizing a collection of journal papers. After this introductory chapter, Chapter 2 is a literature review paper on infrastructure resilience and its relationship with asset management frameworks; this paper is being published by the International Journal of Critical Infrastructures. Chapter 3 is a paper explaining the resilience assessment methodology developed as part of this research, also being published in the International Journal of Critical Infrastructures. Chapter 4 is a paper currently under review by the journal of infrastructure systems; the paper explains the application of this resilience assessment methodology to actual water distribution networks. Chapters 5 is not a journal paper, and it is entirely devoted to the verification and validation of ERASMUS. Chapter 6 is a concluding remarks chapter designed to provide, along with Chapter 1, a framework for the dissertation as a whole and starting points for future work. Finally, Appendix I contains the MATLAB code developed for ERASMUS thus far.

1.8. References

- Chesson, J. (1976). "A Non-Central Multivariate Hypergeometric Distribution Arising from Biased Sampling with Application to Selective Predation." *Journal of Applied Probability*, 13(4), 795–797.
- Fog, A. (2008a). "Sampling Methods for Wallenius' and Fisher's Noncentral Hypergeometric Distributions." *Communications in Statistics - Simulation and Computation*, 37(2), 241–257.
- Fog, A. (2008b). "Calculation methods for Wallenius' noncentral hypergeometric distribution." *Communications in statistics. Simulation and computation*, 37(1-2), 258–273.
- Hollnagel, E., Nemeth, C. P., and Dekker, S. (2008). *Resilience Engineering Perspectives (Ashgate Studies in Resilience Engineering)*. Ashgate Publishing Company.
- Hollnagel, E., Woods, D. D., and Leveson, N. (2006). *Resilience Engineering: Concepts And Precepts*. Ashgate Publishing.
- Petroski, H. (2010). "Declining Infrastructure, Declining Civilization." *The Chronicle Review*.
- U.N. (2012). *Resilient People, Resilient Planet. A future worth choosing (Overview)*. U.N. High Level Panel on Global Sustainability, New York.

CHAPTER 2

Resilience of Civil Infrastructure Systems: Literature Review for improved Asset Management

Leon F. Gay¹, Sunil Sinha¹

¹ Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, Virginia; U.S.A.

Correspondence: Leon F. Gay, Department of Civil and Environmental Engineering, 115 Patton Hall, Virginia Tech, Blacksburg, VA., 24060, U.S.A. E-mail: leonf@vt.edu

Abstract

Infrastructure resilience has drawn significant attention in recent years, partly because the occurrence of low-probability and high-consequence disruptive events like hurricane Katrina, the Indonesian tsunami, the terrorism attack in New York, and others. Since civil infrastructure systems support society welfare and viability, continuous infrastructural operation is critical. Along protection methods, resilience concepts support the achievement of near-continuous infrastructure operation. A variety of frameworks, models, and tools exist for advancing infrastructure resilience research. Nevertheless, translation of resilience concepts into practical methodologies for informing civil infrastructure operation and management remains challenging. This paper presents a state-of-the-art literature review on civil infrastructure resilience, particularly water distribution systems, enabling practical applications of infrastructure resilience towards improved system management. The literature review has two stages, quantitative and qualitative. A definition of Infrastructure resilience is proposed which provides a foundation for the operationalization of infrastructure resilience concepts, enabling the inclusion of practical resilience considerations in formal management systems such as infrastructure asset management systems.

Keywords: Critical Infrastructure, Resilience, Civil Infrastructure Systems, Asset Management

2.1. Introduction

In this paper, infrastructure is defined as the basic physical and organizational structures and facilities needed for the operation of society (Oxford Dictionaries 2010). Civil infrastructure systems such as transportation infrastructure, water supply, sewerage, power, and telecommunications provide vital services to contemporary society. Civil infrastructure systems are comprised by tangible and intangible components that develop ubiquitous, interdependent, and complex socio-economic and technical networks.

Due to the current worldwide urbanization trend (U.N. High level Panel on Global Sustainability 2012), the population size depending on near-continuous performance of urban civil infrastructure systems has increased in recent years (Anon 2006). In theory it is possible to develop resilience-based methodologies and tools to support near-continuous operation of those

systems (Park et al. 2011). Utilized in an integrated dual protection and resilience approach, those methodologies and tools can support infrastructure performance during and after many kinds of potentially disruptive events, including those of man-made or natural origin (DHS 2009). However, despite significant advances, design and implementation of practical resilience-based methodologies and tools for improving operation and management of infrastructure systems remains challenging.

The number of published papers on resilience of civil infrastructure systems has increased significantly in recent years, mainly due to public realisation of the extent of contemporary society's dependence on uninterrupted function of civil infrastructure systems. This literature review is intended to provide a foundation for advancing practical developments on operation and management of civil infrastructure systems. The paper includes a discussion of the concept of resilience in key disciplines identified during the first stage of this literature review process.

The U.S. Department of Homeland Security (DHS) compiled a list of Critical Infrastructure and Key Resources (CI/KR) containing eighteen infrastructure systems whose function must be protected and quickly restored in case of disruption (P. A. Collins & Baggett 2009; Haines et al. 2008). Normal daily operation of critical civil infrastructure systems includes variations and disruptions, but most of them remain unnoticed as service is restored quickly (States 2010). These small disruptions or "normal failures" are ordinary and expected disruptions that happen frequently and have minimum consequences (Mays 2004). Major threats come from extraordinary civil infrastructure disruptions that might have catastrophic consequences and ripple through entire economic and societal systems (Gopalakrishnan & Peeta 2010; Grigg 2003; Mays 2004; Spellman 2007). Extraordinary disruptions may be caused by high-impact, low-probability events such as natural disasters (Nelson et al. 2007) or man-made disruptive events like accidents or deliberate attack (Mendonca & Wallace 2007). Although civil infrastructure resilience is a term mainly applied for addressing sudden onset of disruptive events, it has been suggested that slow-occurring processes such as system ageing or drought need also be considered disruptive events for resilience purposes (Calida & Katina 2012; Prieto 2009). As a result, resilience concepts are currently utilized to address both sudden onset and slow onset disruptive events. In addition, research on resilience "requires renaissance persons able to work in an environment that is not only interdisciplinary but also multidisciplinary and transdisciplinary" (Jackson 2009).

Desirable and undesirable processes and systems can be resilient. Research on resilience is not only focused on how to increase resilience, but rather how to change the resilience of a process or system in order to sustain or terminate such process. For example, while the resilience of civil infrastructure systems is to be promoted until they can be substituted for new and improved systems, the resilience of certain processes such as human poverty is undesirable. Furthermore, in specific cases a system may be deliberately not recovered, in order to substitute it for a more cost effective or otherwise better alternative. Civil infrastructure system resilience needs to

consider system performance in all three stages: before, during, and after a disruptive event occurs. Advancing the understanding and applications of civil infrastructure system resilience will contribute to more effective and efficient critical infrastructure protection.

Other authors have compiled literature reviews of resilience in a variety of disciplines (Manyena 2006; Gilbert 2010). However, there is a lack of literature reviews on resilience for supporting the development of practical management applications for infrastructure systems. This paper is intended to fill that gap presenting a literature review of the current status of resilience in civil infrastructure systems. The presented discussion is focused mainly on resilience papers contributing to infrastructure system management, including design, analysis, and operation aspects.

2.2. Short history of Resilience

The word “resilience” originated from Latin “*resilio*”, composed by “re” (again) and “salire” (to spring, jump) and literally means “to bounce back”. An early application of “resilience” was in elasticity theory to represent the amount of energy stored in an elastically deformed body. Later, the term resilience was utilized in psychology circa 1940. “Resilience” was used as the ability of an individual to recover from traumatic experiences, such as children during World War II (Masten et al. 1990). Resilience was utilized to represent the capacity of subjects to cope with, and recover from, traumatic experiences. A paper that advanced significantly the concept of resilience was “Resilience and Stability of Ecological Systems” (Holling 1973). After applications on psychology (Masten et al. 1990) and ecology (Holling 1973; Walker & Salt 2006), other fields integrated the term resilience including industrial processes (Wei & Ji 2010), industrial safety and logistics (Fiksel 2003), sociology (Somers 2009), economics (E. Vugrin et al. 2010), social science (Gilbert 2010; K. Tierney & M. Bruneau 2007), engineering (Blackmore & Plant 2008; Blackmore & C. Wang 2009; P. M. Murray-Tuite 2006; P. Murray-Tuite 2007), business management (Hamel & Valikangas 2003; McManus et al. 2008; Sheffi 2007; Somers 2009) and computer science (Agarwal et al. 2011; Cohen et al. 2000). Despite general agreement on the broad meaning of resilience as the ability of a system to “bounce back” from disruption, varied definitions exist depending on the intended application (Manyena 2006; E. Vugrin et al. 2010).

Currently, the concept of resilience is generating significant interest for application in design, operation and management of civil infrastructure systems (O’Rourke 2007; O’Rourke et al. 2002; Santora & Wilson 2008). As mentioned, many civil infrastructure systems are critical “lifelines” which if severely disrupted may cause tremendous negative impacts on the economic and social structures of human communities and even severely affect ecosystems (Amin 2000; Boin & McConnell 2007). However, the development of practical civil infrastructure resilience methodologies and tools for system operation and management is challenging and shaped by concepts of resilience prevalent in other disciplines informing infrastructure management.

Resilience of civil infrastructure systems is frequently measured using performance metrics. Figure 2.1 shows an example of a performance-based resilience curve, a “functionality curve” or “Resilience triangle” (Michael Bruneau et al. 2003; Gian Paolo Cimellaro et al. 2007; McDaniels et al. 2008; Zobel 2010). The horizontal axis represents time, and the vertical axis performance. In this case the impact of disruption on infrastructure performance is assumed to be instantaneous (Points A and B occur both at time $t = t_0$).

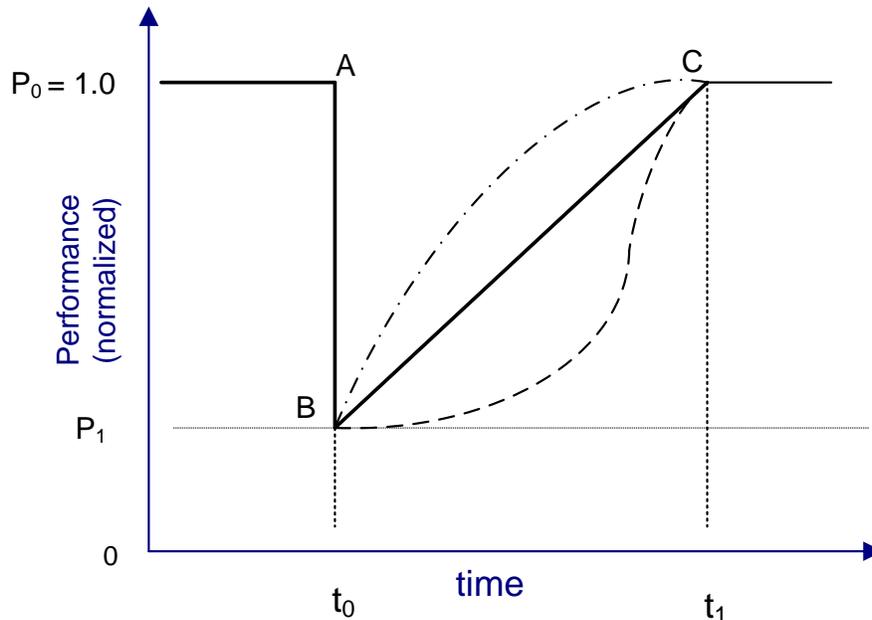


Figure 2.1 Basic Performance-Based Resilience Curve (functionality curve).

In Figure 2.1, the recovery B-C is assumed linear (continuous line). The linearity assumption is not necessarily valid in every case, and other recovery function shapes have been proposed such as trigonometric (dashed line) and exponential (dash dot line) (G. P. Cimellaro et al. 2008). A trigonometric recovery function may represent an initially slow recovery, while an exponential function may be used for rapid-starting recovery processes. In Figure 1 it is assumed that after recovery, the system performance returns to pre-disruption level and is constant over time.

2.3. Methodology

The literature review was conducted in two stages (Figure 2.2): First, a quantitative stage of resilience-related material search in bibliographic databases. Virginia Tech has access to nearly 700 online databases in a wide range of fields. The searched databases include Compendex, Inspec, the National Technical Information Service (NTIS), and the American Society of Civil Engineers (ASCE) civil engineering database, among others. These databases contain papers published in the U.S., U.K. and Europe, covering a significant portion of the current academic publications on resilience. Searches were limited to journal articles, conference proceedings,

books, and reports. The search was conducted only in English language, utilizing the Subject/Title/Abstract (S/T/A) search field (Figure 2.2).

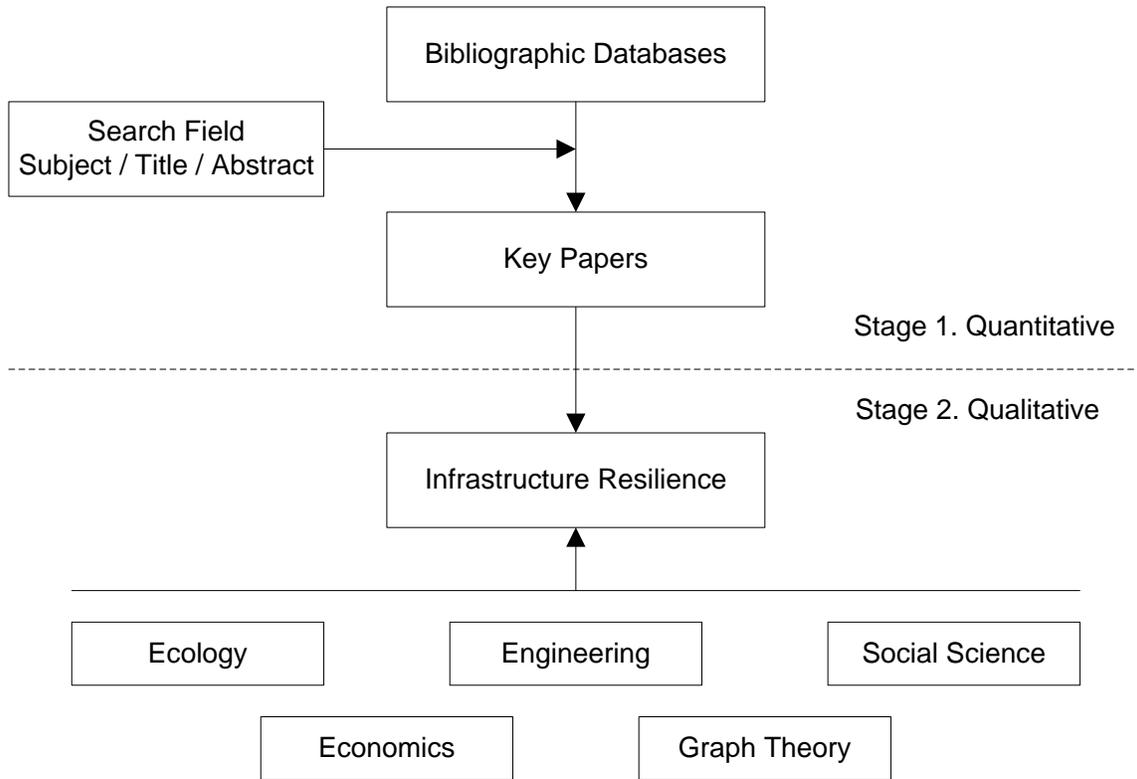


Figure 2.2 Two Staged Process utilized for Literature Review

The second stage of this literature review is a discussion of the concept of resilience in five key disciplines related to civil infrastructure systems (bottom half of Figure 2.2). Those five disciplines were identified in the first stage as key fields for understanding resilience in civil infrastructure systems.

2.3.1 Quantitative Overview of the Literature

Resilience is an active area of research worldwide and there is a significant amount of publications on the topic. A comprehensive literature review is warranted periodically.

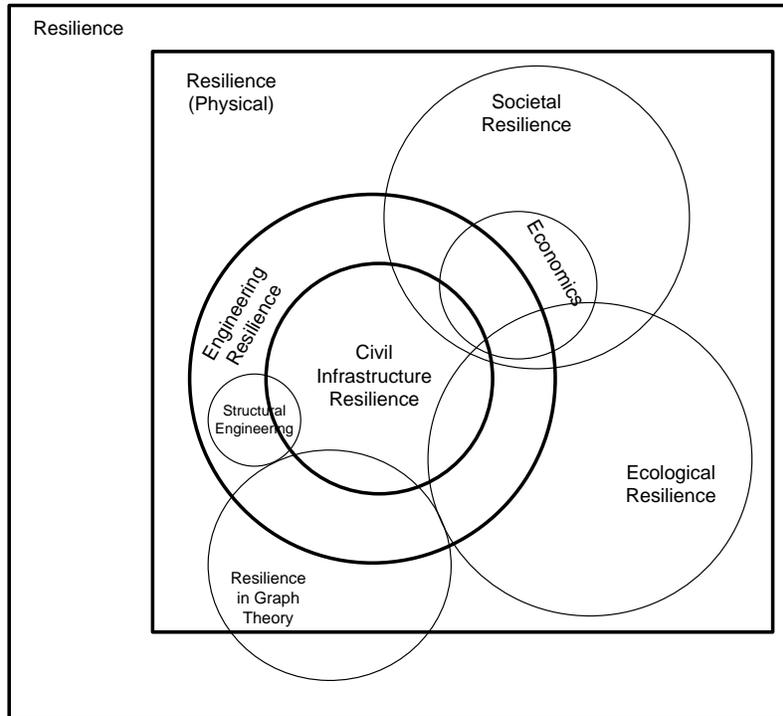


Figure 2.3 Conducted Searches, Represented as Nested Sets and Subsets.

Figure 2.3 is a conceptual model of the quantitative stage of literature review. A decision was made to start searching from a general set of papers related to any kind of resilience, and then take each search a step down toward civil infrastructure resilience, advancing from the general to the particular. Search levels (bold lines) in Figure 2.3 are described below. The key disciplines identified are also included in this diagram.

a) Resilience. The outside square in Figure 2.3 is the universal set of papers that mention either “resilience”, “resiliency”, or “resilient”. This set includes papers in all database topics such as computer science, information technology, biology, ecology, sociology, etc.

b) Resilience (Physical). This set contains papers that mention “resilience”, “resiliency” or “resilient”, but are not about computer science or information systems. This search discards all papers which have computational systems and cyber infrastructure as object of study. Papers including computing tools were not excluded.

c) Engineering Resilience. Papers in “Physical” resilience are classified in three groups: ecological, societal, and engineering resilience. Ecological resilience is concerned with systems that reach new equilibriums after disrupted. In contrast, engineering resilience is about systems intended to recover pre-disruption performance level after disruption. Civil infrastructure resilience belongs in the engineering resilience set.

d) Civil infrastructure resilience. Engineering resilience includes systems other than civil infrastructure, such as industrial processes. Civil infrastructure resilience is a subset within the

engineering resilience field. At this step, we are interested only in resilience papers for civil infrastructure.

Notice that in Figure 3 papers related to engineering, graph theory, ecology, social resilience and economics all intersect with civil infrastructure resilience and other fields in a variety of ways.

During the first stage, around 19,489 papers were found in the first search level (which is the most general level). In the next search (Resilience, physical) 956 papers; Engineering Resilience, 248 papers. From this quantitative stage, 152 key papers (journal and conference), books, and reports were identified. From key material, 60 items include some model of resilience. A relatively frequent approach found to measuring resilience is system dynamics (Forrester 1958; Sterman 2000).

Keywords utilized in published papers reveal associated applications, concerns, and issues. In our case, keywords may suggest how resilience is defined and utilized in papers counted on the quantitative stage of this review.

Table 2.1 Top Ten Keywords for Each Search Level, and Number of Occurrences

	1. Resilience	Freq.	2. Resilience (Physical)	Freq.
1	Algorithms	1262	Ecosystems	175
2	Image Coding	1239	Ecology	110
3	Computer Simulation	1124	Forestry	105
4	Network Protocols	936	Climate Change	94
5	Mathematical Models	781	Environmental Impact	77
6	Wireless Telecomm Systems	744	Biodiversity	74
7	Internet	628	Soils	72
8	Image Compression	565	Vegetation	66
9	Optimization	552	Sustainable Development	56
10	Distrib. Computer Systems	549	Strategic Planning	54
	3. Engineering Resilience	Freq.	4. Civil Infrastructure R.	Freq.
1	Risk Management	29	Risk Assessment	6
2	Risk Assessment	29	Disasters	5
3	Ecosystems	27	Risk Management	5
4	Water Resources	22	Climate Change	5
5	Strategic Planning	19	Water Resources	4
6	Decision Making	18	Economic And Social Effects	3
7	Sustainable Development	18	Decision Making	3
8	Climate Change	18	Strategic Planning	3
9	Disasters	17	Sustainable Development	3
10	Planning	17	Water Supply	3

Table 2.1 contains the top ten most used keywords in papers for each search. Keywords in all papers containing either “resilience”, “resiliency” or “resilient” (top left quadrant) are mostly dominated by papers about cyber infrastructure security, computer science and information systems.

For resilience papers that are not about cyber infrastructure, resilience is mainly related to ecology and sustainability concerns, including climate change. In the case of engineering resilience, the interest is mostly about risk management, risk assessment; and ecosystem preservation; for civil infrastructure systems, resilience is mainly about climate change, risk, disasters, and water resource management. Note that some relevant applications of resilience concepts, such as in design and construction of facilities are missing. This is due to practical limitations in the number of synonyms searched in database.

2.3.2 Qualitative Overview of the Literature

2.3.2.1 Civil Infrastructure System Resilience

From the first stage of this literature review, key material on resilience was identified for further review. Key material was selected because explicitly mentions “resilience”, “resiliency” or “resilient” in the Title, Abstract, or Subject, and belongs to one of the five identified disciplines directly related to civil infrastructure systems. The resulting 152 papers, books, and reports provided a mostly complete picture of the status of the concept of civil infrastructure resilience.

The concept of resilience is still evolving (Willingham 2008). Although the basic understanding of resilience as “ability to bounce back” is generalized, each discipline gives resilience specific characteristics according to its own scope and objectives. As a result, concepts of resilience vary. The first stage contributed to the identification of key disciplines for understanding civil infrastructure resilience, as follows.

Networked infrastructure systems operate within the dynamics of natural, social, and built environments (Pearce & Vanegas 2002). The societal environment drives infrastructure function through demand (water, power, sanitation, communication, etc.) and the natural environment imposes constraints on resources available for satisfying those demands (Figure 2.4). For example, there is limited space for roads or limited water for withdrawal from a reservoir or lake. In addition, the natural environment also impacts infrastructure performance in other ways such as climatic variation and the onset of extreme climatic events.

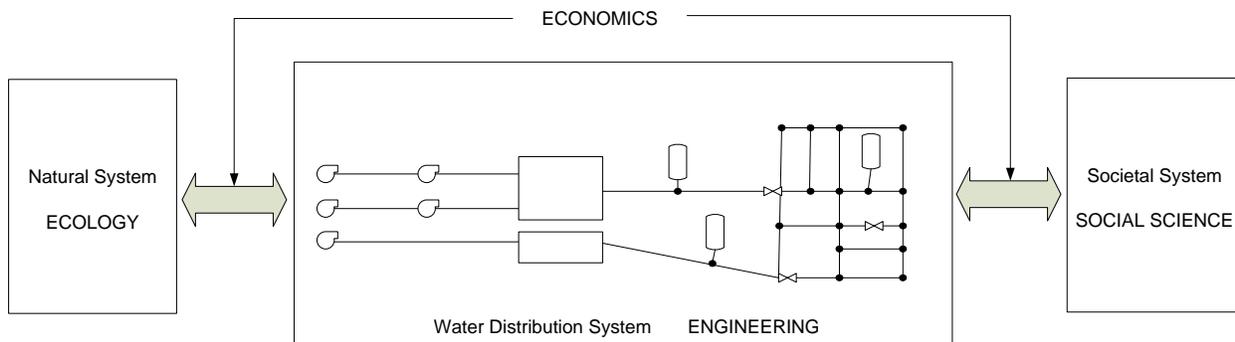


Figure 2.4 Relationship among Four Selected Disciplines

Figure 2.4 represents a water distribution system and its context. The design, management, operation, and performance of the system belong mostly in the engineering field. However, the infrastructure system performance is driven by social demands, since the system was built to satisfy a societal need. At the same time, the infrastructure system is an interface between social demand and the natural environment providing resources to satisfy such demand (safe drinking water, in this case). The dynamics among these three systems have significant impact on system management. Such dynamics are compounded by economic and financial considerations. As a result, four key fields are engineering, social science, ecology, and economics.

As a result of the context of civil infrastructure systems represented in Figure 4, the development of resilience in those fields also impacts the development of frameworks, models, and tools for infrastructure resilience management. These four disciplines were identified in the first stage of the literature review as key fields. Given that some critical civil infrastructure systems can be conceptualized as networks, advances in resilience from graph theory may provide an essential tool to understand infrastructure networks resilience.

2.3.2.2 Graph Theory Approach to Resilience

Graph theory approach to resilience is applicable to all networked civil infrastructure, such as water, sewer, road systems, telecommunications, and power (Chen 1990; Matisziw et al. 2008). Graph theory utilizes different types of graphs including random networks, small-world networks, and scale-free networks (Albert et al. 2000; Amin 2000; Amin 2002; Callaway et al. 2000). A network is a graph where the edges (links) have a limit capacity and each edge conveys a flow (Ahuja et al. 1993). Graph theory approach to resilience considers the impact of randomly chosen or deliberately selected node or link removals (L. Duenas-Osorio et al. 2004; Leonardo Duenas-Osorio et al. 2007). Random element removal is suggested to simulate natural disasters or accidents; and removal of selected nodes and links simulates deliberate attacks intended to cause maximum damage, such as terrorism (Albert et al. 2000; Callaway et al. 2000; Latora & Marchiori 2001).

The resilience of networks is evaluated in a variety of ways, including network performance and connectivity analysis. Graph theory provides fundamental understanding of network resilience (Morehead & Noore 2007; Omer et al. 2009; Ostfled 2005). Graph theory tools and principles are applicable across the four disciplines represented in Figure 4. A variety of novel metrics and approaches are being explored for addressing resilience of networks, such as spectral graph theory, and others.

2.3.2.3 Engineering Approach to Resilience

Diverse specialties within engineering have developed resilience concepts such as industrial engineering, safety, and reliability, among others. Some resilience developments significant for civil infrastructure systems generated from structural engineering. The current structural engineering approach to infrastructure resilience is significantly influenced by earthquake

engineering (Tabucchi et al. 2010). Most papers in structural engineering resilience (and 18% of key papers selected in the first stage of this review) come from the Multidisciplinary Center for Extreme Event Research (MCEER) “R4” framework and therefore they share similar methodologies. The R4 framework considers resilient systems as having four attributes: Robustness, Redundancy, Resourcefulness, and Rapidity (Michael Bruneau & A. M. Reinhorn 2003; Michael Bruneau et al. 2003; Gian Paolo Cimellaro et al. 2006; Gian Paolo Cimellaro et al. 2007).

Since the structural engineering approach has its origin mostly in earthquake engineering (see for example (Reed 2009)), derived mathematical models use specific structural tools and concepts including fragility curves, loss functions, structural and non-structural damages, and recovery functions to represent system failure and recovery processes. Significant engineering advances on civil infrastructure resilience resulted as a response to the grand challenges for disaster reduction (Marburger 2005; MCEER 2005), particularly the fifth challenge (“Assess disaster resilience using standard methods”). Other engineering approaches include rule-based models (Reed et al. 2011) and those for design and analysis of water networks (Nazif & Karamouz 2009; Todini 2000).

2.3.2.4 Ecology Approach to Resilience

Ecology-based approaches to resilience are mainly concerned with the availability and quality of natural resources, and understanding specific ecosystem processes such as population change. Ecology resilience considers the ability of a system to reach equilibrium after certain threshold has been reached. Ecological resilience acknowledges the fact that ecosystems frequently do not return to the same previous state after disruption, but instead reach a new equilibrium, as occurs in other fields such as economics. The ecology approach to resilience inspired developments in the engineering resilience field, significantly with the paper “Resilience and Stability of Ecological Systems” (Holling 1973). Ecological resilience includes complex models with regime shifts, thresholds, and multiple equilibriums (Abel et al. 2006). Many civil infrastructure systems are built interfaces between the natural environment and societal needs, and therefore are affected by dynamic ecologic processes and also feed impacts back on the natural environment. Ecosystem resilience is related to sustainable development, and therefore a resilient built environment (including infrastructure systems) incorporates ecological considerations. A summary of the use of resilience in ecology was published by Lance Gunderson (Gunderson 2000).

2.3.2.5 Social Science Approach to Resilience

The social science approach to resilience has a variety of methods and perspectives (Allenby & Fink 2005; Berkes 2007; Coaffee 2008). Societal resilience includes, among others, the role of agents such as organizations and businesses (Prud’homme 2008; West & Lenze 1994; Quarantelli 1998), community response to disasters (Anon 2006; Mileti 1999), emergency management, societal impacts from infrastructure failure (M. Collins et al. 2011), and

community effects of infrastructure interdependencies. Civil infrastructure systems are socially driven. Society generates demands on civil infrastructure systems, and infrastructure performance generates feedbacks affecting social response. Societal resilience is important for infrastructure because the ultimate goal of civil infrastructure resilience is to minimise social consequences from system failure. Preservation of civil infrastructure performance is a means toward a societal objective.

2.3.2.6 Economics Approach to Resilience

The economic approach to civil infrastructure resilience is based on evaluating financial implications of system preparedness, failure, and recovery such as revenue loss, restoration and recovery cost, and economic impact on community activities (Jain & McLean 2009; Qiao et al. 2007; E. Vugrin et al. 2010; Weick & Sutcliffe 2007). Some economic resilience definitions include only post-disruption recovery, and economic resilience is classified in two main types, inherent and adaptive (Rose 2004). Inherent resilience is exercised during normal circumstances, and adaptive resilience is utilised during extraordinary disruptions.

Costs considered in economic resilience are not only direct damages, but also the cost of adaptation, preparedness, and mitigation options are included (E. D. Vugrin & Turnquist 2012). The evaluation of all indirect costs of a disruptive event at community level is still challenging. Failure costs are frequently compared with the cost of available mitigation and adaptation options, including emergency preparedness and opportunity costs (Rose 2004). Disaster consequences are generally measured in economic terms, and provide guidance on benefit-cost ratios, evaluation of investments, preparedness expenses, and other decision-making processes involving economic and financial considerations (Anon 2006). Economic resilience is a key component of societal resilience.

2.4. Discussion

Definitions

From the literature review, it is clear that there are a variety of definitions for resilience. Most definitions concur that resilience is the ability to “bounce back”. However, definitions of the concept of resilience vary according to the application intended in each field. Two major distinctions exist regarding the definition of resilience, as an outcome or as a process (Manyena 2006). Complete discussions on resilience definitions can be found in specific papers and reports (Gilbert 2010; Manyena 2006).

The world’s urbanization trend (U.N. High level Panel on Global Sustainability 2012) is increasing the percentage of total world population exposed to urban infrastructure failures, since urban population growth and infrastructure interdependency implies higher consequences from urban civil infrastructure disruption. Developments on infrastructure resilience can contribute to address this challenge.

Resilience is still difficult to translate into practical applications and procedures for civil infrastructure operation and management. This challenge remains an active research area (Allenby & Fink 2005; ASME-ITI 2009; Blackmore & Plant 2008). Most authors agree that system resilience cannot be guaranteed, and some argue that only the capacity for resilience can be measured, but not resilience itself (Fiksel 2003; Fiksel 2006; Hollnagel et al. 2008; Hollnagel et al. 2006).

Resilience is related to reliability and vulnerability. In some cases, vulnerability and resilience are assumed to be opposites (Klein et al. 2003) while in other cases they are considered separate concepts. In this paper, vulnerability and resilience are deemed separate concepts that do not imply each other. In general (Kjeldsen & Rosbjerg 2004; Mays 1989), reliability refers to the probability that a system will remain in a non-failure state for a period of time; resilience refers to the ability of a system to return to non-failure state after a failure has occurred, and vulnerability refers to the likely damage resulting from a disruptive event.

