Safe-To-Fail Infrastructure for Resilient Cities under Non-Stationary Climate

by

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ABSTRACT

Motivated by the need for cities to prepare and be resilient to unpredictable future weather conditions, this dissertation advances a novel infrastructure development theory of “safe-to-fail” to increase the adaptive capacity of cities to climate change. Current infrastructure development is primarily reliant on identifying probable risks to engineered systems and making infrastructure reliable to maintain its function up to a designed system capacity. However, alterations happening in the earth system (e.g., atmosphere, oceans, land, and ice) and in human systems (e.g., greenhouse gas emission, population, land-use, technology, and natural resource use) are increasing the uncertainties in weather predictions and risk calculations and making it difficult for engineered infrastructure to maintain intended design thresholds in non-stationary future. This dissertation presents a new way to develop safe-to-fail infrastructure that departs from the current practice of risk calculation and is able to manage failure consequences when unpredicted risks overwhelm engineered systems.

This dissertation 1) defines infrastructure failure, refines existing safe-to-fail theory, and compares decision considerations for safe-to-fail vs. fail-safe infrastructure development under non-stationary climate; 2) suggests an approach to integrate the estimation of infrastructure failure impacts with extreme weather risks; 3) provides a decision tool to implement resilience strategies into safe-to-fail infrastructure development; and, 4) recognizes diverse perspectives for adopting safe-to-fail theory into practice in various decision contexts.

Overall, this dissertation advances safe-to-fail theory to help guide climate adaptation decisions that consider infrastructure failure and their consequences. The results of this dissertation demonstrate an emerging need for stakeholders, including policy makers, planners, engineers, and community members, to understand an impending “infrastructure trolley problem”, where the adaptive capacity of some regions is improved at the expense of others. Safe-to-fail further engages stakeholders to bring their knowledge into the prioritization of various failure costs based on their institutional, regional, financial, and social capacity to withstand failures. This approach connects to sustainability, where city practitioners deliberately think of and include the future cost of social, environmental and economic attributes in planning and decision-making.

DEDICATION

For my family and friends who have supported me and kept me happy throughout my PhD journey in Arizona.

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The study of resilience and safe-to-fail opened me to view the world in a new way and to meet my committee members and collaborators who have provided me their valuable insights both in research and the PhD life.

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CHAPTER 1

INTRODUCTION

1.1. Problem statement

During the last few decades, many regions around the world have experienced growing climate-related challenges i.e., sea-level rise, extreme weather, ecosystem disturbance, and etc. Cities where infrastructure serve large populations are facing new risks that are coming from non-stationarity of weather (A Revi et al., 2014). Urban infrastructure built during the last few decades are planned to provide persistent service to people, thus designed to be robust to any form of shock to the system as predicted based on historical data. However, the uncertain nature of weather events is expanding due to climate change and infrastructure systems are experiencing disruptions despite they are built according to the engineering criteria that require a scrupulous calculation of probable risks (Olsen, 2015). There have been several catastrophic infrastructure failures due to extreme weather events such as the levee and flood wall failures during Hurricane Katrina in New Orleans in 2005 (U.S. Senate Committee on Homeland Security and Governmental Affairs, 2006), communication and power network failures during Hurricane Sandy in New York City in 2012 (Solecki & Rosenzweig, 2014), and drainage system failures during Hurricane Harvey in Houston in 2017 (Sebastian, Antonia Lendering et al., 2017). While weather phenomena themselves were more or less expected considering the geographic characteristics and meteorological history of the areas, what was not expected was the actual intensity and impact of hurricanes experienced due to the failure of infrastructure systems that were designed to withstand these events. Failures of these infrastructure led to unforeseen consequences including human loss, property damage, public service loss, critical infrastructure disruption that are interdependent with others, business and livelihood interruption, health hazard, environmental loss, adverse influences on regional economy, and many more that were not anticipated.

Current infrastructure development is primarily reliant on identifying probable risks to engineered systems and making infrastructure reliable to maintain its function up to a designed system capacity, i.e., fail-safe (Figure 1.1). Recent advancements in climate models favor future climate scenarios projection to evaluate the intensity and frequency of extreme weather events and to provide the ranges of climatic risks that may be experienced by infrastructure. However, changes happening in the earth system (e.g., atmosphere, oceans, land, and ice) and in human systems (e.g., greenhouse gas emission, population, land-use, technology, and natural resource use) are increasing the uncertainties in weather predictions and making it difficult for engineered infrastructure to uphold the risk threshold against unforeseen weather events in non-stationary future climate (Gurgel, Henry Chen, Paltsev, & Reilly, 2016; U.S. Global Change Research Program, 2018). Future infrastructure development needs a new approach that departs from the current practice of risk calculation and is able to manage failure consequences when unpredicted risks overwhelm engineered systems. From the lessons of recent hurricanes, one way to prepare for unpredictable climate is to anticipate possible consequences by overwhelmed risks and infrastructure failures. Whereas lots of effort have been made in estimating the optimal risk threshold in order to design robust infrastructure, there has been less attention on what might happen to the robust infrastructure or the region that the system serves when risks exceed the risk threshold of engineered infrastructure (Dunford, Harrison, & Rounsevell, 2015; Guikema, 2009; IPCC, 2013; Olsen, 2015; Tye, Holland, & Done, 2015). In a non-stationary future, new infrastructure development practice are vital to protect the infrastructure and its surrounding environment and vulnerable populations against extreme climatic risks and infrastructure failure.

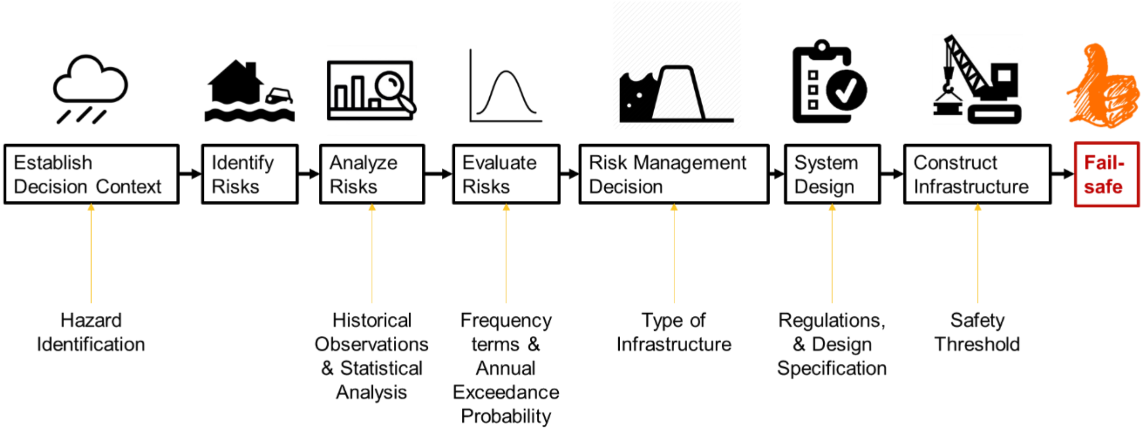

Figure 1.1. Current development process of fail-safe infrastructure focusing on the probabilistic risk calculation

“Safe-to-fail” has emerged as a new infrastructure theory that anticipates the failure of infrastructure, thus strategically designing the system to minimize and contain the failure (Steiner, 2006). As experienced with recent extreme weather events, when robust (fail-safe) infrastructure fail, the impacts of those failure can be catastrophic and make already vulnerable populations more vulnerable. There is growing concern that current infrastructure that are designed to be “fail-safe”, i.e., infrastructure that are designed to resist functional and structural failure, would not endure the climate non-stationarity. However, the few studies that have explored the safe-to-fail concept do not critically examine the approach or contrast it with traditional infrastructure designs. The few studies that have addressed the crucial need of infrastructure design paradigm change to safe-to-fail affirmed that selected resilience strategies can facilitate the system to allow failure and minimize the impacts (Ahern, 2011; J. Park, Seager, Rao, Convertino, & Linkov, 2013). Despite, no studies have examined how safe-to-fail infrastructure contribute to increasing a region's adaptive capacity to climate change, why and how different decision considerations are needed for developing infrastructure to be safe-to-fail vs. fail-safe, and what decision tools are available to implement resilience strategies into safe-to-fail infrastructure development practices. Cities around the world move faster towards needing climate adaptation solutions and infrastructure's significant role in tackling climate change is emphasized (Wise et al., 2014). To respond to a need for a new practice in developing and restructuring built infrastructure that were largely implemented in the twentieth century (Chester et al., 2014; Creutzig et al., 2016; Eakin et al., 2007; Miller, Chester, & Munoz-Erickson, 2018; Redman & Miller, 2015), a more critical framing of safe-to-fail is vital.

1.2. Research objectives

With the aim of more critical framing of safe-to-fail theory, this dissertation addresses the following objectives:

1. To define infrastructure failure, formalize the safe-to-fail theory, and compare decision considerations for safe-to-fail vs. fail-safe infrastructure development under non-stationary climate;

2. To develop a method to include the potential impact of infrastructure failure in risk evaluation for safe-to-fail infrastructure development;
3. To provide a decision tool to incorporate resilience strategies into safe-to-fail infrastructure development;
4. To recognize diverse perspectives when adopting resilience strategies and safe-to-fail theory into the practice of infrastructure development in various decision contexts.

1.3. Chapter summary

Chapter 2: New definition of safe-to-fail	
Research Questions	What is safe-to-fail? How might safe-to-fail be useful in promoting climate change adaptation and resilient infrastructure? What are decision considerations for safe-to-fail infrastructure in comparison to fail-safe?
Approach	Review theoretical perspectives on previous safe-to-fail studies and current infrastructure development practice
Deliverable	Submitted article in Earth’s Future (June 2018)
Intellectual Merit	Identify new standpoint of decision considerations in developing resilient infrastructure under non-stationary climate: infrastructure trolley problem. Suggest a way to consider and plan for different failure consequences in the safe-to-fail development process. Address the need of stakeholder engagement in developing infrastructure

Chapter 3: Infrastructure vulnerability assessment for urban flooding in Phoenix	
Research Questions	How do we assess the impact of infrastructure failure by extreme weather events in a region and incorporate it in the risk evaluation for safe-to-fail infrastructure development? How do drainage system failures disrupt the level of service provided by roadways in Phoenix?
Approach	Use a hydrological model to simulate nodal flooding in Phoenix. Evaluate the vulnerability of infrastructure to flooding by assessing the service disruption of roadways caused by storm drainage overflow during a 100-year storm event
Deliverable	Published article in Climatic Change (October 2017) in combination with Chapter 4
Intellectual Merit	Demonstrate an approach to evaluate infrastructure vulnerability by considering the level of service and experienced risks

Chapter 4: Decision-making with resilience strategies for safe-to-fail infrastructure	
Research Questions	How do different perspectives of safe-to-fail guide decision-making for infrastructure systems? How do resilience strategies apply in safe-to-fail infrastructure development?
Approach	Establish decision criteria for safe-to-fail and fail-safe infrastructure and demonstrate various researchers' perspectives on safe-to-fail via literature review. Develop an integrated infrastructure adaptation

	decision framework using multi-criteria decision analysis (MCDA) and combining the infrastructure vulnerability analysis from Chapter 3 and the decision making perspectives on safe-to-fail infrastructure.
Deliverable	Published article in Climatic Change (October 2017) in combination with Chapter 3
Intellectual Merit	Position multi-criteria decision analysis (MCDA) as an effective way to organize resilience strategies and facilitate decision making across different perspectives on safe-to-fail for climate change adaptation solutions

Chapter 5: Expert elicitation on resilient and safe-to-fail infrastructure	
Research Questions	How do stakeholders interpret the concepts of resilience and safe-to-fail? What are the shared and/or discrete perspectives exist when considering resilience strategies in various decision contexts?
Approach	Use Q-methodology to explore practitioners' perspectives on adopting resilience strategies for resilient and safe-to-fail infrastructure
Deliverable	Peer-reviewed article intended for Frontiers in Built Environment by November 2018
Intellectual Merit	Confirm the need for stakeholder engagement in infrastructure development by observing a variety of perspectives on resilience and safe-to-fail produced in different decision contexts

CHAPTER 2

NEW DEFINITION OF SAFE-TO-FAIL

This chapter is in review in the journal *Earth's Future* and appears as submitted prior to review. The citation for this article is: Kim, Y., Chester, M.V., Eisenberg, D.A., Redman, C.L. (2018) The Infrastructure Trolley Problem: Positioning Safe-to-fail Infrastructure for Climate Change Adaptation. *Earth's Future*, in review.

2.1. Introduction

The evolving role of infrastructure coupled with changing environmental conditions raises the question: is it possible to create an infrastructure system that will not catastrophically fail? Given the increasing frequency of extreme events (Guerreiro, Dawson, Kilsby, Lewis, & Ford, 2018) and the challenges for infrastructure to withstand these events, there is a growing need to consider infrastructure failures explicitly in the development process. Thinking about infrastructure failures in development may at first sound inappropriate since development practices focus on balancing system cost and performance through technical models to achieve an optimum functional capacity rather than disaster management. However, non-stationary climate risks challenge the robustness afforded by traditional infrastructure development practices, and thus, catastrophic infrastructure failures may be inevitable (Boin & McConnell, 2007). If infrastructure systems are bound to fail, then decision-makers face an "infrastructure trolley problem", i.e., they must make decisions about who incurs the consequences experienced when infrastructure is eventually compromised. The trolley problem is a popular philosophical experiment in ethics: should you pull a lever to divert a runaway trolley from its current path where it will hit multiple people, to another path where it will hit one? This choice juxtaposes various moral viewpoints (Thomson, 1985). The infrastructure trolley problem means that the trade-offs of damages experienced from future disasters must be managed prior to construction. This perspective is a stark change from previous approaches to planning and development, but is rooted in the emerging issues that infrastructure systems face. Building upon historical perspectives of the role infrastructure performs in urban development, this work presents an overview of climate and infrastructure challenges, suggests a new perspective for defining infrastructure failures, demonstrates dilemmas in the development process, and provides initial guidance for developing infrastructure systems that are safe-to-fail.

2.1.1. Evolution of infrastructure development

Infrastructure development during the nineteenth and twentieth centuries focused on utilizing existing natural resources to bolster anthropocentric activities like resource provision and economic development. A series of civil works projects, such as the New Deal in early 1930s, not only rejuvenated the U.S. economy, but also built hallmark infrastructure like the Lincoln Tunnel and Hoover Dam, many of which are still in operation today. More recently, the role of infrastructure to carry basic services (e.g., distribution pipelines for potable water) and provide protection (e.g., flood walls for storm surge) has become critically important. In the late nineteenth century U.S., the word ‘infrastructure’, which originated from a French engineering term meaning ‘beneath-structure’, was used to describe the construction work conducted below or prior to roadbeds (Carse, 2016). In the mid to late twentieth century, large construction projects became the basis of economic development and the definition of infrastructure expanded to mean “the foundation underlying a nation's economy (transportation and communication systems, power facilities, and other public services) upon which the degree of economic activity (industry, trade, etc.) depends” (Greenwald, 1965). This definition includes public works for technologies, organizations, regulations on common resources, and built artifacts to support societies (i.e., hard infrastructure) (Slota & Bowker, 2017). In the twenty-first century, the word infrastructure has deeply penetrated society and is broadly described as knowledge systems, ecosystem, policies and institutions (i.e., soft infrastructure) alongside essential services for living and protecting people from hazards – not just physical “hard” infrastructure. Furthermore, some infrastructure are further specified as “critical”, “assets, systems, and networks, whether physical or virtual, … considered so vital to the [nation] that their incapacitation or destruction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof.” (U.S. Department of Homeland Security, 2013). Now, infrastructure, especially in cities, are ubiquitous systems that balance nature with humans and shape ways of living. Dams reserve water, generate hydro-powered electricity, protect downstream human and ecosystem habitats from inundation, and stabilize water flow for mitigating sediment erosion or for dry seasons. Roadways and railroads demarcate lands and specific pathways of travel from one place to another with long lifetimes – from the New Deal until today and beyond – hard, soft, and critical infrastructure are unavoidable shapers of society.

While the meaning of the word infrastructure changed significantly in the last century, planning and development practices, embedded technologies, and the services provided by infrastructure remain largely unchanged in the same time period. Built infrastructure (infrastructure hereafter) are planned, designed, constructed, operated, and maintained to ensure systems remain functional, safe, and sturdy for long service lives, i.e., fail-safe, typically 50 years to sometimes more than 100 years. Many stakeholders like politicians, city authorities, safety officers, engineers and designers are involved in the development of infrastructure by means of codes, regulations, capital, laws, policies, and institutions that guide infrastructure performance against hazards (Rasmussen, 1997). The standardization of development practices are codified and intended to produce functional, long-lasting systems with acceptably low risks of failures (Olsen, 2015). Although contemporary design standards provide greater consistency and reliability than in the 1930s, development practices themselves have remained stagnant over time and have yet to match the dynamism of modern society. For example, approaches to managing infrastructure risks by calculating possible hazards, and basing designs on acceptable tolerances have not changed much since their initial inception in the 1960s (Olsen, 2015). Traditionally, engineers design for probable conditions to ensure a fail-safe system and incorporate safety margins to account for unknowns beyond the predictable risks. Risk predictions are often based on historical observations and statistical analysis, which then are translated into frequency terms or annual exceedance probability (AEP) of specific events (Kennedy & Paretti, 2014). While these historical development practices appear effective for constructing reliable infrastructure, the breadth of hard, soft, and critical systems are not often considered. Associated infrastructure developed to reduce predicted risks may have the unintended consequence of increasing risk to unpredicted events. For example, elevated levees give people the confidence of being protected against flood in a low lying area so as to build houses, when, in fact, floods surpassed the predicted intensity, the risk of unintended levee breach may cause extensive damages to the area. Advancing new development practices that consider the breadth of complexity in contemporary use of the word infrastructure is necessary to face future challenges.

2.1.2. Infrastructure in a future of non-stationary climate

A key limitation of historical infrastructure development practices is their inability to adapt to recent volatility in climate. During the development process, weather-related hazards are often expressed as prepackaged datasets and charts showing the statistics on temperature, precipitation, wind speed, and etc. that engineers use to characterize the intensity of weather events (e.g., a 100-year event) to be used as an operational threshold. Given the recent variability in weather, these models have not been useful in planning infrastructure performance for risks under a changing and unpredictable environment. Future climate projections are not required in planning and strategic decision-making activities despite years of data and model development from the scientific community (Lempert, 2016; Olsen, 2015; Shortridge, Guikema, & Zaitchik, 2017; Weaver et al., 2013). Infrastructure design standards and the infrastructure themselves remain difficult to change even when political, social, economic, and environmental systems change around them (Chester & Allenby, 2018). The result is that dams, pipelines, roadways, power plants, and other infrastructure manage risks like antiquated systems, rather than transcend them.

Meeting the challenge of unprecedented weather extremes requires new infrastructure development, operation, and management practices. A fundamental component of engineering development involves predicting or characterizing future conditions with sufficient precision that the consequences of design choices can be evaluated. For example, spillways are designed with the intent of safely managing 100-year frequency flood. The traditional approach for engineering design is to assume that the characteristics of future events will resemble the past, and that the past can be represented by a sample of observations drawn from the same physical process from which the future will be predicted (i.e., stationarity) (Milly et al., 2008). Historically, cities have successfully adapted to changing climates by constructing infrastructure (Adger & Vincent, 2005), yet changes associated with physical and natural processes into the future are adding far more complexity to climate predictions. Conventional adaptation efforts may not be sufficient for managing risks in the future if they are simply reliant on current models and data. The growth of cities is leading the increase of the magnitude of 100-year-flood peaks (Konrad, 2003; Moglen & Shivers, 2006), a phenomenon that has been observed in urban basins across the U.S. and around the world. Consideration of so-called "non-stationarity" not captured in historical development practices is important for advancing strategies for future infrastructure.

On-going debate in the scientific community on whether to use stationary models versus non-stationary models to predict the frequency and/or intensity of future climate extremes highlights the need for infrastructure development practices that adapt to future weather extremes. High resolution stationary models can improve the representation of extreme weather in certain regions (Mahajan, Evans, Branstetter, Anantharaj, & Leifeld, 2015). Stationary models are more reliable and practical than non-stationary models by enhancing the credibility of predicted extreme frequencies with uncertainty assessment

(Serinaldi & Kilsby, 2015). Still, increasing attention has been devoted to using models that take non-stationarity trends into account for extreme frequency analysis by incorporating climatic covariates such as time and temperature (Milly et al., 2008). Several studies have demonstrated that non-stationary models are a better fit for representing the extremes than stationary models, such as using generalized extreme value models (GEV) (H. Kim, Kim, Shin, & Heo, 2017) for a target region (Cheng, AghaKouchak, Gilleland, & Katz, 2014; Gilroy & McCuen, 2012; Tramblay, Neppel, Carreau, & Najib, 2013). Regardless of model usage, the general consensus across climate studies is that there are increasing uncertainties in predicting extremes due to urbanization and anthropogenic changes. Historical development practices that rely on statistical, frequency-based data cannot capture these unpredictable future events. Hence, infrastructure development practices meant to manage future disasters must have means to embrace this unpredictability by strategic decisions that incorporate knowledge elicited by climate scientists, policy makers, as well as engineers for effective infrastructure risk management (Gilroy & McCuen, 2012; Katz, 2010; Lins, 2012).