Enabling resilience in daily infrastructure operation and management requires a comprehensive resilience scope that includes physical and intangible assets, and is transdisciplinary, stochastic, and spans varied time domains from urgent emergency response to long-term recovery processes. Such improved concept of civil infrastructure resilience for infrastructure operation and management can be achieved defining infrastructure resilience as “*the capacity of a civil infrastructure system to minimise performance loss due to disruption, and to recover a specified performance level within acceptable predefined time and cost limits*”. The specified performance level for recovery might be the pre-disruption performance level or any other. This definition is similar to previous resilience definitions (Haines et al. 2008), but in our case we refer specifically to infrastructure performance and system management. This definition is compatible with concepts of resilience in the identified key disciplines related to operation and management of civil infrastructure systems. Since recovery time and cost are included, the definition enables the design, evaluation, and implementation of mitigation and adaptation options.

The proposed definition has the following advantages:

- a. It is parametric, enabling infrastructure resilience measurements in terms of a set of parameters (in this case performance, recovery time, and recovery cost). The set of considered parameters can be modified always using the same approach of comparing a set of parameter values with a range of socially acceptable value limits.
- b. Refers to certain acceptable parameter values. Resilience is not a system attribute, it is rather defined in terms of the system external context. A system considered resilient in some context, may not be such in a different context. It is the combination of system parameters and context expectations which define whether a system is considered resilient.

Frameworks

Different frameworks have been developed for civil infrastructure resilience (Attoh-Okine et al. 2009; Michael Bruneau et al. 2003; Gian Paolo Cimellaro et al. 2010; McDaniels et al. 2008). Most frameworks include some form of functionality curve similar to Figure 2.1. However, there are two main types of frameworks for civil infrastructure resilience from a management perspective, either considering resilience as an outcome or as a process. An economic framework (E. Vugrin et al. 2010) considers an analogous curve to Figure 1.1 called “systemic impact”, and argues that in order to fully capture a system’s resilience the systemic impact should be complemented with a “restoration effort” curve. Restoration effort measures the economic resources required to recover pre-disruption performance level in the system. The restoration effort is measured by recovery cost, and of two systems recovering at the same rate, the one requiring less resources (effort) to recover is considered more resilient.

Another framework that have had significant impact on the development of resilience methodologies and tools in civil infrastructure systems was proposed in the Multidisciplinary Center for Extreme Events Research (Michael Bruneau & A. M. Reinhorn 2003; Michael Bruneau et al. 2003). This framework considers that a resilient system has four attributes known as the four R’s (R4): Robustness, Redundancy, Resourcefulness and Rapidity (MCEER 2005). The R4 framework also considers four dimensions of civil infrastructure systems: Technical, Organizational, Social, and Economic. Nearly 18% of key papers reviewed are based on the R4 framework. Although the R4 framework inspired many developments on civil infrastructure resilience, a practical application for management remains challenging.

The definition of civil infrastructure resilience proposed in this paper helps develop a more comprehensive framework applicable to daily infrastructure management. Such comprehensive framework will consider the stochasticity of disruptive events and recovery processes, the engineering and societal dimensions of civil infrastructure systems, the economic implications associated with failure and recovery of those systems, and the network characteristics influencing system resilience. Furthermore, a comprehensive civil infrastructure resilience framework will assess resilience of individual systems considering internal and external factors, enable effective system management, and allow the estimation of impacts from managerial decisions on system resilience.

Models

Specific models of civil infrastructure resilience were derived from the described frameworks, although other resilience models exist. For example, a model utilizes the analogies between structural trusses and water networks in terms of network analysis (Templeman & Yates 1984). A Petri net is a mathematical modelling language that has been also used to assess system resilience (Luna et al. 2010). Other approaches include Dempster-Shafer belief functions (Attoh-Okine et al. 2009; Shafer 1976) and geographic-based systems (Zhou et al. 2010). Although resilience concepts for civil infrastructure systems are frequently different from those in cyber

infrastructure, in some cases similarities may exist (Peplin 2011). As it was mentioned, system dynamics are also frequently used to address infrastructure system resilience.

Performance Criteria and metrics

Most published papers on resilience of civil infrastructure systems utilise a specific definition of resilience, tailored for the intended application. Those definitions are frequently based on only one aspect of civil infrastructure resilience such as ecological, societal, psychological, economic, or engineering considerations. However, the performance of civil infrastructure systems is affected by all these factors simultaneously, and effective infrastructure management requires joint consideration of all those fields. In this paper is argued that a more holistic and clearly measurable definition of civil infrastructure resilience is needed for improved operation and management of those systems, for example, for estimating the impact from maintenance backlogs on overall system resilience, or defining the limits for socially acceptable time and cost of recovery.

Civil infrastructure resilience does not result only from physical system attributes. Although civil infrastructure system attributes such as asset condition, network design, and others increase or decrease the system probability of resilience in case of a disruptive event, resilient civil infrastructure is rather defined by the interaction of internal system attributes and external contextual demands. As a consequence, it is argued in this paper that the same system may or may not be considered resilient in different socio-economic contexts.

Civil infrastructure resilience is the outcome of a stochastic process which cannot be exactly predicted or guaranteed (Hollnagel et al. 2006). In consequence, an improved resilience assessment methodology for civil infrastructure systems is necessarily probabilistic. For example, in civil infrastructure systems subject to disruptive events, damage extent, recovery cost, and recovery time are all essentially probabilistic processes.

Resilience concepts in social sciences and economics provide our definition of civil infrastructure resilience with objectives for system performance and metrics for recovery cost and time. In addition, societal factors determine acceptable recovery times and costs, and introduce human and organizational factors.

Graph theory provides civil infrastructure resilience specific tools for networked infrastructure. Since most civil infrastructure systems include networks of physical assets, resilience advances in graph theory contribute to advance understanding of civil infrastructure resilience.

The engineering perspective on physical asset design, construction, operation, and maintenance and the use of performance metrics are useful for achieving improved civil infrastructure resilience management. An advanced civil infrastructure resilience concept allows consideration of slow onset hazards in resilience assessment such as ageing (Frangopol et al. 2004; Prieto 2009).

In the literature, also built-in resilience of systems is being explored (Bosher 2009). Advances in understanding built-in resilience are relevant since many resilience characteristics are implicit in network design (Alberti & Marzluff 2004). Such characteristics increase or decrease the probability of obtaining a resilient response from the civil infrastructure system when disrupted. The presented definition of civil infrastructure resilience allows consideration of system ageing and inherent network features for assessment of system resilience.

System resilience is transdisciplinary. Civil infrastructure resilience depends not only on physical asset performance, organization, resources, people, or the community. Resilience results from the interaction of all those system components. Many advanced infrastructure resilience models found in the reviewed literature are stochastic and network-based. Despite the abundance of literature on resilience, there are almost no papers addressing the consideration of resilience along traditional risk assessment and management methodologies and tools within a formal system management framework, such as infrastructure asset management. Such work is essential to integrate infrastructure resilience in the infrastructure system's formal management mainstream knowledge.

Civil infrastructure resilience is currently promoted in public documents such as the U.S. National Infrastructure Protection Plan, which includes a dual protection-resilience approach to preserving infrastructure performance (DHS 2009). In the U.K., the National Policies for Gas Supply Infrastructure (EN-4) and Renewable Energy Infrastructure (EN-3) include consideration of system resilience (Dept. of Energy and Climate 2011a; Dept. of Energy and Climate 2011b). However, effective translation of resilience from public documents to operationalization is still incipient worldwide.

Resilience of civil infrastructure systems is frequently included as a secondary topic in models for analysing infrastructure dependency on other systems (Zhang & Peeta 2011) and modelling (Conrad et al. 2006). Although interdependencies and dependencies increase risk of widespread failure (O'Rourke 2007), it is possible to analyse civil infrastructure system resilience capacity independently, because individual systems may or may not be resilient based on its own resources. Furthermore, a set of interdependent and dependent infrastructure systems constitute a meta-system, and the resilience of this meta-system may be different from the resiliencies of its individual systems. As an example, consider water distribution systems. To increase preparedness against possible disruptions, water utilities in the U.S. can enter mutual assistance agreements known as WARN (Anon 2008). A participating water system has access to external support for response and recovery in case of disruption through WARN, which in fact increases the system's apparent resilience against some disruption types. However, the individual system is not necessarily more resilient: A widespread disruptive event is a common mode failure type (Rausand & Høyland 2008) and will probably affect all utilities in a given region, forcing each utility to rely on its own resources and practically neutralising WARN benefits. Moreover, a system integrated in a WARN might assume there is no need to further develop its own

individual resilience resources. Although WARNs are beneficial, they are not substitutes for developing the system's own individual resilience, independently from uncertain external help. Analysing individual civil infrastructure systems for resilience will produce more conservative assessments and better prepared systems in the long term, even for regional common mode failure events.

2.5. Conclusion

Other literature review papers addressed resilience from diverse perspectives, such as community preparedness, disaster emergency response, behavioural sciences, and economics. However, a literature review for addressing civil infrastructure resilience as an important component of improved formal infrastructure management frameworks is lacking. For example, the concept of sustainable infrastructure is currently being translated from high level theoretical frameworks to daily applications. Infrastructure resilience also has to evolve from a theoretical concept to specific frameworks, models, metrics and tools for improved system management in practice. The objective of this paper is to contribute with a literature review on civil infrastructure resilience, for enabling the development of practical applications of infrastructure resilience concepts towards improved system operation and management.

The review comprised two stages; a quantitative stage for identification of key journal papers, conference proceedings, books, and reports related to infrastructure system resilience, and a qualitative stage for reviewing key publications identified in the first stage. The literature review was performed utilizing available online databases at Virginia Tech, covering a wide variety of disciplines. Finally, a definition of infrastructure resilience is introduced that allows its use with practical methodologies and tools for improved system operation and management.

Each of the key disciplines identified in the literature review can contribute to advance a practical application of resilience to civil infrastructure system management: Engineering addresses system design, operation, performance, maintenance, and reliability, among other fundamental issues. Ecology provides approaches to identify thresholds and multiple equilibriums; social science provides tools related with management of human and organizational factors in community resilience and acceptable performance limits; economics addresses life cycle costs and enables cost benefit analysis of disruption including mitigation and adaptation options. Graph theory is a fundamental tool for understanding networked systems.

The introduced definition of infrastructure resilience is a particular case of defining resilient infrastructure in terms of a comparison of a set of n parameters with their context expectations (mainly social and environmental in this case). In consequence, infrastructure resilience can be defined in a n -dimensional space. For example, if system resilience is measured only by recovery time, we can compare this parameter with an acceptable time limit and decide whether the system is resilient, producing an uni-dimensional measure of resilience. The introduced definition is tri-dimensional (performance, recovery time, recovery cost) but many other parameters could be also integrated as required, utilising the same parametric resilience concept.

Acknowledgements

The authors would like to thank the U.S. National Science Foundation (NSF) for the partial funding of this research work. We would also like to thank the support of the Sustainable Water Infrastructure Management (SWIM) Laboratory in the Institute of Critical Technology and Applied Science (ICTAS) at Virginia Tech. CONACYT Mexico also supported this research work and the development of this paper.

2.6. References

- Abel, N., Cumming, D.H.M. & Anderies, J.M., 2006. Collapse and Reorganization in Social-Ecological Systems: Questions, Some Ideas, and Policy Implications. *Ecology and Society*, 11, p.25.
- Agarwal, P. et al., 2011. The resilience of WDM networks to probabilistic geographical failures. In *Proceedings of the 30th Conference on Computer Communications, to appear*.
- Ahuja, R.K., Magnanti, T.L. & Orlin, J.B., 1993. *Network flows : theory, algorithms, and applications*, Englewood Cliffs, NJ: Prentice Hall.
- Albert, R., Jeong, H. & Barabási, A.-L., 2000. Error and attack tolerance of complex networks. *Nature*, 406(6794), pp.378–382. Available at: http://www.nature.com/openurl?url_ver=Z39.88-2004&rft.genre=article&rft.issn=0028-0836&rft.volume=406&rft.issue=6794&rft.space=378 [Accessed January 28, 2011].
- Alberti, M. & Marzluff, J.M., 2004. Ecological resilience in urban ecosystems: Linking urban patterns to human and ecological functions. *Urban Ecosystems*, 7(3), pp.241–265. Available at: <http://www.springerlink.com/content/w2k2705776j6t84n/abstract/> [Accessed May 12, 2012].
- Allenby, B. & Fink, J., 2005. Toward Inherently secure and resilient societies. *Science*, 309.
- Amin, M., 2000. National Infrastructures as Complex Interactive Networks. In *Automation, Control, and Complexity: An Integrated Approach*. John Wiley and Sons, pp. 263–286.
- Amin, M., 2002. Toward Secure and Resilient Interdependent Infrastructures.
- Anon, 2006. *Disaster resilience: an integrated approach*, Springfield, Ill: Charles C Thomas.
- Anon, 2008. Water & Wastewater Agency Response Networks (WARN). Available at: <http://apps.awwa.org/EbusMain/Default.aspx?TabID=283> [Accessed September 12, 2011].
- ASME-ITI, 2009. *All-Hazards Risk and Resilience: Prioritizing critical infrastructure using the RAMCAP Plus Approach*, New York: ASME.
- Attoh-Okine, N.O., Cooper, A.T. & Mensah, S.A., 2009. Formulation of Resilience Index of Urban Infrastructure Using Belief Functions. *Systems Journal, IEEE*, 3(2), pp.147–153. Available at: 10.1109/JSYST.2009.2019148 [Accessed September 8, 2010].
- Berkes, F., 2007. Understanding uncertainty and reducing vulnerability: lessons from resilience thinking. *Natural Hazards*, 41, p.13.

- Blackmore, J.M. & Plant, R.A.J., 2008. Risk and Resilience to Enhance Sustainability with Application to Urban Water Systems. *Journal of Water Resources Planning and Management*, 134, pp.224–233.
- Blackmore, J.M. & Wang, C., 2009. Resilience Concepts for Water Resource Systems. *J. of Water Resources Planning and Management*, 135, p.9.
- Boin, A. & McConnell, A., 2007. Preparing for Critical Infrastructure Breakdowns: The Limits of Crisis Management and the Need for Resilience. *Journal of Contingencies and Crisis Management*, 15(1), pp.50–59. Available at: <http://onlinelibrary.wiley.com/doi/10.1111/j.1468-5973.2007.00504.x/full> [Accessed October 8, 2010].
- Bosher, L., 2009. *Hazards and the Built Environment: Attaining built-in resilience*, T & F Books UK.
- Bruneau, Michael et al., 2003. A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra*, 19, p.19.
- Bruneau, Michael & Reinhorn, A.M., 2003. Seismic Resilience of Communities - Conceptualization and Operationalization.
- Calida, B.Y. & Katina, P.F., 2012. Regional industries as critical infrastructures: a tale of two modern cities. *International Journal of Critical Infrastructures*, 8(1), pp.74–90. Available at: <http://dx.doi.org/10.1504/IJCIS.2012.046555> [Accessed August 20, 2012].
- Callaway, D.S. et al., 2000. Network robustness and fragility: Percolation on random graphs. *Physical Review Letters*, 85(25), pp.5468–5471.
- Chen, W.-K., 1990. *Theory of nets : flows in networks*, New York, NY: Wiley.
- Cimellaro, G. P. et al., 2008. Seismic resilience of health care facilities. In *14 th World Conference on Earthquake Engineering: Innovation Practice Safety*.
- Cimellaro, Gian Paolo, Reinhorn, A.M. & Bruneau, Michael, 2007. MCEER's vision on the seismic resilience of health care facilities. In *ANIDIS 2007*. p. 8.
- Cimellaro, Gian Paolo, Reinhorn, A.M. & Bruneau, Michael, 2006. Quantification of Seismic Resilience. *8th U.S. National Conference on Earthquake Engineering*.
- Cimellaro, Gian Paolo, Reinhorn, A.M. & Bruneau, Michel, 2010. Framework for analytical quantification of disaster resilience. *Engineering Structures*, 32(11), pp.3639–3649. Available at: <http://www.sciencedirect.com/science/article/B6V2Y-511H39D-1/2/ee32f20bb599f39738d5582c63a70c60> [Accessed January 5, 2011].
- Coaffee, J., 2008. Risk, resilience, and environmentally sustainable cities. *Energy Policy*, 36(12), pp.4633–4638. Available at: <http://www.sciencedirect.com/science/article/B6V2W-4TPND6D-4/2/3e0d13421531b2b72fc0321677db658e> [Accessed December 2, 2010].
- Cohen, R. et al., 2000. Resilience of the Internet to Random Breakdowns. *Physical Review Letters*, 85(21), p.4626. Available at: <http://link.aps.org/doi/10.1103/PhysRevLett.85.4626> [Accessed January 28, 2011].

- Collins, M., Carlson, J. & Petit, F., 2011. Community resilience: Measuring a community's ability to withstand. In *2nd International Conference on Disaster Management and Human Health: Reducing Risk, Improving Outcomes, Disaster Management 2011, May 11, 2011 - May 13, 2011*. WIT Transactions on the Built Environment. Orlando, FL, United states: WITPress, pp. 111–123. Available at: <http://dx.doi.org/10.2495/DMAN110111> [Accessed August 22, 2011].
- Collins, P.A. & Baggett, R.K., 2009. *Homeland security and critical infrastructure protection*, Westport, Conn.: Praeger Security International.
- Conrad, S.H. et al., 2006. Critical national infrastructure reliability modeling and analysis. *Bell Labs Technical Journal*, 11(3), pp.57–71. Available at: <http://dx.doi.org/10.1002/bltj.20178> [Accessed August 22, 2011].
- Dept. of Energy and Climate, 2011a. *National Policy Statement for Gas Supply Infrastructure and Gas and Oil Pipelines (en-4)*, The Stationery Office.
- Dept. of Energy and Climate, 2011b. *National Policy Statement for Renewable Electricity Infrastructure (en-3)*, The Stationery Office.
- DHS, D.O.H.S.W., 2009. *National Infrastructure Protection Plan: Partnering to Enhance Protection and Resiliency*,
- Duenas-Osorio, L., Craig, J. I & Goodno, B. J, 2004. Probabilistic response of interdependent infrastructure networks. *2nd annual meeting of the Asian-pacific network of centers for earthquake engineering research (ANCER)*. Honolulu, Hawaii. July, pp.28–30.
- Duenas-Osorio, Leonardo et al., 2007. Interdependent Response of Networked Systems. *Journal of Infrastructure Systems*, 13, pp.185–194.
- Fiksel, J., 2003. Designing Resilient, Sustainable Systems. *Environmental Science and Technology*, 37, p.10.
- Fiksel, J., 2006. Sustainability and Resilience: toward a systems approach. *Sustainability: Science, Practice, & Policy*, 2, p.8.
- Forrester, J.W., 1958. Industrial Dynamics: A Major Breakthrough for Decision Makers. *Harvard Business Review*, 36(4), pp.37–66.
- Frangopol, D.M., Kallen, M.-J. & Noortwijk, J.M. van, 2004. Probabilistic models for life-cycle performance of deteriorating structures: review and future directions. *Progress in Structural Engineering and Materials*, 6(4), pp.197–212. Available at: <http://doi.wiley.com/10.1002/pse.180>.
- Gilbert, S.W., 2010. *Disaster Resilience: A Guide to the Literature*, Gaithersburg, MD: NIST. Available at: http://www.nist.gov/manuscript-publication-search.cfm?pub_id=906887 [Accessed December 19, 2010].
- Gopalakrishnan, K. & Peeta, S., 2010. *Sustainable and Resilient Critical Infrastructure Systems: Simulation, Modeling, and Intelligent Engineering*, Springer.
- Grigg, N.S., 2003. Water utility security: Multiple hazards and multiple barriers. *J. of Infrastructure Systems*, 9, p.7.

- Gunderson, L.H., 2000. Ecological Resilience--In Theory and Application. *Annual Review of Ecology and Systematics*, 31, pp.425–439. Available at: <http://www.jstor.org/stable/221739> [Accessed January 10, 2012].
- Haimes, Y., Crowther, K. & Horowitz, B.M., 2008. Homeland security preparedness: Balancing Protection with Resilience in Emergent Systems. *Systems Engineering*, 11, p.22.
- Hamel, G. & Valikangas, L., 2003. The quest for resilience. *harvard business review*, 81(9), pp.52–65.
- Holling, C.S., 1973. Resilience and stability of ecological systems. *Annual review of ecology and systematics*, 4, pp.1–23.
- Hollnagel, E., Nemeth, C.P. & Dekker, S., 2008. *Resilience Engineering Perspectives (Ashgate Studies in Resilience Engineering)*, Ashgate Publishing Company.
- Hollnagel, E., Woods, D.D. & Leveson, N., 2006. *Resilience Engineering: Concepts And Precepts*, Ashgate Publishing.
- Jackson, S., 2009. *Architecting Resilient Systems: Accident Avoidance and Survival and Recovery from Disruptions*, Wiley.
- Jain, S. & McLean, C.R., 2009. Recommended practices for homeland security modeling and simulation. In *Winter Simulation Conference (WSC), Proceedings of the 2009*. Winter Simulation Conference (WSC), Proceedings of the 2009. pp. 2879–2890.
- Kjeldsen, T.R. & Rosbjerg, D., 2004. Choice of reliability, resilience and vulnerability estimators for risk assessments of water resources systems / Choix d'estimateurs de fiabilité, de résilience et de vulnérabilité pour les analyses de risque de systèmes de ressources en eau. *Hydrological Sciences Journal*, 49(5), p.1. Available at: <http://www.informaworld.com/10.1623/hysj.49.5.755.55136> [Accessed December 28, 2010].
- Klein, R., Nicholls, R. & Thomalla, F., 2003. Resilience to natural hazards: How useful is this concept? *Environmental Hazards*, 5, p.10.
- Latora, V. & Marchiori, M., 2001. Efficient Behavior of Small-World Networks. *Physical Review Letters*, 87.
- Luna, R., Balakrishnan, N. & Dagli, C.H., 2010. Postearthquake Recovery of a Water Distribution System: Discrete Event Simulation Using Colored Petri Nets. *Journal of Infrastructure Systems*, 17(1), pp.25–34. Available at: [http://dx.doi.org/10.1061/\(ASCE\)IS.1943-555X.0000039](http://dx.doi.org/10.1061/(ASCE)IS.1943-555X.0000039) [Accessed August 22, 2011].
- Manyena, S.B., 2006. The concept of resilience revisited. *Disasters*, 30(4), pp.434–450.
- Marburger, J., 2005. Grand Challenges for Disaster Reduction.
- Masten, A.S., Best, K.M. & Garmezy, N., 1990. Resilience and Development: Contributions from the Study of Children Who Overcome Adversity. *Development and Psychopathology*, 2(04), pp.425–444. Available at: <http://journals.cambridge.org/action/displayAbstract?fromPage=online&aid=2490828> [Accessed February 1, 2011].

- Matisziw, T.C., Murray, A.T. & Grubestic, T.H., 2008. Exploring the vulnerability of network infrastructure to disruption. *The Annals of Regional Science*, 43(2), pp.307–321. Available at: <http://www.springerlink.com/content/h5q1126tk5871022/> [Accessed August 23, 2011].
- Mays, L.W., 1989. *Reliability analysis of water distribution systems*, American Society of Civil Engineers (ASCE).
- Mays, L.W., 2004. *Water supply systems security*, McGraw-Hill.
- McDaniels, T. et al., 2008. Fostering resilience to extreme events within infrastructure systems: Characterizing decision contexts for mitigation and adaptation. *Global Environmental Change*, 18, p.9.
- MCEER, 2005. *White Paper on the SDR Grand Challenges for Disaster Reduction*, Buffalo, NY: MCEER.
- McManus, S. et al., 2008. Facilitated Process for Improving Organizational Resilience. *Natural Hazards Review, ASCE*, 9, p.10.
- Mendonca, D. & Wallace, W.A., 2007. Adaptive Capacity: Electric Power Restoration in New York City following the 11 September 2001 Attacks.
- Mileti, D.S., 1999. *Disasters by design: a reassessment of natural hazards in the United States*, National Academies Press.
- Morehead, R. & Noore, A., 2007. Novel Hybrid mitigation strategy for improving the resiliency of hierarchical networks subjected to attacks. *Physica A, ELSEVIER*, 378, p.10.
- Murray-Tuite, P., 2007. Perspectives for Network Management in Response to Unplanned Disruptions. *Journal of Urban Planning and Development*, 133(1), pp.9–17. Available at: <http://link.aip.org/link/?QUP/133/9/1> [Accessed January 27, 2011].
- Murray-Tuite, P.M., 2006. A Comparison of Transportation Network Resilience under Simulated System Optimum and User Equilibrium Conditions. In *Simulation Conference, 2006. WSC 06. Proceedings of the Winter*. Simulation Conference, 2006. WSC 06. Proceedings of the Winter. pp. 1398–1405.
- Nazif, S. & Karamouz, M., 2009. Algorithm for Assessment of Water Distribution System's Readiness: Planning for Disasters. *J. of Water Resources Planning and Management*, 135, p.9.
- Nelson, D.R., Adger, W.N. & Brown, K., 2007. Adaptation to Environmental Change: Contributions from a Resilience Framework. *Annual Review of Environment and Resources 2007*, 32, p.27.
- O'Rourke, T.D., 2007. Critical Infrastructure, Interdependencies, and Resilience. *The Bridge*, 37, p.7.
- O'Rourke, T.D., Lembo, A.J. & Nozick, L.K., 2002. Lessons learned from the world trade center disaster about critical utility systems.
- Omer, M., Nilchiani, R. & Mostashari, A., 2009. Measuring the resilience of the global internet infrastructure system. In *2009 IEEE International Systems Conference, March 23, 2009 -*

- March 26, 2009. 2009 IEEE International Systems Conference Proceedings. Vancouver, BC, Canada: Inst. of Elec. and Elec. Eng. Computer Society, pp. 156–162. Available at: <http://dx.doi.org/10.1109/SYSTEMS.2009.4815790> [Accessed August 15, 2011].
- Ostfled, A., 2005. Water Distribution Systems Connectivity Analysis. *J. of Water Resources Planning and Management*, 131, p.9.
- Oxford Dictionaries 2011, ‘definition of infrastructure from Oxford Dictionaries Online’, viewed 6 January, 2011, http://oxforddictionaries.com/view/entry/m_en_us1258048#m_en_us1258048.
- Park, J., Seager, T.P. & Rao, P.S.C., 2011. Lessons in risk- versus resilience-based design and management. *Integrated Environmental Assessment and Management*, 7(3), pp.396–399. Available at: <http://onlinelibrary.wiley.com/doi/10.1002/ieam.228/abstract> [Accessed May 14, 2012].
- Pearce, A.R. & Vanegas, J.A., 2002. Defining sustainability for built environment systems: an operational framework. *International journal of environmental technology and management*, 2(1), pp.94–113.
- Peplin, C., 2011. Similarities in Monitoring Civil & Computer Infrastructure.
- Prieto, B., 2009. Infrastructure Resiliency: Do We Have The Focus Right? - The Infrastructure Security Partnership (TISP). Available at: <http://www.tisp.org/index.cfm?cid=11838&pid=10261> [Accessed December 28, 2010].
- Prud’homme, A.M., 2008. *Business continuity in the supply chain: Planning for disruptive events*.
- Qiao, J. et al., 2007. Allocating security resources to a water supply network. *IIE - Transactions*, 39(1), p.95. Available at: <http://www.informaworld.com/10.1080/07408170600865400> [Accessed October 8, 2010].
- Quarantelli, E.L., 1998. *What Is a Disaster?: Perspectives on the Question*, London: Routledge.
- Rausand, M. & Høyland, A., 2008. System Reliability Theory: Models, Statistical Methods, and Applications. In *System Reliability Theory*. John Wiley & Sons, Inc., pp. 605–624. Available at: <http://onlinelibrary.wiley.com/doi/10.1002/9780470316900.refs/summary> [Accessed September 1, 2012].
- Reed, D.A. et al., 2011. A framework for optimizing civil infrastructure resiliency. In *Structures Congress 2011, April 14, 2011 - April 16, 2011*. Structures Congress 2011 - Proceedings of the 2011 Structures Congress. Las Vegas, NV, United states: American Society of Civil Engineers (ASCE), pp. 2104–2112. Available at: [http://dx.doi.org/10.1061/41171\(401\)183](http://dx.doi.org/10.1061/41171(401)183) [Accessed August 15, 2011].
- Reed, D.A., 2009. Multi-Hazard Analysis of Electric Power Delivery Systems. In *2009 ASCE Technical Council on Lifeline Earthquake Engineering Conference, TCLEE 2009: Lifeline Earthquake Engineering in a Multihazard Environment, June 28, 2009 - July 1, 2009*. TCLEE 2009: Lifeline Earthquake Engineering in a Multihazard Environment. Oakland, CA, United states: American Society of Civil Engineers, p. 30. Available at: [http://dx.doi.org/10.1061/41050\(357\)30](http://dx.doi.org/10.1061/41050(357)30) [Accessed August 22, 2011].

- Rose, A., 2004. Defining and measuring economic resilience to disasters. *Disaster Prevention and Management*, 13(4), pp.307–314. Available at: <http://www.emeraldinsight.com/journals.htm?articleid=871056&show=abstract> [Accessed May 24, 2012].
- Santora, M. & Wilson, R., 2008. Resilient and sustainable water infrastructure. *Journal / American Water Works Association*, 100(12), pp.40–42.
- Shafer, G., 1976. *A Mathematical Theory of Evidence*, Princeton, N.J: Princeton University Press.
- Sheffi, Y., 2007. Building a Resilient Organization. *The Bridge*, 37, p.7.
- Somers, S., 2009. Measuring Resilience Potential: An Adaptive Strategy for Organizational Crisis Planning. *Journal of Contingencies and Crisis Management*, Vol. 17, Issue 1, pp. 12-23, March 2009. Available at: <http://ssrn.com/paper=1394697>.
- Spellman, F.R., 2007. *Water Infrastructure Protection and Homeland Security*, Lanham, Md: Government Institutes.
- States, S., 2010. *Security and Emergency Planning for Water and Wastewater Utilities*, American Water Works Association.
- Sterman, J.D., 2000. *Business Dynamics: Systems thinking and modeling for a complex world*, New York: Mc Graw Hill.
- Tabucchi, T., Davidson, R. & Brink, S., 2010. Simulation of post-earthquake water supply system restoration. *Civil Engineering and Environmental Systems*, 27(4), pp.263–279. Available at: <http://dx.doi.org/10.1080/10286600902862615> [Accessed August 22, 2011].
- Templeman, A.B. & Yates, D.F., 1984. Mathematical similarities in engineering network analysis. *Civil Engineering Systems*, 1(3), pp.114–122.
- Tierney, K. & Bruneau, M., 2007. Conceptualizing and measuring resilience: a key to disaster loss reduction. *TR News*, (250).
- Todini, E., 2000. Looped water distribution networks design using a resilience index based heuristic approach. *Urban Water, ELSEVIER*, p.7.
- U.N. High level Panel on Global Sustainability, 2012. *Resilient People, Resilient Planet. A future worth choosing (Overview)*, New York: United Nations.
- Vugrin, E. et al., 2010. A Framework for Assessing the Resilience of Infrastructure and Economic Systems. In *Sustainable & Resilient Critical Infrastructure Systems*. Berlin-Heidelberg: Springer-Verlag.
- Vugrin, E.D. & Turnquist, M., A., 2012. *Design for Resilience in Infrastructure Distribution Networks*, Sandia National Laboratories.
- Walker, B. & Salt, D., 2006. *Resilience Thinking: Sustaining ecosystems and people in a changing world*, Washington, D.C.: Island Press.

- Wei, D. & Ji, K., 2010. Resilient industrial control system (RICS): Concepts, formulation, metrics, and insights. In *Resilient Control Systems (ISRCs), 2010 3rd International Symposium on*. pp. 15–22.
- Weick, K.E. & Sutcliffe, K.M., 2007. *Managing the Unexpected: Resilient Performance in an Age of Uncertainty*, Jossey-Bass.
- West, C.T. & Lenze, D.G., 1994. Modeling the Regional Impact of Natural Disaster and Recovery: A General Framework and an Application to Hurricane Andrew. *International Regional Science Review*, 17(2), pp.121 –150. Available at: <http://irx.sagepub.com/content/17/2/121.abstract> [Accessed August 17, 2011].
- Willingham, M., 2008. Focusing on regional resilience. *Proceedings of the IEEE*, 96(5), pp.755–757. Available at: <http://dx.doi.org/10.1109/JPROC.2008.917713> [Accessed August 22, 2011].
- Zhang, P. & Peeta, S., 2011. A generalized modeling framework to analyze interdependencies among infrastructure systems. *Transportation Research Part B: Methodological*, 45(3), pp.553–579. Available at: <http://www.sciencedirect.com/science/article/pii/S0191261510001219> [Accessed August 30, 2011].
- Zhou, H. et al., 2010. Resilience to natural hazards: a geographic perspective. *Natural hazards*, 53(1), pp.21–41.
- Zobel, C.W., 2010. Comparative visualization of predicted disaster resilience. In *Proceedings of the 7th International ISCRAM Conference*.

CHAPTER 3

Stochastic Simulation Methodology for Resilience Assessment of Water Distribution Networks

Leon Gay¹, Sunil Sinha¹

¹ Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, Virginia; U.S.A.

Correspondence: Leon F. Gay, Department of Civil and Environmental Engineering, 115 Patton Hall, Virginia Tech, Blacksburg, VA., 24060, U.S.A. E-mail: leonf@vt.edu

Abstract

Water distribution systems enable social and economic development and sustain people quality of life. However, these systems face significant performance challenges including ageing, natural disruptive events, and man-made disruptions. Physical protection of networked infrastructure distributed over large geographical areas is unfeasible. A cost-effective alternative is to enhance the water distribution system resilience: Ensuring reduced system damage in case of disruption, and enhancing system capacity to recover lost performance within acceptable time and cost limits. This paper presents a novel network-based methodology to evaluate resilience of water distribution systems. This methodology utilizes stochastic simulation on a network model to generate statistical data on the resilience probability of the actual water infrastructure system. The methodology is a management decision support tool for enhancing system preparedness, enabling acceptable recovery parameters, and improving the evaluation of capital investment alternatives. The network-based approach can be extended to complex networks integrating physical and non-physical assets.

Keywords: Stochastic Simulation, Resilience Assessment, Water Distribution Networks, Acceptable Recovery, Network Modelling

3.1. Introduction

Near-continuous operation of civil infrastructure systems such as water distribution systems, road networks, telecommunications, and power grids is required to support the sustained development of contemporaneous society. However, these infrastructures are susceptible to a variety of disruptive events, either natural or anthropogenic. Since the protection of large geographically distributed systems is not economically viable, an alternative is to increase system resilience (DHS 2009). A resilient system is expected to quickly recover lost performance.

Different resilience indexes have been used on water distribution systems as proxies for system reliability (Todini 2000; Baños et al. 2011). Although resilience and reliability of infrastructure systems are related, they are clearly separate concepts (Kjeldsen & Rosbjerg 2004). The development of true resilience measures applicable to networked infrastructures such as water

distribution systems is a necessary step towards increased community disaster preparedness and reduced risks to populations depending on those systems (States 2010; Mays 2004).

The research on civil infrastructure resilience to unforeseen disruption includes a variety of methodologies such as graph theory (Duenas-Osorio, Craig & Goodno 2004; Duenas-Osorio et al. 2007), Dempster-Shafer theory of evidence (Attoh-Okine, Cooper & Mensah 2009), system dynamics (Han & Lee 2010), and polynomials (Bruneau et al. 2003; Cimellaro, Reinhorn & Bruneau 2010; Chang, Svekla & Shinozuka 2002).

Despite advances in developing methodologies and tools for assessing infrastructure system resilience, a practical approach that utilizes the language of utility staff and established engineering methods is lacking. This paper introduces a methodology intended to contribute in filling such gap.

In this paper, civil infrastructure resilience is defined as *the capacity of an infrastructure system to minimize damage due to a disruptive event, and to recover pre-disruption performance level within acceptable predefined time and cost limits*. Although the application of resilience concepts into civil infrastructure system operation is challenging (Hollnagel, Woods & Leveson 2006) this methodology provides a basis to achieve such application. Resilience is not a system attribute, and therefore it is not possible to say undoubtedly *a priori* whether a system will be “resilient” in case of disruption. The resilience of a system depends not only on internal system characteristics, but also on the accomplishment of minimum performance limits considered “resilient” by the community served. As a consequence, a “resilient system” is defined in terms of both internal and external factors. Furthermore, measuring system resilience consists on estimating system probability of resilience: Given that resilience is not a system attribute, “system resilience” cannot be deterministically predicted, and a stochastic approach is required.

Civil infrastructure systems have certain attributes such as topology, geographical location, physical condition, energy consumption, efficiency, etc. Many of such attributes can be measured utilizing performance metrics. In the case of a water distribution system, performance metrics are frequently referred to delivered water in terms of quantity and quality: A water distribution system is built for meeting water demands at specific flow rates and with required water quality standards.

Successful operation of a water distribution system depends not only on the performance of a network of physical assets, but also on other factors such as social context, organizational features, management framework, and so forth. Measuring the probability of system resilience thus implies measurement of physical assets’ performance and then referring such performance to a broader context-defined framework which includes societal expectations.

The methodology presented in this paper for measuring the probability of system resilience in water distribution systems compares the network assets’ performance after a disruptive event with their expected performance in terms of its social and organizational contexts.

It is suggested that a resilient system is such whose performance after a disruptive event is likely to be within a predefined range of acceptable performance values, including limited performance loss and expedited, affordable recovery. The probability of system resilience is measured using a frequency-based posterior probability, where such probability is disruptive event type-dependent. Accordingly, the resilience of a system is estimated measuring the impact from a disturbance on the system, and comparing such impact with externally-defined limits.

Externally-defined limits on system performance considered resilient are necessary. If adequate recovery time and cost limits are not defined, any infrastructure system could be considered “resilient”, independently of how much time or effort would take to recover performance levels. Clearly that is not the case. A resilient infrastructure system is expected to recover within certain time frame and under budget.

Each utility operating a water distribution system has a limited budget and resources to deal with unforeseen disruptions. Recovery time is also critical, given that community resilience depends significantly on expedited restoration of drinking water availability.

A tool being used to address water utilities’ resource limitations on dealing with large scale disruption is the integration of mutual help agreements such as the Water Agency Response Networks known as WARN (Anon 2008). However, resilience assessment of a system under isolation is still relevant. First, because this produces a simpler and more conservative resilience measure. Second, in case of a widespread disruptive event over a large geographical area (Common cause failure), such mutual help might not be available.

System probability of resilience can be measured using an arbitrary set of n parameters. For example, an uni-dimensional measure of system resilience could be recovery time. Based on such parameter, it is possible to define as acceptable a 24-hr limit and consider that a system which recovers from disruption in less than 24 hours is therefore “resilient”. Conversely, measuring resilience using ten parameters would assume that a resilient system will perform in such a way all ten parameter values are within acceptable limits. The utilization of more parameters for defining system resilience may allow more accurate resilience assessments, but an adequate balance is required between enough parameters to provide a reasonably accurate assessment and favourable cost-benefit ratio for the resilience assessment. In this paper is suggested that assessing system resilience with three parameters, namely System damage extent, recovery time, and recovery cost, is an adequate starting point.

3.2. Resilience Assessment Methodology

The methodology presented in this paper for estimating probability of resilience in water distribution systems is based on stochastic simulation. A network model of the actual water distribution system is assembled and subject to varying magnitudes of a specific type of disruptive event. System performance (damage) and estimated recovery time and recovery costs are recorded for each repetition and aggregated into a dataset. The dataset is then utilized to

obtain the probability of system resilience within a specific confidence interval using statistical inference.

The network model is subject to many disruptive event scenarios, and in each one a random set of network assets fail. Each disruptive scenario represents a failure mode for the system and a different damaged network configuration. The number and characteristics of simultaneously failed assets are associated to the type and magnitude of the simulated disruption. This is further discussed later.

Figure 3.1 represents a conceptual model of this methodology. The input parameters include network characteristics, failure and response parameters, and recovery information. These inputs are utilized to obtain statistical data from the network under a variety of failure modes, generated through stochastic simulation. The model output include system performance in terms of system damage, recovery time, and recovery cost. In this way, it is possible to estimate a system's probability of resilience as a posterior probability.

The resilience assessment procedure for any water distribution system has the following steps:

1. Assemble a Network Model of the system
2. Assign failure probabilities to groups of assets
3. Generate a set of scenarios
4. Apply each scenario to the network model and record generated data
5. Analyse generated data
6. Compare system performance with resilient performance limits

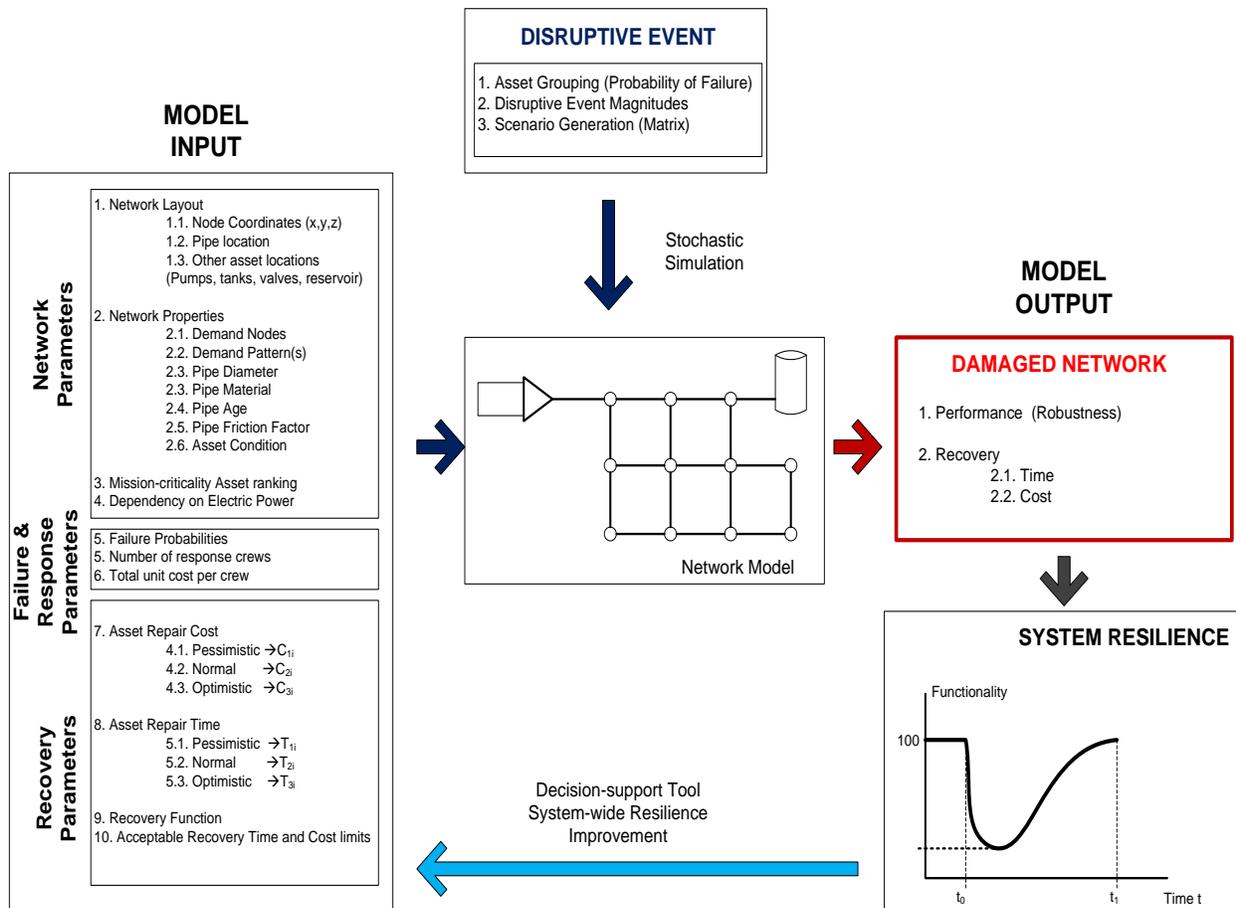


Figure 3.1 Conceptual Model of ERASMUS

Assemble a network model of the system

The first step is to assemble a network model of the real water distribution system to be assessed. The network model utilizes the hydraulic analysis engine EPANET 2 to obtain performance metrics for damaged network configurations. Performance metrics are related to water quantity and quality, such as water delivered to demand nodes or chemical tracing in the network.

Although EPANET in principle has no capacity to perform hydraulic analysis of damaged networks, approaches have been developed to deal with this challenge (Davis et al. 2009).

The network model is constructed applying a skeletonization process and assembled using the following types of assets: Reservoirs, pumps, tanks, valves, nodes, and pipes. The network model resolution will usually include transmission and distribution mains, but not service lines.

A network-based methodology provides significant advantages, including:

- a. A graphical representation of the real system, which enables effective identification of topological features relevant for system resilience and easily relates to system operation.

- b. Allows the use of performance metrics with immediate practical meaning in terms of water quantity and quality.
- c. A network-based model is scalable. Although this methodology currently utilizes only a network of physical assets, the network approach can be extended to include intangible assets as well.
- d. A network and its parameters can be easily modified afterwards to perform sensitivity analysis and evaluate the impact of capital improvements, layout changes, or other changes possibly affecting overall system resilience.

Assign failure probabilities groups of assets

In a network with n assets, the total number of different asset failure combinations is 2^n . When the network is operating normally, all assets are assumed to be in working condition. The methodology assumes that without asset failure there is no system disruption and hence modelling a disruptive event is equivalent to simulate one or more asset failures. Each combination of one or more simultaneous asset failures constitutes a possible network failure mode. Notice that for including water quality issues the definition of asset failure will need to be modified.

Probabilities of failure assigned to network assets under a specific type of disruptive event depends on certain criteria. First, each asset will have some degree of susceptibility to damage based on the asset's own characteristics and type of disruptive event considered. For example, while an elevated storage tank may be damaged by strong winds, a buried pipe will likely not. Second, assets susceptible to the same disruptive event are not necessarily of the same type. For example, an earthquake may damage pipes and tanks as well. Finally, assets susceptible to damage may have different degrees of susceptibility. For example, although all elevated tanks may be damaged by strong winds, they are not equally likely to be damaged because they may have different elevations, locations, or hazard exposures. Most disruptive events are not homogeneous and do not impact equally every specific asset in the network. For this reason, asset failures are generated randomly, even for the same asset types.

For analysis, all assets are assigned to groups with specific probabilities of failure. All assets in the same group are assumed to have the same probability of failure. An arbitrary number of groups can be used, but we propose eleven as shown in Table 3.1.

Table 3.1 Probability of Failure Groups

Group	Prob. Failure
0	1.0
1	0.9
2	0.8
3	0.7
4	0.6
5	0.5
6	0.4
7	0.3
8	0.2
9	0.1
10	0.0

Group 0 may contain those assets guaranteed to fail during the considered disruptive event, and therefore their failure is included in all utilized failure modes. Conversely, group 10 may contain assets not susceptible to the specific type of disruptive event being considered, and their failure will not be included in any failure mode.

Assets are assigned to a specific group utilizing a simple heuristic method based on each asset's and the disruptive event characteristics. For example, to simulate damage by strong wind or flooding, assets can be assigned to a specific group based on their elevation; for deliberate attack, assets can be grouped according to their criticality, and so on.

Grouping assets according to probability of failure also allows for consideration of asset condition. Has been suggested that impacts from ageing and deteriorated infrastructure systems need to be addressed in resilience assessments (Prieto 2009). This can be achieved by considering system ageing a hazard and relating asset probability of failure with asset condition. Although system deterioration is a slow developing process (slow onset) in relation with other traditional hazards such as flooding or tornadoes (sudden onset), it is still a hazard susceptible of resilience analysis (Calida & Katina 2012).

Generate a set of scenarios

Most real networks have too many assets to consider all possible system failure modes. This methodology generates a statistically significant random set of failure modes. The number of failure modes in the scenario matrix is related to the number of assets in the network. Small networks may require consideration of less failure modes than larger networks.

The set of failure modes (also called scenarios) is intended to represent varying magnitudes of disruptive events. The set of scenarios is contained in a Scenario Matrix, *S*. The rows of the

scenario matrix are failure modes, and the columns are all network assets. A network with n assets subject to k scenarios will have a scenario matrix of order (k,n) as shown.

$$S = \begin{bmatrix} S_{11} & S_{12} & \dots & S_{1n} \\ S_{21} & S_{22} & \dots & S_{2n} \\ \vdots & \vdots & & \vdots \\ S_{k1} & S_{k2} & \dots & S_{kn} \end{bmatrix} \quad (1)$$

S is a binary matrix. If the element s_{ij} is zero, asset j is assumed to be working properly on failure mode i , and 1 otherwise (failed). Normal system operation is the baseline scenario (a null vector).

Not all magnitudes of disruptive events magnitudes are equally probable to occur. While small disruptions in water distribution networks are relatively frequent, large scale failures involving many assets tend to have lower occurrence probability. Figure 3.2 represents a distribution of natural disruptive events impacting a water distribution system.

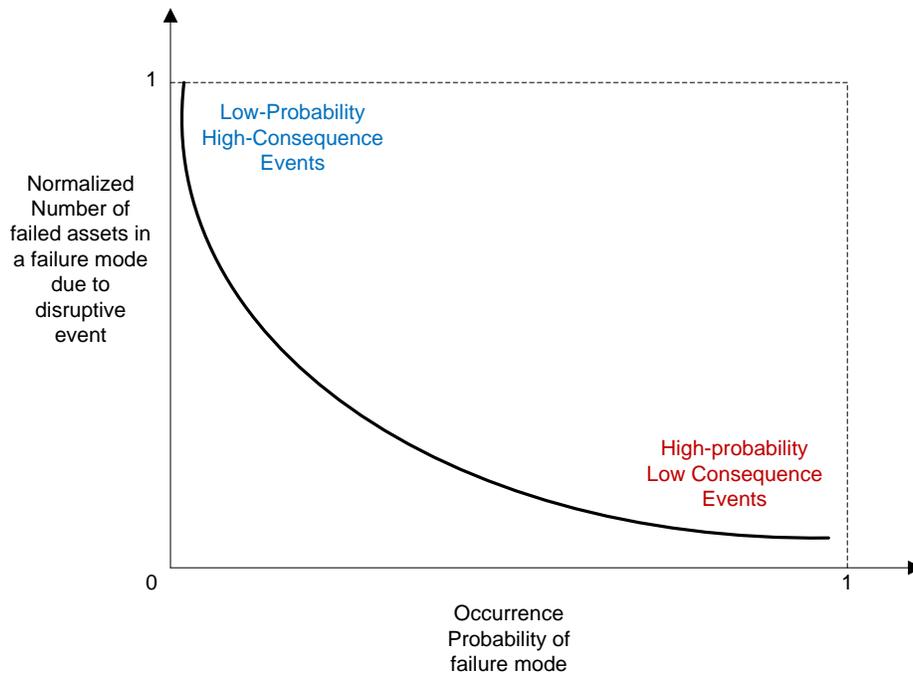


Figure 3.2 Failure Modes are Distributed in the Scenario Matrix following a Power Law.

Failure modes associated with certain types of natural disruptive events in the scenario matrix S are distributed following a power law according to return period. Other types of disruptive events may have other probability distributions. For example, man-made disruptions, either deliberate or accidental may not follow this probability distribution.

For natural events, the curve shown in Figure 3.2 is generated from the return period in years, T . The power law in this case is obtained calculating the probability that a disruptive event will occur in any given year, P (Event). We know that if the event under consideration has a return period of T years, such probability is:

$$P(Event) = \frac{1}{T} = T^{-1} \quad (2)$$

Failure modes for the scenario matrix are generated randomly choosing assets to fail from the probability groups (except group 10). The assets to fail in each scenario are selected using the biased sampling method, which causes failed assets in any failure mode to follow a multivariate Wallenius' non-central hypergeometric distribution (mwnchypg) (Chesson 1976; A. Fog 2008; Agner Fog 2008). The probability mass function of a mwnchypg distribution has the form (Chesson 1976; A. Fog 2008; Agner Fog 2008):

$$mwnchypg(\mathbf{x}; n, \mathbf{m}, \mathbf{w}) = \Lambda(\mathbf{x})I(\mathbf{x}) \quad (3)$$

Where

$$\Lambda(\mathbf{x}) = \prod_{i=1}^c \binom{m_i}{x_i} \quad (4)$$

And

$$I(\mathbf{x}) = \int_0^1 \prod_{i=1}^c \left(1 - t^{w_i/d}\right)^{x_i} dt \quad (5)$$

Given that

$$d = \mathbf{w}(\mathbf{m} - \mathbf{x}) = \sum_{i=1}^c w_i(m_i - x_i) \quad (6)$$

With the vectors

$$\mathbf{x} = (x_1, x_2, \dots, x_c) \quad (7)$$

$$\mathbf{m} = (m_1, m_2, \dots, m_c) \quad (8)$$

$$\mathbf{w} = (w_1, w_2, \dots, w_c) \quad (9)$$

In equations (3) to (9), c is the number of groups in a population, m is the number of members in each group, and w are the weights associated with the groups. The set of failure modes contained in the scenario matrix (Eq.1) is assembled using the following procedure: First, the total number of scenarios to assemble is defined. Then, the total number of scenarios is broken down in such a way that there are few scenarios for large failures and many more scenarios for small failures, if

a power law distribution applies (Figure 2.2). Finally, each scenario is assembled using biased sampling, therefore causing a Wallenius' probability distribution to arise.

The utilized method for biased sampling is an urn simulation (Agner Fog 2008) in which assets for a failure mode are chosen according to the probability of failure of the group where they belong and also the number of assets in the group. This method simplifies the multivariate sampling process to an univariate problem:

$$mwnchypg(x; 1, m, w) = p(i) = \frac{m_i w_i}{\sum_{j=1}^c m_j w_j} \quad (10)$$

Where m is the number of assets in group i and w is the probability of failure of the associated group.

Apply each scenario to the network model and record generated data

A simulation tool called ERASMUS (Effective Resilience Assessment Methodology for Water Utilities) is being developed for applying this methodology. In this tool, hydraulic analyses of the water distribution network are performed using the hydraulic analysis engine EPANET 2. The network model under normal operation (baseline scenario) is calibrated before the resilience assessment analysis. Calibration ensures that the assembled network model adequately represents hydraulic performance of the actual system.

During the resilience assessment, the ERASMUS tool performs a stochastic simulation coordinating the consecutive application of all failure modes in the scenario matrix to the network model, and gathering resulting data on system performance.

The current applications of this methodology include only water quantity as a system performance metric. The water quantity delivered to demand nodes on each failure mode is compared with the amount of water delivered during normal operation, calculating a performance ratio with values on the range [0,1]. Performance measures in terms of water quality will be included in future work.

Analyse generated data

Each failure mode will likely cause a reduced amount of water delivered at demand nodes. Therefore, a measure of system robustness can be represented by the ratio of water amount delivered in a specific damaged network configuration divided by total water delivered under normal system conditions.

If R_i is the robustness of system under the failure mode S_i , and the probability of such failure mode is $P(S_i)$, the expected system robustness is:

$$R_o(D) = \sum_i R_i P(S_i) / \sum_i P(S_i) \quad (11)$$

Where $R_o(D)$ is the expected value of robustness of the system under the disruptive event D, resulting from a weighted average of network robustness values obtained in failure mode runs.

The occurrence probability of each failure mode can be easily obtained as a conditional probability of all asset failures in that mode. Although all asset failures in a failure mode result from the same disruptive event, all those asset failures are assumed independent, which is mostly true. In cases where this assumption is false, estimation of the probability of each scenario is modified.

The simulation tool also generates information on system recovery time and cost after a disruptive event. Recovery time is the estimated time required to recover the system from disruption and achieve the pre-disruption performance level. Recovery cost is the total cost of repair or replacement required to restore such pre-disruption performance. Recovery cost includes direct and indirect costs of materials and labour, and revenue loss from system downtime.

Given that recovery time and cost are uncertain before a disruptive event occurs, their values are estimated with specific utility information through a triangular probability distribution. The triangular distribution is frequently utilized to estimate uncertain values based on three assessments: minimum, most likely, and maximum estimates. While utilities may not know beforehand the cost and time required for repairing specific assets, they are likely to have good estimates for those three values, from historical and personnel experience records.

If the minimum, most likely, and maximum values for a parameter are a, c, and b respectively, the probability density function of a triangular distribution is given by

$$f(x|a, b, c) = \begin{cases} 0 & \text{for } x < a \text{ or } x > b \\ \frac{y(x-a)}{(c-a)} & \text{for } a \leq x < c \\ \frac{y(b-x)}{(b-c)} & \text{for } c \leq x < b \end{cases} \quad (12)$$

Where

$$y = \frac{2}{(b-a)} \quad (13)$$

And

$$f(x|a, b, c) = y \quad \text{for } x = c \quad (14)$$

The triangular probability distribution provides estimates for recovery time and cost on each failure mode. However, the same recovery time and cost values can be utilized along with different recovery functions (Fig. 2.3).

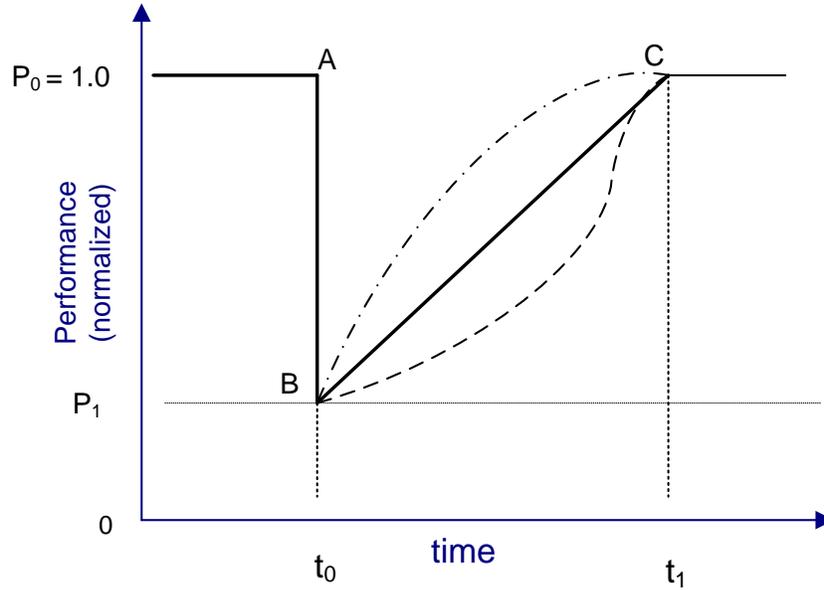


Figure 3.3 Different Types of Recovery Functions in a Functionality Curve

Figure 3.3 contains a hypothetical functionality curve. The vertical axis is system performance, and the horizontal axis is time. A functionality curve represents system performance before and after disruption at time t_0 . Residual performance P_1 is the system robustness R_0 and the section between points B and C is the recovery section of the curve. A recovery function determines the shape of the recovery section. In the literature on resilience assessment, three types of recovery functions have been identified (Bruneau et al. 2003; Cimellaro et al. 2006, 2008, 2010). These three types of recovery functions are briefly explained as follows.

a. Linear

A linear recovery function is used when there is not enough information to assume any other function shape (continuous line in Figure 3.3). A linear recovery function has the form

$$f(t) = a \left(\frac{t-t_0}{t_1-t_0} \right) + b \quad (15)$$

b. Trigonometric

A trigonometric recovery function (dashed line in Figure 3.3) may occur when the utility is not well prepared to respond to the disruptive event. This type of recovery function has a very slow start, and the rate of recovery increases over time. A trigonometric recovery function has the form

$$f(t) = \frac{a}{2} \left(1 + \cos \left(\frac{\pi b [t-t_0]}{t_1-t_0} \right) \right) \quad (16)$$

c. Exponential

An exponential recovery function (dash-dot line in Figure 3.3) may represent the recovery of a well prepared utility. As soon as the system is damaged, recovery starts at a high rate. The exponential recovery function has the form

$$f(t) = a \left[\frac{-b(t-t_0)}{t_1-t_0} \right] \quad (17)$$

ERASMUS can utilize all these three types of recovery functions. The recovery function selected in a specific case depends on particular conditions of the assessed system, such as available resources, location, etc. Different recovery functions are sometimes explored in the same analysis for a more complete resilience assessment of the system.

Compare system performance with resilience performance limits

As mentioned before, the probability of resilience of a water distribution system can be estimated through stochastic simulation utilizing a set of n parameters. The simulation tool utilizes three parameters: expected system damage, recovery time, and recovery cost. Expected system damage is the difference between pre-disruption performance level P_0 (Fig. 3.3) and disrupted performance P_1 (also known as Robustness).

Figure 4 is a conceptual representation of assessing infrastructure system resilience utilizing stochastic simulation in a three dimensional space. This scatter graph shows some hypothetical data points (circles). Each one of those points was obtained assuming a particular failure mode of the water distribution network and estimating the three parameters (axes). Each data point consists of three values (x_1, x_2, x_3) : recovery time, recovery cost, and damage for each failure mode.

The rectangular prism defined by limits t_a , c_a , and d_a contains those data points for which the system performance parameters are considered acceptable. The probability of system resilience can be approximated as the posterior probability (Ang & Tang 1975):

$$P(R) = \lim_{n \rightarrow \infty} \left(\frac{s}{n} \right) \quad (18)$$

Where n is the total number of data points and s is the number of such data points x which satisfy

$$x | (x_1 < ta) \cap (x_2 < ca) \cap (x_3 < da) \quad (19)$$

Resilient performance limits of acceptable limits for recovery time and recovery cost are mostly defined by the system administrator (utility) or regulatory agencies (AWWA 1984; Mays 2004; States 2010). Since recovery cost is dependent upon recovery time, it is expected that the data points will be scattered around a curve with positive slope, as shown in Fig. 3.4.

It is also noteworthy to point out that different acceptable performance limits may coexist in a single water distribution network. For example, other critical infrastructures such as hospitals and power generation plants may have distinct tolerances to water service disruptions than households or offices. Ancillary water distribution systems, such as those for fire fighting, also have other acceptable performance expectations.

Data generated during the simulation can provide other statistical information on system performance features, such as measures of central tendency and spread.

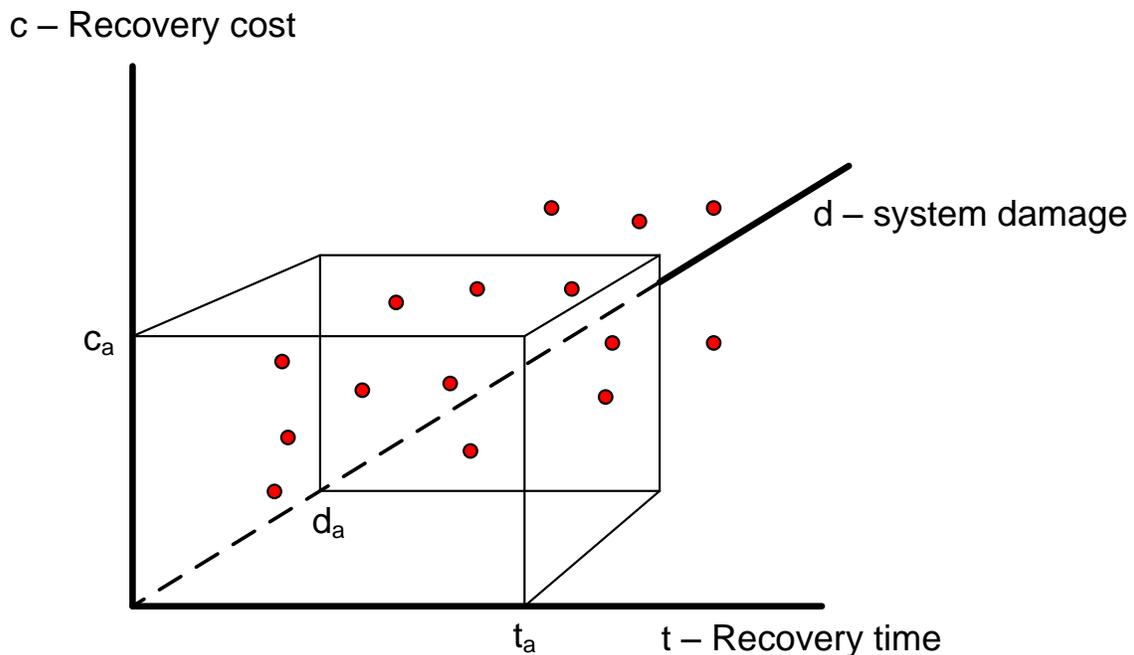


Figure 3.4 Stochastic Simulation Evaluation of System Resilience
(t_a : allowable time; c_a : allowable cost; d_a : allowable damage)

3.3. Application Example

Consider the hypothetical network shown in Figure 3.5.