2.1.3. Resilient infrastructure development and climate change adaptation

In this work, we build on theories of infrastructure resilience to advance a new development paradigm responsive to future weather extremes. Resilience has become a popular concept describing managing perturbations, challenges, or shocks in systems. The concept is being used in various disciplines including business, psychology, ecology, engineering, and disaster risk management (Alexander, 2013; Rose, 2017). Especially in disaster risk management, resilience has been highlighted as a key attribute defined as "the ability to plan and prepare for, absorb, recover from, and adapt to adverse events"

(The National Academies, 2012). In response, resilient infrastructure systems have been extensively recognized as an alternative to traditional infrastructure by managing unforeseen and unknown threats (S. E. Chang, McDaniels, Fox, Dhariwal, & Longstaff, 2014; Chester & Allenby, 2018). Given that the notion of resilience has a malleable and multidisciplinary nature, there is no clear-cut standard that measures ‘infrastructure resilience’. Thus, implementing resilience in practice entails unavoidable subjective representation of the concept by decision-makers in consideration of implementation context embodying social, ecological, and technological systems in the affected region.

Numerous studies suggest that resilience is a key feature that societies must consider when adapting to non-stationary climate (S. E. Chang et al., 2014; Chester & Allenby, 2018; McDaniels, Chang, Cole, Mikawoz, & Longstaff, 2008; J. Park et al., 2013). However, there is often a gap when communicating resilience from research to practice, and from the concept to application on infrastructure development. There are few studies that explore how resilience is interpreted and perceived by practitioners or suggest a guiding decision framework that promotes resilient infrastructure (DeVerteuil & Golubchikov, 2016; Meerow & Stults, 2016). Resilient infrastructure development requires the consideration not only of biophysical but also social and institutional factors such as institutional capacity, spatial variability, social vulnerability, and level of serviceability of existing infrastructures. Decision-makers who govern climate adaptation and infrastructure development strategies are in the position to understand these complex factors. However, there is a lack of understanding how to incorporate this intricacy of decision context departing from the current infrastructure design standard and development practices. Thus, it is important to suggest a new infrastructure development paradigm recognizing how resilience, which is conceptually defined and promoted by researchers in various disciplines, can be pragmatically embedded in developing resilient infrastructure system.

We propose the use of the recently introduced concept of "safe-to-fail" as a guiding decision approach for developing resilient infrastructure system under non-stationary climate, which encourages decision-makers to engage with dilemmas of infrastructure risk management through assessing institutional capacity responding to various types of failure consequences. Among the few strategies suggested for developing resilient infrastructure systems (J. Park et al., 2013), a "safe-to-fail" approach is becoming increasingly attractive to communities vulnerable to natural disasters and non-stationary climate risks (Y. Kim et al., 2017a; Tye et al., 2015). Safe-to-fail infrastructure development aims to guide infrastructure investment and design for unpredicted risk scenarios and build adaptive capacity for affected communities. The safe-to-fail infrastructure development can also support decision-makers to consider resilience in social, ecological, and technological dimensions by engaging with local governments, practitioners, community members, and utility owners, because they face "infrastructure trolley problem" situations where future infrastructure failures will affect stakeholders in unequal ways. Safe-to-fail can guide these decisions by anticipating infrastructure failures to ensure controlled aftermaths, and thus, help decision- makers be more strategic in infrastructure development process. This includes guidance on how much to invest in infrastructure development, what infrastructure functions to maintain, where to direct the impact of failures, which assets and values to prioritize for protection, and how and when to recover from disruption, and which organization to react at emergency. We establish a guiding decision paradigm of safe-to-fail for infrastructure systems and discuss how to manage failure consequences.

2.2. What is safe-to-fail?

The concept of safe-to-fail originates from green infrastructure and safety science literature (Lister, 2007; Möller & Hansson, 2008). Both the green infrastructure and safety science perspectives are valuable for new decision theory since they accept unexpected failures as inevitable. Yet, there is no consensus on what failure means or how this concept guides the development of resilient infrastructure. In particular, green infrastructure and safety science literature emphasize different design objectives, namely: i) experimental design strategies that expect a failure, and ii) a system that fails while causing minimum harm. Here we overview the existing literature and more precisely define relevant concepts to support safe-to-fail infrastructure development and its decision paradigm.

2.2.1. The emerging concept of safe-to-fail

Green infrastructure literature focuses on small-scale design innovations with expectation of innocuous failures (i.e., trial and errors and learning-by-doing) and strengthening the ecological value of infrastructure (Ahern, 2011; Lister, 2007; Novotny, Ahearn, & Brown, 2010b). Failure in this sense is an experience that can be useful in the future, so an adaptive approach is limited by reliable experiments to planning and design where failure impacts can be naturally absorbed in the ecosystem (Lister, 2007; Novotny et al., 2010b). Green infrastructure studies suggest that science, professional practice, and stakeholder participation need to be integrated with urban development to achieve intended ecosystem services (Ahern, Cilliers, & Niemelä, 2014). Specific examples that demonstrate this perspective are green infrastructure and low impact development practices such as permeable pavements, bioswales, and urban tree canopies that capture rainfall and attenuate drainage flows (Ahern, 2011).

The safety science perspective argues that reducing risks and adding safety barriers are necessary to contain the impact of infrastructure failure within designed system tolerances (Butler et al., 2014; Möller & Hansson, 2008; Mugume, Gomez, Fu, Farmani, & Butler, 2015). Failure here means service disruptions, and thus, these studies tend to focus on system recovery practices. Particular examples that illustrate this perspective are underground nuclear waste repositories (Möller & Hansson, 2008) and storage tanks or parallel pipes in urban drainage systems (Mugume et al., 2015). This characterization of safe-to-fail includes risk analysis and critical infrastructure security studies which emphasize awareness of unforeseen risks (Blockley, Agarwal, & Godfrey, 2012; Boin & McConnell, 2007). A study of critical infrastructure crisis management based on risk analysis underlines the adaptive behavior of infrastructure managers in an effective and rapid response to an aftermath of system breakdown (Boin & McConnell, 2007). Another study calls on engineers to recognize the ‘low-chance but potentially high-impact’ risks arising from interdependencies of complex infrastructure where the system behavior may not be fully understood, and to design the system as robust to unforeseen risks (Blockley et al., 2012). This safe-to-fail framing in safety science recognizes unpredicted risks that may cause a rare system break-down and a need of processes to ensure systems degrade in a way that allows some control of the safety of people. In the resilience engineering perspective, the risk-based approach is further questioned by Park et al. by advocating for a resilience-based approach that advances from a fail-safe overconfidence mentality of large and robust infrastructure that leads to a lack of failure preparations (J. Park et al., 2013; Jeryang Park, Seager, & Rao, 2011).

What is missing from current safe-to-fail literature is an operational definition of infrastructure failure. While the goal of safe-to-fail literature has largely been to explore design strategies in the areas of green infrastructure and safety science to better manage infrastructure performance under risks, there is disagreement on what infrastructure failure or safe-to-fail means. Without a clear definition of failure, the current literature is insufficient to address climate non-stationarity. For instance, novel green infrastructure practices provide additional ecosystem services such as multifunctionality (Ahern et al., 2014), however, studies do not elucidate how the additional features control failure consequences in uncertain futures.

2.2.2. Infrastructure failure

Currently in infrastructure planning, the word “failure” is almost exclusively considered in prevention activities. We refer to current infrastructure development practices as “fail-safe” because they focus on making “failure” a rare and preventable event as long as plans and designs are followed and maintained. We extend this notion to define *infrastructure failure* in two parts: (1) when infrastructure stop serving its intended service, and (2) when infrastructure disruption by a hazard causes social, economic, and environmental impact. Type-1 failures arise when infrastructure are overwhelmed by predicted risks or discontinues its intended function, e.g., failure to convey excessive rainfall runoff through the drainage structure due to limited pipe capacity. Type-2 failures arise when infrastructure are overwhelmed by consequences of Type-1 failure resulting in severe damage to the system itself, ecosystem services, physical assets, and livelihood. While fail-safe is focused on avoiding Type-1 failure, we argue that safe-to-fail requires us to consider Type-2 failures as well in the development process and to re-evaluate the risks, particularly in situations where Type-2 failures occur without knowing the cause or prognosis of Type-1 failures due to an unforeseeable threat.

We argue that catastrophic failures occur in contemporary fail-safe infrastructure, not because of a lack of data on potential risks, but a lack of consideration for the consequences caused when infrastructure themselves fail. Our definition of infrastructure failures responds to the uncertainty of future climate risk by focusing attention on understanding consequences when infrastructure services are lost rather than the reason the services are lost in the first place. A number of studies have demonstrated the significance of understanding conceivable impacts of infrastructure failure, i.e., Type-1 failure and resulting Type-2 failure, highlighting the relationships of infrastructure service loss and its consequences (Aromar Revi et al., 2014; Wilbanks & Fernandez, 2014).

- When infrastructure fail to control floods: destruction of properties and public infrastructure, contamination of water sources, water logging, loss of business and livelihood options, and increase in water-borne and water-related diseases.
- When infrastructure fail to mitigate extreme heat: exacerbation of urban heat island effects, heat-related health problems, increased air pollution, increase in energy demand for warm season cooling.
- When infrastructure fail to secure water resources: increase water shortages, electricity shortages (where hydropower is a source), water-related diseases

(through use of contaminated water), food prices and food insecurity from reduced supplies.

- When infrastructure fail to protect coastal area from storm surge: effects on populations, property, coastal vegetation and ecosystems, threats to commerce, business, and livelihoods.
- When infrastructure fail to manage power and energy networks: electricity shortages, propagating failure across multiple systems due to strong interdependency of the power grids with other infrastructure systems (e.g., water distribution system uses electric power to pump water, transit networks, electric power plants, ICT).
- When infrastructure fail to support transportation: impact on mobility on livelihood (e.g. daily commute) and related economy (e.g., freight and retail industry, fuel delivery for plants), loss of evacuation route, emergency services.

Understanding infrastructure failure in terms of Type-1 and Type-2 failures expands upon existing safe-to-fail literature to guide infrastructure development practices. When infrastructure failure is discussed in existing literature, it often refers to structural disruption, component malfunction, operational error, and physical breakdown (Blockley et al., 2012; Möller & Hansson, 2008). These failures are derived from a development perspective that understands infrastructure not as ubiquitous systems, but as composed of multiple elements performing isolated tasks. We redefine failure to focus on the service disruptions caused by infrastructure losses, and expand this perspective to include the intended or unintended consequences infrastructure may bring to affected populations and regions. We further argue that failures occur when infrastructure compromise or stop functioning regardless of the cause, rather than a breakdown in a particular part of structure. We build upon resilience scholarship that examines infrastructure as systems rather than isolated parts. In this respect, there is less importance on calculating the exact probability of extreme climatic risks or component losses in infrastructure design, because the definition of Type-1 and Type-2 failures are not contingent on initiating events. Thus, both stationary and non-stationary models of future climate risks can be considered in infrastructure development practices through this definition.

2.2.3. Defining safe-to-fail and fail-safe infrastructure

Whereas several authors discuss the concept of safe-to-fail, no studies have systematically assessed the implications that the safe-to-fail concept has on infrastructure development practices. We assert that this is due to both a lack of definition of infrastructure failure and a lack of addressing how safe-to-fail infrastructure supports adaptation to changing and unforeseeable future climate. Using our definition of failure, the important features delineating fail-safe and safe-to-fail development are the different decision approaches for incorporating failure consequences that infrastructure are designed for.

2.2.3.1. Fail-safe

We define fail-safe infrastructure as built systems that are designed to avoid failure and to be fully functional up to safety thresholds, but lose all function when thresholds are exceeded. Under the fail-safe approach, a given system is characterized in one of two states: functioning or failed. Fail-safe infrastructure maintains the functioning state at all costs, and failure is typically understood as losing system function, i.e., Type-1 failure. The stability of fail-safe infrastructure ensures their services (e.g., flood protection) available in the near-term, yet in unpredictable future events like natural disasters may cause catastrophic service losses. This means fail-safe infrastructure is unable to manage unintended consequences because they are developed to be robust in the near-term (10-30 years) and are difficult to maintain and at greater risk of failure in the long-term (40-100 years). The consequences of fail-safe infrastructure failure is often catastrophic because these consequences do not inform design. Risks that transcend designed safety thresholds thereby cause significant damages to the infrastructure itself and other dependent systems. After-failure actions for fail-safe systems are usually rebuilding and restoration back to the previous functioning state.

Historical and current infrastructure development practices are fail-safe as the consequences of failure are not considered during development process. Current infrastructure focus on optimizing the service delivery given financial constraints and safety thresholds. This development approach is incomplete as large infrastructure with low probability of failure, long-lifetimes, and oversized to handle unforeseen threats will inevitably fail. The fail-safe approach emphasizing near-term reliability and risk management may only increase future damages, as the larger and more permanent an infrastructure is, the greater the damages caused by its failure (Jeryang Park et al., 2011). While incorporating failure consequences in risk analysis may seem feasible, even the best models cannot fully prescribe future non-stationarities including extreme weather, population growth, social demographics, urban form, and policies (Christensen et al., 2007; Shortridge et al., 2017). Moreover, model results do not provide an understanding of system status when stresses exceed the functional range of system capacity. While the durability or safety of local elements can be improved based on climate model forecasts, the consequences of system failure are not computationally simulated. Hence, engineers and decision-makers that are involved in multiple stages of infrastructure development need to recognize the possible failures that are not captured in models.

Oversizing, a robustness strategy, has been the primary mechanism used to avoid failure (Olsen, 2015) in fail-safe infrastructure. Design standards are a key element to oversizing by setting minimum thresholds for robustness that is serviceable, safe, durable, and constructible. Design standards reflecting changing stresses to systems such as increased storm frequencies and intensities, high variability of available water sources, groundwater depletion, extreme heat, and environmental loads can also increase the robustness of infrastructure to future climates (Muller, Biswas, Martin-Hurtado, & Tortajada, 2015; Slota & Bowker, 2017). However, oversizing is fail-safe because it is based on the assumption that failure is avoidable, and will not serve a future with unpredictable climate extremes. For example, oversizing is not efficient in non-stationary climate conditions where high uncertainties exist, because the analytics of prediction models may diverge from the range of design criteria.

The design standards and development practices used in New Orleans prior to Hurricane Katrina exemplify the limitations of oversizing and fail-safe infrastructure. Heavy precipitation is the most expected weather phenomenon in New Orleans due to its geography. The city enlisted planners and engineers to upgrade flooding protection measures such as levees and floodwalls. However, the plan was insufficient to take into account the inevitable complexity of interdependent infrastructure (Leavitt & Kiefer, 2006). Moreover, the infrastructure failures at the scale of what happened by Hurricane

Katrina were not considered by engineering design standards because the wind speeds were very rare according to the statistical hazard prediction (Boin & McConnell, 2007; Wilbanks & Fernandez, 2014). Several national and international reports on infrastructure systems highlight the significant need of maintenance and upgrade (Fay & Morrison, 2007; National Research Council, 2010; OECD, 2007), but maintaining these systems only with stagnated standards means that they are limited in capacity to respond to the changing environment. Taken together, traditional, robust infrastructure development strategies which resist external shocks that disrupt their integrity and/or protect their local urban environment could not be expected to survive weather extremes like Hurricane Katrina. Climate change further brings to question the efficacy of traditional fail-safe development practices into the future.

2.2.3.2. Safe-to-fail

We define safe-to-fail infrastructure as built systems designed to lose function in controlled ways, thus different types of failure consequence are experienced as expected based on prioritized decisions even when safety thresholds are exceeded in unpredicted risks. Under a safe-to-fail approach, a given system can fall into at least three different states: functioning, limited functioning/contained failure, and full failure with chosen consequences. Here, the functioning state is a normal state where the system performs all of its intended function within the designed capacity against a predicted range of hazards. Limited functioning or contained failure is when the system stops its service and causes Type-1 failure, but limit the impact of Type-2 failure within the system. Full failure and loss of system function still occurs in safe-to-fail systems, but the consequences of the Type-1 failure are controlled to ensure that the overall impact of Type-2 failure (i.e., loss of life, ecosystem, economy, physical assets and disruption of livelihood) are minimized based on development decisions. Thus, safe-to-fail development practice requires that the system remains adaptable to control the consequences at full failure by recovering lost function or transforming to serve new purposes. Safe-to-fail considers unpredicted risks caused by non-stationary climate and support long-term climate adaptation (Tye et al., 2015). Creating safe-to-fail infrastructure systems helps climate adaptation by forcing cities to examine their institutional capacity to manage unpredictable risks and to develop more adaptive coping mechanisms to future risks. This is possible because frequent, controlled infrastructure failures help prevent risky development practices from becoming locked-in prior to unpredictable weather extremes and re-assess the calculated risks. Moreover, loss of infrastructure services forces city planners and engineers to constantly reassess infrastructure service needs to help cope with changing climates (Blockley et al., 2012).

In safe-to-fail infrastructure development, multi-stakeholder engagement is a key element for assessing the institutional capacity to respond to infrastructure failure consequences. Safe-to-fail infrastructure development combines design standards, supporting policy, and stakeholder engagement to create infrastructure where the consequences of failure are managed. In a safe-to-fail approach, it is important to plan and design for the consequences of both Type-1 and Type-2 failure scenarios. This requires incorporating knowledge of multiple stakeholders to take into account the spatial context and complexity of interdependent infrastructure systems. It is more straightforward to manage consequences in Type-1 failure scenarios, because planning of limited system functions and recovery practices is already possible in fail-safe infrastructure development. For example, many infrastructure systems already have planned failure operations that limit system function to reduce damages, including drainage pump shutdown to avoid overheating and load shedding in power systems. Safe-to-fail development practices are more intricate, since managing Type-2 failure requires consideration of the social, economic, and environmental attributes in the affected region. Damages caused by Type-2 failures require multiple stakeholders including practitioners, local governments, communities, and engineers to understand consequences and to decide how interdependent systems should fail to strategically prepare for anticipated damages.

The “Room for the River” strategy used in the Netherlands is a good example of safe-to-fail infrastructure development practice that uses a combination of design, policy and stakeholder engagement (Zevenbergen et al., 2013). The city of Lent, where flooding has been a chronic problem and was becoming more intense, intentionally expanded flood-prone areas into nearby farmland, where the Dutch decision-makers chose to transform into vegetated flood buffer during heavy rainfall and recreational parks in dry days. When heavy precipitation occurs, high volume of water are diverted from the river to buffers and parks. While it compromises the economic and recreational values of park, it significantly reduces the overall human loss, and economic loss by catastrophic damages.

Indian Bend Wash, a greenbelt stretching 18 kilometers through Scottsdale, Arizona − one of the major cities in the Phoenix Metropolitan Area − is an example of safe-to-fail infrastructure by managing the consequences of heavy rainfall events. Instead of using a design standard of concrete channel suggested by the Army Crops, Scottsdale practitioners opted for a bioretention basin consisting of parks, golf courses, and other activities. The primary function of this vegetated retention area is to infiltrate runoff, attenuate flows, and reduce flooding. When a record storm (over-100-year frequency) hit the area in 2014, the Indian Bend Wash accommodated excessive runoff in the designated wash, reducing the intensity of flooding in nearby areas. When the rain stopped, the wash helped drain city streets and neighborhoods (The City of Scottsdale 2004). Indian Bend Wash exemplifies safe-to-fail because it serves the same primary function as conventional storm drainage systems, but was developed with involvement of local practitioners and citizens and further designed to control the consequences when the wash stops accommodating excessive runoffs by considering the infrastructural recovery capacity of nearby area from flooding. Thus, greater investment in safe-to-fail infrastructure is one way to advance current infrastructure development practices to manage the unpredictable weather events that climate change brings.

2.3. Safe-to-fail and the infrastructure trolley problem

The potential benefits of safe-to-fail development to adapt to unpredictable climate risks brings additional dilemmas to infrastructure development. The safe-to-fail approach urges stakeholders to make explicit decisions about failure consequences, meaning that decisions made today will have a direct connection to eventual undesirable futures. The addition of failure considerations in the development process further incorporates multiple stakeholders, their context specific needs, and assumptions about failure consequences. This complicates already difficult decision-making processes and crates dilemmas for infrastructure development. We refer one practical dilemma as an *infrastructure trolley problem*, i.e., prioritizing the consequences of infrastructure failures by choosing winners and losers. This also raises societal and ethical questions regarding whom and what should be prioritized to remain safe when infrastructure fail (Cutter, 2016).

A practical way to demonstrate this dilemma is by considering oversizing and stakeholder engagement activities of infrastructure development in cost-benefit analysis (CBA). CBA is a major decision support framework used by governments and institutions to organize and calculate social and economic costs and benefits, inherent trade-offs, and economic efficiency of a policy, program, or project (Kull, Mechler, & Hochrainer-Stigler, 2013). For infrastructure development, CBA provides a quantitative way to prioritize risk reduction and service provision activities based on comparing benefits of an actual or planned investment with direct and indirect costs due to Type-1 failures (Table 2.1). In comparison,

Table 2.2 shows additional cost categories that are difficult to calculate, rarely included in infrastructure development CBAs, and generally associated with Type-2 failures, including social costs and losses due to business disruption, and intangible costs. Fail-safe infrastructure development practices like oversizing are not amenable to CBAs that consider these costs presented in Table 2, because it is difficult to know how to set design thresholds for Type-2 failure consequences such as homelessness, loss of business revenue, interdependent service failures, loss of heritage, and psychological stress. In contrast, stakeholder engagement activities common in safe-to-fail development allow decision-makers to consult with a broader range of consequences, and may prioritize avoiding Type-2 social loss, business interruptions, and intangible costs before calculated Type-1 depending on their capacity to manage different failure types and associated costs.

Table 2.1. Cost categories resulted from Type-1 failure and considered in fail-safe infrastructure development by design standards (adapted from OECD 2015, 2016; IRDR 2017)

Cost category	Associated impacts
Direct tangible costs	Property losses (Residential and commercial) Infrastructure damage (transportation, bridges, sewage etc.) Agricultural loss Cost of emergency services and disaster assistance

Indirect costs	Increase in government debt Negative impacts on stock market prices Cost of reconstruction and recovery Cost of planning and implementation of risk prevention measures

Table 2.2. Additional cost categories resulted from Type-2 failure and considered in safe-to-fail infrastructure development by multi-stakeholder engagement (adapted from OECD 2015, 2016; IRDR 2017)

Cost category	Associated impacts
Direct social loss	Deaths Missing People affected (e.g., displaced, homeless, livelihood damaged)
Losses due to business interruption	Loss of revenue Increase in unemployment Losses due to the absence of public services (e.g., telecommunication, transportation, gas, water, electricity)
Intangible costs	Environmental losses Health impacts Cultural heritage losses Psychological stress

The strength of the safe-to-fail approach is that it encourages decision makers to assess the different types of costs in their decision context and recognize the acceptable costs based on their institutional capacity to manage infrastructure failure, protect vulnerable population and critical assets, identify affected regions, and recover from failure. The infrastructure trolley problem, based on utilitarian decision theory, suggests that the best decision is to prioritize the needs of many over the needs of few (Bennis, Medin, & Bartels, 2010). Fail-safe infrastructure development practices like oversizing have implicit bias in how the needs of the many are defined, as they are only possible when costs are amenable to calculation. Safe-to-fail offers a transformative utilitarian approach by considering a greater range of costs, but introduces the following dilemma: being explicit about institutional capacity and failure consequences (i.e., costs) is highly context dependent and limits the use of standard design protocols and precedent development practices. For example, choosing how to prioritize costs and how infrastructure manages Type-2 failures may introduce costs that we are not able to calculate, limiting the use of CBA for decision support. Safe-to-fail aims to addresses this dilemma by emphasizing stakeholder engagement to rank the relative importance and ramifications among different cost categories, and thus, the estimation of overall cost can be adjusted in order to focus on prioritizing between different types of cost and the trade-offs. Still, safe-to-fail cost prioritizations may be in conflict with standard practices for managing Type-1 failures indoctrinated in law, and untenable in the near-term. There is also no guarantee that this process will work (i.e., result in clear and actionable development plans), slowing the adaptation of existing systems to rapidly changing climate when simpler and standardized methods could speed up efforts. In addition, safe-to-fail requires more careful attention of decision-makers to embrace marginalized groups in the stakeholder engagement that tend to be more vulnerable to unpredictable risks to inform decisions of cost prioritization.

Room for the River offers a good example of how to overcome this dilemma. The Dutch decision-makers choose to divert the high volume of water from the river to a nearby vegetated area when heavy precipitation occurs in order to safely flood the high-risk areas. This decision compromises nearby vegetated areas during flooding and creates direct tangible costs and losses due to business interruption, but prioritizes reducing social loss, indirect costs, and intangible costs that might incur due to uncontrolled levee failure. Although the project took about 10 years to implement the new infrastructure development and risk management practices while consulting with local governments, practitioners, engineers, civic societies, and community members, the decisions have been well informed to affected regions and population and the project has been evaluated as a successful example of long-lasting sustainable infrastructure solution to chronic flooding problem.

2.4. Conclusion: towards safe-to-fail infrastructure development under non-stationary climate

Safe-to-fail infrastructure development supports climate change adaptation strategies that consider the uncertainties inherent in climate models and/or risk analysis. While climate prediction has improved substantially, there remains significant uncertainty in these projections due to interrelationships of systems, nonlinearities in biophysical processes, adoption of greenhouse gas emitting technologies, and the adoption or lack of greenhouse gas mitigation policy (Chester et al., 2014; Hulme, 2016). This reaffirms a need for a new infrastructure development paradigm that manages unforeseen risks by building adaptive capacity without compromising the urban systems upon failure. Traditionally, infrastructure are designed as fail-safe – they are designed against infrequent weather events and such that they cannot fail. Yet when failure occurs the consequences to human life, economic loss and other infrastructure are enormous. Risk-based fail-safe approaches are often contingent on statistical analysis of identified risk, thus, often do not account for the uncertainties associated with future climate change, making them inadequate for resilience. Safe-to-fail is valuable for a climate impacted future by introducing uncertain and unidentified future risks in infrastructure development.

Safe-to-fail development connects to the resilience of social, ecological, and technological systems, as infrastructure will influence future social, environmental, and economic costs incurred by climate change. Cities build infrastructure to adapt to climate change, but basing development decisions on climate models (both stationary and non-stationary) and risk analyses may not serve resilience by resulting in fail-safe systems that are robust to Type-1 failures. Safe-to-fail encapsulates these practical engineering methods and expands upon them with a multidisciplinary perspective that considers failure consequences and Type-2 failures. Safe-to-fail development requires consideration of infrastructure's biophysical capacity (e.g., safety thresholds) and social capacities to respond to risks such as institutional capacity, spatial variability, social vulnerability, and serviceability.

Green infrastructure is often conflated with safe-to-fail, but they are different. Green infrastructure is a valuable practice enhancing natural processes while delivering environmental, social, and economic benefits of infrastructure. However, green infrastructure designed without consideration of Type-2 failures are fail-safe. A common example is small-scale rain gardens that experience ponding leading to nearby flooding, possible health impacts and ecosystem disruptions. Green infrastructure systems designed with Type-2 failures in mind, like bioretention basins in the Room for the River project and the Indian Bend Wash, are safe-to-fail. These two examples further provide evidence for how to prioritize decisions with broad stakeholder engagement as a means to achieve safe-to-fail development.

Still, safe-to-fail development is challenging because the risks and performance of long-lasting infrastructure are often difficult to predict, and approaches to achieve “safe-failure” may inhibit the use of practical engineering methods. Particularly for hard infrastructure, it is challenging to make alterations to adapt to changing stresses post-construction and development decisions on un-calculable costs. Safe-to-fail infrastructure development requires a broader scope of knowledge and decision support than fail-safe, and extra steps in the development process to consider context specific information including geography, existing infrastructure services, social vulnerability, different types of failure cost, and institutional adaptation capacities among others. One approach to achieve safe-to-fail is to use multi-stakeholder engagement to help decision-makers to determine the acceptable level of "failure" and its cost. Thus, the functions of safe-to-fail infrastructure may vary in different cities and regions depending on what assets and values are prioritized for protection and what their capacities are for undertaking different types of failure costs. Ideally, for every city, a safe-to-fail infrastructure system can be developed by deciding whom or what should remain safe during failed infrastructure states, with consequential trade-offs between different assets, values, locations and people.

CHAPTER 3

INFRASTRUCTURE VULNERABILITY ASSESSMENT FOR URBAN FLOODING IN PHOENIX

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3.1. Introduction: Urban growth and infrastructure risk to climate change

According to the Intergovernmental Panel on Climate Change (IPCC) many of the global risks of climate change will be concentrated in urban areas (IPCC, 2014). As U.S. cities continue to grow by altering landscapes, increasing impervious areas, and building more civil infrastructures, roadways in particular are becoming increasingly vulnerable to urban flooding (Meyer, Brinckerhoff, Rowan, Snow, & Choate, 2013; Aromar Revi et al., 2014). Several climate studies predict that the U.S. Southwest - spanning Arizona, New Mexico, Utah, Nevada, and California - will be hotter and drier in the twenty-first century (e.g., Seager et al., 2007), and that precipitation will occur in more intense bursts (Hunt & Watkiss, 2011).

The vast majority of urban growth in the U.S. is asphalt and concrete based “gray infrastructure”, such as roads, buildings, and parking lots (D. G. Brown et al., 2014; Wilbanks & Fernandez, 2014). This type of urban expansion leads to an increase of impervious surfaces and consequently a larger amount of surface generated runoff. Stormwater drainage systems, including sewers, detention basins, and infiltration trenches, are used to remove runoff by controlling its flow rate and velocity. When drainage structures exceed their capacity, water may accumulate on roadways, leading to potential damages to properties (e.g., houses, cars and commercial activities) and other infrastructures, and cause service disruptions to communities and businesses (S. E. Chang, 2016). Roadways and stormwater drainage systems are often closely related and interdependent in urban areas particularly when at risk of flooding. In response, many cities use storm drainage systems at large scales to manage surface water effectively. However, the unpredictability of future weather risks suggests that even redundant and oversized infrastructure may be vulnerable to future extreme rainfall that can far exceed existing design criteria (Willems, Arnbjerg-Nielsen, Olsson, & Nguyen, 2012).

When local drainage structures exceed their capacity to accommodate surface runoff generated by rainfall in the system, water accumulates on roadways and cause localized flooding. As cities are becoming more structured and urbanized – with more impermeable surfaces – their adaptive capacity to increasing surface runoff during heavy precipitation is becoming limited and, thus, they are more vulnerable to extreme flooding (Garfin, Jardine, Merideth, Black, & LeRoy, 2013). Furthermore, a number of climate studies predict that the U.S. will experience more frequent and intense precipitation (i.e. the heaviest 1% of annual precipitation) in the future. This trend is expected to happen even in the regions where the future climate is projected to be hotter and drier than the current (Melillo, Jerry M., Terese (T.C.) Richmond, and Gary W. Yohe, 2014) such as the U.S. Southwest including Arizona, and thus external shocks (i.e. flooding) will greatly impact infrastructure systems in populated urban area (Garfin et al., 2013).

To manage non-stationary flooding risks due to increased and unpredictable future precipitation, there have been efforts to (i) quantify changes in future extreme precipitation (Dominguez, Rivera, Lettenmaier, & Castro, 2012; Garfin et al., 2013; Hawkins et al., 2015; Piras, Mascaro, Deidda, & Vivoni, 2016), (ii) estimate the risk of urban flooding (Ashley, Balmforth, Saul, & Blanskby, 2005; Wilbanks & Fernandez, 2014), (iii) assess the impact of climate change and flooding on urban infrastructures (H. Chang, Lafrenz, Jung, & Figliozzi, 2011; Kirshen, Ruth, & Anderson, 2008; Meyer et al., 2013; Sayers, Galloway, & Hall, 2012; Schmitt, Thomas, & Ettrich, 2004; Semadeni-Davies, Hernebring, Svensson, & Gustafsson, 2008; Suarez, Anderson, Mahal, & Lakshmanan, 2005; Willems et al., 2012), (iv) suggest adaptation strategies for urban areas (Arnbjerg-Nielsen & Fleischer, 2009; Fratini, Geldof, Kluck, & Mikkelsen, 2012; Keath & Brown, 2009; Liao, 2012; Salinas Rodriguez et al., 2014; R. L. Wilby & Keenan, 2012), and (v) improve infrastructure design (CIRIA, 2014; Liu, Chen, & Peng, 2014). Even though climate models could be useful tools to account for non-stationary conditions by assessing the impact of future precipitation events on infrastructure performance, their direct use is still challenged by the coarse spatial (25 - 100 km) and temporal (24-hr) resolutions, which are not commensurate for hydrological analysis in small watersheds (Piras et al., 2016; Willems et al., 2012). Downscaling techniques at the regional scale have been developed to improve climate model resolution (Skamarock et al., 2012; R. L. Wilby & Dawson, 2013) and adopted in impact studies (Piras et al., 2016). Still, these estimates of future changes in precipitation extremes are still highly uncertain and provide limited support to future infrastructure design (Hunt & Watkiss, 2011). Furthermore, there is also the issue of cascading uncertainties introduced with each model, from emissions scenarios to the hydrological models used to determine impacts (Robert L. Wilby & Dessai, 2010). Novel approaches are needed for infrastructure planning and design that incorporate the uncertainty of climate model predictions and difficulty in predicting the frequency and intensity of future weather extremes.

In this chapter, we assess the vulnerability of infrastructure caused by the failure of interdependent system and demonstrate how infrastructure service will be disrupted by the impact of extreme precipitation. To assess this, we use the case of storm drainage system that are interconnected with major roadways in Phoenix, Arizona.

3.1.1. Background information of case study area: Phoenix, Arizona

Phoenix is the sixth most populated city in the U.S. with 1.6 million people (U.S. Census Bureau, 2016) and is located in the valley of Arizona's Sonoran Desert with arid or semi-arid climate in Southwest U.S. (Garfin et al., 2013) (Figure 3.1). The city experienced rapid population growth during the latter half of the twentieth century and rapid urbanization came along with it. While this growth bolstered economic and regional development, it may have important future social and environmental implications. This rapid growth of the region is predicted to continue for decades as Phoenix is projected to have 2.3 million residents by 2050 (Maricopa Association of Governments, 2016). The growing population and commercial and industrial activities may expose more people to future extreme flooding. While the city engineers had developed large and robust roads to withstand severe rainfall (Roberge, 2002), extreme weather events are still putting the infrastructure and economy of Phoenix at risks. Since the majority of residents and tourists in Phoenix area use cars as their primary transportation method, road infrastructure flooding is a serious future threat to the region’s economy. The climate in Arizona is characterized by dry and warm conditions for most of the year with extreme variability in both temperature and precipitation due to its arid and semi-arid climate, where evaporation far exceeds precipitation (Chuang et al., 2015; Sheppard, Comrie, Packin, Angersbach, & Hughes, 2002). Precipitation in Arizona is highly variable both in space and time as a result of (i) a marked seasonality with a wetter summer season dominated by the North American monsoon (Adams & Comrie, 1997) and a drier winter season, (ii) high inter-annual variability, and (iii) a strong orographic control (Mascaro, 2017). A number of climate projections indicate that, in Southwest U.S., the occurrence of extreme daily precipitation events during the winter season is expected to be more pronounced in the upcoming decades despite decreases in yearly total precipitation, causing potential changes in flood frequency (Garfin et al., 2013).

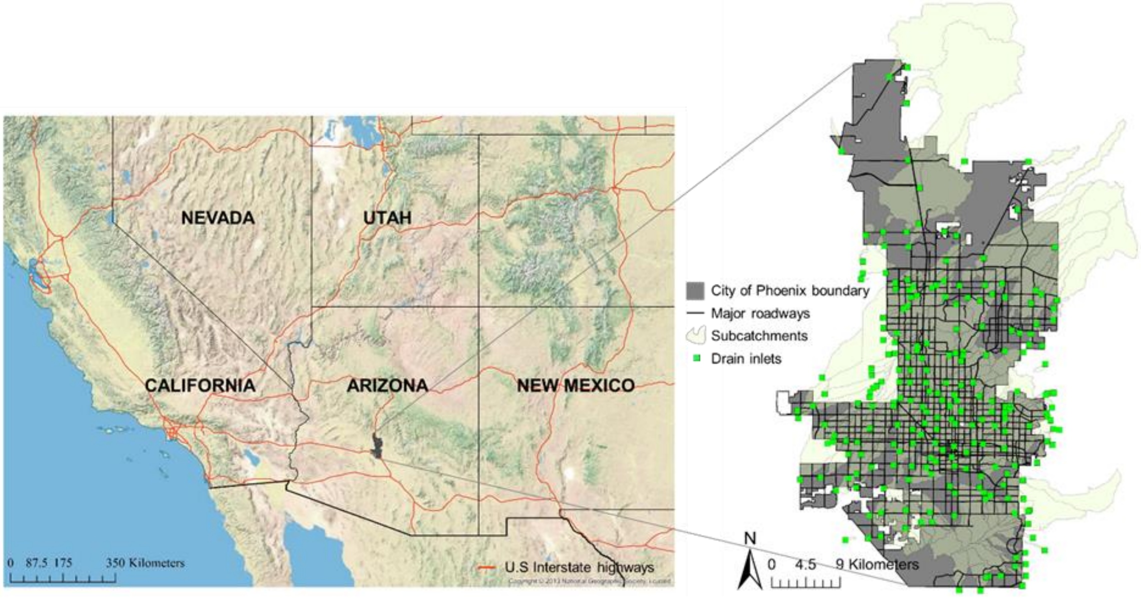

Figure 3.1. Map of the Southwest U.S. (left) and city of Phoenix, Arizona (Right). The Southwest U.S. spans multiple states, including: Arizona, New Mexico, Utah, Nevada, and California. City of Phoenix is located at the intersection of major U.S. freeways, where this map shows the city boundary, major roadways (i.e. interstate highway, AZ state route, U.S. highways, principal and minor arterials, and major collectors), subcatchments, and the 230 modeled stormwater drain inlet nodes at roadway intersections.

3.2. Methods

We performed a flood estimation analysis using the Environmental Protection Agency (EPA) Storm Water Management Model (SWMM) to determine which road types are susceptible to flooding in Phoenix in current and future climate (blue box in Fig. 1). The 2014 storm event – which registered intensities associated with up to a 984 year return period (~ 0.001 of annual exceedance probability) – but when averaged over the city of Phoenix resulted in a 116 year return period (~ 0.009 of annual exceedance probability) for 24-hr storm events, was used as a test case (FCDMC, 2014). We collected hourly rainfall observations over 24-hr storm events from 41 gages of the Flood Control District of Maricopa County (FCDMC). The EPA SWMM Climate Adjustment Tool (SWMM-CAT) was then utilized to estimate the rainfall values in future climate conditions for the same event, assuming a return period of 100 years.

The SWMM model was then used to simulate the response of the Phoenix stormwater drainage system in current and future climate scenarios. Geospatial datasets of terrain, impervious areas and maps of the City of Phoenix were utilized to configure the model. We modeled the main pipes of the drainage system, identifying a total of 230 inlets located at freeway, arterial, and collector intersections. These inlets also represented the drainage outlets of urban subcatchments modeled in SWMM. The rainfall-runoff simulations produced volume, peak flow rate and duration of the flood hydrographs at each inlet for 24-hr storm events. The simulations were repeated with seven different precipitation inputs (i.e., the observed event and the three future scenarios in the near and far future term) to compare flooding results for the historical and future conditions.

3.2.1. Future precipitation projections: Storm Water Management Model Climate Adjustment Tool (SWMM-CAT)

In this study, we focus on a storm event that occurred in Phoenix on September 8, 2014. We acquire hourly rainfall data from 41 rain gages located in Phoenix managed by the Flood Control District of the Maricopa County (FCDMC). These data are aggregated at daily scale to compute the adjustment factors with SWMM-CAT. For the 24-hr rainfall accumulations, the FCDMC reported a mean return period across the 41 stations of 116 years (FCDMC, 2014). Since SWMM-CAT provides adjustment factors for a maximum return period of 100 years, we use the factors associated with 100-year return period for all gages.

SWMM-CAT is an add-in tool to the EPA Storm Water Management Model (SWMM) that allows estimating monthly temperature, evaporation and precipitation, as well as the 24-hour rainfall amounts for different return periods in future climate based on historical values (L. Rossman, 2014). These estimates are provided through location-specific adjustment factors, which are multiplicative for precipitation and additive for temperature and evaporation. The calculation of these factors is based on statistically-downscaled climate simulations of nine global circulation models (GCMs) from the World Climate Research Programme (WCRP) CMIP3 archive. Within SWMM-CAT, simulations are calculated for the A1B “middle of the road” greenhouse gas emission scenario, which is characterized by rapid economic growth, peak global population in mid-century, the quick spread of new and efficient technologies, the global convergence of income and ways of life, and a balance of both fossil fuel and non-fossil energy sources (IPCC, 2007). This scenario is from the older generation of emissions pathways, SRES – Special Report on Emissions Scenarios (SRES). The SRES A1B scenario is similar to the newer RCP – Representative Concentration Pathway scenario 6.0 (Melillo, Jerry M., Terese (T.C.) Richmond, and Gary W. Yohe, 2014). SWMM-CAT provides the adjustment factors in a grid of 0.5 degrees in latitude and longitude (~50 km) for two different future time periods, including 2020 - 2049 (‘near future’) and 2045 - 2074 (‘far future’). To account for the climate model uncertainty, an ensemble-based approach is used to define three climate scenarios, labeled as ‘Hot and dry’, ‘Median change’, and

‘Warm and wet’. Starting from the ensemble distribution of annual projected changes of precipitation and temperature simulated by the nine GCMs at each downscaled grid cell, the ‘Hot and dry’ (‘Warm and wet’; ‘Median change’) scenario uses the adjustment factors from the model that is closest to 95th (5th; 50th) percentile temperature change and 5th (95th; 50th) percentile rainfall change (L. Rossman, 2014).