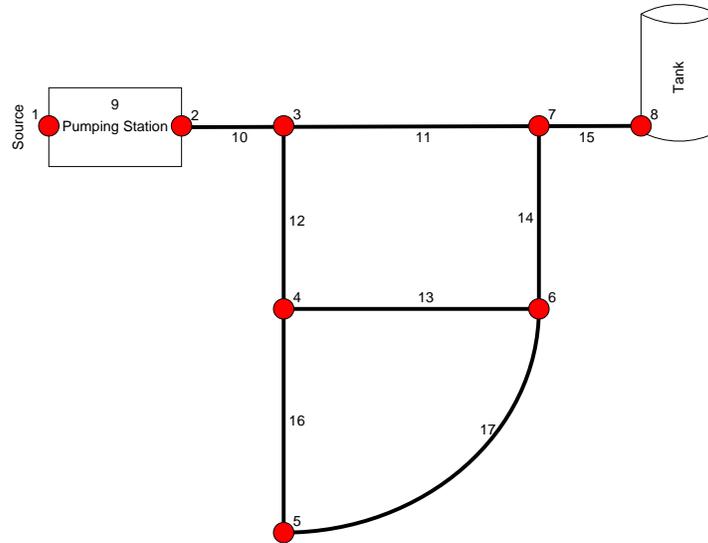


Figure 3.5 Hypothetical Water Distribution Network. (Modified from Rossman 2000)

This network has a total of 17 assets including a reservoir, pumping station, storage tank, pipes and nodes. The network delivers water through four demand nodes (3,4,5,6). Assume we want to assess the resilience of this network to ageing.

After assembling the network model, assets are assigned to a probability of failure group (Table 3.2), in this case according to their physical condition. For example, an asset in poor condition may be in group 1 with a probability of failure of 0.90.

Table 3.2 Asset grouping

Group	Prob. Failure	Assets
0	1.0	-
1	0.9	13
2	0.8	12
3	0.7	-
4	0.6	-
5	0.5	11
6	0.4	10
7	0.3	9
8	0.2	14
9	0.1	8,15,16,17
10	0.0	1 - 7

A binary scenario matrix containing failure modes is assembled utilizing biased sampling. For illustrative purposes this example only includes ten failure modes, although in a real case many

scenarios are required to achieve results with statistical significance. The scenario matrix rows are failure modes, and columns are assets with non-zero probability of failure (assets in groups 0 to 9), in this case are assumed to be asset numbers 8 to 17. The complete scenario matrix obtained is:

$$S = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

A hydraulic analysis is performed for each failure mode, in order to determine how much water is delivered by the damaged network in each case. In this example, only failure modes 1,5, and 10 allow water delivery. We obtain an expected system robustness to ageing of 0.338.

Assigning hypothetical recovery time and cost values to each asset and utilizing a triangular probability distribution, we can obtain recovery times and costs in each failure mode and the tri-dimensional graph shown in Figure 3.6.

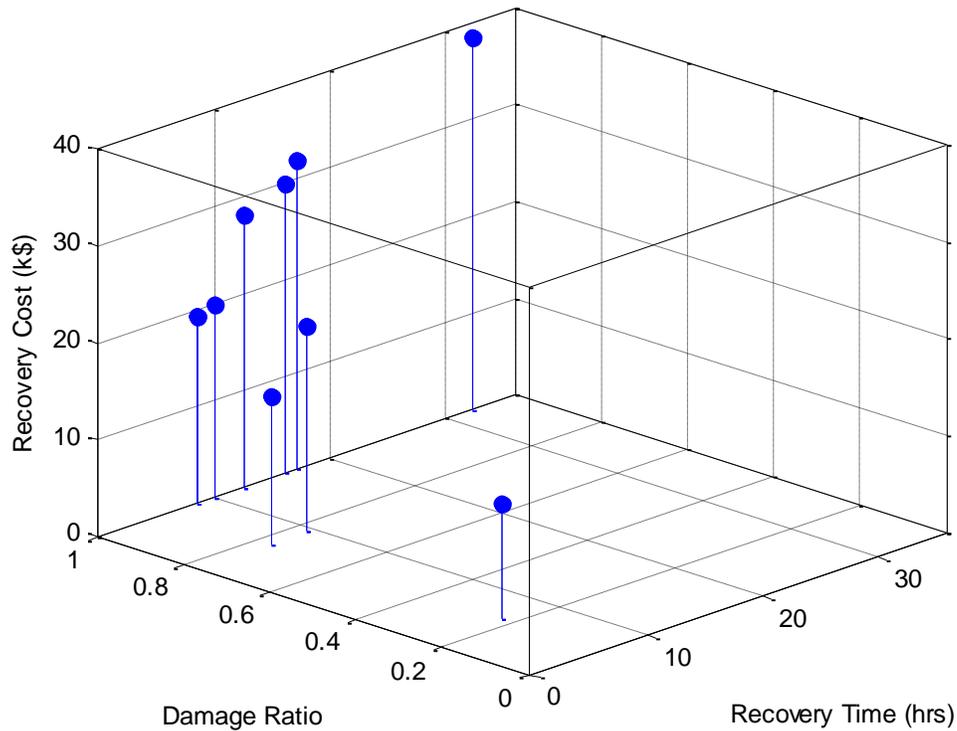


Figure 3.6 Data points in three dimensions

Each failure mode generates a data point in Figure 3.6. The resilience of the network depends on the limits for resilience as explained in Fig 3.4. For example, if this utility considers for a resilient system the limits: robustness of at least 0.20, recovery time of 10 hrs, and a maximum recovery cost of 20 thousand dollars, we can say that the probability of resilience of this system is 3/10 or 33%. This is a very coarse estimation for illustrative purposes based only on ten failure modes.

3.4. Conclusions

This paper presents a stochastic simulation methodology for resilience assessment of water distribution systems, where resilience is conceptualized not as a system attribute, but the result of a stochastic process and the intersection of infrastructure system performance and societal expectations.

This methodology and its associated tool (ERASMUS) can be utilized as a decision support tool in an infrastructure asset management frameworks. Resilience assessments in asset management are useful for evaluating a variety of system aspects such as the system's emergency preparedness, the efficiency of investment alternatives for capital improvement programs, and the impact of maintenance backlogs on system resilience, among others.

Advantages of this methodology in assessing water distribution system resilience include use of a novel conceptualization of system resilience, a network approach scalable to non-physical assets, the capability of incorporating the condition of system assets in resilience assessments, and the ability of considering ageing as a hazard to system performance.

Limitations of this methodology include limited consideration of other infrastructure system interdependencies, and possibly conservative resilience assessments. Conservative assessments can result from the fact that this methodology does not consider external help with system recovery such as the one that can be available through the Water Agency Response Networks (WARN) agreements.

Acknowledgements

The authors would like to thank the U.S. National Science Foundation (NSF) for the partial funding of this research work. We would also like to thank the support of the Sustainable Water Infrastructure Management (SWIM) Laboratory in the Institute of Critical Technology and Applied Science (ICTAS) at Virginia Tech. CONACYT Mexico also supported this research work and the development of this paper.

3.5. References

- Ang, AH. & Tang, WH 1975, *Probability concepts in engineering planning and design*, Wiley New York.
- Anon 2008, 'Water & Wastewater Agency Response Networks (WARN)', viewed 12 September, 2011, <<http://apps.awwa.org/EbusMain/Default.aspx?TabID=283>>.
- Attoh-Okine, NO, Cooper, AT & Mensah, SA 2009, 'Formulation of Resilience Index of Urban Infrastructure Using Belief Functions', *Systems Journal, IEEE*, vol. 3, no. 2, pp. 147–153, viewed 8 September, 2010, <10.1109/JSYST.2009.2019148>.
- AWWA 1984, *Emergency Planning for Water Utility Management*, American Water Works Association, Denver, CO.
- Baños, R, Reca, J, Martínez, J, Gil, C & Márquez, AL 2011, 'Resilience Indexes for Water Distribution Network Design: A Performance Analysis Under Demand Uncertainty', *Water Resources Management*, vol. 25, no. 10, pp. 2351–2366, viewed 27 September, 2012, <<http://www.springerlink.com/index/10.1007/s11269-011-9812-3>>.
- Bruneau, M, Chang, SE, Eguchi, RT, Lee, GC, O'Rourke, TD, Reinhorn, AM, Shinozuka, M, Tierney, K, Wallace, WA & von Winterfeldt, D 2003, 'A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities', *Earthquake Spectra*, vol. 19, p. 19.

- Calida, BY & Katina, PF 2012, 'Regional industries as critical infrastructures: a tale of two modern cities', *International Journal of Critical Infrastructures*, vol. 8, no. 1, pp. 74–90, viewed 20 August, 2012, <<http://dx.doi.org/10.1504/IJCIS.2012.046555>>.
- Chang, S, Svekla, W & Shinozuka, M 2002, 'Linking infrastructure and urban economy: simulation of water-disruption impacts in earthquakes', *Environment and Planning B: Planning and Design 2002*, vol. 29, p. 22.
- Chesson, J 1976, 'A Non-Central Multivariate Hypergeometric Distribution Arising from Biased Sampling with Application to Selective Predation', *Journal of Applied Probability*, vol. 13, no. 4, pp. 795–797, viewed 3 January, 2012, <<http://www.jstor.org/stable/3212535>>.
- Cimellaro, GP, Reinhorn, AM & Bruneau, M 2010, 'Framework for analytical quantification of disaster resilience', *Engineering Structures*, vol. 32, no. 11, pp. 3639–3649, viewed 5 January, 2011, <<http://www.sciencedirect.com/science/article/B6V2Y-511H39D-1/2/ee32f20bb599f39738d5582c63a70c60>>.
- Davis, CA, Romero, N, O'Rourke, TD & Nozick, LK 2009, 'Los Angeles Water Supply Response to 7.8 M Earthquake', *TCLEE 2009*, American Society of Civil Engineers, Oakland, CA, United states, pp. 1–12, viewed 29 September, 2012, <<http://ascelibrary.org/doi/abs/10.1061/41050%28357%29118>>.
- DHS, DOHSW 2009, *National Infrastructure Protection Plan: Partnering to Enhance Protection and Resiliency*.
- Duenas-Orsorio, L, Craig, JI & Goodno, BJ 2004, 'Probabilistic response of interdependent infrastructure networks', *2nd annual meeting of the Asian-pacific network of centers for earthquake engineering research (ANCER). Honolulu, Hawaii. July*, pp. 28–30.
- Duenas-Orsorio, L, Craig, JI, Goodno, BJ & Bostrom, A 2007, 'Interdependent Response of Networked Systems', *Journal of Infrastructure Systems*, vol. 13, pp. 185–194.
- Fog, A 2008, 'Calculation methods for Wallenius' noncentral hypergeometric distribution', *Communications in statistics. Simulation and computation*, vol. 37, no. 1-2, pp. 258–273.
- Fog, A 2008, 'Sampling Methods for Wallenius' and Fisher's Noncentral Hypergeometric Distributions', *Communications in Statistics - Simulation and Computation*, vol. 37, no. 2, pp. 241–257, viewed <<http://www.tandfonline.com/doi/abs/10.1080/03610910701790236>>.
- Han, SU & Lee, SH 2010, 'System Dynamics Modeling of a Safety Culture Based on Resilience Engineering', *Construction Research Congress 2010: Innovation for Reshaping Construction Practice: Proceedings of the 2010 Construction Research Congress, May 8-10, 2010, Banff, Alberta, Canada*, p. 389.
- Hollnagel, E, Woods, DD & Leveson, N 2006, *Resilience Engineering: Concepts And Precepts*, Ashgate Publishing.

- Kjeldsen, TR & Rosbjerg, D 2004, 'Choice of reliability, resilience and vulnerability estimators for risk assessments of water resources systems / Choix d'estimateurs de fiabilité, de résilience et de vulnérabilité pour les analyses de risque de systèmes de ressources en eau', *Hydrological Sciences Journal*, vol. 49, no. 5, p. 1, viewed 28 December, 2010, <<http://www.informaworld.com/10.1623/hysj.49.5.755.55136>>.
- Mays, LW 2004, *Water supply systems security*, McGraw-Hill.
- Prieto, B 2009, 'Infrastructure Resiliency: Do We Have The Focus Right? - The Infrastructure Security Partnership (TISP)', viewed 28 December, 2010, <<http://www.tisp.org/index.cfm?cdid=11838&pid=10261>>.
- Rossman, LA 2000, 'EPANET 2: users manual', EPA.
- States, S 2010, *Security and Emergency Planning for Water and Wastewater Utilities*, American Water Works Association.
- Todini, E 2000, 'Looped water distribution networks design using a resilience index based heuristic approach', *Urban Water*, *ELSEVIER*, p. 7.

CHAPTER 4

Application of Novel Stochastic Simulation Methodology for Resilience Assessment of Water Distribution Networks

Leon F Gay¹, Sunil Sinha²

Abstract

Water distribution infrastructure provides an essential societal service enabling economic development and improving quality of life. Despite their importance, water distribution systems in the US are in general deteriorated and underfunded, which poses significant public challenges. Asset management frameworks assist utilities to improve system condition and performance and hence strengthen their financial position. But asset management is currently focused mainly in performance management, with relatively little consideration of sustainability and resilience issues. A more advanced holistic asset management framework has to include these three aspects: performance, sustainability, and resilience management. This paper presents the application of a novel methodology and tool for assessing the resilience of any water distribution network, in such a way that can be integrated into an advanced asset management framework. Measuring resilience is a first step towards the design of system resilience improvement strategies and enables advanced asset management frameworks. The resilience to flooding of a small town water distribution network was assessed, and it was found that the system can be characterized as ‘resilient’, considering the available community resources. In most flooding cases simulated, the water system is likely to recover in under two weeks with less than \$50,000.

Keywords: Stochastic Simulation, Resilience, Flooding, Asset Management, Integrated Simulation.

4.1. Introduction

Resilient infrastructure systems are able to recover from disruption efficiently while minimizing performance loss. Although such a statement is useful as a general guideline for understanding the concept of resilience in the field of infrastructure management, it is not yet specific enough for deciding whether a water distribution system is or is not “resilient”.

A characteristic of infrastructure system resilience is that it cannot be decided whether a system is resilient by analyzing the system in isolation. The performance of every infrastructure system is to be evaluated against societal expectations, because such a system satisfies a societal demand and an acceptable level of service is defined according to those expectations. Infrastructure resilience

¹ Doctoral Candidate at the Civil and Environmental Engineering Department. Virginia Tech, 115 Patton Hall, Blacksburg VA 24060

² Associate Professor, Civil and Environmental Engineering Department, Virginia Tech. 117-C Patton Hall, Blacksburg, VA 24060

is therefore defined comparing system performance with the societal expectations of the infrastructure context. Those expectations include recovery cost and time after disruption.

Certain acceptable limits for recovery cost and time are necessary to decide whether a water distribution network is or is not resilient. Utilities and communities have finite financial resources, and the daily need for safe water establishes a rather short time limit for tolerable service disruption. Even within the same service area, different tolerances exist for acceptable disruption limits. For example, a hospital may have less tolerance to water unavailability than a household.

Resilient infrastructure has then to be defined in terms of a set of internal and external parameters. In this paper we use three parameters to assess water distribution networks resilience: Performance loss, recovery cost, and recovery time. In order to decide how resilient the system is, we compare damaged system parameters with external acceptable parameter limits.

A stochastic simulation methodology decision support tool was developed that allows infrastructure asset managers to know the probability of obtaining a resilient response from any given water distribution network. Such knowledge may be useful in terms of deciding investment levels for system preparedness, emergency resources, risk level posed by maintenance and renewal backlogs and alternate strategies, adequate level of system protection investment, and other relevant planning tasks.

In this paper, civil infrastructure resilience is defined as *the capacity of an infrastructure system to minimize performance loss due to a disruptive event, and to recover pre-disruption performance levels within acceptable predefined time and cost limits.*

Civil infrastructure systems have certain attributes such as topology, geographical location, physical condition, energy consumption, efficiency, etc. Many of such attributes can be measured utilizing performance metrics. In the case of a water distribution system, performance metrics are frequently referred to delivered water in terms of quantity and quality: A water distribution system is built to meet water demand at specific flow rates and with required water quality standards.

4.2. Resilience Assessment Methodology: ERASMUS

The Effective Resilience Assessment Methodology for Water Utilities (ERASMUS) is a stochastic simulation methodology developed for assessing the resilience of water distribution networks. According with the definition of infrastructure resilience suggested in the previous section, ERASMUS develops a set of failure scenarios and obtains from each one three parameters of resilience: system performance, recovery cost, and recovery time (Gay, L. and Sinha, S. 2012a). A skeletonized network model of the actual water distribution network to analyze is assembled and subject to varying magnitudes of a specific type of disruptive event. The methodology by default assumes that frequency of occurrence and magnitude of natural disruptive events like flooding, earthquake, or hurricane are related by a power law: Low impact disruptive events tend to occur significantly more often than high impact events. For man-made disruptive events, such power law may be substituted for other type of probability distributions where appropriate.

Resilience assessment of a water distribution network in ERASMUS is performed utilizing the following generic procedure:

1. Assemble a Network Model of the system

Currently ERASMUS utilizes a water quantity system performance measure based on delivered flow rate to demand nodes. The hydraulic analysis engine utilized is EPANET 2.0. The network model may be obtained from other hydraulic modeling software (such as WaterGems or WaterCAD) in EPANET file format. Skeletonization will be required in most cases in order to prepare the model for successful and more efficient analysis.

2. Assign failure probabilities to groups of assets

Each individual asset is assigned to a group with a specific probability of failure. Such probability of failure is based on asset characteristics and the type of disruptive event assumed. These probabilities can be also utilized to relate the resilience assessment with asset management parameters like asset condition, criticality, vulnerability, or others.

3. Generate a set of scenarios

ERASMUS generates a set of failure modes or scenarios, utilizing the probabilities assigned in the previous step. The scenarios are generated by biased sampling (Chesson 1976). Since a system with n assets may have up to 2^n failure modes, it is not practical or necessary to analyze all of them. The set of scenarios contains enough scenarios to ensure adequate statistical accuracy of the results.

4. Apply each scenario to the network model and record generated data

Each scenario is analyzed in order to obtain the resilience parameters: performance, recovery cost, and recovery time. Performance is obtained from hydraulic analysis of the damaged network following the methodology of GIRAFFE (NEES 2008), while recovery cost and recovery time are estimated from construction cost and productivity data (R.S. Means Company 2011).

5. Analyze generated data

The data generated through simulation runs is statistically analyzed to extract information on the system resilience to the specific type of disruptive event being considered. The complete simulation is controlled by a specifically developed MATLAB code.

6. Compare system performance with resilient performance limits

As it was discussed in the introduction, the resilience of a water distribution network cannot be obtained solely from the estimation of system performance under a variety of disruption scenarios. Acceptable limits on recovery time and cost play an essential role in defining whether the observed performance can be considered resilient. For example, different agents may have different performance requirements for the same system. A hospital may

have more stringent service interruption standards than a household, or different utilities may not have the same financial capacity to face expenses derived from a specific disruption. The last step involves determining such expected resilience levels.

4.3. Application of ERASMUS to Water Distribution Network One (WDN-1)

ERASMUS was applied for assessing the resilience of the Water Distribution Network (WDN) of a small town on the US East coast. The chosen disruptive event to consider was flooding, given the town geographical location, geology, topography, and extreme event history.

The main hazard in the town comes from flash flooding. Flooding events can be riverine or flash flooding. Riverine flooding occurs gradually along waterway areas due to events such as many continuous days of rain. Since it is relatively gradual, riverine flooding typically allows the implementation of preparedness and mitigation actions. Significant riverine floods occurred in the WDN-1 area in 1878, 1916, and 1940.

In contrast, flash flooding poses a greater risk due to its sudden onset nature, resulting from tropical storms or hurricanes. Flash flooding is the most common type of flooding in the WDN-1 area. Some significant flash floods occurred in 1972, 1973, 1978, 1985, 1991, 2002, and 2003. Most of the information about these disruptive events comes from the Federal Emergency Management Agency (FEMA) and the US Corps of Engineers (USACE). The information was reviewed to achieve more accurate flooding modeling.

A particular risk comes from dam breaks. There are 16 dams in the geographical region of WDN-1, which includes 3 dams considered of high risk due to the densely populated inundation zones that would be affected in case one of these dams fail. A dam break will probably produce a worst case disruptive scenario for WDN-1. In general, the main hazards for water distribution systems from flood include:

- a. Finished water contamination,
- b. Water main breaks due to soil scour or drag from debris
- c. Water storage tank damage
- d. Power loss

For our simulation, we are considering the following hazards: Water main break, power loss, and water storage tank damage. We are not considering water quality issues at this time.

A model of WDN-1 for hydraulic analysis was assembled and skeletonized. The model's hydraulic behavior under normal conditions is validated comparing it to the real network performance. The normal system operation is the baseline scenario against which the performance of different damaged system configurations will be compared.

A diagram of the skeletonized water distribution network WDN-1, including elevations, is shown in Figure 4.1. The network has a total of 2796 assets comprised by 2 reservoirs, 1266 nodes, 1513 pipes, 6 pumps, and 9 tanks of different sizes.

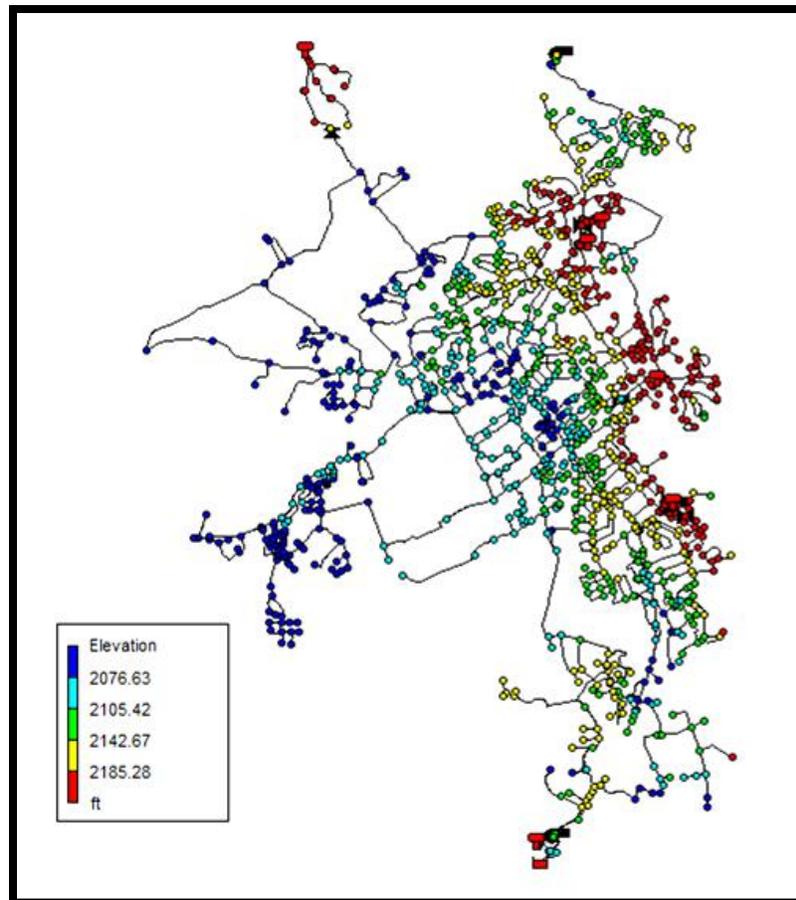


Fig. 4.1 WDN-1 Network Model with Elevations

For assessing WDN-1 resilience to flooding, a power law probability distribution is utilized for assembling a set of disruptive scenarios, where those areas of the network with lower elevations are more likely to be flooded than higher ones. The network performance was analyzed under 1500 randomly generated scenarios. The set of scenarios is contained in a scenario matrix showing which network assets are assumed to fail on each scenario. Therefore, the scenario matrix has dimensions 1500 x 2796. The scenario matrix contains only zeros and ones. Any element of the scenario matrix is zero if the given asset does not fail in the specific scenario, or one otherwise.

Figure 4.2 contains a diagram of the scenario matrix, where the non-zero elements are represented by a dot. The scenarios near the top of the matrix have many more failing assets than the lower ones because of the power law distribution of disruptive events of varied magnitudes. Top rows represent high-impact and low probability scenarios. The left side of the scenario matrix is empty because reservoir and node failures are not allowed in this case, only pipe, pump, and tank failures.

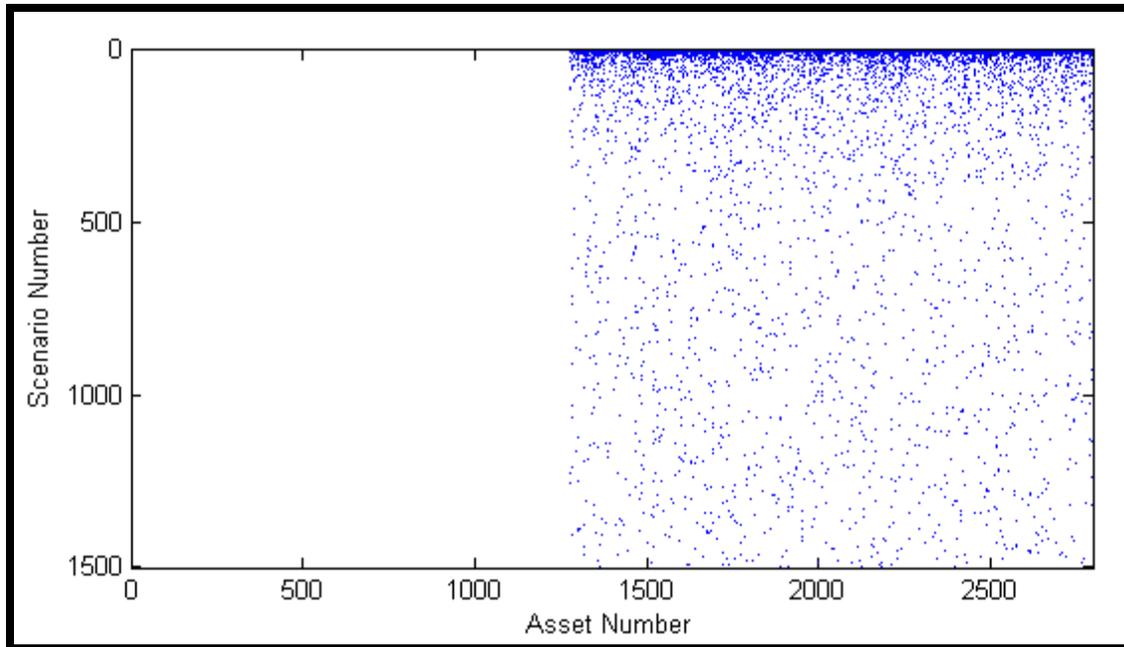


Fig. 4.2 WDN-1 Scenario Matrix Composition. A dot represents element value 1, and 0 otherwise. Rows are scenarios, and columns are the asset global numbers.

Each scenario is applied to the network in order to obtain system performance in terms of total water quantity delivered to demand nodes. The hydraulic analysis is performed by EPANET 2.0, and the entire simulation is coordinated utilizing MATLAB code. Each scenario produces a normalized performance measure whose value can range from 0 (No water delivered) to 1 (Normal volume of water delivered: Equals baseline scenario). All the 1500 performance measures obtained are then aggregated in a single expected value for system performance under flooding, utilizing the scenario probabilities as weights. The aggregated expected performance can be associated with system robustness (Bruneau et al. 2003; Cimellaro et al. 2010).

WDN-1 aggregated robustness to flooding was estimated at 0.905. This value represents the expected value of system performance under flooding. According to this result, WDN-1 can be expected to be able to deliver around 90.5% of the normal water quantity despite flooding events. Notice that this is an expected value and therefore it does not mean that in any single flooding event the system performance will necessarily be 90%. The standard deviation for system normalized performance was 0.381.

In addition to system performance on diverse failure modes, system recovery is analyzed utilizing recovery time and recovery cost estimates for each scenario. Given the significant uncertainty of individual scenario recovery cost and time, a triangular probability distribution is utilized. For each asset, three values of recovery time and cost are determined, namely pessimistic, optimistic, and more likely values. While such method does not ensure an accurate estimation of the cost and time associated with recovering the system performance from a given disruption, it provides an

acceptable estimate for our current analysis. The three values for cost and time of recovery were obtained from RS means Heavy Construction Data (R.S. Means Company 2011), and adjusted for date (2012) and location (City index).

The utilization of a triangular distribution for estimating recovery cost and time allows to accommodate the significant uncertainties associated with this information. In addition, most of cost and time information by asset on system recovery is unknown. Utilities may find easier to estimate three values instead of attempting to define a unique value for each asset.

Figure 4.3 represents the ‘resilience cloud’ of one simulation run. Each point is obtained graphing the expected system performance, recovery cost, and recovery time for each scenario. There are 1500 points in the graph although many of them are clustered.

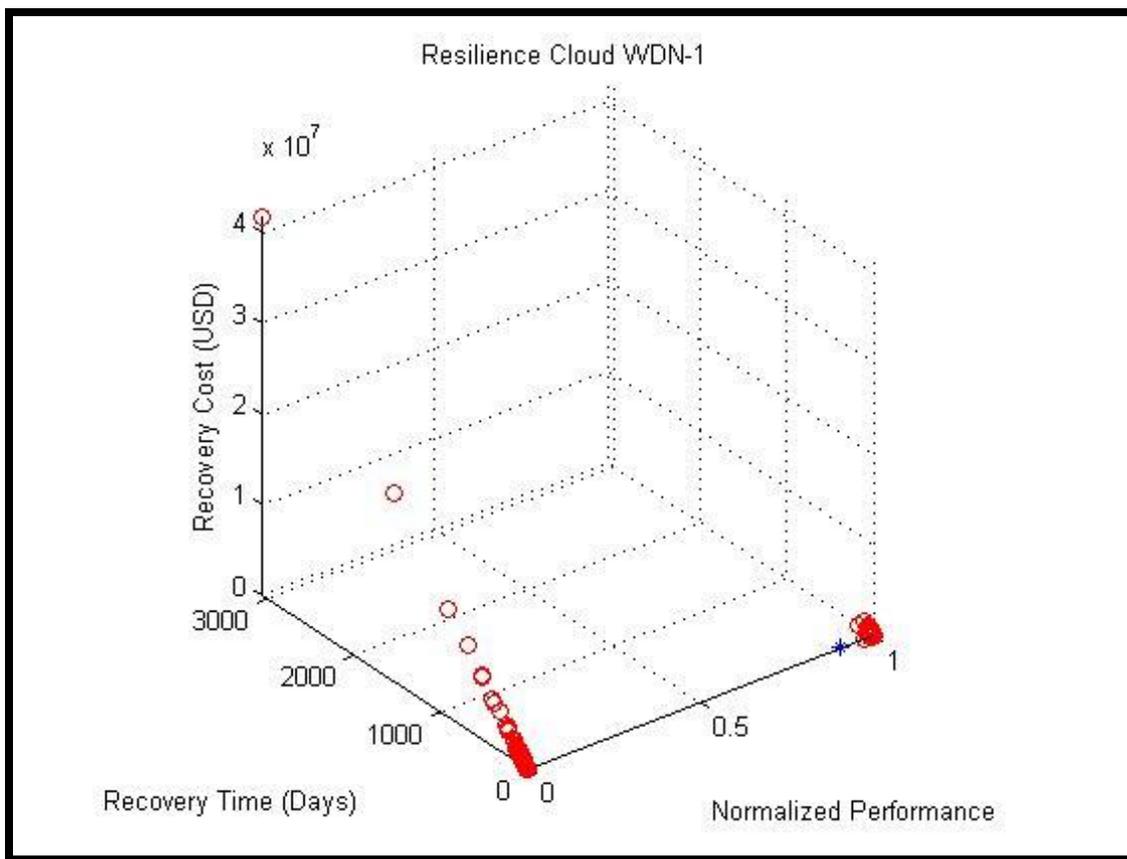


Fig. 4.3 Cloud Diagram of WDN-1 Flooding Resilience

The data point at the top left belongs to the worst case scenario, where system performance is zero (no water delivered), and recovery cost and recovery time are maximum. This is the most low-probability and high-impact scenario considered in this simulation run. Other scenarios produce zero performance (bottom left). However, most of the data points are clustered at the bottom right of the chart, in the zone of the high-probability and low-impact scenarios, which according to

experience and our power law scenario distribution are the most frequently observed failure modes.