3.2.2. Drainage network model in SWMM

The SWMM model is used to simulate the rainfall-runoff transformation and runoff routing processes in the main pipes of the drainage network in the Phoenix urban area for the storm event of September 8, 2014. For this aim, SWMM requires the delineation of subcatchments draining into the inlet locations of the stormwater drainage system. The Street Transportation Department of City of Phoenix (City of Phoenix, 2013) provides maps of the main pipes, which indicates that the drain inlets are primarily located at roadway intersections. As a result, we identify a total of 230 inlet locations at the intersections of the major roadways, as shown in Figure 3.1. We use the digital elevation model (DEM) at 1/3 arc second (~10 m) resolution obtained from the U.S. Geological Survey (USGS) to identify the subcatchment area, slope, and width using the libraries available in ArcGIS. In addition, we utilize the map of percent impervious area from USGS to derive the mean percent value in each subcatchment. We input these parameters in the rainfall-runoff simulation in SWMM. We choose the modified Horton scheme to simulate the infiltration process using the default parameters in SWMM. Given that the model is applied during a single storm event, the evapotranspiration process is not simulated. The map of the drainage system of the City of Phoenix also provides the diameter of the major conduits (1.28 - 10.06 m) and indicates that their material is reinforced concrete. Based on this information, we adopt a Manning roughness coefficient of 0.013 for our simulations. Each of 230 subcatchments draining to the corresponding inlet is associated with the nearest rain gage of the FCDMC network. The SWMM model is then applied to simulate the response of the Phoenix stormwater drainage network using the rainfall observations at hourly resolution and the adjusted values in future scenarios.

3.2.3. Roadway flooding vulnerability evaluation

To strategically prioritize infrastructure solutions for Phoenix, we determined the type and location of the most vulnerable roads to urban flooding from the SWMM simulation results during September 8, 2014 storm event. Urban drainage systems are designed to reduce flood damage by carrying stormwater safely away from properties and streets. When overflow at drain points are not contained within the drainage network, it results in roadway flooding. Drainage pipelines are often planned with the city's road development under or alongside roadways (Schmitt et al., 2004). We confirmed from the city's drainage and roadway GIS maps that Phoenix drainage systems were mostly designed to interrelate with roadway networks (Y. Kim et al., 2017b).

The rainfall-runoff simulation results returned the total flood volume over the event duration at the nodes, which are associated with roadway intersections. Specifically, in this model, flooding refers to all water that overflows a node, whether it ponds or not (L. A. Rossman, 2015). From this information, we identified roadway segments that were connected within one kilometer distance to the intersections reporting flooding conditions, their functional classification, and Annual Average Daily Traffic (AADT). We identified four different functional roadways (i.e. interstate highway; U.S.

highway and Arizona state route; local principal and minor arterials; and major collector) and, using this information, we calculated an index to obtain a first-level quantification of vulnerability to flooding for each road segment by multiplying the estimated flood volume (liter/day) with AADT (cars/day) representing the sensitivity to flooding threat and flooding consequences (i.e. level of service), respectively.

3.3. Results

3.3.1. Future precipitation projection

We find very similar values across the entire Phoenix area, with a mean increase of the 24-hr rainfall depth years of 9.7 %, 9.4 %, and 8.7 % (17.7 %, 17.2 %, and 16.0 %) for the ‘near future’ (‘far future’) scenario (Figure 3.2). As an example, the FCDMC rain gage with ID 4510 recorded 8.99 cm rainfall in 24 hours; this value is scaled to 9.86, 9.83, and 9.77 cm (10.60, 10.53, and 10.43 cm) for the ‘Hot and dry’, ‘Median change’, and ‘Warm and wet’ scenarios in the near future (far future), respectively by climate adjustment factors. Among the three different climate change scenarios, the ‘Hot and dry’ scenario leads to the most intense precipitation in both projected future periods. These results are in line with climate change studies of the U.S. Southwest which predict that Phoenix will likely be hotter and drier while experiencing more extreme rainfall in the winter season in the coming decades (Dominguez et al., 2012; Garfin et al., 2013).

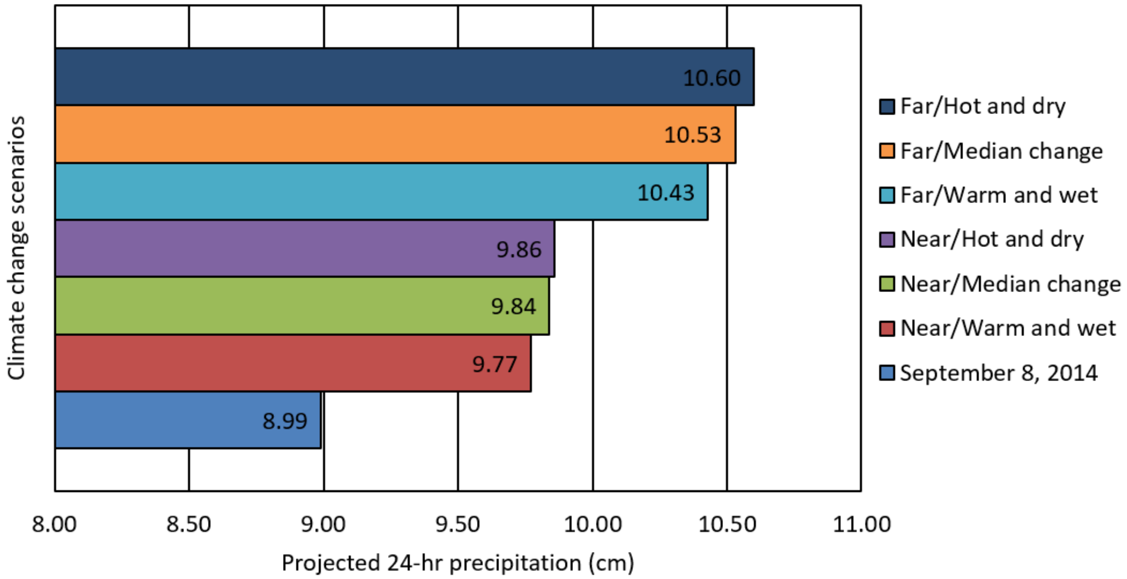

Figure 3.2. Comparison of projected precipitation for 24-hr at the rain gage #4510 for the historical maximum precipitation (September 8, 2014), and two future terms (2020 - 2049 and 2045 - 2074) in the Warm and wet, Median change, and Hot and dry climate change scenarios.

3.3.2. Flooding intensity and impacts on road infrastructures

The SWMM model simulates the flooded volume at each inlet, representing the water volume that overflows a node whether it ponds or not (L. A. Rossman, 2015). Due to the lack of available observational data, the model performances with observed precipitation forcing are qualitatively tested by comparing the location of flooded nodes with that of flooded roadways reported by news, social media (i.e. searched with a hashtag #Phxtraffic on Twitter page of ADOT) and agency reports (Fritz, 2014; Hendley, 2014; The Republic, 2014). Results of this comparison are reported in Figure 3.3, which shows that flooded roadways are mostly located in proximity or downstream of the inlet nodes whose drainage subcatchments are characterized by positive overflow volume. Once tested, we also simulate the flooded nodes in future climate scenarios.

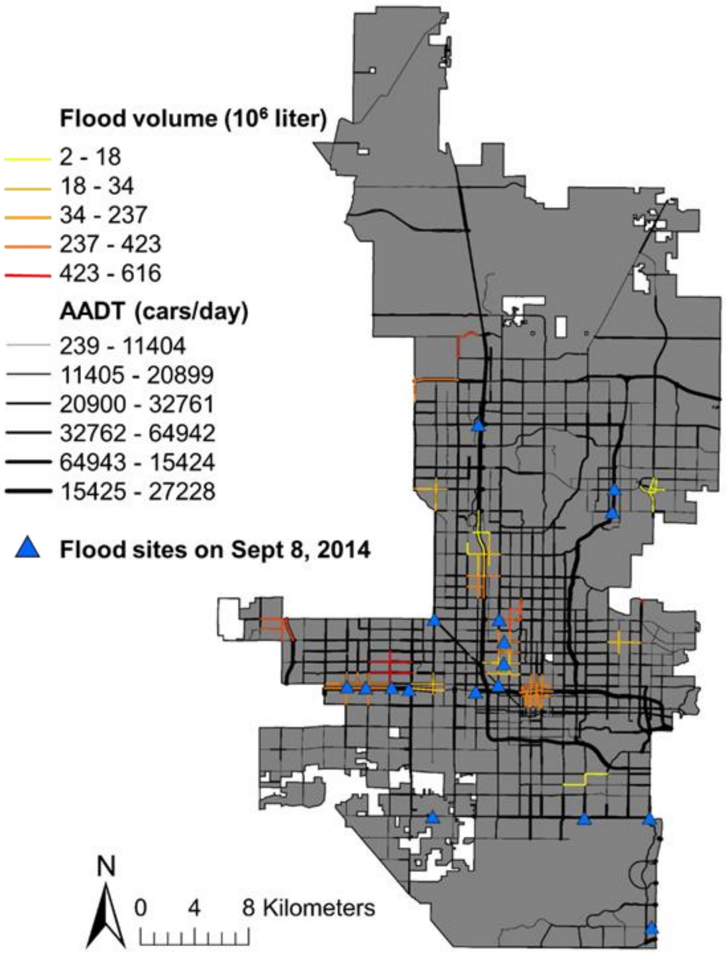

Figure 3.3. The flood map of Phoenix based on simulated 230 storm drain inlets to the drainage system for September 8, 2014 24-hr storm event. Actual flood sites reported on September 8th 2014 are presented as blue triangles for comparison. Flooding intensity is presented in liters. Annual Average Daily Traffic (AADT) of major roadways is presented in cars per day including interstate highway, AZ state route, U.S. highway, principal and minor arterials, and major collectors.

Figure 3.4 shows the number of flooded nodes for the historical and the two future periods for different classes of total runoff volumes, which are computed based on the Jenks natural breaks classification method (Jenks, 1967). While the total number of flooded nodes does not significantly increase (22 in 2014, 25 in the ‘near future’ and 28 in the ‘far future’), the model predicts that total flood volume for a 24-hr period will be likely increased at these locations into the future. In the ‘near future’, total intersection flooding volume is projected to increase by 21.9, 21.4 and 20.0 % for ‘Hot and dry’, ‘Median change’, and ‘Warm and wet’ climate scenarios compared to 2014, respectively. The ‘far future’ will experience even greater increases in flooding volume, i.e., 35.2, 34.6, and 32.6 %, respectively.

The rainfall-runoff simulation identifies flood conditions in 22 out of 230 nodes. A city-wide flood index map based on these 22 flood nodes from our simulation results matches fairly well with the flooded sites that were reported from various media sources in 2014. The SWMM simulations with future precipitation show that while the number of flood-affected locations will not change significantly from 2014, these locations will experience increased flooding volume by 20.0 - 35.2 % in the future. The results corroborate a number of climate change studies discussing increasing future risk of heavy precipitation (e.g., Hunt and Watkiss 2011; Meyer et al. 2013; IPCC 2014), and further that vulnerable infrastructures today are predicted to be exposed to more intense flooding. As such, considerations for “safe-to-fail” strategies are critical in increasing the options available to cities to protect against flooding events.

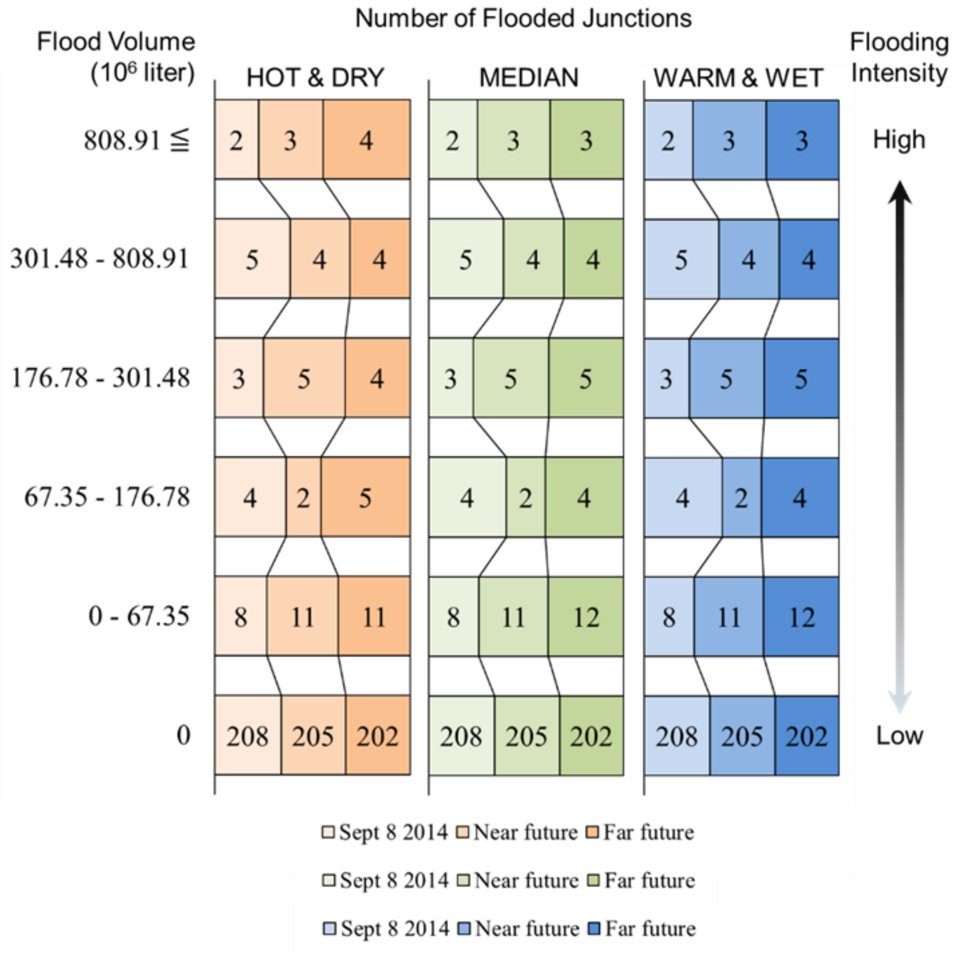

Figure 3.4. Comparison of simulated total flood volume for 24-hr at each node for the historical maximum precipitation (September 8, 2014), and two future terms (2020 - 2049 and 2045 - 2074) in the 'Hot and dry', 'Median change', and 'Warm and wet' climate change scenarios. More nodes are experiencing higher flooding volumes with the 100-year storm event into the future

3.3.3. Roadway flooding vulnerability

The roadway segment-specific vulnerabilities for the event of September 8, 2014 are mapped for the city of Phoenix in Figure 3.5. The vulnerability results indicate several infrastructure design and management considerations. The most vulnerable road types are local arterials followed by interstate highways and local major collectors. While major collectors are more likely affected by flooding, they facilitate about 13 times less traffic than interstate highways, resulting in a similar vulnerability. Furthermore, even though interstate highways and major collectors show similar vulnerability to flooding, we expect that the consequences of flooding on these roads are dissimilar. When higher classification roads like interstate highways are unavailable for service, it is more difficult to provide alternatives or detour routes while achieving the same level of service. Also, when high capacity components of infrastructure fail, it is likely that a cascading failure occurs impacting other areas of the system.

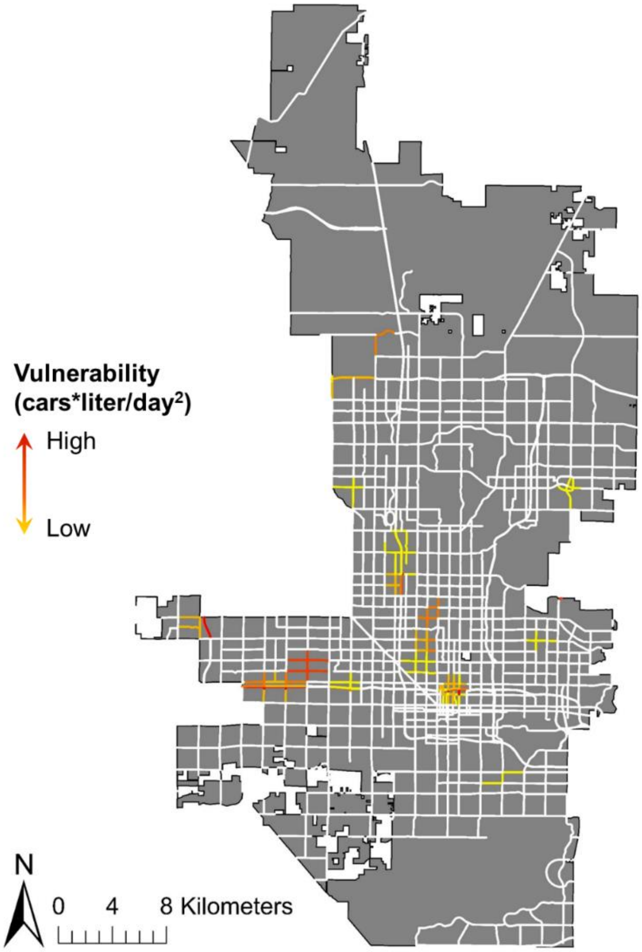

Figure 3.5. Map of Phoenix roadways vulnerability to flooding for the event of September 8, 2014. Red networks are the most vulnerable roads in terms of daily traffic loads and flooding volume. White coded roads are identified as being unlikely affected by drainage flooding.

3.4. Conclusion

In this study, we suggest to assess the risk coming from extreme weather events by infrastructure vulnerability assessment based on the serviceability of infrastructure and the intensity of extreme weather event. Although the common approach of risk analysis by risk triplets: threat x threat probability x consequences attempts to include the impact of threat by including the consequences in the risk calculation, this consequence is often limitedly considered for the hindered infrastructure system performance. What is missing in current risk analysis is the extent of consequences from infrastructure failure that are experienced by population that the infrastructure serve, surrounding environment, and the interdependent system to them. Through our Phoenix roadway flooding vulnerability study, we demonstrate one approach to examine the extended consequences of infrastructure failure by evaluating the impact of storm drainage failure tolerated by the interdependent roadway system, thus the service interruption that are experienced by the local traffic.

The roadway flooding vulnerability result implies several considerations for Phoenix infrastructure design and management. While major collectors experience the higher peak flow rates during flood events, they facilitate 13 times less traffic than interstate highways, resulting in a low vulnerability score. Principal arterials are the most vulnerable to urban flooding and interstate highway and minor arterials follow. Even though interstate highway and minor arterial show similar vulnerability to flooding, we expect the consequences of flooding impact on these roads are dissimilar. When larger roads like interstate highway are unavailable for service or damaged from flooding, it is more difficult to provide alternative or detour routes without affecting the original level of service for the detour link. Moreover, since it is also a busier road type than minor arterial, it will affect more people’s mobility by its service deterioration. Also, when the large robust infrastructure that is designed unlikely to fail fails, it is likely to be a cascading failure that impacts the entire system than being resilient to failures within the system. The next chapter shows how these issues are captured in the MCDA to support the decision making process considering different characteristics and functions of infrastructure.

CHAPTER 4

DECISION-MAKING WITH RESILIENCE STRATEGIES FOR SAFE-TO-FAIL INFRASTRUCTURE

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4.1. Introduction: “Safe-to-fail” and “fail-safe” infrastructures

Focusing explicitly on risk-based approaches to infrastructure design is insufficient for managing future extreme flooding events. Currently, the primary way to assess potential flood damages due to extreme weather is risk analysis. This approach is based on the risk triplet – threats × threat probability × consequences (Kaplan & Garrick, 1981) – where the estimation of threats, threat probabilities, and consequences is often based on historical data. Flood risk management uses the same fundamental approach via calculating risks with historical data and developing flood management and infrastructure solutions across the largest breadth of identified threats. Thus, proposed solutions are often large, gray infrastructures with low probability of failure, instantiated for decades, and oversized to handle unforeseen threats. Common examples of these types of infrastructures include concrete levees, dams, retention basins, culverts, and canals.

Despite the anticipated use of risk management for infrastructure adaptation to climate change (National Research Council (U.S.) Committee on Climate Change and

U.S. Transportation, 2008; Transportation Research Board, 2011), the risk management approach is incomplete in an uncertain future climate scenario. Risk-based approaches do not incorporate an understanding of what may happen when risk mitigation solutions themselves fail (e.g., failure to hold rainfall runoff within the drainage structure). Failure in this sense is the catastrophic response when flooding solutions break down and cannot serve their intended purpose. Frequently, the larger and more permanent an infrastructure is, the greater the damages caused by its failure (Jeryang Park et al., 2011). The damages experienced in the wake of Hurricane Katrina emphasize this fact, as a false sense of security provided by large levees amplified overall damages to the city (Jeryang Park et al., 2011). While incorporating these consequences in risk analysis may seem feasible, as discussed above, even the best models lack the precision to fully estimate future extreme weather, population growth, social demographics, urban form, and policies (Christensen et al., 2007; Shortridge et al., 2017). Instead, climate change adaptation requires a new approach to infrastructure design that, while recognizing and managing risk, focuses on adaptive solutions that, in the event of failure, do not compromise the entire urban system, i.e., “safe-to-fail”.