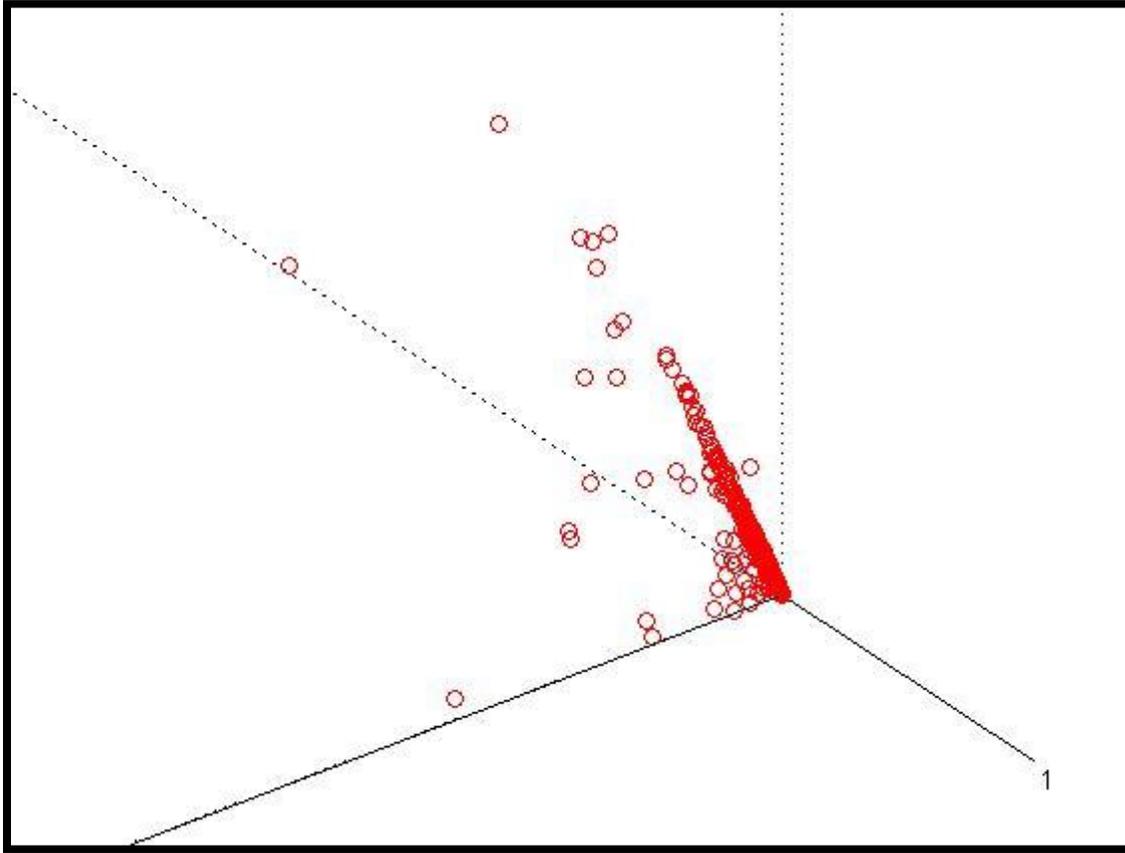


Fig. 4.4 Detail of the Cloud Diagram for Flooding Resilience

Figure 4.4 contains a detail of bottom right corner of the three-dimensional chart in Figure 4.3. This is the cluster of all the low-impact and high-probability failure scenario data points. The number 1 belongs to the performance scale. Most of these data points result from failure modes causing only marginal damage to the water distribution network, and therefore the normalized performance metric (system robustness) results very close to 1.

Figure 4.5 is the same cloud diagram as shown in Figure 4.3, but utilizing logarithmic axes for recovery time and recovery cost. The utilization of logarithmic scales allow better visualization of the data points. The normalized performance axis is still linear, therefore the diagram still appears to have all data points at both extremes, either performance one or zero. In reality, most data points imply performances near to one (for most scenarios, which have high-probability and low-consequence) or near to zero. The scenarios with low-probability and high-consequence tend to be associated with zero system performance, because either the performance is actually zero, or because the significant number of assets failing in those scenarios cause hydraulic modeling errors. Some hydraulic modeling errors may produce false zero system performance values.

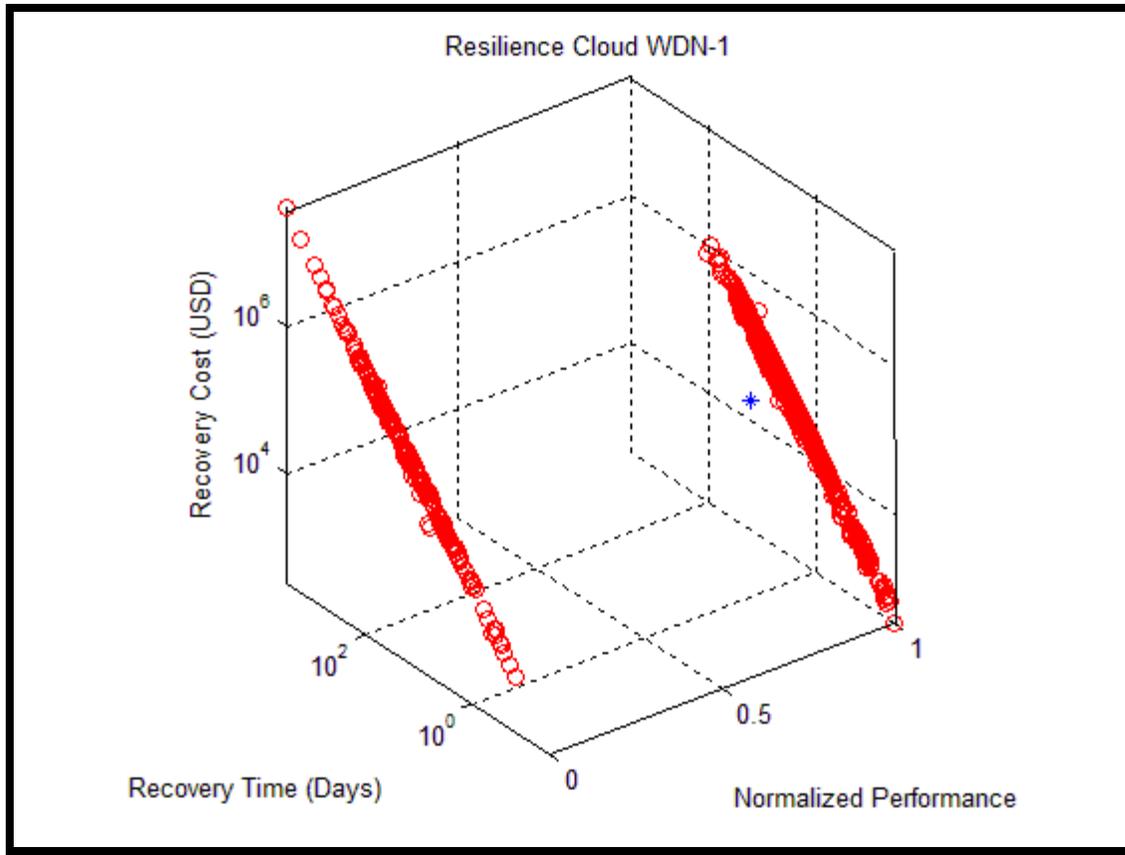


Fig. 4.5 Cloud Diagram shown using two logarithmic axes

Functionality curves are utilized to represent the resilience of an infrastructure system (Bruneau and Reinhorn 2004; Chang and Shinozuka 2004; McDaniels et al. 2008). ERASMUS generated a functionality curve for WDN-1 under flooding. Aggregating the recovery time as we did with performance in a single expected value, we can obtain a functionality curve as the one shown in Figure 4.5. The expected values for system performance and recovery time are obtained from the corresponding values on each scenario and aggregated utilizing each scenario probability as weights. For this simulation, the aggregated expected recovery time is 3.92 days and the aggregated expected recovery cost is around \$53,500 (2012 USD).

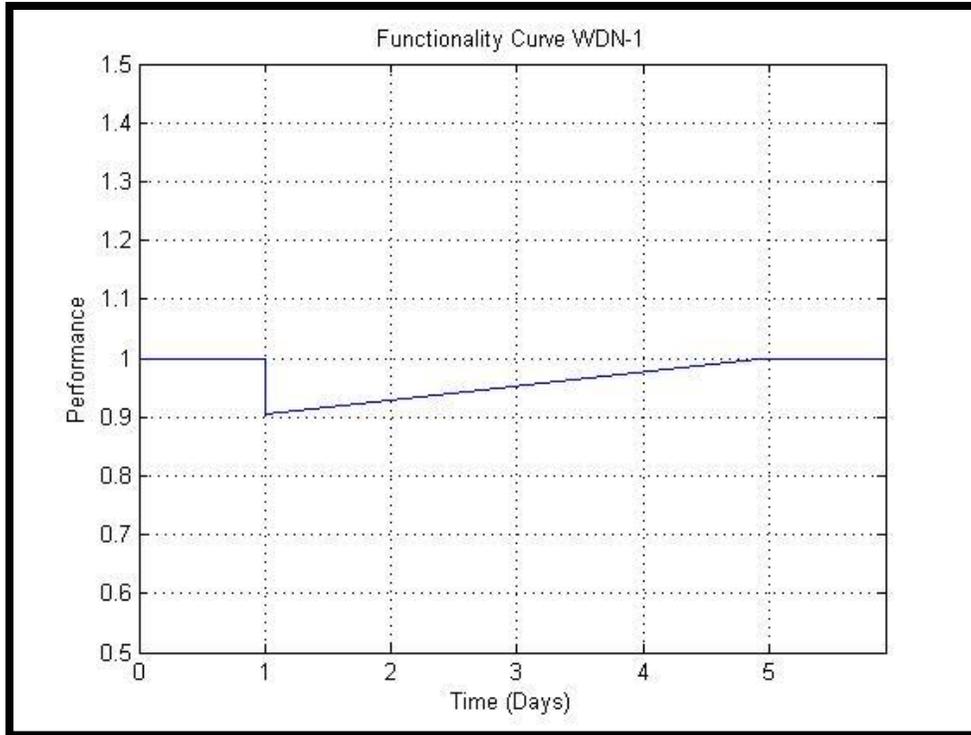


Fig. 4.6 Flooding Functionality Curve WDN-1

The functionality curve shown in Figure 4.6 has a linear recovery section (between times 1 and 5) because there was no other information on the shape of the recovery section. The recovery section may actually have a curved shape, but additional information is needed in order to define such shape. Also, it is assumed in ERASMUS that after recovery is complete, WDN-1 recovers the same pre-disruption performance level. This might not always be the case (see the discussion section).

It is expected that future versions of ERASMUS will be able to determine the most likely recovery section shape in the functionality curve, revealing whether the recovery is to be expected linear, concave, or convex.

Figure 4.7 shows how the estimated values for expected system performance are changing after certain number of scenarios analyzed. For example, after 400 scenarios the expected system performance, or robustness, would be only 0.850. By completing 1500 scenarios, the expected performance value is not changing significantly and getting close to 0.905, which is the obtained value for the aggregated expected performance, or WDN-1 expected robustness. 1500 scenarios are enough to obtain a 95% confidence interval.

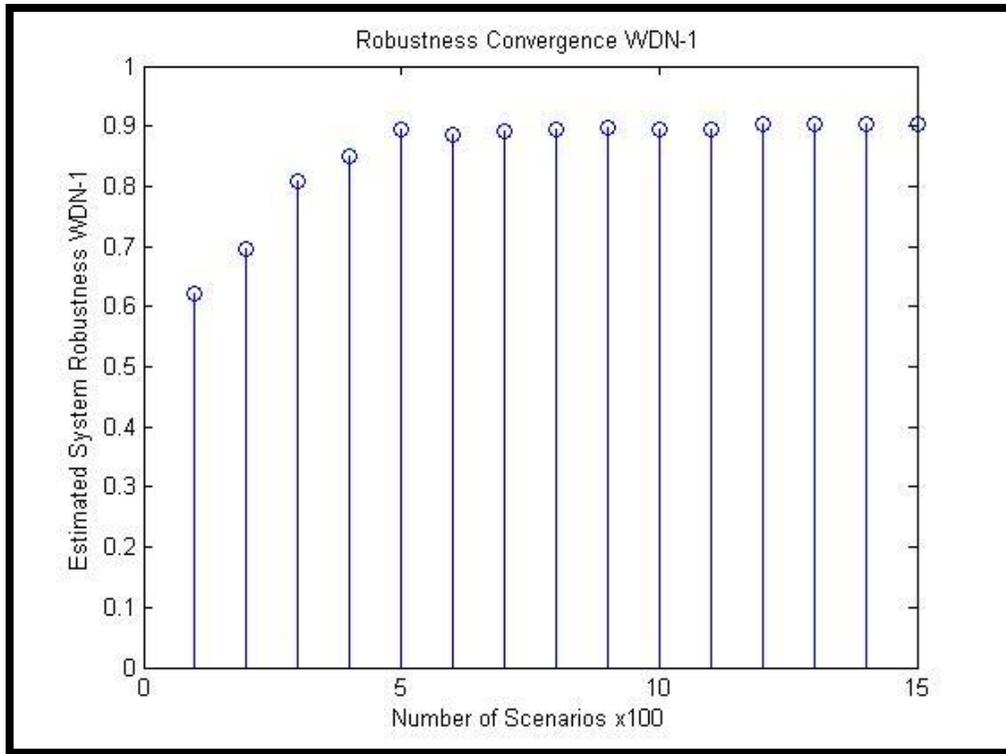


Fig. 4.7 Effect of Number of Analyzed Scenarios on Expected System Robustness

The coefficient of variation of the mean for expected performance on the 1500 scenarios was estimated at 0.012. Remember that each scenario represents a failure mode. Running the simulation with 1500 scenarios is likely to provide in this case enough accuracy in the aggregated estimates for system performance, recovery cost, and recovery time.

System resilience is not a system attribute (Hollnagel et al. 2006) and therefore we cannot know whether WDN-1 can be considered resilient utilizing only the information we obtained thus far. We suggest (Gay, L. and Sinha, S. 2012a; b) that an infrastructure system may only be defined as “resilient” taking into account the societal expectations of the context. For that reason, a resilience index was estimated utilizing different combinations of recovery cost and recovery time that may be considered acceptable for the utility and various agents in the service area of the town served by WDN-1.

Table 4.2 contains different combinations of acceptable recovery cost (2012 USD) and recovery time (Days). Each combination produces a resilience index. Those resilience indices are estimated counting the number of data points (see Figures 3.3 and 3.4) that comply with the limits for acceptable recovery cost and recovery time, while having a performance value above an acceptable performance minimum. The number of data points complying with these limits are then divided by the total number of data points (1500). For this simulation, an acceptable minimum performance

value was set arbitrarily at 0.80, which means that only those points with a normalized performance of at least 80% were counted toward estimating the various resilience indices shown.

Table 4.1 System Resilience according with societal/utility expectations

		Acceptable Recovery Cost (2012 US Dollars)									
		0	19,519	39,039	58,558	78,078	97,597	117,116	136,636	156,155	175,675
Acceptable Recovery Time (Days)	0.0	0.200	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202
	1.4	0.207	0.412	0.416	0.416	0.416	0.416	0.416	0.416	0.416	0.416
	2.9	0.207	0.425	0.517	0.526	0.526	0.526	0.526	0.526	0.526	0.526
	4.3	0.207	0.425	0.534	0.600	0.609	0.611	0.611	0.611	0.611	0.611
	5.8	0.207	0.425	0.534	0.612	0.659	0.665	0.666	0.668	0.668	0.668
	7.2	0.207	0.425	0.534	0.612	0.663	0.691	0.693	0.699	0.699	0.699
	8.7	0.207	0.425	0.534	0.612	0.663	0.698	0.716	0.723	0.725	0.726
	10.1	0.207	0.425	0.534	0.612	0.663	0.698	0.718	0.743	0.745	0.747
	11.6	0.207	0.425	0.534	0.612	0.663	0.698	0.718	0.745	0.753	0.756
	13.0	0.207	0.425	0.534	0.612	0.663	0.698	0.718	0.745	0.755	0.761

Figure 4.7 represents the values contained in Table 4.1, using a resilience index surface.

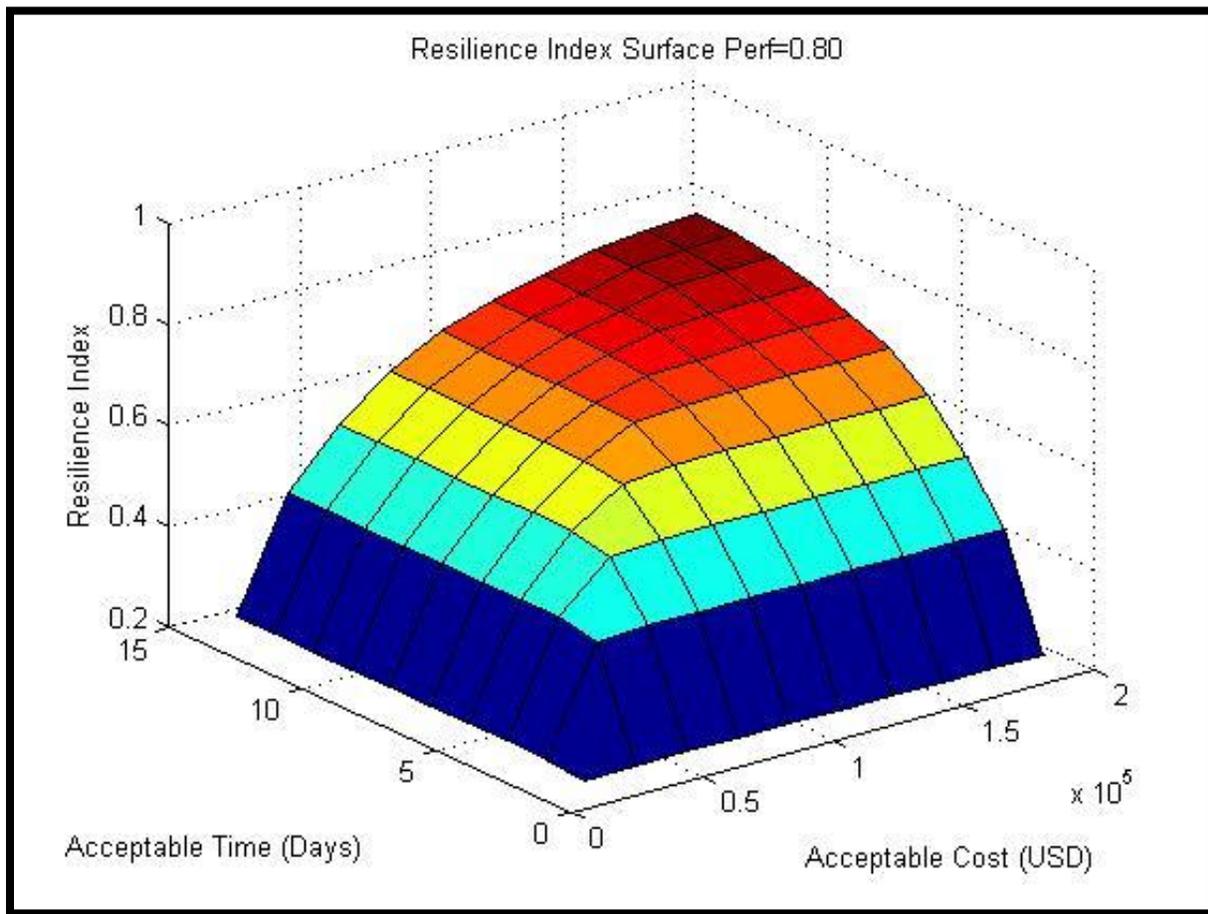


Fig. 4.8 Resilience Index Surface for WDN-1 flooding

Figure 4.8 shows that WDN-1 may have different degrees of resilience, depending on the acceptable recovery time and recovery cost values chosen. Since each resilience index is estimated using the proportion of data points complying with certain limits to the total number of scenarios, they represent a posterior probability. For example, if we assume that an acceptable recovery cost is under \$100,000 and an acceptable recovery time is no more than 10 days, the resilience index is 0.698, which is the same as to say that there is a 69.8% probability that WDN-1 will be “resilient” in case of flooding. We consider the system resilient if our acceptable limits are not exceeded: Performance over 80%, recovery cost under \$100,000 and recovery time under 10 days.

4.4. Discussion

The concept of resilience is utilized in different ways in the infrastructure literature. Sometimes it is utilized as a proxy for estimating system reliability (Baños et al. 2011), or as a tool for optimizing the design of water distribution networks (Todini 2000). Such applications of the resilience concept have proven useful. Nevertheless, it is important to regain the meaning of infrastructure resilience as a strategic management topic, to understand and develop resilience as the ability of an infrastructure system to preserve performance despite disruption, and being able to recover efficiently in terms of recovery time and cost.

Resilience as a strategic topic can be integrated with asset management and sustainability for creating more useful and robust truly advanced Asset Management Frameworks. Current asset management developments are mainly concerned with performance management. Sustainability is a contemporaneous imperative, and so is resilience if we want to preserve infrastructure function as a keystone of societal and economic development for the future. In this paper infrastructure resilience is understood as a strategic concept at the same level of performance and sustainability management.

Diverse methodologies and tools have been developed for assessing water distribution system resilience in the strategic management sense, utilizing diverse approaches including theory of evidence (Attoh-Okine et al. 2009) and system dynamics (Dauelsberg and Outkin 2005; Han and Lee 2010), among others. However, current resilience assessment methodologies have limited practical utility application. ERASMUS is intended to reduce the gap between the development of an academic infrastructure resilience concept and its practical application.

The simulation results indicate that WDN-1 has relatively high resilience with the probability values utilized. Although recovery from the worst case failure scenario may cost significant amount of time and cost, the probability of such scenario is extremely low. More likely disruptive scenarios have more manageable recovery costs and times. The volume of water the system is capable of delivering is unlikely to go very low in any flooding event under our assumptions.

The utility managing WDN-1 can benefit from the ERASMUS resilience assessment in different ways. First, results suggest that emergency planning can reasonably expect a maximum outage within acceptable limits for the town. Second, if the asset probabilities of failure are adjusted

according to known asset conditions, the impacts of Capital Improvement Programs (CIP) or maintenance backlogs on the overall system resilience can be evaluated in financial terms.

The results of the stochastic simulation suggest that analyzing only 1500 from the possible 2^{1528} failure modes produce accurate enough results for practical application as decision support tool, with an estimated 95% confidence interval. Despite these benefits from ERASMUS, challenges remain. For example, the methodology assumes that WDN-1 will recover pre-disruption performance levels, while practical experience indicates that may not be the case. After some disruptive events, the utilities may decide to upgrade or renew the system, or some inhabitants may decide to leave the service area, and therefore system performance in terms of water demand may not be the same after disruption. Another challenge is the lack of accurate field asset recovery cost and time information. The uncertainties associated with estimating these cost and time cannot be overemphasized. More and better quality data is required to increase the accuracy of ERASMUS results. Finally, costs do not include unforeseen conditions, and future major disruptions are complex events affecting the community as a whole. For example, a flooding event may impact other infrastructures, water demand patterns, water quality, or other aspects affecting the ability of the utility to attend the system recovery needs as assumed in the methodology.

The resilience index surface shown in Figure 4.8 may provide useful information for system management. Varying the acceptable recovery time and cost values, it is possible to estimate the probability that such acceptable limits are to be exceeded. Also, within the same service area different acceptable recovery values may exist for different purposes: hospitals, firefighting, households, or industry, for example. Figure 4.7 may help decide what resilience level is adequate and cost efficient for WDN-1 under various assumptions.

4.5. Conclusions

This paper presents the application of a stochastic simulation methodology for resilience assessment of water distribution systems (ERASMUS) to the water distribution network of a small town in the East coast. In ERASMUS, infrastructure resilience is conceptualized as the result from a stochastic process shaped by system performance and societal expectations. The conducted analysis produced the following conclusions:

1. WDN-1 has high flooding resilience in terms of performance under our current simulation assumptions. The network is unlikely to loss more than 10% of water delivery capacity due to flooding.
2. The worst case scenario recovery cost and time are very significant. However, the probability of occurrence for such a scenario is extremely low.
3. More likely disruption scenarios from flooding involve relatively easy repairs, considering the characteristics of the utility managing WDN-1.

4. The expected values aggregated over all the analyzed scenarios are 0.905 for system normalized performance, 3.92 days for recovery time, and \$53,500 for recovery cost. These values were estimated using mathematical expectation, and do not constitute predictions for individual disruptive events. It is also important to note that these values depend on the assumed probabilities of failure during the simulation.

ERASMUS provides information as a decision support tool for improved asset management. The utilized version of ERASMUS is the first version and thus very basic. Significant refinements and improvements are to be expected in the future, since the stochastic simulation and approach utilized by ERASMUS constitute a promising foundation for resilience assessment of infrastructure networks.

Acknowledgements

The authors would like to thank the U.S. National Science Foundation (NSF) for the partial funding of this research work. We would also like to thank the support of the Sustainable Water Infrastructure Management (SWIM) Center and the Institute of Critical Technology and Applied Science (ICTAS) at Virginia Tech. CONACYT Mexico also supported this research work and the development of this paper.

4.6 References

- Attoh-Okine, N. O., Cooper, A. T., and Mensah, S. A. (2009). "Formulation of Resilience Index of Urban Infrastructure Using Belief Functions." *Systems Journal, IEEE*, 3(2), 147–153.
- Baños, R., Reça, J., Martínez, J., Gil, C., and Márquez, A. L. (2011). "Resilience Indexes for Water Distribution Network Design: A Performance Analysis Under Demand Uncertainty." *Water Resources Management*, 25(10), 2351–2366.
- Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., and Von Winterfeldt, D. (2003). "A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities." *Earthquake Spectra*, 19, 19.
- Bruneau, M., and Reinhorn, A. (2004). "Seismic resilience of communities-conceptualization and operationalization." *Proceedings, International Workshop on Performance-based Seismic-Design, Bled, Slovenia, June 28–July*.
- Chang, S., and Shinozuka, M. (2004). "Measuring improvements in the disaster resilience of communities." *Earthquake spectra*, 20, 17.
- Chesson, J. (1976). "A Non-Central Multivariate Hypergeometric Distribution Arising from Biased Sampling with Application to Selective Predation." *Journal of Applied Probability*, 13(4), 795–797.
- Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. (2010). "Framework for analytical quantification of disaster resilience." *Engineering Structures*, 32(11), 3639–3649.
- Dauelsberg, L. R., and Outkin, A. V. (2005). "Modeling economic impacts to critical

- infrastructures in a system dynamics framework.” *Proceedings of the 23rd International Conference of the System Dynamics Society*, 21.
- Gay, L., and Sinha, S. (2012a). “Stochastic Simulation Methodology for Resilience Assessment of Water Distribution Networks.” *International Journal of Critical Infrastructures*.
- Gay, L., and Sinha, S. (2012b). “Resilience of Civil Infrastructure Systems: A State-of-the-Art Literature Review toward Improved Asset Management.” *International Journal of Critical Infrastructures*.
- Han, S. U., and Lee, S. H. (2010). “System Dynamics Modeling of a Safety Culture Based on Resilience Engineering.” *Construction Research Congress 2010: Innovation for Reshaping Construction Practice: Proceedings of the 2010 Construction Research Congress, May 8-10, 2010, Banff, Alberta, Canada*, 389.
- Hollnagel, E., Woods, D. D., and Leveson, N. (2006). *Resilience Engineering: Concepts And Precepts*. Ashgate Publishing.
- McDaniels, T., Chang, S., Cole, D., Mikawoz, J., and Longstaff, H. (2008). “Fostering resilience to extreme events within infrastructure systems: Characterizing decision contexts for mitigation and adaptation.” *Global Environmental Change*, 18, 9.
- NEES. (2008). *GIRAFFE Simulations*. Cornell University.
- R.S. Means Company. (2011). *RS Means heavy construction cost data*. R.S. Means Co, Kingston, MA.
- Todini, E. (2000). “Looped water distribution networks design using a resilience index based heuristic approach.” *Urban Water, ELSEVIER*, 7.

CHAPTER 5

Model Verification and Validation

5.1. Introduction

Verification and validation are performed throughout the simulation process to ensure the obtained model is successful in terms of initially stated simulation objectives. For this research, verification and validation of the stochastic simulation model were performed utilizing the simplified modeling process shown below.

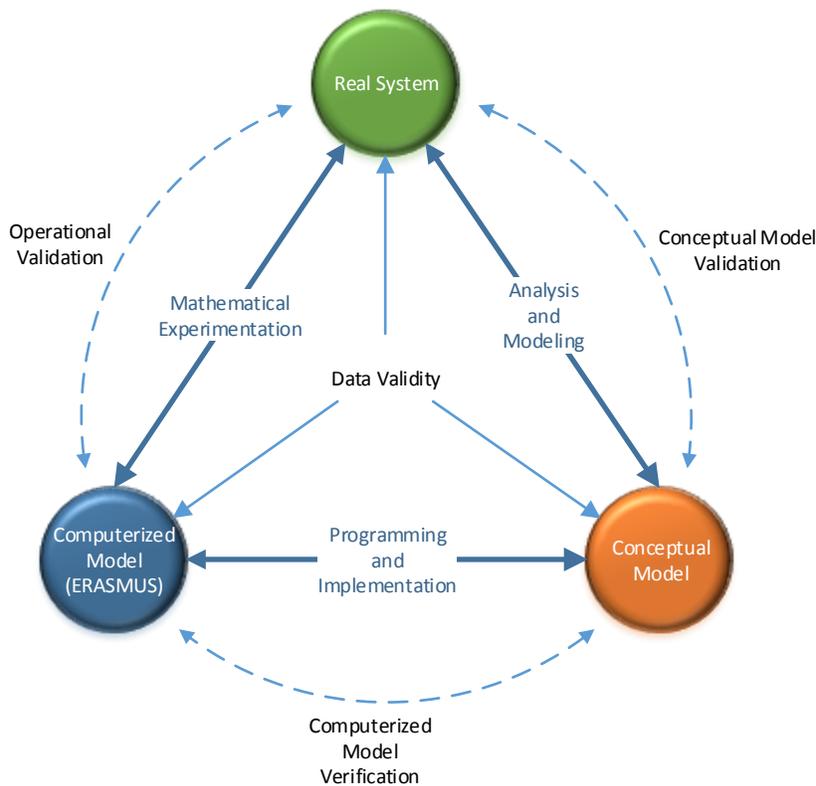


Figure 5.1 Simplified Modeling Process including Verification and Validation. Modified from (Sargent 2009).

Figure 5.1 represents a simplified modeling process explicitly showing the different verification and validation stages (Sargent 2009). This modeling process involves three main components: The real system to be modeled (top), the conceptual model developed for representing the real system (Bottom right), and the computerized model (Bottom left). For our research the real model is any given water distribution network, the conceptual model is the developed resilience assessment methodology, and the computerized model is the resilience assessment tool known as ERASMUS (Effective Resilience Assessment Methodology for Water Utilities).

The first step of the modeling process is to develop a conceptual model that represents the real system. The conceptual model must capture all relevant characteristics of the real system according

to the simulation objectives, without incorporating unnecessary complexity or oversimplifying. The conceptual model is obtained by a process of analysis and modeling, and validated in terms of whether it is an acceptable representation of the real system. The conceptual model validation is based on whether the conceptual model includes only those key aspects of the real system that have significant effect on the real system behavior to be replicated. This validation ensures that the conceptual model outputs are similar to those expected from the real system, and that therefore its results will enable the achievement of the simulation objectives.

Once the conceptual model has been constructed and validated, the next step is to program the computerized model. Computerized model verification ensures that model programming and implementation are correct with respect to the conceptual model (Sargent 2009). In other words, verification is the process to ensure that the model was “built right” (Balci 1998).

The verified computerized model is utilized to simulate the real system, enabling mathematical experimentation; the computerized model is operationally validated by comparing obtained results from simulation with observations from the real system or from other models. Model validation is intended to ensure that simulation outputs are within a satisfactory accuracy range (Sargent 2009). The operational validation objective is to ensure the “right model” was built (Balci 1998).

Finally, as shown in Figure 5.1, all components and steps throughout the modeling process ought to be supported by valid data that is correct, clean, and useful. Data validity enables successful simulation runs that produce accurate enough and useful results for decision making.

As a model intended for application in water distribution networks as well as a decision support tool for water utilities’ staff, ERASMUS was subject to the verification and validation procedure described in Figure 5.1. Since ERASMUS represents the foundation of a novel full resilience assessment methodology and tool, its operational validation is an ongoing process that will eventually lead to full validation after many real-world applications.

During the development of ERASMUS, two actual water distribution network resilience analyses were utilized for verification and validation purposes. The two cases are described below.

1. Water Distribution Network 1 (WDN-1). A resilience analysis to flash flooding of the water distribution system of a small town in the US East coast. WDN-1 network model is constituted by a total of 2796 assets (pipes, pumps, junctions, tanks, and reservoirs). This was the pilot case, utilized mostly for model verification.
2. Water Distribution Network 2 (WDN-2). A resilience analysis to earthquake was performed for a section of the water distribution system of a city in the US West coast. WDN-2 network model is constituted by a total of 10188 assets, and was utilized mostly for operational validation.

In general, computerized model verification was performed for ERASMUS utilizing the pilot case WDN-1 (small town application example), and the operational validation was performed utilizing

both cases (the pilot case WDN-1 and the city case WDN-2). However, certain degree of verification and validation was included in both cases. It is expected that more application cases may be required before achieving complete operational validation.

Simulation Objectives.

The verification and validation process requires previous definition of a set of clear simulation objectives. The simulation objectives of ERASMUS are to:

1. Replicate the hydraulic performance of a real Water Distribution Network in terms of water quantity delivered to demand nodes under normal and damaged network configurations, a parameter known frequently as system “serviceability” (Our basic Performance metric).
2. Obtain estimates of time and cost required for recovering normal system performance from each of the damaged configurations, also known as failure modes or scenarios.
3. Utilizing the generated information, provide useful metrics of system resilience that can be utilized as a decision support tool for managing risk in the real water distribution network considered.

5.2. Conceptual Model Validation

During the development of the resilience assessment methodology, the conceptual model was validated utilizing expert opinion. The conceptual model was presented at several conferences and journal papers, obtaining mostly favorable reviews and comments.

The conceptual model provides a straightforward approach for assessing probabilistic resilience level of a given water distribution network subject to a specific type of disruptive event. The methodology is not intended for resilience prediction or to substitute vulnerability analysis. The information provided by this methodology can help improve system preparedness against specific disruptive events enabling more informed management.

The conceptual model is a satisfactory representation of resilience in the real system according to the research and simulation objectives. It captures the three key parameters stated in the simulation objectives, namely expected network performance, recovery cost, and recovery time. In addition, the conceptual model allows for future expansions and improvement, and has practical applicability as part of a holistic asset management framework.

5.3. Computerized Model Verification

ERASMUS is an integrated simulation model, because it is constructed utilizing MATLAB and the hydraulic analysis engine EPANET 2.0 simultaneously. MATLAB is a widely utilized programming language and computing environment, while EPANET is a verified and validated hydraulic analysis software developed by the U.S. Environmental Protection Agency (Rossman 2000) and freely distributed. Although EPANET has no capability to analyze damaged water networks, such limitation is addressed utilizing an algorithm similar to that of GIRAFFE

(Graphical Iterative Response Analysis for Flow Following Earthquakes) that was developed for earthquake water network damage at Cornell (NEES 2008). The decision of utilizing EPANET 2.0 instead of GIRAFFE for ERASMUS hydraulic analyses responds to the need of having a general, easy to use component, able to address a variety of hazards including earthquakes.

The computerized model verification process for ERASMUS is shown in Figure 5.2. Certain inputs are selected for the model, either “Test Data” or “Field Data”. In our case, both types of data were utilized. Test data (also known as artificial data) was applied first, and when the test data verification was complete, then field data from WDN-1 was applied.

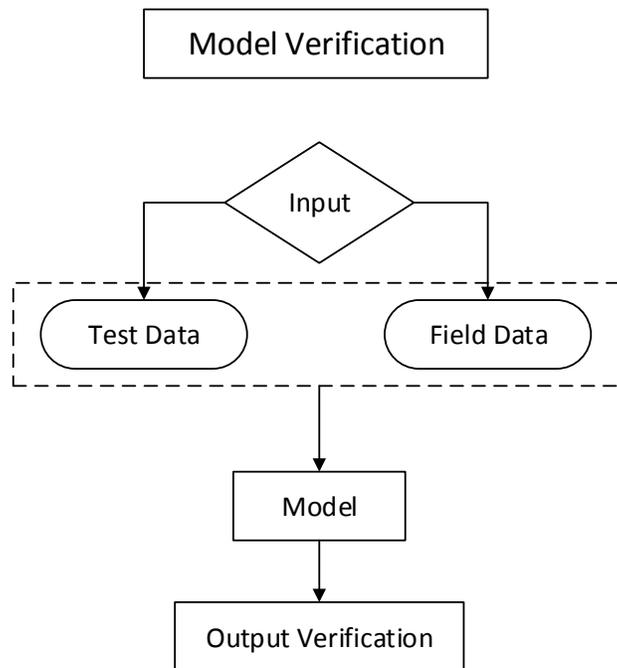


Figure 5.2. Model Verification Process (Modified from Uslu and Sinha, n.a.)

Output obtained from using either test data or field data were compared with real expected results from experience and discussed with experts to ensure they are reasonable. The model verification was performed mostly on field data from WDN-1, although some artificial data was utilized during the development of ERASMUS coding as well.

The computerized model verification utilizing field data from WDN-1 has four sections:

- a. Worst / best case failure modes (scenarios).
- b. Verification of system Performance results.
- c. Verification of Recovery Time and Cost results.
- d. Overall Resilience Index assessment

Each one is explained individually. The verification was based on simulation runs containing 1500 failure modes or scenarios on each run. Running 1500 scenarios was proven enough in this case, given that the aggregated expected system performance converged.

a. Worst / best case failure modes

Table 5.1 contains the performance, recovery time, and recovery cost parameters obtained in the extremes of the 1500 scenarios analyzed. Since our scenarios follow a power law distribution as shown in Figure 3, it is expected that the first scenarios will have the greatest values for recovery time and recovery cost, while a minimum system performance (These are High impact-Low probability scenarios).

Table 5.1. Boundary Scenarios Parameters

Scenario Number	Failed assets	Normalized Performance	Recovery Time (Days)	Recovery Cost (USD)
1	1500	0.00	3088.58	41,856,387
2	500	0.00	1551.07	20,930,915
3	300	0.00	915	11,982,310
1497	1	1.00	0.15	2,029
1498	1	1.00	5.45	76,533
1499	1	1.00	11.63	370,751
1500	1	1.00	1.87	29,555

Conversely, the last scenarios (Low impact – High probability scenarios) have practically no impact on system performance and relatively low recovery costs and time. These observations are consistent with expectations.

Notice that recovery time and cost only include direct and indirect costs for WDN-1 (material, labor, and tools). They do not include external costs to the water distribution system operation such as road blocks, down power lines, emergency water substitution, etc. For this reason, the shown cost is only the recovery cost and not necessarily the total cost associated with a specific disruptive event.

b. Verification of Performance results.

Water distribution network performance values were obtained from each one of the 1500 scenarios analyzed on each simulation run. As it was mentioned, the scenarios are assumed to follow a power law, as shown in Figure 5.3 for the first 160 scenarios.

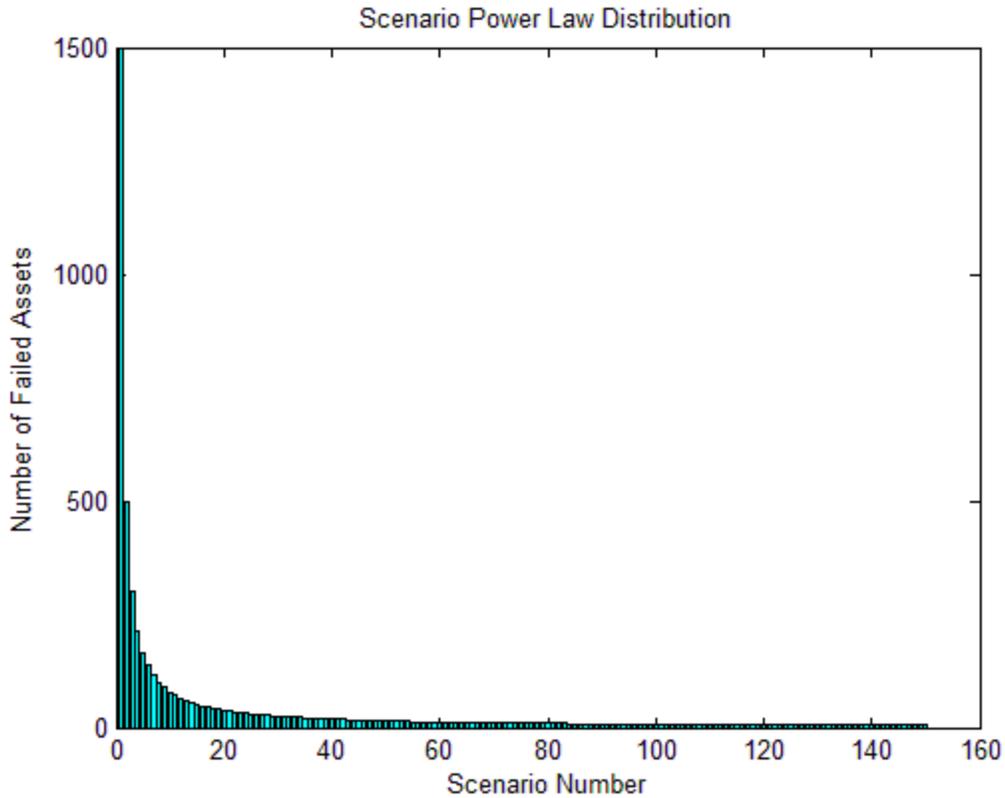


Figure 5.3 Power Law Distribution of Failure Scenarios (only 160 shown from 1500)

All failure scenarios are assumed to follow this distribution in order to mimic the natural extreme events periods of return: High impact disruptive events tend to have lower occurrence probabilities than low impact and high probability events. For this reason, the scenarios utilized in the simulation follow the same distribution, having a few scenarios causing major damage (left side on Figure 5.3), and many low impact scenarios (right side). Higher impact scenarios are modeled assuming more assets failing simultaneously. The magnitude of the disruptive event is represented through the number of failed assets. In our simulation, all assets are assumed to fail according to certain probabilities, independently of whether they are critical or not. In future simulations, it can be assumed that critical assets have higher probability of failure in the appropriate type of disruptive event, like deliberate attack. Finally, notice that the scenarios were generated randomly, but reordered as shown in Figure 5.3.

The verification of system performance results was obtained analyzing performance outputs from 1500 scenario runs. The set of 1500 performance metrics was divided in three sections of 500 sequential scenarios each. The first section contains the 500 scenarios with higher impact and lower probability (scenarios 1-500), while the last 500 scenarios contain those of lower impact but higher probability (scenarios 1001-1500). The average performance value in each section is expected to increase, given that section 2 contains less severe scenarios than section 1, and section 3 less severe scenarios than section 2.

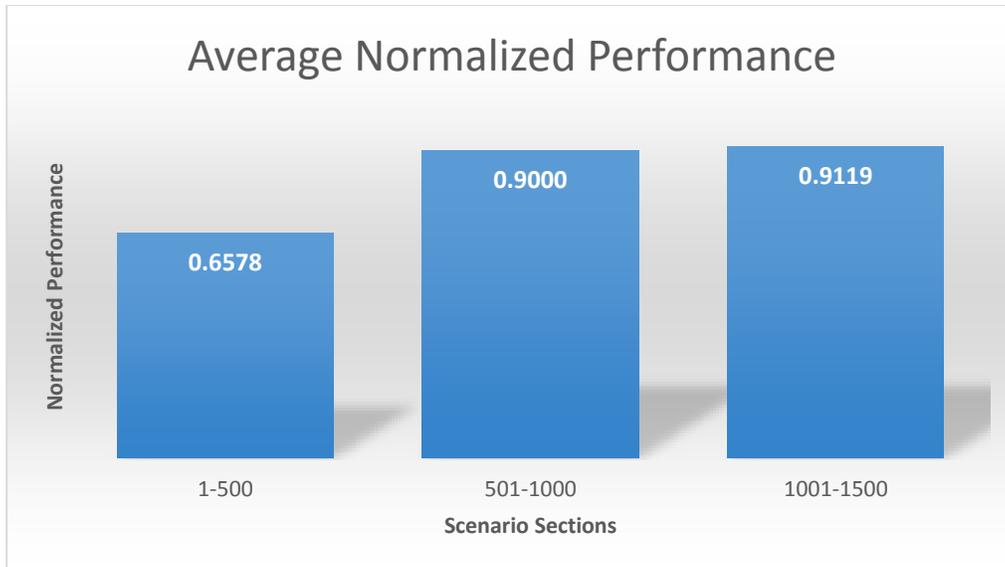


Figure 5.4 Average Normalized Performance for Three Failure Scenario Sections.

Figure 5.4 shows the obtained averages for normalized performance on each one of the three sections of performance metrics. Scenarios 1-500 contain the high impact scenarios, and therefore the average system performance is relatively low. On the opposite side, the scenarios 1001 to 1500 are low impact scenarios, which on average produce higher normalized performance values, as expected. The three sections' performance values are later aggregated into a single value for expected system performance under a specific type of disruptive event (flash flooding, in the case of WDN-1). The average normalized performance for all scenarios together was obtained as 0.823, while the standard deviation is 0.381.

c. Verification of Recovery Time and Cost results.

Since estimates of recovery time and recovery cost apply to each of the same failure scenarios from which performance is obtained, they are also expected to follow a power law distribution as shown in Figure 5.3. In this case, we calculated the average estimates for recovery time and recovery cost for each one of the same three sections shown in Figure 5.4.

Figure 5.5 shows the average recovery time values (in days) for each one of the three failure scenario sections. While the average recovery time for the first 500 scenarios is over 36 days, this value reduces significantly for the other two sections at around 3-4 days on average. Notice that the last 500 scenarios have a higher recovery time average than the previous 500 scenarios. This is possible from the variability of random scenarios on each section.

Analogously, Figure 5.6 shows the average recovery costs (in 2012 US Dollars) associated with each one of the three scenario sections. As it happened with recovery time (Figure 5.5), the first 500 scenarios have significantly higher recovery costs on average, while the other two sections are very similar.

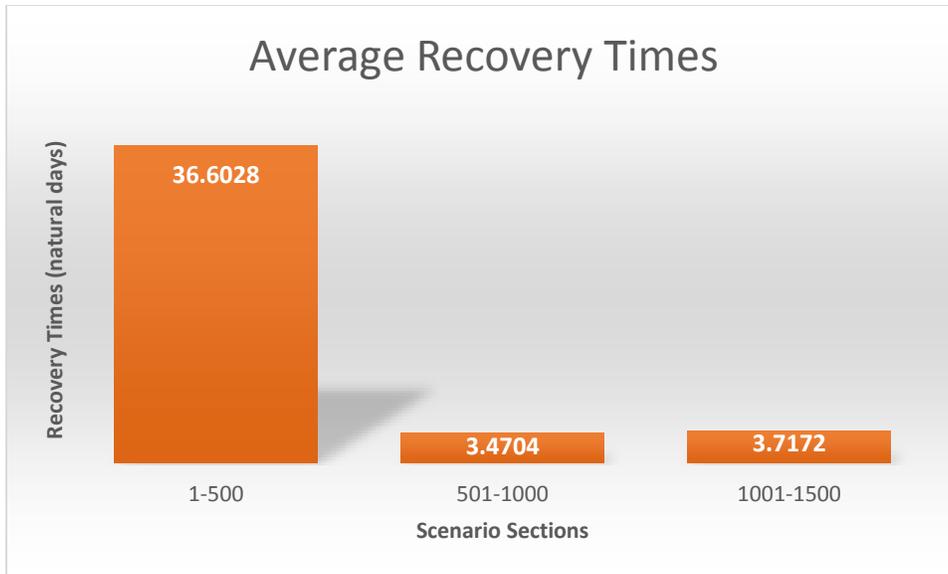


Figure 5.5 Average Recovery Times for Three Failure Scenario Sections

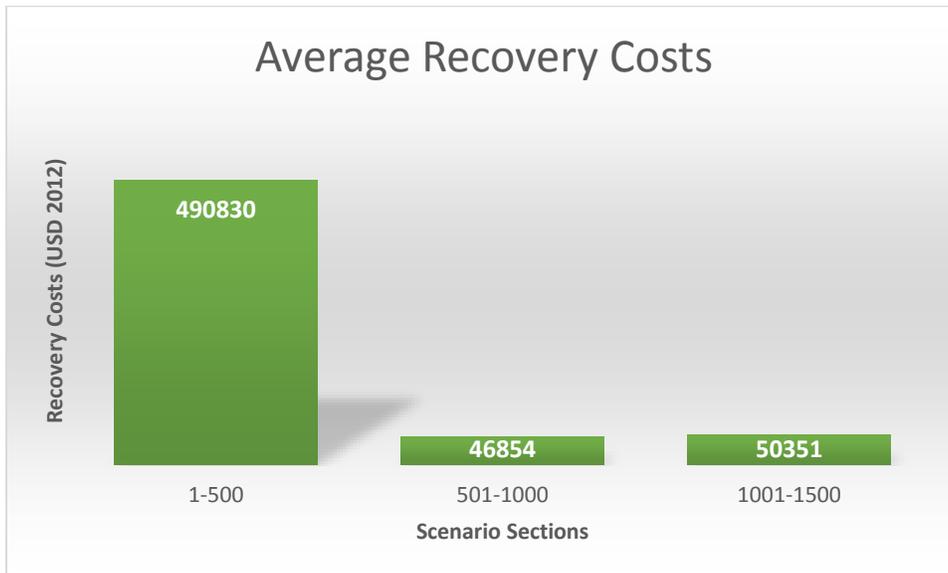


Figure 5.6 Average Recovery Costs for Three Failure Scenario Sections

Although at a first glance the fact that last section averages are higher than the second section may seem counterintuitive, they are explained by the randomness of the scenarios (failure modes). Each scenario on the first section (scenarios 1-500) has an average of 11.75 asset failures, while the average for sections 2 (scenarios 501-1000) and 3 (scenarios 1001-1500) is only 1 on each case.

The relationship between recovery time and recovery cost is very strong, as expected (Figure 5.7). The reason is that recovery cost includes time-dependent information, such as labor cost. Those scenarios with larger system down times are therefore more expensive.

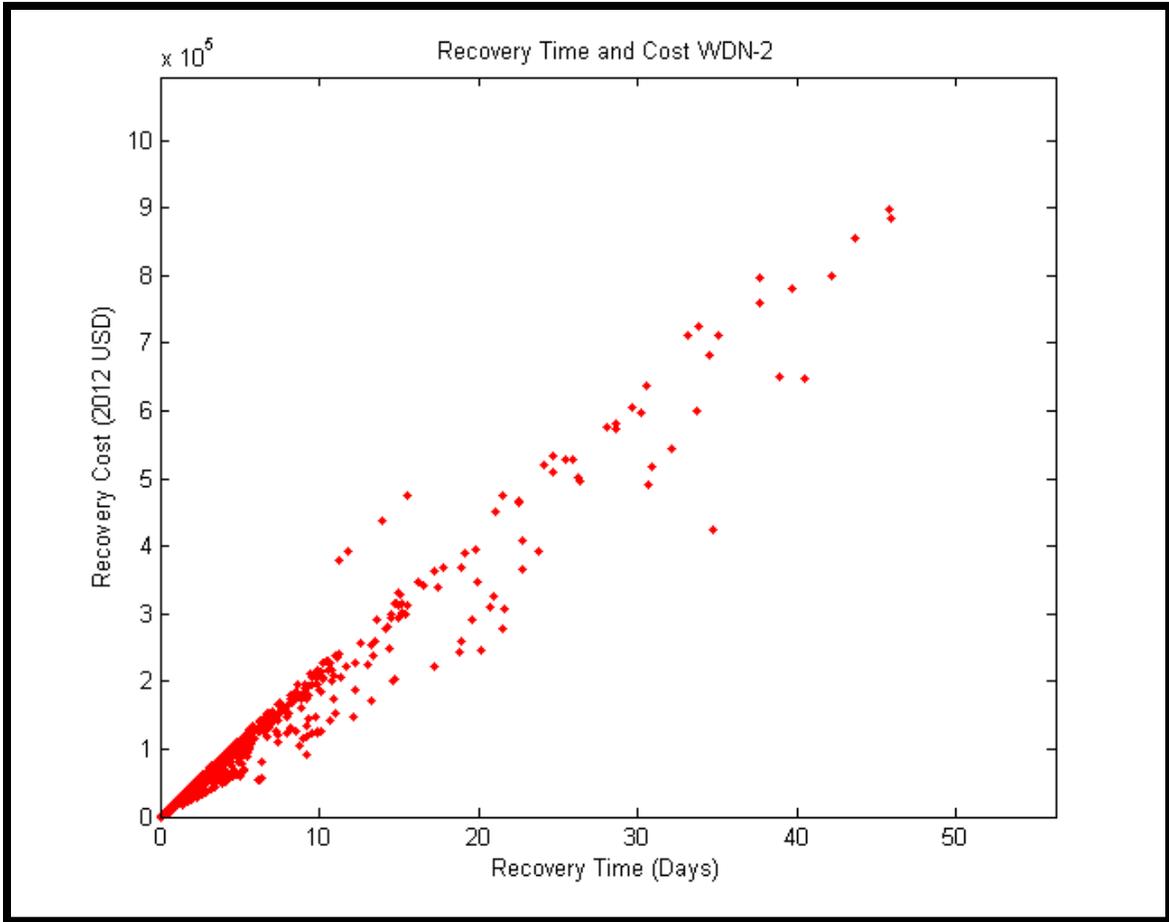


Figure 5.7 Relationship between Recovery Cost and Recovery Time for WDN-2 Case.

d. Overall Resilience Index Assessment

A fourth indicator useful for computerized model verification is comprised by the values of resilience indexes shown in Figure 5.8. As expected, the posterior probability of resilience (resilience index) increases with increasing acceptable recovery time and cost values. The resilience index values for WDN-1 under different combinations of acceptable recovery parameters generates a “resilience index surface”. For example, the red area on the resilience index surface belongs to an acceptable cost over \$100,000 and recovery time over 10 days; which explains the relatively high level of expected resilience as nearly 0.8. This means that the utility managing WDN-1 should be able to recover full system performance under these limits in around 80% of the flooding cases.

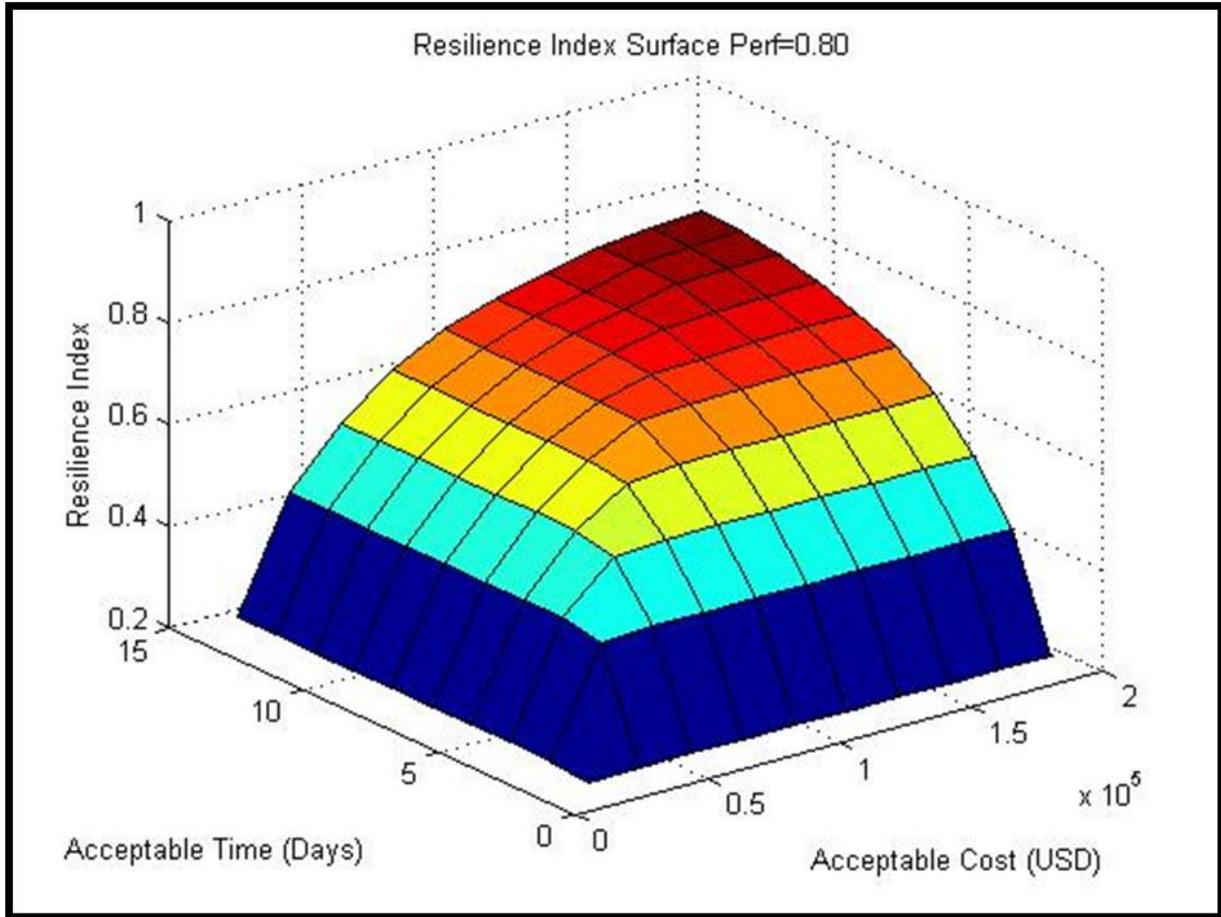


Figure 5.8 Resilience Index Surface for WDN-1 under Flooding.

The resilience index surface may also be utilized to measure the required resources under a variety of scenarios and constraints. In the same service area, some organizations may find different acceptable limits to water service disruption, for example. The resilience index surface enables discussion of “what if” scenarios.

5.4. Operational Validation

Figure 4.9 represents the validation process applied in this research. First, field data from real water distribution networks (WDN-1 and WDN-2) is utilized for conducting simulation runs in ERASMUS. Obtained model results are then compared with independent external information for model validation.

The possible sources of external information for validating the ERASMUS resilience assessment model are three (Figure 5.9):

- a. Results from other Models.

This option is limited due to the lack of comparable models for resilience assessment of water distribution networks. Although other models exist, there is no standard format for

presenting results or measuring resilience. However, standard scenarios exist for assessing the variety of impacts from different hazards such as Earthquake or Flooding (such as those from HAZUS-MH, or the “ShakeOut” scenario).

For operational validation of ERASMUS, we utilized an earthquake scenario considered a “standard” scenario in earthquake engineering, called “The ShakeOut scenario” (Jones and Bernknopf 2008).

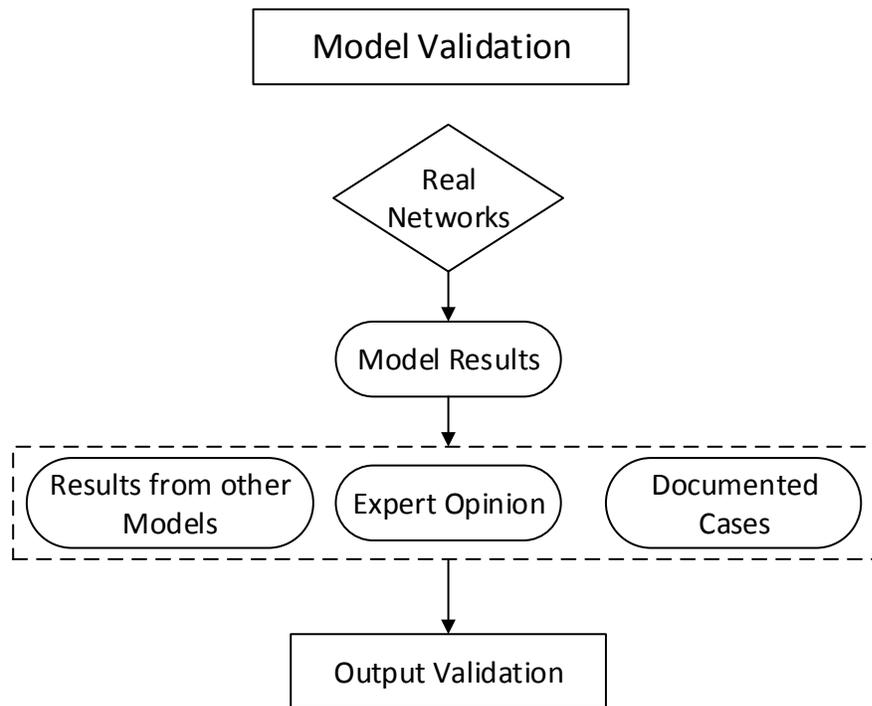


Figure 5.9. Operational Validation process utilized in ERASMUS (Modified from Uslu and Sinha, n.a.)

b. Expert Opinion

Expert opinion was extensively utilized during the development of ERASMUS to facilitate model validation. An external committee was formed to provide feedback on both the conceptual model and the computerized model. The external committee is formed by the following participants:

1. Sue McNeil, PhD

Dr. McNeil is professor at the University of Delaware and former Director of the Disaster Research Center at the same university.

2. Kevin Morley, PhD

Dr. Morley is a resilience expert in the American Water Works Association (AWWA). He contributed significantly to the development of the J-100 ANSI Standard, RAMCAP Plus.

3. Craig Davis, PhD

Dr. Davis is an expert at the Los Angeles Department of Water and Power (LADWP). His work includes earthquake damage assessment and modeling for the utility, as well as the study of system resilience and response to seismic events.

4. Stephen Cauffman

Deputy Chief of the Materials and Structural Systems Division at the National Institute for Standards and Technology (NIST) in Maryland. Mr. Cauffman is strongly promoting the development of research on resilience of the built environment within NIST.

5. Russell Green, PhD

Dr. Green is a professor in the Department of Civil and Environmental Engineering at Virginia Tech. His expertise is on earthquake engineering, seismic hazard analysis, and geotechnical risks.

The role of the external committee is to provide feedback for advancing and validating this research. While expert opinion per se does not validate a simulation model, it significantly reduces the probability of including erroneous assumptions and procedures. The expert opinion from multiple backgrounds and expertise in this case provides a stronger foundation for model validity.

c. Documented Cases.

Utilizing documented cases of disruptive events impacting water distribution networks, it is possible to compare field observations from these cases with results obtained from ERASMUS simulation runs. Most of the documentation for this purpose was obtained from the United States Geological Survey (USGS), particularly many documents related with the 1989 Loma Prieta earthquake in California. The USGS reports are publicly available and provide a significant amount of specific information that supports model validation.