Safe-to-fail” is largely discussed within the climate adaptation community and we suggest that the framework be adopted specifically within resilience-based infrastructure design. While “safe-to-fail” should be more critically examined as a resilience strategy, herein we do not propose a new definition of “safe-to-fail”. Instead, the purpose of this work is to provide guidance for how to apply “safe-to-fail” for infrastructure resilience by combining climate models, infrastructure engineering methods, and decision analysis. Our “safe-to-fail” design support framework considers different characteristics and failure modes of the infrastructures studied and demonstrates its feasibility by applying it to a case study of urban flooding. To manage future floods, several authors promote using fewer "fail-safe" and more "safe-to-fail" flooding solutions (Ahern, 2011) by transitioning from risk-based to resilience-based infrastructure design paradigms (Eisenberg et al., 2014; Linkov et al., 2014; J. Park et al., 2013). A work by Ahern (2011) argues that previous notions of urban sustainability emphasized durable and stable urban form that could persist for generations. In contrast, a focus on non-equilibrium conditions like those projected with climate change models emphasizes a "safe-to-fail" perspective to anticipate, contain, and minimize unprecedented and unexpected events (Ahern, 2011).

A "safe-to-fail" design strategy embraces the inevitability of unforeseen extreme weather by centering design decisions on urban resilience characteristics – the adaptive capacity of the urban system (Meerow, Newell, & Stults, 2016). Adaptive capacity refers to the ability to respond to inevitable and unexpected threats by facilitating desired infrastructure services. This definition of resilience corresponds with the desired characteristics of "safe-to-fail" infrastructure, as a transition from a "fail-safe" to "safe-to-fail" design requires a corresponding perspective, including:

- Focusing on maintaining system-wide critical services instead of preventing component failure (Möller & Hansson, 2008).
- Minimizing the consequences of the extreme event rather than minimizing the probability of damages (J. Park et al., 2013).
- Privileging the use of solutions that maintain and enhance social and ecosystem services (Ahern, 2011).

- Designing decentralized, autonomous infrastructure systems instead of centralized, hierarchical systems (J. Park et al., 2013).
- Encouraging communication and collaboration that transcend disciplinary barriers rather than involving multiple, but distinct disciplinary perspectives (Ahern, 2011; Tye et al., 2015).

Moreover, embracing this perspective requires a broader range of decision-making criteria that influence recoverability and adaptive capacity of systems than risk-based approaches, including: preserving ecosystem services, providing social equity, enabling innovation, and improving catastrophe response processes.

The majority of the discussion focuses on “fail-safe” design strategies, i.e., strategies that strengthen infrastructure against more intense environmental conditions. A key hypothesis adopted to develop “fail-safe” strategies is climate stationarity, yet climate change studies indicate the potential need to reconsider this assumption (Milly et al., 2008; Solecki & Rosenzweig, 2014). A few studies have examined the necessity of infrastructure planning and design for climate change adaptation, yet none has fully explored “safe-to-fail” strategies for fostering climate change adaptation and resilience in urban areas, i.e., strategies that allow infrastructure to fail in its ability to carry out its primary function but control the consequences of that failure.

As “safe-to-fail” infrastructure design is a relatively new concept, little information exists as to how to apply the concept broadly to infrastructure, or specifically in the context of stormwater. Moreover, we argue that existing literature does not clarify “fail-safe” and “safe-to-fail” concepts in a manner useful for deciding between similar roadway flooding solutions. As such, we focus on the conceptual and qualitative differences between systems employing one design concept over the other, such as “fail-safe” systems that are prone to rare catastrophic failures where “safe-to-fail” systems are adaptive to manage catastrophe yet suffer failures more often (Ahern, 2011). Different authors provide conflicting perspectives characterizing the same design strategies (e.g., build redundancy) as “fail-safe” (J. Park et al., 2013; T. P. Seager, 2008) and “safe-to-fail” (Ahern, 2011). To overcome these issues, we developed our own framework that identifies the “fail-safe” and “safe-to-fail” characteristics of flooding solutions already in use to adapt roadways to climate change by reviewing existing literature. To generate the decision criteria for stormwater infrastructure, we first developed a rainfall-runoff simulation of roadway vulnerability to flooding in Phoenix, Arizona, and created a catalogue of adaptation strategies including their characteristics. We then developed a multi-criteria decision analysis (MCDA) framework for prioritizing adaptation strategies depending on stakeholder preferences for particular characteristics.

4.2. Methods

We use the city of Phoenix and its roadways as our case study location. We develop an integrated infrastructure adaptation framework consisting of a quantitative roadway flooding-vulnerability estimation and a qualitative flooding solution evaluation. The combined technical and qualitative analyses answer the following research questions: (1) How might extreme rainfall due to climate change induce flooding of Phoenix roadways?; (2) What “safe-to-fail” adaptation strategies exist and what roadway infrastructure solutions feature them?; (3) What are prioritized solutions for Phoenix considering various resilience-based design perspectives?

4.2.1. Integrated “safe-to-fail” infrastructure adaptation framework and Phoenix case study

An integrated assessment method for infrastructure development in response to climate change is essential for decision-making. The integrated assessment method facilitates the decision-making process for infrastructure designers and planners by elucidating the overlooked interdependent nature of urban infrastructure systems (e.g., drainage – roadway systems) and considering resilience-based infrastructure design strategies to complement the traditional static analysis of risk-based design (Figure 4.1). In order to develop a “safe-to-fail” infrastructure design strategy and decision support tool for urban areas, we focused our attention on a single case study in the City of Phoenix, Arizona. On September 8, 2014, the Phoenix area experienced a series of intense thunderstorms and the largest rainfall on record in 115 years, with a depth that reached 8.38 cm over 24 hours (National Weather Service Forecast Office, 2014). During this event the area experienced rainfall with return periods up to 984 years (FCDMC, 2014). The resulting runoff flooded 200 houses and 30 roads. Vehicles on interstate highway 10 were submerged because one of the pumping stations experienced unexpected failure. This example demonstrates the “fail-safe” nature of highway infrastructure and that decisions made on historical risk analysis data can result in cascading system failure when an unexpected component failure occurs.

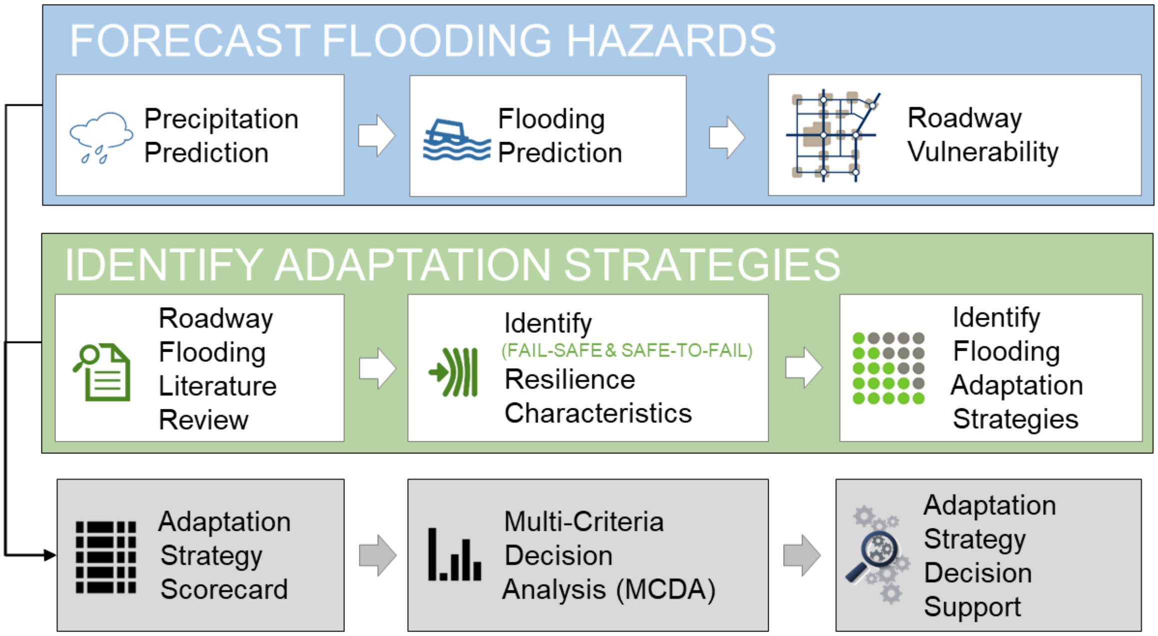


Figure 4.1. A schematic diagram of the integrated "safe-to-fail" infrastructure adaptation framework, the framework combines multiple assessments, including flooding projection, infrastructure vulnerability assessment, and multi-criteria decision analysis (MCDA) supporting adaptation strategy decision making.

4.2.2. Flooding solution database

We assess 26 climate change adaptation case studies and produce a list of 31 distinct roadway flooding solutions, i.e., processes, infrastructures, and system design considerations (Table 4.1). We use Google Scholar search engine ("Google Scholar," 2016) and Web of Science database ("Web of Science," 2016) to identify academic literature that discuss "fail-safe" versus "safe-to-fail" and risk versus resilience-based design strategies. We review these articles to collect a list of "fail-safe" and "safe-to-fail" characteristics that support climate change adaptation. Then, we use Environment Complete ("Environment Complete," 2016), GeoRef ("GeoRef," 2016), Web of Science

(“Web of Science,” 2016), Ecological Society of America Publications (“Ecological Society of America Publications,” 2016), EDP Sciences (“EDP Sciences,” 2016), and GreenFILE (“GreenFILE,” 2016) to identify climate change adaption case studies for roadway flooding. In addition to scholarly and peer-reviewed publications, we explore municipal websites for US-based transportation and roadway infrastructure case studies, including cities near Phoenix within Maricopa County, Los Angeles, New York City and Chicago among others. We review these articles to develop a database of infrastructure roadway flooding solutions for Phoenix. Table S1 lists a database of 31 potential roadway flooding solutions (i.e., processes, infrastructures, and system design considerations) for Phoenix, derived from the academic literature, design guidance, and municipal case studies.

Table 4.1. Roadway solutions identified from climate change adaptation case studies

Roadway Flooding Solution	Source
Standard Curb Cut	(Chau, 2009; City of Glendale, 2015; City of Los Angeles, 2009; MacAdam, 2012)
Grated Curb Cut	(City of Glendale, 2015)
Curb Cut Sediment Capture	(Chau, 2009)
Meandering or Linear Swale	(CDOT, 2010; Chau, 2009; City of Glendale, 2015; City of Los Angeles, 2009; Economides, 2014; Matsuno & Chiu, 2001)
Vegetated Bioretention Basin	(City of Los Angeles, 2009; City of Phoenix, 2013; Economides, 2014; MacAdam, 2012; Novotny, Ahearn, & Brown, 2010a)
Bioretention Cell	(CDOT, 2010; Chau, 2009; Matsuno & Chiu, 2001; SAH Pilot Study, 2014)
Planter	(Chau, 2009; City of Glendale, 2015; City of Los Angeles, 2009)
Porous Asphalt	(Chau, 2009; City of Los Angeles, 2009)

Porous Concrete	(CDOT, 2010; Chau, 2009; City of Glendale, 2015; City of Los Angeles, 2009; Economides, 2014; Matsuno & Chiu, 2001; US EPA, 2000a)
Structural Grids	(Chau, 2009; City of Glendale, 2015; City of Los Angeles, 2009; US EPA, 2000a)
Permeable Pavers	(CDOT, 2010; Chau, 2009; City of Glendale, 2015; City of Los Angeles, 2009; Economides, 2014)
Infiltration Trench	(CDOT, 2010; Chau, 2009; City of Los Angeles, 2009; Gill, Handley, Ennos, & Pauleit, 2007)
Underdrains	(CDOT, 2010; SAH Pilot Study, 2014)
Activated Floodway	(MnDOT, 2014; J. Park et al., 2013)
Green Roofs	(CDOT, 2010; Chau, 2009; City of Glendale, 2015; Economides, 2014)
Cisterns	(CDOT, 2010; Chau, 2009; City of Glendale, 2015; Matsuno & Chiu, 2001; US EPA, 2000b)
Open Channel Conveyance	(City of Phoenix, 2013)
Road weather information systems	(Doll et al., 2014; Matsuno & Chiu, 2001; Transportation Research Board, 2011; US EPA, 2000a)
Vegetation Management	(CDOT, 2010; Chau, 2009; City of Glendale, 2015; City of Los Angeles, 2009; Doll et al., 2014; Economides, 2014; MacAdam, 2012; Matsuno & Chiu, 2001; Novotny et al., 2010a)
Flow regulation devices	(SAH Pilot Study, 2014; US EPA, 2000b)
Curvilinear Streets	(Matsuno & Chiu, 2001)
Raised Subgrade	(Rattanachot, Wang, Chong, & Suwansawas, 2015)
Chicanes & Bump-outs	(Chau, 2009; MacAdam, 2012)
Dual culvert cells	(MnDOT, 2014)
Multi-span bridge	(MnDOT, 2014)
Discouraging Land Subsidence	(Watson & Adams, 2010)
Traffic Diversion	(Transportation Research Board, 2011)
Infrastructure Maintenance	(Matsuno & Chiu, 2001; Transportation Research Board, 2011)
Relocate Service Buildings	(SAH Pilot Study, 2014)
Flood Storage	(Gill et al., 2007)
Street Width Reduction	(MacAdam, 2012)

4.2.3. Characteristics of adaptation strategies

We reviewed “safe-to-fail”, resilience, and urban flooding literature to develop “safe-to-fail” infrastructure criteria of potential roadway flooding solutions. From the articles reviewed, we identified infrastructure characteristics and adaptation strategies. We further determined whether it epitomized “fail-safe” or “safe-to-fail” concepts using five categories of comparison criteria adopted from same 10 documents: design principles, design objectives, design focus, failure impacts, and design disciplines.

From the 10 “safe-to-fail” articles reviewed, we find a total of 19 unique “fail-safe” and “safe-to-fail” infrastructure characteristics and design strategies. Initially, the 10 articles list a combined 31 characteristics and design strategies as either “fail-safe” or “safe-to-fail”. However, many of these characteristics share similar definitions and descriptions despite being presented by different authors and having different names. By combining similar characteristics and strategies, we reduce the initial list of 31 to a final list of 19 distinct characteristics. Due to conflicting definitions and perspectives among authors, we also have to re-assess each criterion to determine whether it epitomized “fail-safe” or “safe-to-fail” concepts. Using the same 10 articles, we adopt five categories of comparison criteria: design principles, design objectives, design focus, failure impacts, and design disciplines (Table 4.2). Taken together, assessing the 19 characteristics with these five comparison criteria produces a list of six “fail-safe” (Table 4.3) and 13 “safe-to-fail” (Table 4.4) solution characteristics and design strategies. Due to the qualitative nature of processing academic literature, reviewing applied case studies, and assessing infrastructure solutions, multiple reviewers are assigned to each document to establish reliability of results, and reviewers discuss all assessments collectively (Al Rasbi et al., 2016).

Table 4.2. "Fail-safe" and "Safe-to-fail" perspectives and comparison criteria

	Fail-safe	Safe-to-fail	Source
Design Principles	Preservation of status quo	Adaptation to changing conditions	(J. Park et al., 2013)
	Mitigation	Adaptation	(Cuny, 1991)
	Risk management	Resilience	(Hoang & Fenner, 2015; Liao, 2012)
Design Objectives	Minimization of failure probability	Minimization of failure consequences	(J. Park et al., 2013)
	Failure prevention	Failure recovery	(T. P. Seager, 2008)
Design Focus	Component	System	(Möller & Hansson, 2008)
	Quantitative probabilities and semi-quantitative scenarios	Possible consequences and unidentified causes	(J. Park et al., 2013)
Failure Impacts	Rigid/brittle	Flexible	(Ahern, 2011)
	Rare and catastrophic	Frequent with rapid recovery	(J. Park et al., 2013)
Design Disciplines	Interdisciplinary	Transdisciplinary	(Ahern, 2013)

Table 4.3. "Fail-safe" characteristics and design strategies

Characteristic/ Design strategy	How achieved…?	Source
Armoring	By hardening or stiffening a system or component to exogenous shocks via the addition of new components or functions	(J. Park et al., 2013)
Strengthening	By hardening or stiffening a system or component to exogenous shocks via the upgrade of existing components or functions	(J. Park et al., 2013)

Oversizing	Increasing existing system and component tolerance, capacities, robustness, functionality. Increasing existing "fudge factor”-type heuristics in design	(J. Park et al., 2013)
Isolation	Reducing connectivity, interdependence, functionality, and interactions among system components and between systems where those interactions already existed	(J. Park et al., 2013)
Fail-Silence	Developing a negative feedback mechanism to achieve system self-shutdown in case of component or human failure	(Möller & Hansson, 2008)
Fail-Operation	Enabling systems to continue to work despite failures and faults	(Möller & Hansson, 2008)

Table 4.4. “Safe-to-fail” characteristics and design strategies

Characteristic/ Design strategy	How achieved…?	Source
Multifunctionality/ Flexibility	Through the design of systems or components with extensible functionality, capacity for reconfiguration, intertwining/combined functions, and time-shifted functions	(Ahern, 2011; J. Park et al., 2013)
Redundancy/ Modularization	When multiple elements or components provide the same, similar, or backup functions	(Ahern, 2011)
(Bio and Social) Diversity	By using solutions with a greater number of forms, behaviors, and responses across a wider range of conditions	(Ahern, 2011; Fiksel, 2003)
Multi-Scale Networks/ Connectivity/ Cohesion	Creating linkages within systems that support and maintain functional connectivity	(Ahern, 2011; Fiksel, 2003)
Adaptability/ Adaptation/ Adaptive Capacity	Increasing a system’s capacity to change in response to new pressures and to manage known and unknown events.	(Ahern, 2011; Blackmore & Plant, 2008; Fiksel, 2003)

Efficiency	Designing for system functionality with modest resource consumption	(Fiksel, 2003)
Renewability/ Regrowth	Enabling the recovery of system or component function from endogenous and exogenous forces	(J. Park et al., 2013)
Sensing	Improving the capacity by which new system stresses are efficiently and rapidly incorporated into current understanding	(J. Park et al., 2013)
Anticipation	Improving the capacity to foresee and predict positive and negative future system states	(J. Park et al., 2013)
Learning/ Learning-by-doing	Creating retrospective feedback loops between response actions to assess and develop new knowledge and adaptive strategies,	(Ahern, 2011, 2013; J. Park et al., 2013)
Transformability/ Transformation	Enabling the capacity to create an entirely new system when existing structures are untenable	(Blackmore & Plant, 2008; Mu, Seager, Rao, Park, & Zhao, 2011)
Adaptive Design/ Adaptive Planning & Design/ Innovation	Opening existing analysis, design, and implementation practices to encourage creativity with the goal of gaining knowledge for future solutions	(Ahern, 2013; T. P. Seager, 2008)
Transdisciplinarity	Enabling dissimilar stakeholders to contribute to and benefit from a mutual experience	(Ahern, 2013)

4.2.4. “Safe-to-fail” scorecard and the decision criteria for solution analysis

From our own database that identifies the “fail-safe” and “safe-to-fail” characteristics of flooding solutions already in use to adapt roadways to climate change, we develop a “safe-to-fail” scorecard by assessing solutions specific to the classifications of roadway infrastructure they affect and their “fail-safe” and “safe-to-fail” infrastructure characteristics. Roads are classified into different categories depending on the volume of traffic and types of goods moved. Depending on these classifications, geometric factors (width and number of lanes) and structural designs vary flooding solutions. For example, a curb cut is a useful technology for reducing small volumes of flooding on local roads by directing water to nearby foliage, but are less useful on major roads with multiple lanes that can carry much larger volumes of water. Moreover, paving technologies such as porous asphalt are not useful for managing water on unpaved, backcountry roads, but can be effective on low-volume urban collector streets. For this reason, we identify the relevant functional roadway types for all solutions. In particular, we assess each roadway solution for its relationship to seven functional roadway definitions from the Arizona Department of Transportation (ADOT, 2016): backcountry road, local road, collector road, arterial road, state highway, interstate highway, and U.S. highway. Furthermore, we assess each solution for its infrastructure characteristics.

We assess solutions using a binary coding method: we assign one (1) if the identified solution was implemented to manage flooding for a particular roadway type, and zero (0) if those roadway types were not identified in the case study, if the solution was deemed irrelevant to a roadway type, or could not be applied. In addition, we assess which of the solutions fulfill different “fail-safe” and “safe-to-fail” characteristics and design strategies. Similar to infrastructure roadway classifications, we assess “fail-safe” and “safe-to-fail” characteristics using a binary scoring system: a one (1) means that the solution exhibits the “fail-safe” or “safe-to-fail” characteristics within the context of a specific climate change adaptation case study, and a zero (0) means it does not. This assessment is done based on the decision criteria presented in Table 4.2. In total, we review 26 climate change case studies and 10 articles on “fail-safe” and “safe-to-fail” concepts.

4.2.5. Multi-criteria decision analysis to rank Phoenix flooding solutions

We integrated the vulnerability analysis with the “safe-to-fail” scorecard via the Analytical Hierarchy Process (AHP) multi-criteria decision analysis (MCDA) algorithm to generate a ranked list of roadway flooding solutions based on multiple “fail-safe” and “safe-to-fail” perspectives (green box in Figure 4.1). The AHP (Saaty, 1988) compares the individual scores each solution receives for each sub-criterion, and calculates normalized scores across all solutions for each sub-criterion. Based on our solution assessments, we adopt the AHP algorithm to generate priority vectors with new representative scores for each solution in each sub-criterion. In this work, there are two classes of decision criteria for each roadway solution, namely, functional road classifications and “fail-safe” and “safe-to-fail” characteristics Then, using weighting factors, we combine each sub-criterion into normalized criteria scores and a final total score for each solution. For example, via the literature review we give each roadway flooding solution a score for a given functional roadway type. As a starting point we begin with interstate highways, and through the AHP algorithm we compare all interstate highway solution scores to each other and develop a normalized priority score for that sub-criterion. We then apply a weight to the interstate highway sub-criterion against all other functional road classifications based on its importance to Phoenix, and combine priority scores across sub-criteria to generate a functional roadway classification priority vector. We weight, normalize, and combine the functional roadway classification priority vector with the “fail-safe” and “safe-to-fail” priority vector to generate a total solution score. Finally, we rank solutions based on their solution scores (Figure 4.2). As a result, MCDA allows us to compare multiple, potential decisions, e.g., different potential roadway flooding solutions, by ranking them on their performance across all relevant decision criteria and combining criteria scores into a single solution score (Kiker, Bridges, Varghese, Seager, & Linkov, 2005).

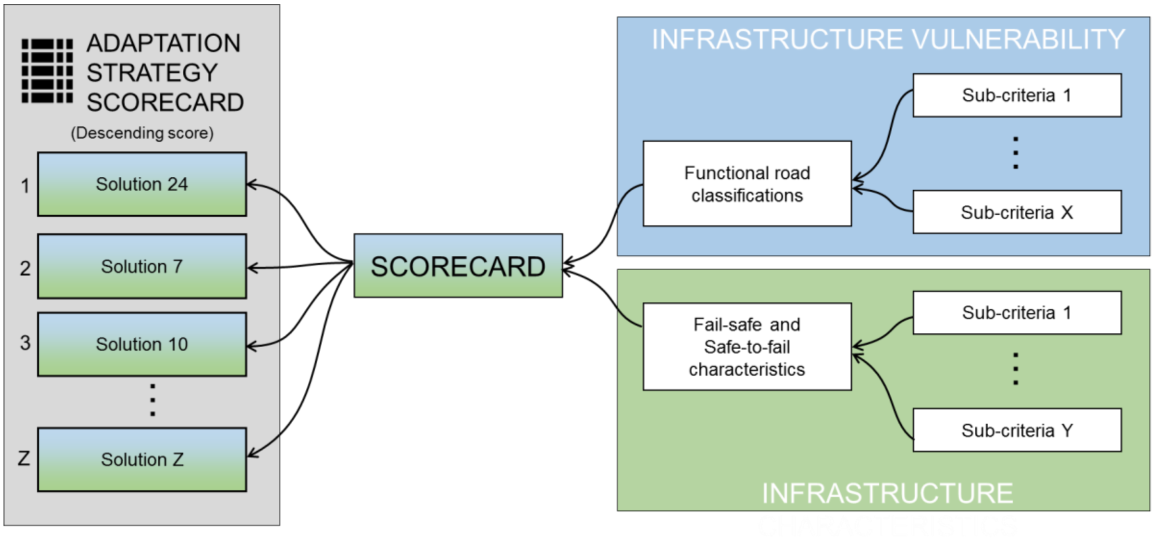


Figure 4.2. Multi-criteria decision analysis (MCDA) for comparing roadway flooding solutions. Sub-criteria for functional road classifications and "fail-safe" and "safe-to-fail" characteristics receive individual scores by comparing them across all solutions. Then, we combine sub-criteria into a single, normalized score through a tiered weighting scheme with two levels. We use the final solution scores to develop a comparative ranking of all potential solutions

Weighting factors introduced in this study for MCDA represent Phoenix roadway vulnerability and "safe-to-fail" preferences for solution comparison. We develop weights for functional roadway classifications via vulnerability calculation from Chapter 3 and "fail-safe" and "safe-to-fail" weights on fundamental design perspectives via literature review Table 4.2. The functional roadway classification weights represent the impact of flooding estimated by simulation models and the percentage of road types affected (Table

4.5). The “fail-safe” and “safe-to-fail” weights represent different design perspectives that favor particular solution characteristics (

Table 4.6). Normally, one uses stakeholder preferences to determine the relative importance of decision criterion. Instead, we developed seven adaptation perspectives that represent contrasting “fail-safe” and “safe-to-fail” characteristics. Three perspectives are generic weighting schemes that consider all criteria within each category equally. We derived four perspectives based on the work of Ahern (Ahern et al., 2014) and Park et al. (J. Park et al., 2013; Jeryang Park et al., 2011) to demonstrate how differing “safe-to-fail” perspectives may change recommended solutions. Both Ahern and Park et al. offer multiple contrasting “safe-to-fail” perspectives that emphasize different design strategies and solution characteristics. For example, work developed by Ahern (Ahern et al., 2014) focuses on transdisciplinarity in one instance, yet de-emphasizes it in another (Ahern, 2011). Similarly, within the same work, Park et al. (J. Park et al., 2013) describe contrasting views on catastrophe management – one focuses on design strategies, and one focuses on sociotechnical processes. Overall, the three generic and four author specific perspectives are:

- All criteria weighted equally – a “fail-safe” and “safe-to-fail” agnostic perspective
- Fail-safe criteria only – a general, risk-based perspective on design
- Safe-to-Fail criteria only – a general, resilience-based perspective on design
- Ahern All – a perspective on “safe-to-fail” design using concepts developed by Ahern et al. (2014)
- Ahern Strategies – a refinement on the Ahern All perspective that focuses on five design strategies (i.e. multifunctionality, redundancy and modularization, (bio and

social) diversity, multi-scale networks and connectivity, and adaptive planning and design) proposed by Ahern (2011) on “safe-to-fail” design.

- Park Strategies – a perspective on “safe-to-fail” design using resilience-based design strategies recognizing changing conditions and unknown hazards summarized by Park et al. (2013).
- Park Processes – a perspective on “safe-to-fail” design focused on sociotechnical processes developed in resilience engineering literature (Woods, Leveson, & Hollnagel, 2012) and refined by Park et al. (2013).

The seven perspectives are a subset of the many perspectives and values on infrastructure design. We used MCDA to prioritize “safe-to-fail” roadway flooding solutions in Phoenix by giving weight to 19 resilience characteristic based on these seven perspectives. Each of the above perspectives identifies all or part of the 19 possible characteristics for resilience-based design as important for “safe-to-fail” infrastructure. No perspective suggests that any one resilience characteristic is more important than any other, thus we assigned equal decision-making importance (i.e., weight) to each characteristic for any given perspective. For instance, the Ahern Strategies perspective highlights five resilience characteristics while this perspective does not have proposition on the rest 14 characteristics, thus we only weighted the highlighted five characteristics equally (0.20). Using the AHP algorithm, we calculated the score of each roadway flooding solution for a given characteristic (e.g., multifunctionality) and then combined scores based on perspective weightings to generate solution rankings for each perspective. Each of seven adaptation perspectives emphasizes different design strategies which can result in distinct rankings for roadway flooding solutions. Taken together, we argue that these seven perspectives provide a comprehensive view on "fail-safe" and "safe-to-fail" prioritization of design that can inform decision-making for future flooding events.

Table 4.5. Road classification and their weights on flood vulnerability

Road Classification (in vulnerability assessment)	Road Classification (in MCDA)	Criteria Weights
None in Phoenix	Backcountry Road	0
Minor Collector	Local Byway	0
None in Phoenix	Living Streets	0
Major Collector	Collector Roads	0.1701
Minor and Principal Arterials (Local Roads)	Arterials	0.6347
Major Collectors & Principal Arterials (State and US Highway)	State Highway (State Route) / U.S. highway (U.S. Route) / County Road	0.0250
Principal Arterial (Interstate Highway)	Expressway / Freeway (Motorway) / Interstate Highway	0.1703
Sum of Weights (must = 1)		1.0

Table 4.6. Seven adaptation perspectives and their associated "Fail-safe" and "Safe-to-fail" characteristics and their weights used in MCDA

Characteristics	All Criteria Equal	Fail-Safe Only	Safe-to-Fail Only	Ahern All	Ahern Strategies	Park Strategies	Park Processes
Armoring	0.053	0.167	0	0	0	0	0
Strengthening	0.053	0.167	0	0	0	0	0
Oversizing	0.053	0.167	0	0	0	0	0
Isolation	0.053	0.167	0	0	0	0	0
Fail-Silence	0.053	0.167	0	0	0	0	0
Fail-Operation	0.053	0.167	0	0	0	0	0
Multifunctionality/	0.053	0	0.077	0.143	0.200	0.143	0

Flexibility							
Redundancy/ Modularization	0.053	0	0.077	0.143	0.200	0	0
(Bio and Social) Diversity	0.053	0	0.077	0.143	0.200	0.143	0
Multi-Scale Networks/ Connectivity/ Cohesion	0.053	0	0.077	0.143	0.200	0.143	0
Adaptability/ Adaptation/ Adaptive Capacity	0.053	0	0.077	0	0	0.143	0.250
Efficiency	0.053	0	0.077	0	0	0	0
Renewability/ Regrowth	0.053	0	0.077	0	0	0.143	
Sensing	0.053	0	0.077	0	0	0	0.250
Anticipation	0.053	0	0.077	0	0	0	0.250
Learning/ Learning-by-doing	0.053	0	0.077	0.143	0.200	0	0.250
Transformability/ Transformation	0.053	0	0.077	0	0	0.143	0
Adaptive Design/ Adaptive Planning & Design/ Innovation	0.053	0	0.077	0.143	0	0.143	0
Transdisciplinarity	0.053	0	0.077	0.143	0	0	0

4.3. Results: Adaptation strategy decision-making

The combination of literature review, flooding vulnerability assessment, and MCDA results show how switching between different “fail-safe” and “safe-to-fail” perspectives changes the recommended roadway flooding solutions. Table 4.7 presents the top five solutions for Phoenix roadway flooding for the seven adaptation perspectives based on MCDA.

Table 4.7. Top five roadway flooding solutions for Phoenix, Arizona (RWIS: modernized roadway weather information system)

Rank	All Criteria Equal	Fail-Safe Only	Safe-to-Fail Only	Ahern All	Ahern Strategies	Park Strategies	Park Processes
1	Vegetated Bioretention Basin	Flood Storage	Vegetated Bioretention Basin	Activated Floodway	Activated Floodway	Discouraging Subsidence	RWIS
2	RWIS	Discouraging Subsidence	Activated Floodway	Vegetated Bioretention Basin	RWIS	Open Channel Conveyance	Activated Floodway
3	Activated Floodway	Multi-span bridge	RWIS	RWIS	Vegetated Bioretention Basin	Vegetated Bioretention Basin	Vegetated Bioretention Basin
4	Flood Storage	Vegetated Bioretention Basin	Open Channel Conveyance	Flood Storage	Vegetation Management	Flood Storage	Vegetation Management
5	Discouraging Subsidence	RWIS	Discouraging Subsidence	Vegetation Management	Discouraging Subsidence	Activated Floodway	Relocate Service Buildings

Several solutions appear as most important for the Phoenix case demonstrating that MCDA method can be useful to consider the design criteria that are not commonly captured in technical design, namely adaptation capacity to climate change. Of the 33 possible solutions found in literature, only nine appear among the top five across all scenarios. This suggests that these nine are the most relevant in regions like Phoenix, where future flooding will primarily affect principal arterial, minor arterial, and interstate highway roads. Furthermore, of these nine, three solutions (i.e. vegetated bioretention, modernized roadway weather information system (RWIS), activated floodway) appear more frequently than the rest, suggesting that these solutions satisfy across the “fail-safe” and “safe-to-fail” perspectives. The highest ranked solution for the All Criteria Equal and Safe-to-Fail Only perspectives is the implementation of a vegetated bioretention basin; this solution appears in the top five for all other perspectives as well. Similarly, the highest ranked solution for Ahern All and Ahern Strategies is Activated Floodway, which appears in the top five for four other scenarios. Based on these results, we recommend that Phoenix implement vegetated bioretention basins, activated floodways and RWIS to better enhance the city’s resilience to unpredictable and uncertain future flooding events.

Differences in recommended solutions reveal the sensitivity of results to switching design strategies. Here, we demonstrate how conflicting risk- and resilience-based design strategies may lead to different roadway flooding solutions. Switching from Fail-Safe Only to Safe-to-Fail Only perspectives leads to a reversal in the importance of flood storage and discouraging land subsidence to vegetated bioretention basins and activated floodway. Switching from Park Strategies to Park Processes has a dramatic shift in recommended solutions, with differing highest ranked solutions and only two of the top five being similar between them. The sensitive nature of choosing one design paradigm over another emphasizes the need for more comparative and integrative work across resilience literature.

Despite this sensitivity, there are several consistencies existing among “safe-to-fail” perspectives which demonstrate the shared resilience-based design approach among particular solutions. In particular, reducing the Ahern All perspective to focus attention on only the authors’ proposed “safe-to-fail” design strategies (Ahern Strategies) does not change the top three recommended solutions. Furthermore, all scenarios except Fail-Safe Only and Park Strategies share the same top three solutions notwithstanding reversals in the order of their ranks. While these similarities among results may be an artifact of context-specific factors such as the focus on roadway flooding and Phoenix, they may also be indicative of converging perspectives on specific solution types. Because Safe-to-Fail Only, Ahern All, Ahern Strategies, and Park Processes produce similar results to All Criteria Equal, these three solutions must have the uncommon trait of fulfilling a broad scope of design strategies. Idiosyncrasies between “safe-to-fail” definitions suddenly become less important, and identifying these transcendental solutions may be more meaningful in future work.

4.4. Conclusion

Given the infrastructure-specific flooding vulnerability results, we can prioritize spatially explicit infrastructure recommendations that are “safe-to-fail” to non-stationary weather extremes. Cities are composed of complex infrastructure systems that are interdependent, multi-functional, and increasingly co-located in ways that decentralize much of the hard-infrastructure, thus recommendations for one system can affect others. “Safe-to-fail” infrastructure design tends to emphasize resilience characteristics that account for the interdependent, complex nature of urban infrastructure including isolation, fail-silence, redundancy and modularization, diversity in system responses, connectivity across multi-scale networks, and adaptive capacity. Risk-based approaches typically design and operate infrastructure in isolation without considering the consequences of failures linked from one system to another (e.g. power supply system failure to drainage pump failure; drainage system failure to roadways flooding) (Blockley et al., 2012). One goal of “safe-to-fail” design is to ensure that unpredicted shocks that affect a single infrastructure system do not cause secondary or tertiary impacts to other systems. “Safe-to-fail” allows decision-makers to better acknowledge interdependent systems in the design stage via failure modes and ensures that infrastructure risks are managed interconnected parts. We position multi-criteria decision analysis (MCDA) as an effective way to organize many “safe-to-fail” characteristics and facilitate decision making across different urban infrastructure characteristics and adaptive solutions. While different characteristics are uniformly weighted within each perspective in this study, incorporating multiple stakeholder and decision-maker preferences may lead to non-uniform and probabilistic weightings that reflect data uncertainty and different social/political/technical capacities. Furthermore, the current results are discrete rankings of solutions, where non-uniform weighting may generate distributions for the importance of each solution which are more difficult to interpret but may provide more useful information to decision-makers to evaluate the cost and benefit of “safe-to-fail” designs in climate change adaptation. Although outside the scope of this work, future work should focus on incorporating expert opinion in developing weighting schemes and identifying the sensitivity of decisions to non-uniform, probabilistic results.

While green and low impact development (LID) practices such as bioswales, vegetated bioretention basins, and living streets easily interpret “safe-to-fail” with their capacity to provide social and ecosystem services in addition to reducing flood impacts, gray infrastructure can also achieve “safe-to-fail” features by coupling technological constraints with social and ecological well-being (Meerow et al., 2016). Furthermore, we define “safe-to-fail” infrastructure as a system that is capable of adapting to uncertain and unpredictable infrastructure failures, such as extreme precipitation events, via social, ecological and technological interactions (SETs) and adaptation practices. For example, in contrast to using a simple LID solution, flooding resilience in The Netherlands is achieved through a combination of infrastructure, policy and action. In particular, communities in The Netherlands developed more resilient infrastructure systems by intentionally expanding flood-prone areas to nearby farmland from the frequent flooded river. By using the farmlands as floodways and developing a subsidy for affected farmers for lost crop production, local flood management districts were able to redirect urban damages to less socially and economically vital regions (Zevenbergen et al., 2013). Another example described in detail by Park et al. includes the strategic destruction of a levee to control extreme flooding in the Mississippi River Valley in 2011 (J. Park et al., 2013). The above two examples emphasize that a resilience-based “safe-to-fail” infrastructure design is less concerned with promoting a specific technology but how systemic interactions of SETs dictate infrastructure feasibility and lowering the overall impacts of failure on social, economic and environmental systems through adaptive actions. This characteristic about “safe-to-fail” infrastructure is also relevant for climate change actions as the IPCC acknowledge that climate change adaptation is place- and context-specific (IPCC, 2014), with no single approach for reducing risks appropriate across all settings. Moreover, infrastructure superficially interpreted as “fail-safe”, e.g., a concrete levee in the Mississippi River Valley example, can also be “safe-to-fail” when managed alongside the adaptive human responses they enable. Thus, risk-based and resilience-based design are not mutually exclusive, but rather supportive of each other, where risk analysis identifies vulnerabilities and damages and resilience analysis highlights systemic dependencies to enable recovery and adaptation (Jeryang Park et al., 2011).

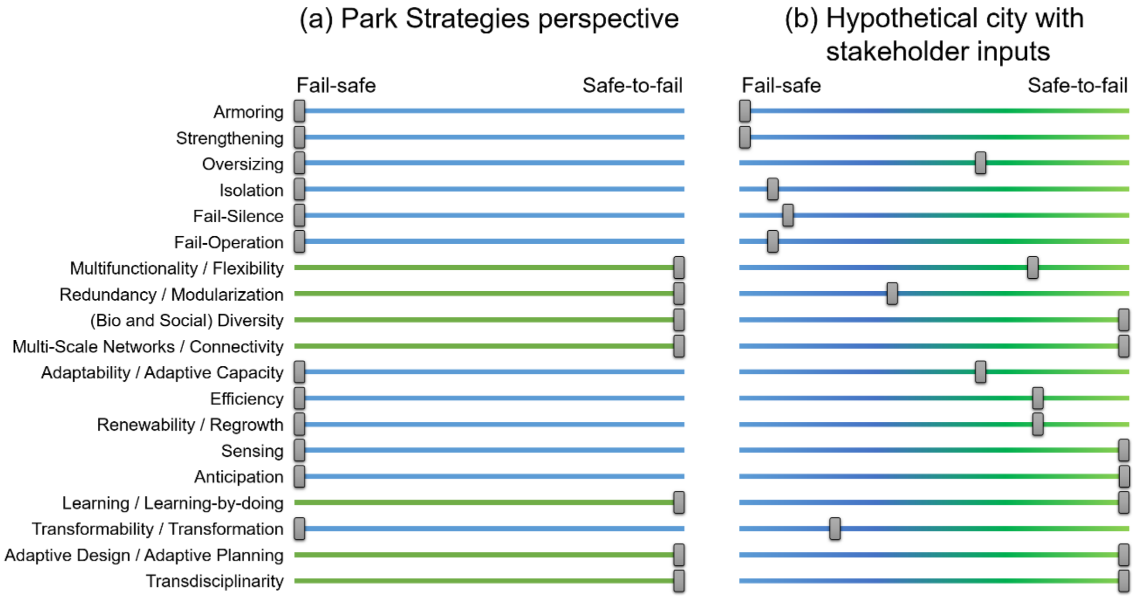


Figure 4.3. The infrastructure resilience strategies and their sliding scales from “Safe-to-fail” to “Fail-safe”. (a) The sliders representing the Park Strategies perspective for Phoenix evaluated in this study considers “Safe-to-fail” and “Fail-safe” as binary categories (blue and green in colors). (b) A hypothetical context-specific perspective that

includes stakeholder values suggested by the authors. In practice, strategies may be on a spectrum from "Fail-Safe" to "Safe-to-fail" (gradient from blue to green in colors) depending on location- and infrastructure-specific context.

Despite limited evidence and the authors' optimism that "safe-to-fail" approaches can improve the resilience of infrastructure and the services they provide against climate change, the topic remains largely unexplored. We provide some initial framing of how certain resilience characteristics fit into "safe-to-fail" versus to "fail-safe" regimes. However, it is possible, and likely, that characteristics do not fit neatly into either "safe-to-fail" or "fail-safe". Moreover, a "safe-to-fail" infrastructure strategy in one city may not be "safe-to-fail" or "resilient" in another city. We imagine that sliding scales can be used to identify different perspectives on "fail-safe" and "safe-to-fail" system characteristics that are context- and infrastructure- specific, and non-uniform weighting of MCDA will help capture these spectrums in decision-making processes (Figure 4.3). For instance, "oversizing" is described as a "fail-safe" infrastructure characteristic based on the Park Strategies perspective (Figure 4.3 a), as increasing the size of drainage pipes does not consider the impact of rainfall-runoff overflow. In contrast, a hypothetical perspective proposed by the authors positions "oversizing" as a "safe-to-fail" strategy (Figure 4.3 b), as some practical examples of increasing the size of bioretention basins near rivers provide "safe-to-fail" flood control (c.f., The Netherlands "Room for the river"). We confirm the need of a new design paradigm that rigorously considers uncertainty in climate predictions during the decision-making process and primes infrastructures to be resilient to unforeseen climate risks. The "safe-to-fail" design strategy offers one approach to consolidate the resilient capacity of infrastructure systems, by focusing attention on reinforcing specific infrastructure characteristics in order to minimize the consequences of systemic failures.