Each of the three possible validation aspects is further explained below.

5.4.1. Results from other Models

The USGS and the California Geological Survey supported the development of a comprehensive earthquake scenario for southern California known as the “ShakeOut Scenario”. The goal of the ShakeOut scenario is to identify key impacts of a major earthquake in southern California, thus enabling its users to improve their preparedness before such impacts occur. A flowchart for the ShakeOut scenario is shown in Figure 5.10.

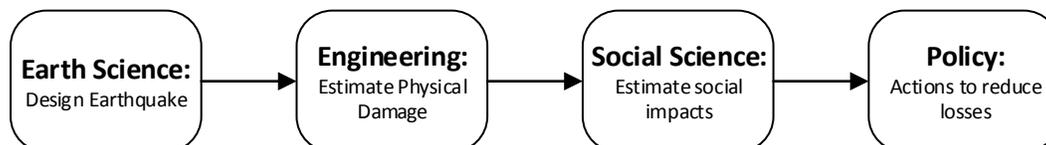


Figure 5.10 *The ShakeOut Scenario flowchart (Modified from Jones et al 2008)*

For the ERASMUS operational validation purposes, we are interested mainly in the engineering phase of this scenario, as well as some key aspects of the earth science phase (two first steps).

In the Earth Science step, the ShakeOut scenario models a magnitude (M) 7.8 earthquake occurring at the southern San Andreas Fault. This earthquake was determined by experts to be the most likely next major seismic event expected to occur in the southern California area, based on the available geological evidence. A major seismic event like this would have a significant impact over the affected communities and the water distribution infrastructure systems in the area. The ShakeOut scenario earthquake is stronger than the 1989 Loma Prieta earthquake, with a magnitude of 7.1. We are interested in the Engineering impacts (second step) of the earthquake assumed in the ShakeOut Scenario, as well as documented impacts of the Loma Prieta earthquake.

Regarding engineering in the ShakeOut Scenario, different authors have identified the ShakeOut scenario effects on the Los Angeles Department of Water and Power (LADWP) water system (Davis and O'Rourke 2011; Romero et al. 2010). Key aspects of these effects are summarized in Table 5.2.

It is important to notice that the ShakeOut Scenario considers the complete LADWP water system, while WDN-2 represents only a small portion of such system. Therefore, it is necessary to adjust some of the values in Table 5.2 for obtaining equivalent parameters applicable to WDN-2.

Table 5.2 Key Parameters in the ShakeOut Scenario

Maximum PGA	0.3	g
Maximum PGV	78	in/s
Shaking Duration	55	sec
Total Pipe Length	38,364,500	ft
Total Pipe Repairs	2700	
Trunk Line Repairs	150	
Repair Rate	0.0704	Rep/1000 ft
Serviceability		
0 hrs	0.760	
24 hrs	0.340	
15 months	1.000	

Where PGA stands for Peak Ground Acceleration, and PGV is Peak Ground Velocity.

Based on historical data from major earthquakes and its effect on different pipeline systems, an empirical fragility curve was obtained by the USGS utilizing regression after the 1989 Loma Prieta Earthquake (Eidinger 1998). The fragility curve obtained is:

$$n = 0.00032(PGV)^{1.98}$$

Where n is the number of expected pipeline repairs in a water distribution network after the earthquake, per thousand feet of pipeline. This fragility curve relates the estimated number of pipeline repairs per 1,000 ft (repair rate, n) with the observed Peak Ground Velocity (PGV). The repair rate is afterwards adjusted utilizing some factors to account for pipe material and joint type. It has been observed that pipelines made with more ductile materials and flexible joints tend to have reduced need for repairs, compared with other construction types.

The ERASMUS run on the WDN-2 system comprises earthquake events of different magnitudes, as opposed to a single seismic magnitude on the ShakeOut scenario. The total pipe length in the WDN-2 network is only 611,830 ft. Since we are running scenarios ranging from 3000 failed assets to 1 failed asset, this represents simulated repair rates from 4.90 repairs/1000 ft. to 0.0016 repairs/1000 ft, which are associated with PGV values in the range of 129 in/sec to 58 in/sec according to the USGS fragility curve.

Given the size of WDN-2, the ShakeOut scenario would correspond to an estimated number of failed assets of around 43 for ERASMUS. In other words, failing 43 assets of WDN-2 would approximately replicate an equivalent ShakeOut scenario in terms of repair rate (0.0704 reps/1000 ft.). The obtained parameters from ERASMUS on the equivalent scenario are shown in Table 5.3.

Table 5.3 ERASMUS Scenarios Equivalent to ShakeOut

Scenario	# Fail Assets	Normalized Performance	Recovery Time (Days)	Recovery Cost (USD)
33	46	0.0000	35.09	710,601.14
34	44	0.0000	37.71	758,950.85
35	43	0.0000	37.63	796,814.02
36	42	0.0000	24.62	532,938.46
37	41	0.0000	30.52	638,322.47

But LADWP is 62.7 times the size of WDN-2 by total feet of pipeline. The ShakeOut scenario estimates a loss of 1.1 Billion on pipeline damage, including water, sewer, and gas.

Analogously, if we apply the pipeline repair rate observed in the Loma Prieta earthquake (0.0067 reps/1000 ft.) to WDN-2, this is equivalent to around 4 failed assets. The results obtained by ERASMUS for a Loma Prieta equivalent scenario are shown in Table 5.4.

Table 5.4 ERASMUS Scenarios Equivalent to Loma Prieta 1989

Scenario	# Fail Assets	Normalized Performance	Recovery Time (Days)	Recovery Cost (USD)
301	4	0.9955	0.98	18,124.93
302	4	1.0000	0.26	5,192.58
303	4	1.0000	2.40	52,375.40
304	4	0.0000	0.62	10,329.64
305	4	0.9979	4.12	85,658.76
306	4	1.0000	7.97	164,816.19
307	4	1.0000	1.02	22,907.10
308	4	0.0000	1.55	32,089.65
309	4	0.9938	1.76	32,835.99
310	4	0.9979	2.19	48,811.99

5.4.2. Documented Cases

Other than the reports mentioned from USGS, there are not many cases of well documented disruptive events that are also detailed enough for our purpose. Each event presents considerable complexity, and most documentation refers to the aggregated economic impacts of the event, emergency response, or casualties. There is a lack of documentation regarding detailed damage to water distribution systems, as well as the recovery time and cost required afterwards only for the water utility.

For example, information of the costs associated with a specific disruptive event usually include damage cost, impacts on the region’s economic activity, revenue lost, and others. Specific financial information about the cost of recovering the water distribution system tends to be aggregated into a grand total.

Another issue is that there is not a standardized format for collecting data. Different disaster reports include different parameters, and those parameters are usually measured differently. This suggests that may be convenient to develop certain standard for collecting information that can be later utilized to obtain system resilience assessments.

5.4.3. Expert Opinion

An external committee was formed to provide assistance with the validation of ERASMUS. The conceptual model was found acceptable in general by the external committee. There were some concerns related to the feasibility of operational validation, although in general the proposed methodology and planned tool were deemed very likely to be adequate representations.

Expert opinion is the strongest point for operational validation of ERASMUS. While comparison with results from other models remains challenging, we consider ERASMUS to be **partially validated** through expert opinion. In fact, since the research objective involves achieving a practical approach that is useful for asset managers and other decision makers, the expert opinion

in terms of asset management is of particular importance. Asset Managers interviewed for this purpose were unanimously supportive of this research and its computerized model. Those asset managers were involved with the two resilience assessment cases developed as part of this research.

Partial validation implies that challenges remain for a full validation of ERASMUS. Although a complete compilation of the developed methodology and tool limitations is included in the next chapter, key concerns are as follows:

1. **The complexity associated with obtaining performance data for many different damaged network configurations.** The ERASMUS capabilities to analyze a variety of scenarios has to be strengthened and expanded further. This is a challenge, given the flexibility of formats in EPANET input files, and the wide variety of errors possible.
2. **The use of EPANET for analyzing damaged network configurations.** As it was mentioned, EPANET has very limited capability to analyze damaged networks. In case of earthquakes, other software may be more adequate, particularly GIRAFFE. However, we did not use GIRAFFE for this research because we have a multi-hazard methodology, and because of the difficulties of coding adequate GIRAFFE controls in MATLAB. In order to use EPANET, we applied the same basic algorithm utilized in GIRAFFE for damaged networks. Future versions may incorporate GIRAFFE.
3. **The practical presentation of simulation results.** The model output has to be improved in order to facilitate its use by water utilities and other stakeholders. It is expected that in the future the methodology will be able to accommodate more diverse decision-support needs and provide more extensive and focused information.

5.5. References

- Balci, O. (1998). "Verification, validation, and testing." *Handbook of Simulation*, John Wiley and Sons, 335–393.
- Eidinger, J. M. (1998). "Water-Distribution System." *The Loma Prieta, California, earthquake of October 17, 1989: Performance of the Built Environment*, Lifelines, A. Schiff, ed., USGS, 63–78.
- Jones, L., Bernknopf, R., Cox, D., Goltz, J., Hudnut, K., and Mileti, D. S. (2008). *The ShakeOut Scenario*. USGS.
- NEES. (2008). *GIRAFFE Simulations*. Cornell University.
- Rossman, L. A. (2000). "EPANET 2: users manual." EPA.
- Sargent, R. G. (2009). "Verification and validation of simulation models." *Simulation Conference (WSC), Proceedings of the 2009 Winter*, 162–176.

CHAPTER 6

Concluding Remarks

6.1. Conclusions

Infrastructure resilience is a very active research field continuously generating new advances and publications. Therefore, continuous literature and practice reviews are needed in order to maintain a current knowledge of resilience.

Some significant advances have occurred since the original literature review for this research was originally performed. First, the interest on developing infrastructure resilience frameworks, models, and tools has increased significantly, as well as the number of references to resilient communities, resilient infrastructure, and to the linkages between resilience and sustainable development. Second, The National Academies published a document (NAS 2012) which proposes, among other actions, the design and implementation of a US National Resilience Scorecard, intended to track resilience improvements over time at the community and infrastructure sector levels. Third, the overall public attention generated by the concept of resilience is producing an overwhelming amount of information on the topic daily, and therefore the urgency and importance of establishing specific standards for resilience cannot be overstated. As the utilization of the resilience concept becomes widespread, so the potential for misinformation. Fortunately, widespread utilization can also support the advancement, understanding, and application of this important concept across economic sectors and at the community level.

The developed resilience assessment methodology as part of this research is intended as a strategic-level decision support tool. The methodology is flexible to accommodate a variety of hazards, and expandable for future modeling additions. However, challenges remain in terms of full operational validation, interoperability with current tools, availability and quality of input information, and usefulness of results. The coding itself can be significantly improved.

Input information for the model is mostly non-existent. Estimates have been made in order to run simulations, but the full potential of the proposed methodology and tool will only be developed as the availability and quality of input information increases. Such information includes asset repair cost and time historical information, asset condition, geological characteristics of the soil beneath a specific water distribution network. Future developments on ERASMUS may probably require further information.

The quality of the output will increase as the quality of input information increases. Evidently, the quality of the model output depends significantly on the quality of input information, and the quality of the coding itself. The model is still in early development stages. This research represents only the “tip of the iceberg”, a foundation for more developed and sophisticated expansions. We believe the developed methodology and tool hold promise, but such promise is not even nearly

fully developed yet. Significant methodology and tool improvements, as well as better information are required before this research can develop its full potential.

This methodology is a promising straightforward approach for assessing infrastructure network resilience based on a network model of physical assets for hydraulic analysis. Nevertheless, the general concept of utilizing a network model can be significantly expanded. For example, assessing system resilience utilizing a network of physical and non-physical assets, such as the current hydraulic network plus organizational structure and emergency response resources, all forming a single network.

Two real world water distribution networks were analyzed utilizing ERASMUS, for resilience assessments to flooding and earthquake. These water distribution networks did not include some key assets like water transmission lines. Nevertheless, the methodology can be equally applied to water networks including them. In almost every infrastructure network, some assets are critical in terms of the significant impact over the entire network from critical assets failure. Regarding critical assets, ERASMUS can manage them in different ways, depending on the analyst preference and the type of disruptive event being considered:

- a. First, critical assets are treated like any other assets in the network. For natural disruptive events (like hurricane, earthquake, etc.) critical assets obtain their probabilities of failure not from the fact that they are critical, but from other characteristics as any other asset.
- b. Second, for deliberate attack on the network, critical assets have higher target value and therefore their probability of failure should be increased to reflect such importance. When assessing the resilience of a water network to deliberate attack, critical assets may have higher assigned probabilities of failure.

Other than their probability of failure, critical assets are always treated as any other asset in a water network.

The stated goal of this research (page 3) is to “Develop a resilience assessment methodology for water distribution systems that relates to infrastructure asset management and is flexible, simple, and expandable”. ERASMUS constitutes such a methodology, although it only represents the “tip of the iceberg”: Much more advanced versions can be produced. Research objectives toward this goal were met as follows:

1. **Identify features that allow deciding whether a system is resilient.** Those features are system performance, recovery cost, and recovery time under failure scenarios of varying magnitudes; they are evaluated according to the respective societal expectations. In addition, it is important to consider different water outage tolerances coexisting in a same service area, such as hospitals, firefighting, households, etc.
2. **Identify aspects of resilience useful for water distribution systems.** Water distribution systems incorporated resilience-enhancing characteristics long time ago, such as the redundancy provided by the use of pipeline network loops. However, other resilience

aspects are just being incorporated such as increased adaptive capacity, adequate and distributed emergency resources (for example spares), and more resilient network configurations such as clustering to avoid failure propagation.

3. **Identify attributes of water distribution systems relevant for resilience assessment.**
The resilience of a water distribution system is impacted by certain attributes, including asset condition, soil type, network topography, pipeline material and construction method, emergency resources in place, and others.
4. **Identify Asset Management tools relevant to resilience assessment and management.**
System resilience must be not only assessed, but managed. Current infrastructure asset management frameworks include tools that are useful for resilience management, such as condition ratings, business risk exposure (Likelihood of failure and Consequence of failure), triple bottom line project evaluation, and possibly others.

Finally, ERASMUS was partially validated mainly through expert opinion. Full operational validation may require many more applications and refinement of this methodology.

6.2. Key Limitations of the Methodology and Computerized Model

The methodology and the computerized tool have significant limitations, which are listed and briefly explained below.

- a. **The network model considers only reservoirs, pumps, tanks, pipes, and nodes.**
The current version of ERASMUS is only capable of considering these five basic asset types. Other assets such as isolation valves can be added in the future, since they might be required to expand the scope of possible performance metrics to include water quality issues.
- b. **Asset nodes are binary (normal/failed).**
In this methodology, assets are considered to have only two possible states, normal (working) or failed (not working). Intermediate states like working but underperforming are not considered now.
- c. **Input information on recovery cost and time has to be estimated**
Some basic information required by this methodology and model is not currently gathered by utilities or their contractors. For example, recovery time and cost information for specific assets are mostly bundled with other cost concepts, which causes the information to be unclear. Specific historical records will have to be maintained in the future.
- d. **System performance is evaluated as a snapshot (static analysis).**
Although EPANET has capabilities for analyzing a water network over time (extended analysis), the current methodology utilizes only static analysis (snapshot). This is due to the complications associated with simulating dynamic processes such as a fluctuating emergency water demand, the impact of gradual repairs, people moving in the service area, and others. Other water system damage simulations over time assume a constant water demand (normal demand) under emergency circumstances, which might not be accurate.
- e. **Recovery time does not assume more than one crew, nor considers external assistance.**

It is assumed that asset repairs are performed by only one crew in a successive fashion. Mutual help agreements such as Water Agency Response Networks (WARN) are not considered. In the case of major disruptive events, the first assumption is mostly untrue, since more than one crew is likely to respond. The second assumption may or may not be true. The decision to not take into account assistance agreements was taken for two main reasons:

1. The resulting resilience assessment of the water distribution network will result more conservative without reliance on external assistance.
2. Certain disruptive events at a regional scale might impact also those otherwise capable of assisting the utility in facing the disruption, effectively neutralizing the possibility of any external assistance, at least for some time.

f. Performance from some scenarios is considered zero when it may not be zero.

Given the flexibility and variety of EPANET input file formats, not all types of possible errors that may arise from running a damaged network model are considered. When an unidentified error type arises, ERASMUS will simply consider the network performance as zero, when in some cases this value might not be true.

g. ERASMUS code may need tweaking depending on the EPANET model utilized as input.

As ERASMUS is applied to more and different water distribution networks, other EPANET input file varieties will be utilized. Adapting the code to work on new file formats will require further coding improvement work. The current code is not able to manage any input file format, only a few.

h. Economic data utilized for recovery cost and time is ‘hardwired’ in the code.

This was done to save time. Nevertheless, in the future will be convenient to make ERASMUS read the most current repair cost and time data from another file. This would save the analyst from having to make sure such information is current.

i. ERASMUS is not intended to substitute any existing model, but to complement them.

ERASMUS is not intended as a one-size-fits-all solution, nor is intended as the only tool needed to adequately assess the resilience of a given system. It is rather intended as a tool to be used as part of a more complete toolbox. For example, if the analyzed network is subject mainly to earthquake, other hazard- specific tools may be required to achieve a better and deeper understanding of system resilience.

j. ERASMUS is only partially operationally validated.

The operational validation of ERASMUS resulted far more challenging than expected. Non-existent data and high-level strategic disruption documentation are widespread, which makes difficult to find detailed hard data that can be applied for operational validation purposes. However, since the research objective was defined in terms of practical applicability of the methodology for infrastructure asset management, the model was partially validated by interviewed asset managers that say they like and can use information generated utilizing ERASMUS.

6.3. Key Strengths of the Methodology and Computerized Model

In contrast with the key limitations addressed in the last section, both the developed methodology and the computerized model have relevant key strengths, explained below:

1. An advanced Concept of infrastructure resilience

By considering infrastructure resilience as the result of comparing factors internal and external to the system, the methodology acknowledges the fact that resilience is not the attribute of a particular system, but is defined in terms of the expectations of the system's context. For example, the same water network would have different measures of resilience in different locations. In addition, such a concept of infrastructure resilience allows the existence of varied resilience measures within the same service area. A hospital, for example, will not have the same tolerance for water service interruption than a household or a school. In conclusion, infrastructure resilience for a particular infrastructure network has not a single value. Its magnitude depends on other external factors and it is therefore, variable.

2. Straightforward measure of infrastructure resilience

The developed methodology and computerized tool are not intended to explain every detail of infrastructure resilience, which is a complex phenomenon. The goal is to provide an utilizable measure of resilience despite such complexity. Stochastic simulation was utilized because it is powerful enough to measure system resilience without the need to model and simulate every single process happening during a disruptive event and the following recovery phase. The methodology is simple and powerful enough for being utilized as a decision support tool.

3. Network – based approach

ERASMUS is based on the analysis of a network model of the real system. Although the network model utilized thus far included only physical assets, the same methodology may be applicable for composite networks including physical and non-physical assets. For example, a water utility is not made only from pipes, valves, pumps, tanks, and reservoirs; other non-physical assets like organizational structure, staff, and decision makers have an impact on network performance. Future versions of ERASMUS may work on these composite networks. The analysis of such a network would provide light on the performance impacts from changes in the organization or in the regulatory context, for example.

4. Flexibility in the performance metric utilized

The performance metric utilized for the analyses in this research was water quantity delivered to demand nodes. However, performance is a broad term that can encompass a variety of metrics, including water quality, financial performance, or others. The developed methodology is flexible enough to allow the use of other performance metrics. The same methodology would be utilized independently of how performance is measured. For example, if a financial metric

is utilized for performance, we would be interested in assessing the financial impact of a variety of possible network failures.

5. Easily related to Infrastructure Asset Management

Current asset management frameworks are mostly concerned with performance management. However, resilience management is also important, along with sustainability management. In order to fully integrate resilience considerations in current asset management frameworks, it is necessary to develop methodologies that are easily related to them. ERASMUS is easily related with asset management because the methodology is simple, and it is based on input parameters that can be estimated with no specialized knowledge. Recovery costs and time are very familiar to asset managers, as well as estimating and managing heuristic probabilities of failure.

6. Multi-hazard capability

The developed methodology and computerized tool are capable of simulating any disruptive event that has an impact on the network model being utilized. As long as the disruptive event can be associated with certain impacts on the network, ERASMUS can be applied.

6.4. Final Remarks regarding Recovery Cost and Time in this research

The recovery costs estimated as part of this research include direct and indirect costs, as presented in the RS Means Heavy Construction Cost Data 2011 (R.S. Means Company 2011). It may be observed that many of the obtained recovery costs for the two real world networks resulted significantly low. This is due to the fact that many simplifying assumptions had to be made for estimating those costs. Key assumptions include the exclusion of mobilization costs (mobilization cost may vary wildly in an emergency situation), a standard excavation size for repairing buried pipe leaks and breaks, a standard reparation size for any failure in a pipe (despite that repairing a leak or a break can be very different), and the exclusion of other uncertain external costs like road blocks, down power lines, and ordering custom-made spares (like some pumps), given the high uncertainty on such costs.

Despite the significant challenges associated with the estimation of recovery costs for any disruptive event, very likely the present cost assessment methodology provides a starting point that can be significantly improved and refined in the future. The methodology in its current form has the framework capability in place to receive those improvements in the future, but current estimations of recovery costs have to be taken cautiously.

6.5. Future Work

The methodology and tools developed as part of this research provide a promising approach for the application of the concept of resilience to networked infrastructure system management. Since this research only addressed basics of the infrastructure resilience topic, there is ample opportunity for future improvements.

Possible future work related to this research is briefly described below:

1. Improve and refine ERASMUS coding.

As it was mentioned throughout this document, the current ERASMUS coding in MATLAB can be significantly improved in the future. Current coding is limited in terms of its ability to determine system performance in every possible network damage case, and its ability to analyze networks with a significantly different input file structure.

2. Integrate the use of GIRAFFE instead of EPANET

For specific utilization on water distribution networks subject to earthquake hazards, it may be more accurate to utilize GIRAFFE instead of EPANET alone. However, this requires code tweaking to allow such functions.

3. Expand possible performance metrics

The current basic version of ERASMUS utilizes only one water distribution network performance metric: Water quantity delivered to demand nodes. However, real-world performance of water distribution networks is multi-dimensional: Performance is defined in terms of water quantity, water quality, level of service, and financial position, among others. The basic structure of the methodology from which ERASMUS generates allows for extended definition of system performance.

4. Expand the concept of network to non-physical assets

As with performance metrics, the current network model utilized by ERASMUS is limited only to physical assets. Nevertheless, the concept of utilizing a network can be extended to non-physical assets as well. If the analyzed network includes physical assets, the utility organization, and other agents, the resulting analysis may provide interesting results with a more holistic coverage of the impacts and response to disruptive events.

5. Refine the probabilities of likelihood of failure

Current likelihoods of failure for individual assets on specific disruptive event scenarios are mostly estimated using heuristics. Developing a data collection system, may be possible in the future to refine the estimation of such likelihood, therefore increasing the accuracy of the model.

6. Integrate with GIS for data input and mapping

Even in terms of current technology, ERASMUS is not a sophisticated tool. The tool can be linked in the future with other advanced tools such as Geographical Information Systems (GIS) in order to automate data collection, presentation of results, and improve the user interface. Instead of having a series of separate, individual tools, utilities with advanced systems may want to interlink those tools and enable a more powerful comprehensive tool.

In summary, a vision for a future version of ERASMUS is an integrated and fully automated software, capable of extracting data from GIS and other tools to provide a complete and multi-

hazard resilience assessment of any networked infrastructure. The future ERASMUS will be able to develop ‘what-if’ scenarios and estimate the resilience consequences of alternated managerial decisions.

6.6 Specific Observations for Future Developments on ERASMUS

The ERASMUS computerized tool in its current form is still very basic. A significant part of the improvements that are possible is the development of a GUI (Graphical User Interface). Currently, ERASMUS is a collection of MATLAB coded modules that are to be run separately and sequentially, because the information generated in any module may be utilized by the next. These modules have to be integrated seamlessly into a more advanced version. In order to give specific points to link ERASMUS with a possible GUI, it is convenient first to present what a fully integrated and developed ERASMUS may look like in the future.

The future ERASMUS is an integrated software that will work seamlessly from a prepared network model to a complete resilience assessment for a specific type of disruptive event. The assumptions are clear and controlled by the user, as well as the network type (physical / non-physical) and the performance metric to be utilized. This future tool is linked with the utility’s GIS to provide more accurate and practical results, and it is also linked with the utility’s historical cost records to maintain an updated database for estimating recovery cost and time.

For achieving this future version of ERASMUS, it is suggested that a GUI is developed from the following linking points:

- a. The GUI has to show the network being analyzed and its asset breakdown;
- b. The GUI has to show the type of disruptive event being considered;
- c. Assets have to be put in groups easily according to a specific asset characteristic like elevation, condition, criticality, or other; depending on the type of disruptive event;
- d. Probability distributions to be utilized have to be defined;
- e. Once all these input parameters are complete, the analysis can be run with a button. A report and graphics are generated.
- f. It is suggested that the first step is to link the ERASMUS modules together, and then link them with the corresponding part of the GUI. Although new modules may be required in the future, current modules are:
 - a. M1: Generation of a set of failure scenarios for running the stochastic simulation
 - b. M2: Definition of type of analysis required for each scenario
 - c. M3: Perform all hydraulic (or other) analyses, aggregate data into files
 - d. M4: Estimate Recovery Time and Cost, generate graphics

The GUI may also need to include controls for accessing current information from other databases within the same utility, such as GIS or historical repair costs.

6.7. References

- NAS. (2012). *Disaster Resilience: A National Imperative*. The National Academies, Washington, D.C.
- R.S. Means Company. (2011). *RS Means heavy construction cost data*. R.S. Means Co, Kingston, MA.

CHAPTER 7

Point of Departure

7.1 Current status of ERASMUS Methodology and Computerized Model

The methodology and computerized tool developed as part of this research are in an early development stage. Therefore, although they set a foundation for a promising resilience assessment approach, further development is necessary to achieve more practical applications and wider industry dissemination.

Significant improvements are required to realize the full potential of ERASMUS. This methodology has the potential to become a powerful and straightforward tool for assessing and managing the resilience of networked infrastructure.

Vision

The vision for a fully developed ERASMUS is to achieve an integrated software package able to perform any resilience assessment almost autonomously. In one end, the analyst indicates the name of the network file to be analyzed along with some basic input parameters, and ERASMUS will produce a finished resilience assessment report.

The current version of ERASMUS is not that advanced yet. The resilience assessment is currently performed in sequential modules that the analyst have to run individually, and the analyst has to intervene during the simulation runs in specific cases when an unexpected error occurs. Further debugging and increasing the software robustness are required.

7.2 Points of Departure

Several immediate improvements are possible for the ERASMUS computerized model. These improvements may become points of departure for further development of ERASMUS. This section presents relevant characteristics of the model that have to be taken into account towards working on those improvements.

1. Network Model

The current version of ERASMUS works with EPANET-format input files for the water network to be analyzed. A significant challenge comes from the flexibility of EPANET on the possible different structures of this file. While EPANET can work on a varied file structure, the current ERASMUS code is significantly rigid. It is usually necessary to open the input file in EPANET before running the ERASMUS simulations for the following reasons:

a. *To make sure the file runs in EPANET*

Frequently, the EPANET-format file was generated by a hydraulic analysis software other than EPANET, and may have unintended errors while running on EPANET. A previous run in EPANET may be necessary to ensure the file runs smoothly.

b. *To perform skeletonization of the network*

The network model skeletonization is often more convenient to achieve in EPANET. For example, when deleting nodes, EPANET will automatically delete pipes connected to those nodes. In addition, the analyst can visually verify that the network integrity is preserved through the skeletonization process. However, a robust ERASMUS module for skeletonization may be desirable in the future.

c. *To remove different demand patterns, since ERASMUS works on steady-state analysis*

ERASMUS currently works only on steady-state conditions, and therefore the analyst has to decide on a coherent demand pattern that does not change. Future versions may be able to perform the resilience assessments on hourly or daily dynamic water demand patterns (extended simulation).

d. *To export the network in format “*.INP” for ERASMUS*

It is suggested that the input file for utilizing ERASMUS is an exported network file (*.INP) instead of the original EPANET file (*.NET). The exported network file tends to have a more stable and predictable structure that works better with the current ERASMUS code. Since the code has to manipulate this file to generate damaged configurations, a stable file structure is highly desirable.

A possible improvement of ERASMUS in the future is to modify the code to utilize GIRAFFE (Graphical Iterative Response Analysis for Flow Following Earthquakes) instead of EPANET, since the ability of EPANET to analyze damaged networks is limited. The main challenge in achieving such change is to design code that allows ERASMUS to control GIRAFFE.

Suggested improvements:

- i. Improve the ERASMUS code to allow more flexible input file structures.
- ii. Create an interface for entering and organizing input files.
- iii. Create a module for automated network skeletonization.
- iv. Develop code for allowing ERASMUS to work with GIRAFFE or EPANET.

2. Performance Metric

In the current version of ERASMUS, the performance metric is the normalized water quantity delivered to demand nodes. The baseline scenario (normal system operation) has a normalized performance of one (a performance of one in the damaged network would indicate that such network configuration is able to deliver the normal water quantity). However, there are many possible performance metrics that can be used in the future, for example water quality (EPANET can trace dispersion of contaminants through a network), financial metrics (revenue/loss), and others.

Suggested improvements:

- i. Introduce alternative performance metrics

- ii. Create an interface for allowing the user to select different types of performance metrics.

3. Stochastic Simulation

During simulation runs, the ERASMUS code controls the execution of EPANET for each failure scenario. However, some network configurations cannot be analyzed by EPANET because they are hydraulically unsolvable, or because an error happens during EPANET execution that is unknown to ERASMUS. In those cases, the network performance in that specific scenario may be considered zero when it is actually not zero. A possible way of addressing this issue is the utilization of GIRAFFE instead of EPANET.

Another challenge with the stochastic simulation might be the required computation time. The process of analyzing network performance in many different failure scenarios can consume significant time and memory, depending on the size and complexity of the network and the capacity of the utilized processor unit. The code has to be made more efficient.

Suggested improvements:

- i. Revise ERASMUS to avoid false zeros for performance of certain scenarios.
- ii. Broaden the variety of EPANET errors the code can handle.
- iii. Increase efficiency of ERASMUS code in terms of speed and required resources.
- iv. Perform the simulation on a more powerful computer, so it can run faster.

4. Result analysis

The organization and presentation of results in the current version of ERASMUS is challenging. A significant challenge comes from the need to manage thousands of scenarios that represent a wide variety of resilience parameter values. For example, when representing recovery costs, some scenarios imply hundreds of millions of dollars, while others only some thousands. The approach utilized for visualizing results and capturing all possible range of values has to be well designed.

Additionally, the current version of ERASMUS may not be taking full advantage of the generated information during the simulations.

Suggested improvements:

- i. Create an interface for visualizing better resulting resilience parameters (loss of performance, recovery cost, and recovery time).
- ii. Create a data collection tool for recovery cost and time data for specific utilities
- iii. Improve the statistical analysis of results, extracting more information.
- iv. Link ERASMUS with Geographical Information Systems (GIS) for increased usefulness and interoperability.

Improvements other than those explained in this section may be possible or even necessary for future versions of ERASMUS. As it was argued, the current version of ERASMUS represents only the foundations of what seems to be a promising approach for assessing the resilience of infrastructure networks. Several improvements are definitely possible.

APPENDIX I

ERASMUS CODE

ERASMUS was originally intended as an integrated and continuous code divided into modules. However, for practical considerations those modules were executed separately, although typically a new module will rely on the information generated by the previous one.

ERASMUS Code is comprised by four modules written in MATLAB R2012a, namely M1 – M4. Each one is listed below:

M1. Generates the random set of failure scenarios

M2. Determines the different type of scenarios generated by biased sampling

M3. Evaluates damaged network performance for each failure scenario using EPANET

M4. Evaluates Expected Recovery Time and Cost for each failure scenario.

It is important to notice that this code is subject to adjustments and further improvement. Although it is the code utilized for running the simulations, it is not considered final or definitive.