CHAPTER 5

EXPERT ELICITATION ON RESILIENT AND SAFE-TO-FAIL INFRASTRUCTURE

5.1. Introduction

Improving infrastructure ‘resilience’, understood as increasing the capacity of infrastructure systems to resist, adapt, or respond to changes, disturbances, and shocks, is now critical to climate adaptation (Linkov et al., 2014; National Infrastructure Advisory Council, 2010; The National Academies, 2012; UNISDR, 2009). Due to broad factors that influence climate change, like urbanization, population change, earth system interactions, land use change, technology shifts, and economic growth, there is a rapid pace of changing environments in which infrastructure is designed and developed to survive. The concept of resilience is promoted by researchers for developing and managing infrastructure systems with the ability to withstand or recover quickly from difficult, changing climate conditions, even the conditions that are not easily foreseen (Biggs et al., 2012; Linkov et al., 2013; Meerow & Newell, 2015; Woods et al., 2012). Still, there is a gap in understanding how resilience (and its associated strategies) defined and promoted conceptually by *researchers* is interpreted and embedded pragmatically by *practitioners* in infrastructure development. Infrastructure engineers, landscape planners, policy makers, and climate risk scientists (i.e., practitioners, hereafter) are the actual experts who make decisions for infrastructure in state, regional, and municipal governments that lead to planning and managing infrastructure systems – not researchers. Previous studies on resilience demonstrate that the concept needs to be understood with an interdisciplinary viewpoint reflecting regional, environmental, economic, and social challenges that practitioners have for climatic risk management decisions (Adger, 2000; Cutter, 2016; Hayward, 2013). Yet, most resilience studies neither observe a practitioner's interdisciplinary viewpoint on infrastructure resilience and climate risks nor identify how their perspectives may differ from the academic literature. Furthermore, there is no straightforward standard that guides decisions for infrastructure resilience nor a protocol for developing resilience strategies, and thus, the application of resilience in practice often entails subjective interpretation of the concept by local practitioners involved in infrastructure development and management decisions (DeVerteuil & Golubchikov, 2016; Meerow & Newell, 2015). To better understand how the concept of resilience is interpreted in practice and capture the interdisciplinary perspective of practitioners on climate change adaptation, new research is needed identifying a practitioner's view of resilience.

The emerging safe-to-fail infrastructure development concept is a resilience approach in academic literature that would benefit from capturing interdisciplinary practitioner perspectives. Safe-to-fail emphasizes incorporating resilience strategies that reflect the diverse adaptive capacities of infrastructure systems. The premise of safe-to-fail is that incorporating resilience strategies in infrastructure development will both mitigate adverse impacts of predicted risks and prioritize infrastructure failure consequences by enhancing certain adaptive capacities to respond to unforeseen risks. Research on safe-to-fail infrastructure development suggests the involvement of multiple stakeholders to determine the current adaptive capacities of the region to climate risks and to identify which resilient capacities should be embedded in new infrastructure designs. Among the stakeholders involved in assessing and embedding adaptive capacity in infrastructure systems, city practitioners hold knowledge of the capacity for government and non-governmental organizations to maintain, operate, and adapt infrastructure systems to climate change via knowledge of current decision considerations, design criteria, and the development process of infrastructure. Although this knowledge is critical to successful implementation of a safe-to-fail approach, there is no work in the literature that links practitioner knowledge to theory to better understand how adaptive capacities identified by researchers would be implemented in a real-world context.

Definitions of resilience exist in literature and the perspectives on safe-to-fail approach has been understood by researchers, but the understanding of practitioner perspectives created by their long-term experience is limited. To investigate diverse and subjective perspectives on resilience and its application in safe-to-fail infrastructure development, this study utilizes the Q-methodology (see Methods) which allows researchers to explore the subjectivity of perceptions on a subject matter. Via the Q-methodology, this study hypothesizes that the way practitioners prioritize safe-to-fail strategies for infrastructure development will vary depending on their knowledge and experiences. Furthermore, previous studies on safe-to-fail suggest that practitioners' viewpoints must be understood to succeed at safe-to-fail infrastructure development, because these perspectives highlight a nuanced understanding of resilience that is not captured in academic literature. For example, in the study of safe-to-fail adaptation for Phoenix roadways flooding (Y. Kim et al., 2017a), seven preliminary safe-to-fail adaptation perspectives are explored that represent contrasting fail-safe and safe-to-fail characteristics. These perspectives, however, are derived only from an academic literature review, and only capture how researchers' distinctive interpretation of safe-to-fail promotes different resilient infrastructure solutions for managing the consequences of urban flooding. While the results of the Phoenix study demonstrate that differing safe-to-fail perspectives may change recommended solution rankings for infrastructure design, they also suggest that more nuanced perspectives on safe-to-fail development may be lacking from resilience literature.

This study also aims to contribute on an understanding of practitioner's perspectives on resilience and safe-to-fail, thereby providing guidance for infrastructure development and climate change adaptation. Current infrastructure design standards and engineering criteria do not explicitly consider resilience strategies. Still, practitioners have been on the front line improving infrastructure performance to respond to a changing environment. These same infrastructure systems already last for decades and respond to changing climate without explicit consideration of resilience strategies. This implies that infrastructure development practices and strategies endorsed by practitioners' may already embed inherent attributes of resilience. Given that the notion of resilience has a malleable and multidisciplinary nature, the objective of this study is to explore the pragmatic interpretation of the resilience concept by practitioners and to recognize diverse perspectives on adopting resilience strategies into safe-to-fail infrastructure development in various decision contexts.

5.2. Methods

5.2.1. Q-methodology

Q-methodology was used in this study to explore the diverse perspectives of practitioners on resilience and safe-to-fail. Q-methodology is a research technique used to study an individual's subjectivity (S. R. Brown, 1993) by collecting tables of organized statements that represents a participants' subjective perspective. It was first introduced by the psychologist Stephenson in his article "Correlating persons instead of tests" in 1935, as a technique that inverses the common correlation analysis (i.e., correlating test variables (Spearman, 1904)) by correlating among human subject instead of the test variables (Stephenson, 1935). The benefit of correlating persons by Q-methodology appears in investigating questions about personal experience and opinions regarding insights, attitudes, values, and beliefs (S. R. Brown, 1980; Ellingsen, Størksen, & Stephens, 2010). Q-methodology has the strength of both qualitative and quantitative research methods, and it allows researchers to explore shared and/or discrete views among participants by its structured study procedure and factor analysis technique. Also, Q-methodology has a benefit of feasibility in discovering significant viewpoints and the range of variability only with few participants to offer a statistical meaningful results (as small as 12 participants because each Q-sort product delivers a substantial amount of information (Barry & Proops, 1999)). A Q-methodology study typically comprises i) development of a Q-sample, a list of statements related to the topic and the study question, ii) conducting Q-sort, a hands-on activity of ranking the Q-sample of statements by study participants on a quasi-normal distribution table (i.e., Q-sort table), iii) semi-structured interviews, iv) factor analysis performed on Q-sorts (i.e., persons) not on variables (i.e., statements or tests), and v) interpretation of identified factors and constructing discourses.

This study uses the Q-methodology to explore how resilience and safe-to-fail concepts are interpreted and applied in infrastructure development by practitioners. The procedure of each step in Q-methodology performed in this study is described in detail in the next sections below. To implement the Q-methodology for resilience and safe-to-fail, study participants (i.e., practitioners) were asked to perform a series of Q-sorting activities (i.e., ranking statements on the Q-sort table) by responding to three questions that reflect different decision contexts involving climate change adaptation, urban infrastructure development, and past natural disasters:

1) Question A. Which statements are more/less relevant for promoting infrastructure resilience in addressing climate and weather risks from your experience and perspective?
2) Question B. Which statements are more/less relevant for promoting safe-to-fail infrastructure in addressing urban flooding in the metro-Phoenix area from your experience and perspective?
3) Question C. Which statements are more/less relevant for promoting resilience considering infrastructure failure consequences during the infrastructure development process in addressing climate and weather risks like Hurricane Harvey?

In addition to asking participants these questions, additional information was provided to participants to help guide Q-sorting activities. For Question A, participants were provided with a common definition and extended explanation of resilience for infrastructure found in academic literature.

> *The National Academy of Sciences defines resilience as "the ability to plan and prepare for, absorb, recover from, and adapt to adverse events" (The National Academies, 2012). In response, resilient infrastructure systems have been extensively recognized as an alternative to traditional infrastructure in managing systems more reliable against unforeseen and unknown threats, i.e., "surprises" (Woods et al., 2012).*

Before ranking the statements for Question B, participants deliberated their decision contexts to guide their sorting on a specific infrastructure matter in the area either for an existing case or a hypothetical case. The decision context included a type of infrastructure, location within the metro-Phoenix area, and a type of weather events (e.g. a 100-year frequency rainfall). A general definition of safe-to-fail was given, while allowing practitioners to interpret the meaning of the term.

> *Safe-to-fail infrastructure are built systems designed to lose function in controlled ways, even when design threshold is exceeded in unpredicted hazards.*

Question C considered failure consequences in the process of developing resilient infrastructure to the past flooding disaster in Houston experienced during Hurricane Harvey in 2017. To provide an explicit decision context for the third question, selected quotes used to describe the Houston case were provided:

> *"But there is, and most Houstonians casually accept the enormous drainage system—the bayous, creeks and gullies—that keep it precariously dry in a former wetland.; The only solution is to widen the waterways, which means buying up adjacent buildings and tearing them down.; Brays Bayou, which has been widened in recent decades, surged over its banks in several spots, spilling feet of*

> *water into adjacent neighborhoods.; The county engineer puts the price tag on a total upgrade at $26 billion, which will not happen soon. (Baddour, 2016)"*

5.2.2. Q-sample: Collecting statements

The Q-sample in Q-methodology refers to the statements, objects, or other artifacts that study participants sort during each of the three sorting activities. The Q-sample for this study is a collection of statements on describing various resilience strategies which reflect various adaptive capacities of infrastructure system to respond to climate risks in certain ways. As one of this study objectives is to investigate how the concept of resilience developed by researchers are understood and interpreted by practitioners, we developed a Q-sample of 19 resilience strategies developed and analyzed to understand researchers' diverse viewpoints on developing resilient infrastructure found in Kim et al. (2017a). The 19 strategies make a comprehensive list encapsulating the discourse, or "the flow of communicability surrounding any topic" (S. R. Brown, 1993), derived from 10 studies on resilience and safe-to-fail infrastructure. Initially, in Kim et al., a total of 43 strategies were collected, which were then coded into either fail-safe or safe-to-fail based on author's perspective. By combining similar strategies that share similar definitions and descriptions among various authors, the initial list of collected statements were aggregated into 19 distinct strategies (See Table 5.1). We adopted these 19 strategies and their descriptions as statements consisting of the Q-sample of this study.

Table 5.1. Q-sample: 19 Resilience strategies for infrastructure development

#	Strategy	How achieved…?
1	Adaptability/ Adaptive Capacity	Increasing a system's capacity to change in response to new pressures and to manage known and unknown events
2	Adaptive Planning Design/Innovation	Opening existing analysis, design, and implementation practices to encourage creativity with the goal of gaining knowledge for future solutions
3	Anticipation	Improving the capacity to foresee and predict positive and negative future system states
4	Armoring	By hardening or stiffening a system or component to exogenous shocks via the addition of new components or functions
5	(Bio and Social) Diversity	By using solutions with a greater number of forms, behaviors, and responses across a wider range of conditions
6	Efficiency	Designing for system performance with modest resource consumption
7	Fail-Operation	Enabling systems to continue to work despite failures and faults
8	Fail-Silence	Developing a negative feedback mechanism to achieve system self-shutdown in case of component or human failure
9	Isolation	Reducing connectivity, interdependence, functionality, and interactions among system components and between systems where those interactions already existed
10	Learning/ Learning-by-doing	Creating retrospective feedback loops between response actions to assess and develop new knowledge and adaptive strategies,
11	Multi-functionality/ Flexibility	Through the design of systems or components with extensible functionality, capacity for reconfiguration, intertwining/combined functions, and time-shifted functions
12	Networks/ Connectivity/ Cohesion	Creating linkages within systems that support and maintain functional connectivity
13	Oversizing	Increasing existing system and component tolerance, capacities, robustness, functionality

14	Redundancy/ Modularization	When multiple elements or components provide the same, similar, or backup functions
15	Renewability/ Regrowth	Enabling the recovery of system or component function from endogenous and exogenous forces
16	Sensing	Improving the capacity by which new system stresses are efficiently and rapidly incorporated into current understanding
17	Strengthening	By hardening or stiffening a system or component to exogenous shocks via the upgrade of existing components or functions
18	Transdisciplinarity	Enabling dissimilar stakeholders to contribute to and benefit from a mutual experience
19	Transformability	Enabling the capacity to create an entirely new system when existing structures are untenable

5.2.3. Q-sort: Ranking the statements

In the Q-methodology, participants are asked to rank the Q-sample using the Q-sort table (Figure 5.1) based on their experience and perspectives. For this study, participants were identified via a local practitioner network and infrastructure agency websites. All potential participants received an invitation email with the purpose of the study. We invited the participants whose responses indicated that their work was related to infrastructure preparedness and flooding. The final study set included total of 16 participants from state, regional, and city governments. A set of study materials including paper copies of a Q-sort table (Figure 5.1), binning table, Q-sample (i.e., list of 19 strategies with descriptions), and a stack of cards with printed statements was distributed to each participant.

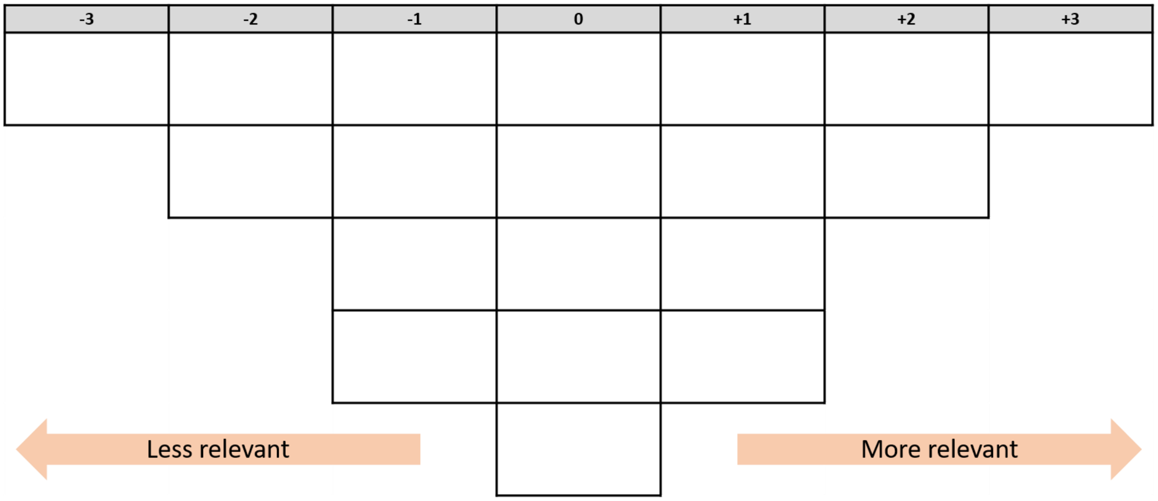


Figure 5.1. The Q-sort table guides participants to rank 19 statements in a quasi-normal distribution reflecting their subjectivity on the topic

Study participants completed one Q-sort for each Question (A-C) in small groups and in three successive stages to observe the changes in perspectives in different decision contexts. A single question stage consisted of three phases: 1) The facilitator explains the background and rationale of the study question to the group of participants; 2) The participants respond to the question by sorting the selected statements with given values in a Q-sort table from +3 (most relevant) to -3 (least relevant); 3) A semi-structured interview of each participant and the group is conducted to identify their reasoning for the Q-sort product. A quasi-normal distribution table for ranking the Q-sort table was used rather than asking practitioners to rate the statements individually to represent their perspective, i.e., the number of columns on each side of the Q-sort table corresponded to the other, with an increased number of Q-sample responses remaining in the middle (S. R. Brown, 1993). The Q-sort table is meant to capture the viewpoint on a certain resilience strategy that practitioners think about in relation to others, rather than in isolation. 16 participants produced 16 Q-sorts for each of Question A and B. 15

participants produced 15 Q-sorts for Question C. One participant had to leave one meeting early due to a schedule conflict. As a result, a total of 47 “Q-sorts” representing diverse perspectives on employing resilience for infrastructure development were collected. The examples of interview questions asked to participants after each stage are:

- Why did you choose <this strategy of the 19 in the Q-sample> as the most/least relevant strategy? Do you have a real-world example demonstrating your reasoning?
- Which of these resilience strategies are most difficult to categorize? Why?
- Which of these resilience strategies are most useful to guide decisions for infrastructure development? Why?
- Can you think of any other resilience strategies important for guiding infrastructure development not included here?
- What criteria did you have in your head for sorting strategies? Is your decision criteria the same for all three questions?

5.2.4. Factor analysis and constructing discourses

The collected Q-sorts were analyzed using factor analysis, a statistical correlation method. The publicly available Q-methodology software PQMethod-2.35 was used for the factor analysis (Schmolck, 2014) on the sets of Q-sorts responding to each question. The following steps for factor analysis were repeated three times, once for each respective study question. The first step of factor analysis is to enter the Q-sorts into the program. Principal components analysis (PCA) was chosen for factor analysis as it is the most common and well-established method (Akhtar-Danesh, 2017). PCA correlates every participant’s Q-sort with every other Q-sort to test the correlation among collected data.

In this study each question has 16 variables (i.e., 16 Q-sorts produced by 16 participants; 15 for Question C) and 19 observations (i.e., Q-sample statements). With PCA, the variance of Q-sorts were observed and extracted as clustered factors representing shared or discrete perspectives, thus allowing researchers to explore the range of viewpoints responding to each question. By default, in the PQMethod, a maximum of eight factors are extracted due to computational limitations. The first factor had the highest level of variance in the dataset, the second factor had the second highest variance, and the rest of six factors thereafter. The resulting cumulative explanatory variances were 90, 91, and 91 % with eight extracted factors for each question of this study, respectively. This means that 90 ~ 91 % of 15~16 Q-sorts can be explained with the eight extracted factors. The next step in the standard study protocol of Q-methodology is to 'rotate' the extracted factors to simplify the representation of each factor's statistical values, which helps the interpretation of each factors into discourses. Varimax rotation technique was used in this study to rotate the factors with Eigenvalues higher than one. This process maximizes the number of Q-sorts associated with only one factor (Cousins, 2017). In the next step, significant factors that can be considered as meaningful shared perspectives. The significance of factors was determined with the common Q-methodology criteria of i) the composite reliability is higher than 90 % and ii) the number of defining variables (Q-sorts) are more than three (Akhtar-Danesh, 2017; Hagan & Williams, 2016; Watts & Stenner, 2005). The composite reliability is calculated by the expression $Rxx = 0.80*p/[1 + (p - 1)*0.80]$, where p is the number of Q-sorts defining a factor (S. R. Brown, 1980). The result produced "idealized" sorts (factor arrays), which explained shared and/or distinct perspectives for each question – one "idealized" sorts for Question A; three "idealized" sorts for Question B; two "idealized" sorts for Question C. The characteristics of "idealized" factors are summarized in Table 5.2, Table 5.3, and Table 5.4. The factor scores (i.e., Z-score, a weighted average of the values given to each statement by participants defining the factor (S. R. Brown, 1980; Ellingsen et al., 2010); range from -3 to +3 in this study) are shown in Figure 5.2, Figure 5.3, and Figure 5.4.