MODULE M1.m

```
%-----  
%ERASMUS Module 1 - GENERATION OF SCENARIO MATRIX  
%-----  
%Receive input from Central Module  
%Output is Scenario Matrix according to Wallenius (Scenario)  
  
%SubModule 1.1 - Read Input File from *.INP  
nsc=input('Number of Scenarios: ');  
  
fid=fopen('zapotex.txt');  
TITLE=textscan(fid, '%s', 1);  
Project=textscan(fid, '%q', 1); %Project Name  
  
JUNCTIONS=textscan(fid, '%s', 1);  
psum=textscan(fid, '%f%f%f%f', 1);  
header1=textscan(fid, '%s %s %s %s', 1);  
Nodes=textscan(fid, '%f %f %f %s');  
  
RESERVOIRS=textscan(fid, '%s', 1);  
header2=textscan(fid, '%s %s %s', 1);  
Reservoirs=textscan(fid, '%f %f %s');  
  
TANKS=textscan(fid, '%s', 1);  
header3=textscan(fid, '%s %s %s %s %s %s %s %s', 1);  
Tanks=textscan(fid, '%f %f %f %f %f %f %f %s');  
  
PIPES=textscan(fid, '%s', 1);
```

```

header4=textscan(fid, '%s %s %s %s %s %s %s %s',1);
Pipes=textscan(fid, '%f %f %f %f %f %f %f %s %s');

PUMPS=textscan(fid, '%s',1);
header5=textscan(fid, '%s %s %s %s',1);
Pumps=textscan(fid, '%f %f %f %s %s %s %s %s');

fclose(fid);

%Obtain number of assets by type in network
numN=psum{2};
numR=psum{1};
numT=psum{3};
numP=psum{5};
numU=psum{4};

nass=numN+numR+numT+numP+numU;

TWDemand=sum(Nodes{3});

fid=fopen('bburg2.txt');

header6=textscan(fid, '%s %s %s %s %s',1);
Asset=textscan(fid, '%f %s %f %f %f'); %asset attributes (file)

header7=textscan(fid, '%s %s',1); %Group probabilities (file)
Group=textscan(fid, '%f %f');

fclose(fid);
ngr=size(Group{1},1);

%SubModule 1.2 - Estimate number of assets to fail in each scenario
%smax governs the top nr failures (worst case scenario)
fprintf('%s%i\n', 'Total number of assets: ',nass)
smax=input('Maximum number of assets to fail: ');
tic
%This operations generate a prob. Distribution for natural events

DeltaP=1/nsc;
s=zeros(nsc,1); %s vector of num. of assets
for i=1:1:nsc %to fail on each scenario (keep)
    s(i)=(2/((2*i-1)*DeltaP));
end
k=s(1);
for i=1:1:nsc
    s(i)=floor((s(i)/k)*smax);
    if s(i)==0, s(i)=1;
    end
end

%SubModule 1.3 - Generate the Scenario Set Matrix

scenario=zeros(nsc,nass); %scenario is the scenario matrix
%if smax=nass first scenario is all fails

```

```

nasgr=zeros(ngr,1);           %number of assets per group nasgr
                              %assets in group 10 not counted
howmany=zeros(nsc,1);

%SubModule 1.3.1 - Fail an asset using urn simulation Wallenius
%Count assets per group nasgr
if smax==nass,
    sta=2;
    for i=1:1:nass
        scenario(1,i)=1;
    end
else sta=1;
end

for aa=sta:1:nsc
    for j=1:1:ngr
        for k=1:1:nass
            if Asset{4}(k)==j,nasgr(j)=nasgr(j)+1;
            end
        end
    end
end

%Record asset numbers per group.
%Fixed vectorgr matrix size
vectorgr=zeros(ngr,nass);
for j=1:1:ngr
    l=0;
    for k=1:1:nass
        if Asset{4}(k)==j,l=l+1;vectorgr(j,l)=k;
        end
    end
end
%vectorgr is a matrix of asset numbers
%contained in each group

for bb=1:1:s(aa)
    %Compute Sum of products wm (denominator for urn)
    Denom=0;
    indiv=zeros(ngr,1);
    for j=1:1:ngr
        indiv(j)=(nasgr(j)*Group{2}(j));
        Denom=indiv(j)+Denom;
    end
    probtemp=indiv./Denom;

%Select a Group of Assets for Failure
u=rand;
lims=zeros(ngr,2);           %lims is a matrix with normalized
                              %prob. limits for each group
for q=1:1:ngr
    if q==1,lims(q,1)=0;else lims(q,1)=lims(q-1,2);
    end
    lims(q,2)=probtemp(q)+lims(q,1);
    if u>lims(q,1) && u<lims(q,2),
        selectgr=q;
    end
end
%selectgr is the group selected for
%a failed asset

```

```

%Select an asset to fail (failasst) inside selectgr
[~,b]=size(vectorgr);
v=zeros(1,b);
for m=1:1:b
    v(1,m)=vectorgr(selectgr,m);
end
vred=v(v~=0);
[~,c]=size(vred);
asnum=randi(c,1);
failasst=vred(1,asnum);           %failasst is the selected asset

%Record the failedasset and reset pertinent variables
scenario(aa,failasst)=1;
howmany=sum(scenario,2);
vectorgr(selectgr,asnum)=0;
nasgr(selectgr)=nasgr(selectgr)-1;

end
end

% fid=fopen('SMatrixz.bin','w');
% fwrite(fid,scenario);
% fclose(fid);
fprintf('%s%i%s%i\r\n','Scenario Matrix size is ',nsc,' by ',nass)
toc

```

MODULE M2.m

```

%-----
%ERASMUS - IDENTIFICATION OF SCENARIO TYPES
%-----
%Receive input from M1 (Scenario Matrix)
%Output is Scenario Types (scentypes)

%Scenario Types
%Type 1 - Only Tanks fail (not enough water / 4 indefinite time)
%Type 2 - Only Pumps and/or Reservoirs fail (enough water / 4 finite time)
%Type 3 - Combination of Types 1 and 2
%Type 4 - No Tank, Pump, or Reservoir fails; only nodes and links
%Type 5 - Combination of Types 1,2,3 with 4
%Type 6 - Total failure, performance zero w/o analysis need

%Step 1- Identify t,u,r asset numbers. tanks,pumps,reservoirs are
%vectors with the global asset numbers
tic
tempo=0;
kt=0; kr=0; ku=0;
tanks=zeros(numT,1);
pumps=zeros(numU,1);
reservoirs=zeros(numR,1);
for i=1:1:nass
    tempo=strcmp(Asset{2}(i),'[TANKS]');
    if tempo==1,

```

```

        kt=kt+1;
        tanks(kt,1)=Asset{3}(i);
    end
    tempo=strncmp(Asset{2}(i), '[PUMPS]');
    if tempo==1,
        ku=ku+1;
        pumps(ku,1)=Asset{3}(i);
    end
    tempo=strncmp(Asset{2}(i), '[RESERVOIRS]');
    if tempo==1,
        kr=kr+1;
        reservoirs(kr,1)=Asset{3}(i);
    end
end
kt=0; kr=0; ku=0;

%Step 2- Identify scenario types
scentypes=zeros(nsc,1); % vector of scenario type for each scenario
scenarion=zeros(nsc,nass); %matrix containing failed asset numbers
for i=1:1:nsc
    for j=1:1:nass
        scenarion(i,j)=scenario(i,j)*j;
    end
end
tu=union(tanks,pumps);
tr=union(tanks,reservoirs);
tur=union(tu,reservoirs);
for i=1:1:nsc
    temt=scenarion(i,:);
    temtred=temt(temt~=0);
    [~,Q]=size(temtred);
    A=sum(ismember(tanks,temtred));
    B=sum(ismember(pumps,temtred));
    C=sum(ismember(reservoirs,temtred));
    D=sum(ismember(tu,temtred));
    E=sum(ismember(tr,temtred));
    F=sum(ismember(tur,temtred));
    if F==(numT+numU+numR),
        scentypes(i,1)=6;
    end
    if E==(numT+numR),
        scentypes(i,1)=6;
    end
    if D==(numT+numU),
        scentypes(i,1)=6;
    end
    if A==Q,
        scentypes(i,1)=1;
    end
    if B==Q || C==Q,
        scentypes(i,1)=2;
    end
    if F~=0 && scentypes(i,1)==0,
        if F<Q,
            scentypes(i,1)=5;
        end
        if F==Q,

```

```

        scentypes(i,1)=3;
    end
end
if E~=0 && scentypes(i,1)==0,
    if E<Q,
        scentypes(i,1)=5;
    end
    if E==Q,
        scentypes(i,1)=3;
    end
end
if D~=0 && scentypes(i,1)==0,
    if D<Q,
        scentypes(i,1)=5;
    end
    if D==Q,
        scentypes(i,1)=3;
    end
end
if (A+B+C)==0,
    scentypes(i,1)=4;
end
end
%Estimate Scenario Probabilities
Scprob=ones(nsc,1);
for i=1:1:nsc
    v=scenarion(i,:);
    vred=v(v~=0);
    [~,ka]=size(vred);
    for j=1:1:ka
        Scprob(i,1)=Scprob(i,1)*(Group{2}(Asset{4}(vred(1,j))));
    end
end

konek=zeros(numN,1);
for y=1:1:numN
    for k=1:1:numP
        if Pipes{2}(k)==y || Pipes{3}(k)==y,
            konek(y,1)=konek(y,1)+1;
        end
    end
end
end
toc

```

MODULE M3.m

```

%-----
%ERASMUS Module 3 - ANALYZE EACH SCENARIO ACCORDING TO TYPE
%-----
%Receive input from Scenario Types Module M2 (scentypes)
%Output is a measure of system performance on each scenario
%Perf is a normalized performance measure [0,1]
diary on
tic
Perf=zeros(nsc,1); %This vector contains the Water Qty delivered in

```



```

tags=zeros(Rp,3);
fnod=zeros(numN,1);

finishd=0;
kont=0;
while finishd~=23,
    if finishd==15,
        numas=1;
        fasset=zeros(1,2);
        fasset(1,2)=loca;
        facum=union(fassel,facum,'rows');
        fassel=zeros(1,2);
        %tags=zeros(Rp,3);
    end
    %First Round: all failed assets in fasset plus spill

for h=1:1:numas
    for k=1:1:Rp
        y=intersect(INMAK(k,:),fasset(h,2),'stable');
        try
            S=y(1);
        catch
            y(1)=0;
        end
        if y(1)~=0,
            if y(1)==INMAK(k,1),
                tags(k,1)=tags(k,1)+1;
                tags(k,2)=tags(k,2)+1;
                fnod(INMAK(k,2),1)=fnod(INMAK(k,2),1)+1;
                tags(k,3)=tags(k,3)+1;
                fnod(INMAK(k,3),1)=fnod(INMAK(k,3),1)+1;
            end
            if y(1)==INMAK(k,2),
                tags(k,1)=tags(k,1)+1;
                tags(k,2)=tags(k,2)+1;
                fnod(INMAK(k,2),1)=fnod(INMAK(k,2),1)+1;
                tags(k,3)=tags(k,3)+1;
                fnod(INMAK(k,3),1)=fnod(INMAK(k,3),1)+1;
            end
            if y(1)==INMAK(k,3),
                tags(k,1)=tags(k,1)+1;
                fnod(INMAK(k,2),1)=fnod(INMAK(k,2),1)+1;
                tags(k,3)=tags(k,3)+1;
                fnod(INMAK(k,3),1)=fnod(INMAK(k,3),1)+1;
                tags(k,2)=tags(k,2)+1;
            end
        end
    end

end

end

% Disconnected pipes have a tags>=1
% Disconnected nodes have fnod>=konek

% Generate fassel
fassel=fasset;

```

```

fvec=fasset(:,2);
for h=1:1:Rp
    if tags(h,1)>=1,
        if sum(ismember(fvec,INMAK(h,1)))==0,
            fassel=[fassel;0 INMAK(h,1)];
        end
    end
end
for h=1:1:numN
    if fnod(h,1)>=konek(h,1),
        if sum(ismember(fvec,h))==0,
            fassel=[fassel;0 h];
        end
    end
end

if finishd==0,
    facum=fassel;
end
if finishd==15,
    [tumul,~]=size(fassel);
    uke=facum(:,2);
    for uu=1:1:tumul,
        if ismember(fassel(uu,2),uke),
            fassel(uu,2)=0;
        end
    end
    ccc=0;
    for uu=1:1:tumul,
        if sum(fassel(uu,:))~=0,
            ccc=ccc+1;
            fassel2(ccc,:)=fassel(uu,:);
        end
    end
    fassel=fassel2;
end
[numal,~]=size(fassel);

% fve2=fassel(:,2);
% %Building Incidence Matrix of Damaged Network
% G=tags(:,1);
% Remp=(Rp-sum(G));
% INMD=zeros(Remp,3);
% xxx=0;
% for k=1:1:Rp
%     if tags(k,1)==0,
%         if sum(ismember(fve2,INMAK(k,2)))==0&&sum(ismember(fve2,INMAK(k,3)))==0,
%             xxx=xxx+1;
%             INMD(xxx,1)=INMAK(k,1);
%             INMD(xxx,2)=INMAK(k,2);
%             INMD(xxx,3)=INMAK(k,3);
%         end
%     end
% end
% % Second Round: Connectivity test for remaining network
% % There is an error here somewhere. Fix later...

```

```

%
% % Adjacency matrix (original network)
% % ADMA=zeros (numN,numN);
% %     for h=1:1:Rp
% %         ADMA (INMAK (h, 2) , INMAK (h, 3) )=1;
% %         ADMA (INMAK (h, 3) , INMAK (h, 2) )=1;
% %     end
% Adjacency Matrix Damaged Network
% [nfas,~]=size (fve2);
% konek2=konek;
% fnod2=fnod;
% for h=1:1:nfas
%     if fassel (h,2)>=numR && fassel (h,2)<= (numN+numT) ,
%         fnod2 (fassel (h, 2) , 1)=konek2 (fassel (h, 2) , 1);
%     end
% end
% R=konek2-fnod2;
% Rred=R (R~=0);
% [Remn,~]=size (Rred);
% ADM1=zeros (numN,numN);
% ADM2=zeros (Remn,numN);
% ADMD=zeros (Remn,Remn);
% for h=1:1:Remp
%     ADM1 (INMD (h, 2) -numR, INMD (h, 3) -numR)=1;
%     ADM1 (INMD (h, 3) -numR, INMD (h, 2) -numR)=1;
% end
% xxx=0;
% for h=1:1:numN
%     if sum (ADM1 (h, :))~=0,
%         xxx=xxx+1;
%         ADM2 (xxx, :)=ADM1 (h, :);
%     end
% end
% xxx=0;
% for h=1:1:numN
%     if sum (ADM1 (:, h))~=0,
%         xxx=xxx+1;
%         ADMD (:, xxx)=ADM2 (:, h);
%     end
% end
% clear ADM1;
% clear ADM2;
% % Degree Matrix Damaged Network
% DEMD=zeros (Remn,Remn);
% DEMD=(ADMD)^2;
% DEMD=DEMD.*eye (Remn);
% Degree Matrix Original network
% % DEMA=zeros (numN,numN);
% % for h=1:1:numN
% %     DEMA (h,h)=konek (h,1);
% % end
% % Laplacian Matrices
% %L0=DEMA-ADMA;
% L1=DEMD-ADMD;
% % Obtain Eigenvalues (Laplacian Spectra)
% %E0=eig (L0);
% E1=eig (L1);

```

```

% % Find Number of Zeros in Eigenvalues
% tolerance=1e-05;
% xxx=0;
% for k=1:1:Remn
%     if E1(k,1)<=tolerance,
%         xxx=xxx+1;
%     end
% end
% Decide whether the network is connected
% A disconnected (fragmented) network will have to be analyzed
% manually
% if xxx==1,
% fprintf('%s\r\n','Remaining network is connected');
% else
% fprintf('%s%i%s\r\n','Remaining network disconnected in ',xxx,'
components');
% end
% End of fassel assembly Module (Cascade.m)

% MODE 1. Modify Baseline scenario file
for k=1:1:numal
    kont=kont+1;
    if k==1 && finishd==0,
        previous='zapotex2.txt';
    else
        previous=file2;
    end
    if finishd==15 && k==1,
        previous='temporal.txt';
    end
    dst=fassel(k,2);
    dsts=num2str(dst);
    uman=num2str(kont);
    file2=strcat('modif',uman,'.txt');
    if k>2,
        kcx=num2str(kont-2);
        delf=strcat('modif',kcx,'.txt');
        delete(delf);
    end
    fid=fopen(previous);
    fid2=fopen(file2,'w');
    trline=0;
    %fprintf('%s%s\n','Writing File: ',file2);
    while ~feof(fid);
        linex=fgets(fid);
        trline=trline+1;
        linen=deblank(linex);
        kut=isspace(linen);
        llx=length(linen);
        sa=1;
        sb=1;
        long1=-1;
        long2=-1;
        long3=-1;
        tro=1;
        pp=0;
        if sum(kut)>1,

```

```

while tro<3,
    pp=pp+1;
    if kut(pp)==1 && tro==1,
        sa=pp+1;
        long1=(sa-2);
        tro=tro+1;
    else
        if kut(pp)==1 && tro==2,
            sb=pp+1;
            long2=(sb-(long1+3));
            tro=tro+1;
        end
    end
end
end
if sum(kut)>2,
    while tro<4,
        pp=pp+1;
        if kut(pp)==1 && tro==3,
            sc=pp+1;
            long3=(sc-(long1+long2+4));
            tro=tro+1;
        end
    end
end
ocur=[1 sa sb];
K=regexp(linen,dsts);
try
    S=K(1);
    if K(1)==1,
        if long1~=length(dsts),
            K(1)=0;
        end
    else
        if K(1)==sa,
            if long2~=length(dsts),
                K(1)=0;
            end
        else
            if K(1)==sb,
                if long3~=length(dsts),
                    K(1)=0;
                end
            end
        end
    end
end
catch
    K(1)=0;
end
try
    S=K(2);
    if K(2)==sa,
        if long2~=length(dsts),
            K(2)=0;
        end
    else
        if K(2)==sb,

```

```

        if long3~=length(dsts),
            K(2)=0;
        end
    end
end
catch
    K(2)=0;
end
try
    S=K(3);
    if K(3)==sb,
        if long3~=length(dsts),
            K(3)=0;
        end
    end
catch
    K(3)=0;
end

if isempty(intersect(K,ocur))==0,
else
    fprintf(fid2,linex);
end
end
fclose(fid);
fclose(fid2);
end

if kont==1,
else
    kcx=num2str(kont-1);
    delf=strcat('modif',kcx, '.txt');
    delete(delf);
end

% Archivo listo para analizar con EPANET

movefile(file2,'temporal.txt');
!epanet2d temporal.txt screp.txt

fidx=fopen('screp.txt');
for yyy=1:1:9
xline=fgets(fidx);
xline=deblank(xline);
end
xline=fgets(fidx);
xline=deblank(xline);
ok=isempty(strfind(xline,'Error'));
if ok==1,
    for yyy=1:1:6
        xline=fgets(fidx);
    end
    head=textscan(fidx,'%s',1);
    datas=textscan(fidx,'%f%f%f%f');
    Presr=datas{4};
    % Checar el valor asignado a Perf en todos los casos

```

```

if isempty(Presr),
    B=0;
    dems=0;
    xtra=0;
else
    presr=datas{4};
    B=abs(Presr)-Presr;
    dems=sum(datas{2});
    xtra=datas{2}(numel(datas{2}));
end

if sum(B)==0,
    Perf(i,1)=dems-xtra;
    finishd=23;
else
    [~,loc]=max(B);
    loca=datas{1}(loc);
    finishd=15;
end

else
    Perf(i,1)=0;
    finishd=23;
end
fclose(fidx);
end

else
    Perf(i,1)=0;

end
end

fid=fopen('Perftwo.txt','wt');
fprintf(fid,'%f\n',Perf);
fclose(fid);
beep
beep
beep

toc
diary off

```

MODULE M4.m

```

%-----
% ERASMUS Module 4 - RECOVERY TIME AND COST EACH SCENARIO
%-----

fidy=fopen('costfile.txt');
head1=textscan(fidy,'%s%s%s%s',1);
recov=textscan(fidy,'%f%s%f%f%f');
fclose(fidy);

%Pipe length stats

```

```

plen=recov{5};
Tplen=sum(plen);
avgplen=Tplen/1513;

% Number of repairs per ft. nrpft
nrpft=0.10;

%Costs 2011 according to RSMeans (plus excavation)
%Standard Excavation Cost per foot
%31-23-16.14-5400
excost=8.10;
%Each
repa=[148;181;244;285;335;920;1025;1075;1175;1475];
%Linear foot
repl=[152;325;735;410;495;660];
%Repairs/day
prodrepa=[15.6;34;21;20;17;6.4;6;5;4.6;4];
%Replacement feet/day
prodrepl=[128;28.96;21.68;60;60;40];
%Cost per day
ccrewa=1412.40;
ccrewl=5221.70;
%Adjustments for Time and Location
infactor12=1.022;
cityindex=0.671;

%Cost adjustments
repa=repa.*(infactor12*cityindex);
repl=repl.*(infactor12*cityindex);

%Estimate Max/Min Costs. c1 min, c2 avg, c3 max.
%Estimate Max/Min times. t1 min, t2 avg, t3 max.
start=1284;
nass=2796;
cass=zeros(nass,3);
tass=zeros(nass,3);

for k=start:1:nass
    u=recov{4}(k);
    len=recov{5}(k);
    numreps=len*nrpft;
    numreps=ceil(numreps);
    if u<=4,
        tass(k,1)=(numreps/prodrepa(1,1));
        tass(k,3)=(len/prodrepl(1,1));
        laba=ccrewa*tass(k,1);
        labl=ccrewl*tass(k,3);
        cass(k,1)=(repa(1,1)*numreps)+(excost*10)+laba;
        cass(k,3)=(repl(1,1)*len)+(excost*len)+labl;
    end
    if u>4 && u<=6,
        tass(k,1)=(numreps/prodrepa(2,1));
        tass(k,3)=(len/prodrepl(1,1));
        laba=ccrewa*tass(k,1);
        labl=ccrewl*tass(k,3);
        cass(k,1)=(repa(2,1)*numreps)+(excost*10)+laba;

```

```

    cass(k,3)=(repl(1,1)*len)+(excost*len)+labl;
end
if u>6 && u<=8,
    tass(k,1)=(numreps/prodrepa(3,1));
    tass(k,3)=(len/prodrepl(1,1));
    laba=ccrewa*tass(k,1);
    labl=ccrew1*tass(k,3);
    cass(k,1)=(repa(3,1)*numreps)+(excost*10)+laba;
    cass(k,3)=(repl(1,1)*len)+(excost*len)+labl;
end
if u>8 && u<=10,
    tass(k,1)=(numreps/prodrepa(4,1));
    tass(k,3)=(len/prodrepl(1,1));
    laba=ccrewa*tass(k,1);
    labl=ccrew1*tass(k,3);
    cass(k,1)=(repa(4,1)*numreps)+(excost*10)+laba;
    cass(k,3)=(repl(1,1)*len)+(excost*len)+labl;
end
if u>10 && u<=12,
    tass(k,1)=(numreps/prodrepa(5,1));
    tass(k,3)=(len/prodrepl(1,1));
    laba=ccrewa*tass(k,1);
    labl=ccrew1*tass(k,3);
    cass(k,1)=(repa(5,1)*numreps)+(excost*10)+laba;
    cass(k,3)=(repl(1,1)*len)+(excost*len)+labl;
end
if u>12 && u <=14,
    tass(k,1)=(numreps/prodrepa(6,1));
    tass(k,3)=(len/prodrepl(1,1));
    laba=ccrewa*tass(k,1);
    labl=ccrew1*tass(k,3);
    cass(k,1)=(repa(6,1)*numreps)+(excost*10)+laba;
    cass(k,3)=(repl(1,1)*len)+(excost*len)+labl;
end
if u>14 && u<=16,
    tass(k,1)=(numreps/prodrepa(7,1));
    tass(k,3)=(len/prodrepl(1,1));
    laba=ccrewa*tass(k,1);
    labl=ccrew1*tass(k,3);
    cass(k,1)=(repa(7,1)*numreps)+(excost*10)+laba;
    cass(k,3)=(repl(1,1)*len)+(excost*len)+labl;
end
if u>16 && u<=18,
    tass(k,1)=(numreps/prodrepa(8,1));
    tass(k,3)=(len/prodrepl(1,1));
    laba=ccrewa*tass(k,1);
    labl=ccrew1*tass(k,3);
    cass(k,1)=(repa(8,1)*numreps)+(excost*10)+laba;
    cass(k,3)=(repl(1,1)*len)+(excost*len)+labl;
end
if u>18 && u<=20,
    tass(k,1)=(numreps/prodrepa(9,1));
    tass(k,3)=(len/prodrepl(1,1));
    laba=ccrewa*tass(k,1);
    labl=ccrew1*tass(k,3);
    cass(k,1)=(repa(9,1)*numreps)+(excost*10)+laba;
    cass(k,3)=(repl(1,1)*len)+(excost*len)+labl;

```

```

end
if u>20 && u<=24,
    tass(k,1)=(numreps/prodrepa(10,1));
    tass(k,3)=(len/prodrepl(1,1));
    laba=ccrewa*tass(k,1);
    labl=ccrew1*tass(k,3);
    cass(k,1)=(repa(10,1)*numreps)+(excost*10)+laba;
    cass(k,3)=(repl(1,1)*len)+(excost*len)+labl;
end
if u>24,
    tass(k,1)=(numreps/prodrepa(10,1));
    laba=ccrewa*tass(k,1);
    zz=(55.5*u)-412;
    cass(k,1)=(zz*numreps)+(excost*10)+laba;
end
if u>24 && u<=36,
    tass(k,3)=(len/prodrepl(2,1));
    labl=ccrew1*tass(k,3);
    cass(k,3)=(repl(2,1)*len)+(excost*len)+labl;
end
if u>36 && u<=48,
    tass(k,3)=(len/prodrepl(3,1));
    labl=ccrew1*tass(k,3);
    cass(k,3)=(repl(3,1)*len)+(excost*len)+labl;
end
if u>48 && u<=60,
    tass(k,3)=(len/prodrepl(4,1));
    labl=ccrew1*tass(k,3);
    cass(k,3)=(repl(4,1)*len)+(excost*len)+labl;
end
if u>60 && u<=72,
    tass(k,3)=(len/prodrepl(5,1));
    labl=ccrew1*tass(k,3);
    cass(k,3)=(repl(5,1)*len)+(excost*len)+labl;
end
if u>72,
    tass(k,3)=(len/prodrepl(6,1));
    labl=ccrew1*tass(k,3);
    cass(k,3)=(repl(6,1)*len)+(excost*len)+labl;
end
end
end

% Cost and Time Info for Tanks and Pumps
% Tanks
cass(1269,3)=1000000;
cass(1270,3)=1000000;
cass(1271,3)=2000000;
cass(1272,3)=2000000;
cass(1273,3)=1000000;
cass(1274,3)=1000000;
cass(1275,3)=200000;
cass(1276,3)=1400000;
cass(1277,3)=1200000;

cass(1269,1)=50000;
cass(1270,1)=50000;

```

```

cass(1271,1)=100000;
cass(1272,1)=100000;
cass(1273,1)=50000;
cass(1274,1)=50000;
cass(1275,1)=1000;
cass(1276,1)=70000;
cass(1277,1)=60000;

tass(1269:1277,3)=30;
tass(1269:1277,1)=7;

% Pumps
cass(1278,3)=200000;
cass(1279,3)=200000;
cass(1280,3)=200000;
cass(1281,3)=200000;
cass(1282,3)=200000;
cass(1283,3)=200000;

cass(1278,1)=10000;
cass(1279,1)=10000;
cass(1280,1)=10000;
cass(1281,1)=10000;
cass(1282,1)=10000;
cass(1283,1)=10000;

tass(1278:1283,3)=30;
tass(1278:1283,1)=7;

% Average Values
for k=start:1:nass
    cass(k,2)=(cass(k,1)+cass(k,3))/2;
    tass(k,2)=(tass(k,1)+tass(k,3))/2;
end
ec=zeros(nass,1);
et=zeros(nass,1);

% Expected Values
for k=1:1:nass
    ec(k,1)=(cass(k,1)+(4*cass(k,2))+cass(k,3))/6;
    et(k,1)=(tass(k,1)+(4*tass(k,2))+tass(k,3))/6;
end

% Recovery Time and Cost per Asset - File
fide=fopen('TOBRas1.txt','wt');
fprintf(fide,'%0s%10s%10s%10s%10s%10s%10s%10s\r\n','ID','c1','c2','c3','t1','t2','t3','Ec','Et');
for k=1:1:nass
    fprintf(fide,'%i%10.2f%10.2f%10.2f%10.2f%10.2f%10.2f%10.2f\r\n',k,cass(k,:),tass(k,:),ec(k,1),et(k,1));
end
fclose(fide);
TTime=zeros(nsc,1);
TCost=zeros(nsc,1);

```

```

% Estimated recovery Time and Cost for Each scenario
for k=1:1:nsc
    v=scenarion(k,:);
    vred=v(v~=0);
    [~,numas]=size(vred);
    for j=1:1:numas
        TTime(k,1)=TTime(k,1)+et(vred(1,j),1);
        TCost(k,1)=TCost(k,1)+ec(vred(1,j),1);
    end
end

perf=zeros(nsc,1);
% Read Performance Measures
fid=fopen('PerfTOB1.txt');
pe=textscan(fid,'%f');
fclose(fid);
perf=pe{1};
perf=perf./TWDemand;

Rob1=sum(perf.*Scprob)/sum(Scprob);
RT=sum(TTime.*Scprob)/sum(Scprob);
RC=sum(TCost.*Scprob)/sum(Scprob);

% Performance, Recovery Time, and Recovery Cost per Scenario - File
fidux=fopen('TOBRscl.txt','wt');
fprintf(fidux,'%0s%15.4f\r','Robustness:',Rob1);
fprintf(fidux,'%0s%15.2f\r','Expected Recovery Time:',RT);
fprintf(fidux,'%0s%15.2f\r\n','Expected Recovery Cost:',RC);
fprintf(fidux,'%0s%7s%12s%12s\r\n','Scenario','Perf','RTime','RCost');
for k=1:1:nsc
    fprintf(fidux,'%i%15.3f%15.2f%15.2f\r',k,perf(k,1),TTime(k,1),TCost(k,1));
end
fclose(fidux);

% Plot Resilience Cloud WDN-1
plot3(perf,TTime,TCost,'ro');
hold;
plot3(Rob1,RT,RC,'*');
grid
axis tight
xlabel('Normalized Performance');
ylabel('Recovery Time (Days)');
zlabel('Recovery Cost (USD)');
axis vis3d;
title('Resilience Cloud WDN-1');

% Plot Functionality Curve WDN-1 (Linear)
figure
x=[0,1,1,1+RT,2+RT];
y=[1,1,Rob1,1,1];
plot(x,y);
grid
xlabel('Time (Days)');
ylabel('Performance');
axis([0 2+RT 0.50 1.50]);
title('Functionality Curve WDN-1');

```

```

% Resilience Index Map

xt=min(TTime);
yt=mean(TTime);
xc=min(TCost);
yc=mean(TCost);

stept=(yt-xt)/10;
stepc=(yc-xc)/10;

% Acceptable Minimum Performance
APerf=0.80;

Rindex=zeros(10,10);
Xe=zeros(10,1);
Ye=zeros(10,1);
xxx=0;
for ele=1:1:10
    ATime=ele*stept;
    Ye(ele,1)=ATime;
    for eme=1:1:10
        ACost=eme*stepc;
        Xe(eme,1)=ACost;
        xxx=0;
        for k=1:1:nsc
            if perf(k,1)>=APerf && TTime(k,1)<=ATime && TCost(k,1)<=ACost,
                xxx=xxx+1;
            end
        end
        Rindex(eme,ele)=xxx/nsc;
    end
end

% Plot Resilience Surface
figure
surf(Xe,Ye,Rindex)
xlabel('Acceptable Cost (USD)');
ylabel('Acceptable Time (Days)');
zlabel('Resilience Index');
title('Resilience Index Surface Perf=0.80');

```