Table 5.2. The factor characteristics of each "idealized" factor for Question A

Factor characteristics for Question A	Factor
	A1
Eigenvalue	4.8102
Number of defining variables	5
Composite reliability	0.952
% explanatory variance	26

Table 5.3. The factor characteristics of each "idealized" factor for Question B

Factor characteristics for Question B	Factor		
	B1	B2	B3
Eigenvalue	5.0659	2.7679	2.0350
Number of defining variables	4	3	4
Composite reliability	0.941	0.923	0.941
% explanatory variance	22	15	19

Table 5.4. The factor characteristics of each "idealized" factor for Question C

Factor Characteristics for Question C	Factor	
	C1	C2
Eigenvalue	4.8856	2.3745
Number of defining variables	3	3
Composite reliability	0.923	0.923
% explanatory variance	26	13

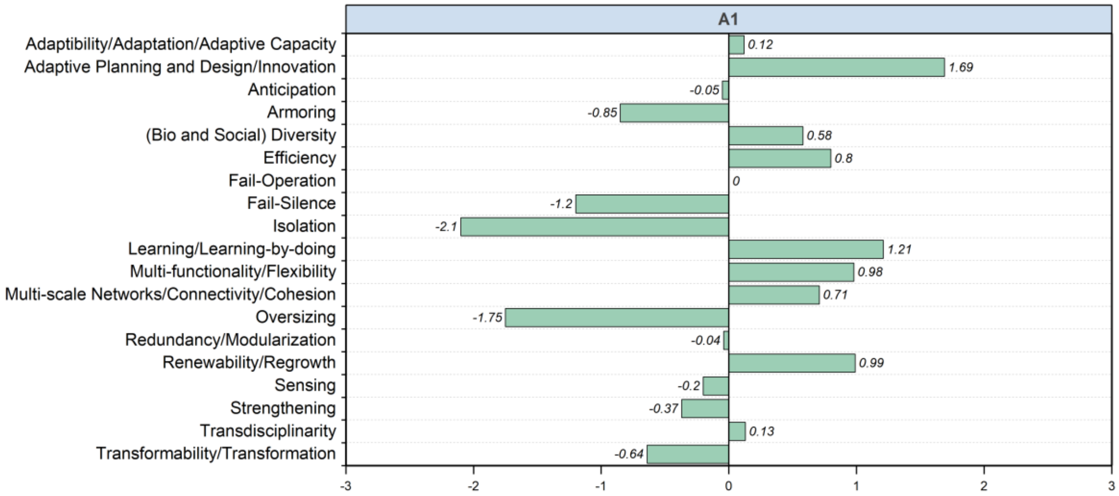


Figure 5.2. Z-scores for "idealized" factors of Question A

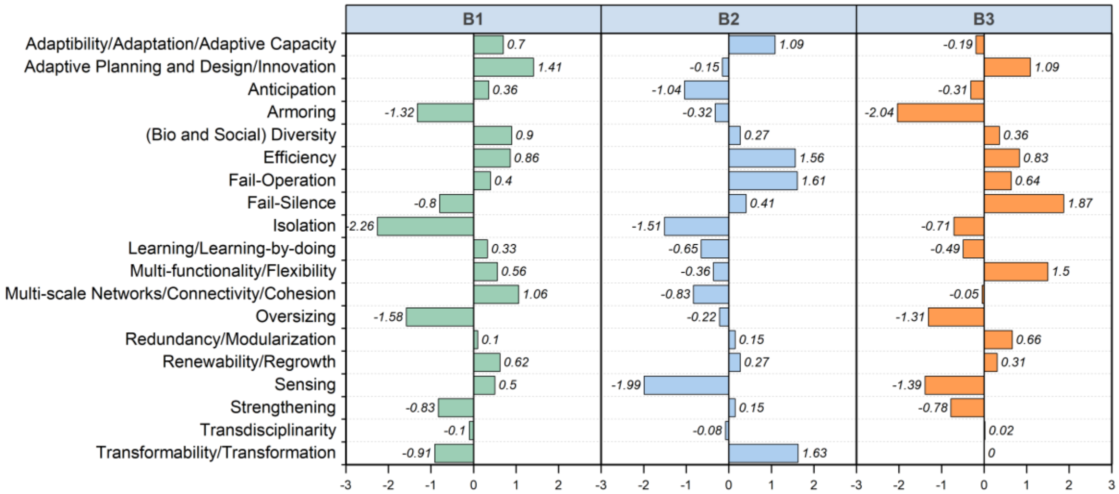


Figure 5.3. Z-scores for "idealized" factors of Question B

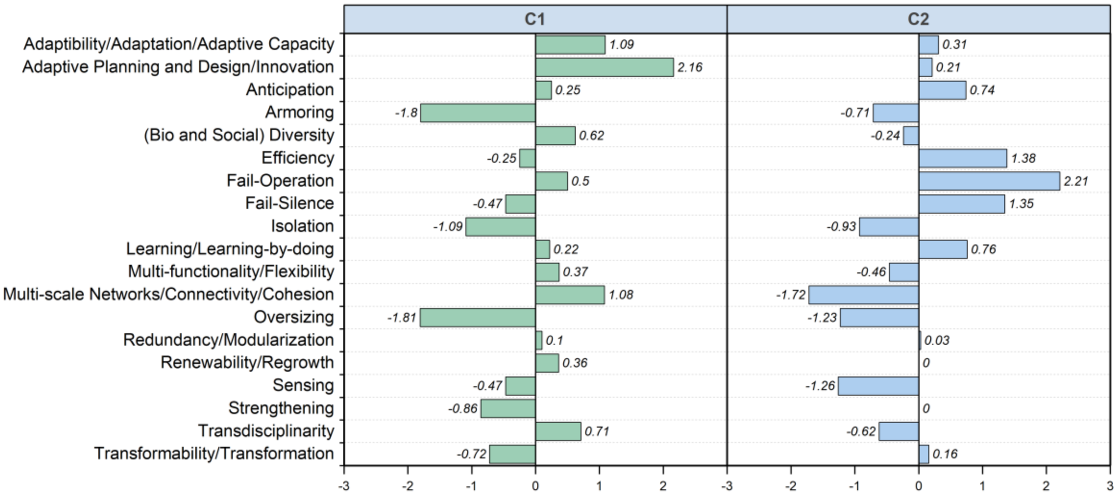


Figure 5.4. Z-scores for "idealized" factors of Question C

The results of "idealized" Q-sorts from factor analysis were interpreted in combination with the interview data for the interpretative discourse construction, which helps understand the quantitative outcome of factor analysis. Interpretative discourse construction is to gain an in-depth understanding of the participants' frame of reference and identify the reasoning behind their resulting Q-sorts as a narrative view rather than a view with representational statements and the rankings. Results of factor analysis provided information on participants that had a statistical significance in producing respective "idealized" Q-sorts. Thus, participants' interview data were selected and interpreted based on their significance of support for each "idealized" Q-sort. Also, distinguishing and consensus statements among "idealized" Q-sorts for each question were reviewed to construct discourses representing shared or discrete perspectives among participants. A distinguishing statement has a Q-sort score (i.e., Z-score ranging from -3 to +3) that is statistically unique for a specific factor, while a consensus statement does not notably distinguish in the Q-sort score between any pair of factors (S. R. Brown, 1993; Cousins, 2017). Constructing discourses based on identified factors were subjected to interpretative analysis using interview data, but focused on capturing respondent's subjectivity with respect to factor analysis without inferring investigator's subjectivity.

5.3. Results

The identified Q-factors were used to construct discourses that illustrate the variety of practitioner perspectives on resilience strategies and safe-to-fail that are reflected in infrastructure development for climate change adaptation. Discourses constructed for each question with the "idealized" factors and the interview data provide vital information for understanding diverse practitioner viewpoints. Discourses further elucidate participants' thoughts on selected statements associated issues with individual resilience strategies and the reasoning participants use for decisions to rank certain strategies in relation to others.

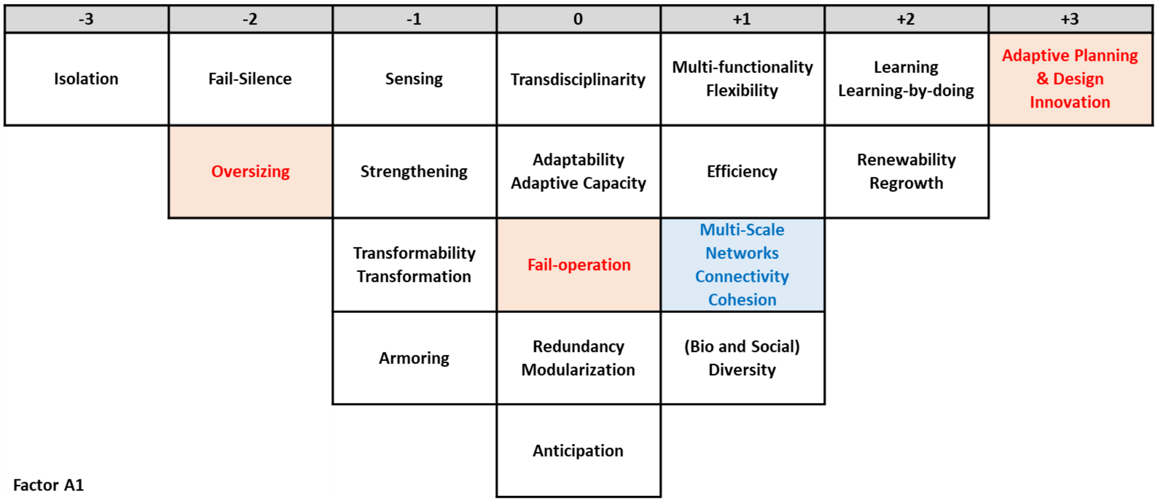
We define the single "idealized" factor for Question A as "*The Realistic Resilience Discourse*". This discourse is a general perspective on resilience for infrastructure development. We define three "idealized" factors for Question B as "*The Adaptive Infrastructure Discourse*", "*The Transformative Infrastructure Discourse*", and "*The Efficient Infrastructure Discourse*". These discourses apply resilience strategies for developing safe-to-fail infrastructure in the metro-Phoenix area. We define the two "idealized" factors for Question C as "*The Soft Infrastructure Discourse*" and "*The Hard Infrastructure Discourse*". Each considers failure consequences in the process of developing resilient infrastructure. The different numbers of "idealized" factors for each study question confirm that different decision contexts affect the variation of viewpoints in spite of applying the same Q-sample of resilience strategies. This shows the advantage of using the Q-methodology for exploring stakeholder’s diverse perspectives on applying resilience strategies to emphasize various adaptive capacities of infrastructure system. The benefit of Q-methodology for prioritization of infrastructure adaptive capacities is also demonstrated since various resilience strategies are considered constructively in relation to each other, rather than emphasize a particular resilience strategy. In comparison, traditional stakeholder study methods such as surveys only result in the popularity or importance on test variables (i.e., resilience strategies in this study) among the randomized large number of study participants. (Barry & Proops, 1999; Cuppen, Bosch-Rekveldt, Pikaar, & Mehos, 2016). In the following sections, the discourses are illustrated for each study question by interpreting both the Q-factor analysis and the discursive analysis of interview data.

5.3.1. General perspective on resilience for infrastructure development

Practitioners’ perspective on applying the concept of resilience for infrastructure development, in general, is driven by their institution’s current capabilities and needs in developing resilient systems. Among the 19 strategies, participants have a consensus on the statement of multi-scale networks/connectivity/cohesion as a moderate relevant strategy (#12, +1) to be considered across institutions and levels of government for encouraging collaboration to promote a coherent resilience strategy across interconnected systems. Creating linkages across systems to maintain functional connectivity as well as to support coordinated management and maintenance across the various levels of governing institution is observed to be relevant for promoting resilient infrastructure by practitioners.

The Realistic Resilience Discourse

This discourse is based on the perspective of promoting resilient system by pursuing new solutions for infrastructure design and management with a recognition that current systems may not be effective in responding to the changing environment with respect to urbanization, population increase, and climatic events. The “idealized” Q-sort is displayed in Figure 5.5. The Realistic Resilience Discourse embeds a strong concern that isolating the system (#9, -3) by “reducing connectivity, interdependence, functionality, and interactions among system components and between systems where those interactions already existed” is not pragmatic. As maintaining interdependency such as power-water and roadway-drainage dependencies is critical to provide reliable infrastructure services to the region, practitioners in this discourse affirm that isolating systems is not realistic.



-3	-2	-1	0	+1	+2	+3
Isolation	Fail-Silence	Sensing	Transdisciplinarity	Multi-functionality Flexibility	Learning Learning-by-doing	Adaptive Planning & Design Innovation
	Oversizing	Strengthening	Adaptability Adaptive Capacity	Efficiency	Renewability Regrowth	
		Transformability Transformation	Fail-operation	Multi-Scale Networks Connectivity Cohesion		
		Armoring	Redundancy Modularization	(Bio and Social) Diversity		
			Anticipation			

Factor A1

Figure 5.5. The “idealized” Q-sort for Factor A1: “The Realistic Resilience Discourse”. Strategy in red color presents the distinguishing statements for this factor, and strategy in blue color presents the consensus statements shared with other factors.

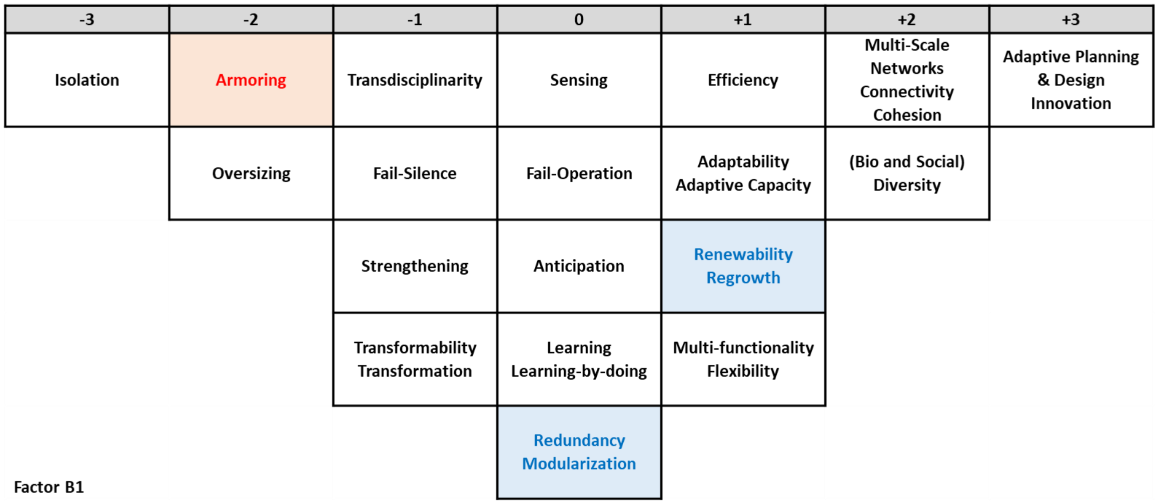
Three statements appeal to distinguish this discourse from other perspectives, namely, “adaptive planning and design innovation” (#2, +3), “fail-operation” (#7, 0), and “oversizing” (#13, -2). This discourse highlights the need for institutions to allow adaptive planning and design to innovate existing analysis, design, and implementation practices with the goal of gaining knowledge for future solutions. Practitioners in this discourse acknowledge that being dependent on standard practices is less relevant to design and mange resilient infrastructure to changing climate. This discourse emphasizes that infrastructure resilience would derive from building upon past successes and failures to infuse new knowledge into the system and to be at the forefront of technology and innovation. It also acknowledges that financial constraints are one of the biggest considerations for implementing infrastructure projects, and cannot be ignored when increasing the resilience of an infrastructure system. Encouraging innovations in design is viewed particularly positively in this discourse, because changes in design and planning occur before institutions start investing money toward a project or physically altering the infrastructure in unaccustomed ways. In the same regard, even though “oversizing” is a common strategy used to increase infrastructure capacity to deal with adverse impacts in traditional infrastructure development, it is considered a less economical solution with the recent changing risk profiles and uncertainty of future climate. Statements positioned along the neutral score such as “fail-operation”, “transdisciplinarity”, and “anticipation” are explained as strategies that practitioners have less technical or institutional capacity to implement, which also emphasizes the practicality of promoting resilience strategies for infrastructure system.

5.3.2. Application of resilience strategies for developing safe-to-fail infrastructure in the metro-Phoenix area

"Idealized" factors for Question B produce three discourses driven by practitioners' professional experience and their current role mitigating flooding risk with infrastructure development and management in the metro-Phoenix area. Among 19 strategies, participants have a consensus across three "idealized" factors on statements like "renewability/regrowth" (#15, +1) and "redundancy/modularization" (#14, 0) as moderately relevant and neutral in developing safe-to-fail infrastructure for confronting flooding issues, respectively. This consensus is attributed to the common features of current flood management solutions in Phoenix. It also demonstrates a common understanding that a "safe-to-fail" approach underscores the safe performance of infrastructure by adding multiple components for backups to provide reliable services and/or enabling the effective recovery of infrastructure from a functional failure (Ahern, 2011; Möller & Hansson, 2008).

The Adaptive Infrastructure Discourse

This discourse is based on developing safe-to-fail infrastructure for stormwater management by focusing on localized flooding in the metro-Phoenix area. The "idealized" Q-sort is displayed in Figure 5.6. This perspective aligns with the general perspective on resilience identified by "The Realistic Resilience Discourse" in Question A, but is more focused on seeking creative and unprecedented solutions for local flooding issues. Practitioners identified in this discourse suggest that creative solutions and knowledge is needed to prepare and design infrastructure for flooding caused by infrequent, but highly variable precipitation events in the area. As the impact of infrastructure failures from localized flood does not often cause fatal damages, practitioners tend to put importance on experimental strategies like "(bio and social) diversity" (#5, +2) and "multi-functionality/flexibility" (#11, +1), that may not work and require testing. Also, these strategies enable the system to adapt when flooding risk thresholds are compromised. Multiple respondents to this discourse describe their rationale for sorting strategies as associating safe-to-fail with characteristics of green infrastructure or best practices that provide solutions to localized flooding. This discourse also emphasizes the need of planning the repair and maintenance across a system's entire life span to support the infrastructure to be safe-to-fail.



-3	-2	-1	0	+1	+2	+3
Isolation	Armoring	Transdisciplinarity	Sensing	Efficiency	Multi-Scale Networks Connectivity Cohesion	Adaptive Planning & Design Innovation
	Oversizing	Fail-Silence	Fail-Operation	Adaptability Adaptive Capacity	(Bio and Social) Diversity	
		Strengthening	Anticipation	Renewability Regrowth		
		Transformability Transformation	Learning Learning-by-doing	Multi-functionality Flexibility		
			Redundancy Modularization			

Factor B1

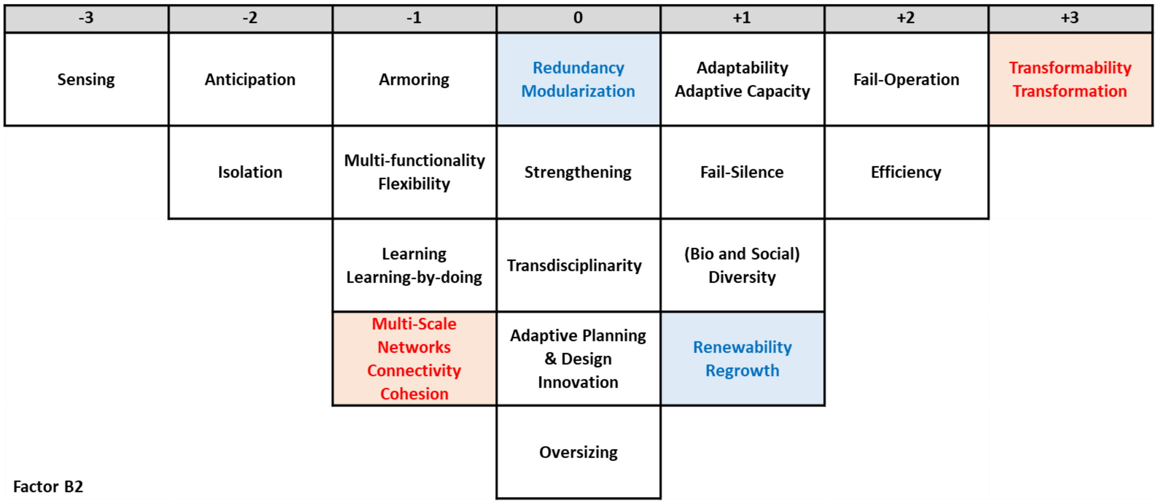
Figure 5.6. The "idealized" Q-sort for Factor B1: "The Adaptive Infrastructure Discourse". Strategy in red color presents the distinguishing statements for this factor, and strategy in blue color presents the consensus statements shared with other factors.

The adaptive infrastructure discourse finds "armoring" (#4, -2) and "isolation" (#9, -3) as unattractive and unfeasible to fund for stromwater management. Also, since stormwater systems are usually set up in accordance with other primary infrastructure (e.g., roads), it is not plausible to reduce system connectivity or add new components and functions to the existing systems. Similarly, "multi-scale networks/connectivity/

cohesion” (#12, +2) is relevant in this discourse because connectivity is not only required by physical structures, but also among the various levels of infrastructure managing institutions.

The Transformative Infrastructure Discourse

This discourse is based on developing safe-to-fail infrastructure with respect to large-scale flooding events and the rapid growth of population and cities in the metro-Phoenix area. The “idealized” Q-sort is displayed in Figure 5.7. Considering population growth in the metro-Phoenix area, participants stressed the need for “transformability/transformation” (#19, +3) strategies to develop safe-to-fail infrastructure against heavy precipitation (e.g., 100-year return period). It emphasizes a need to create an entirely new infrastructure system when existing structures are untenable, such as relocating residential areas away from the current flood hazard zone. The “fail-operation” (#7, +2) and “fail-Silence” (#8, +1) strategies are also emphasized as infrastructure systems managing large-scale floods should be designed for minimizing the impact of failures and associated damages.



-3	-2	-1	0	+1	+2	+3
Sensing	Anticipation	Armoring	Redundancy Modularization	Adaptability Adaptive Capacity	Fail-Operation	Transformability Transformation
	Isolation	Multi-functionality Flexibility	Strengthening	Fail-Silence	Efficiency	
		Learning Learning-by-doing	Transdisciplinarity	(Bio and Social) Diversity		
		Multi-Scale Networks Connectivity Cohesion	Adaptive Planning & Design Innovation	Renewability Regrowth		
			Oversizing			

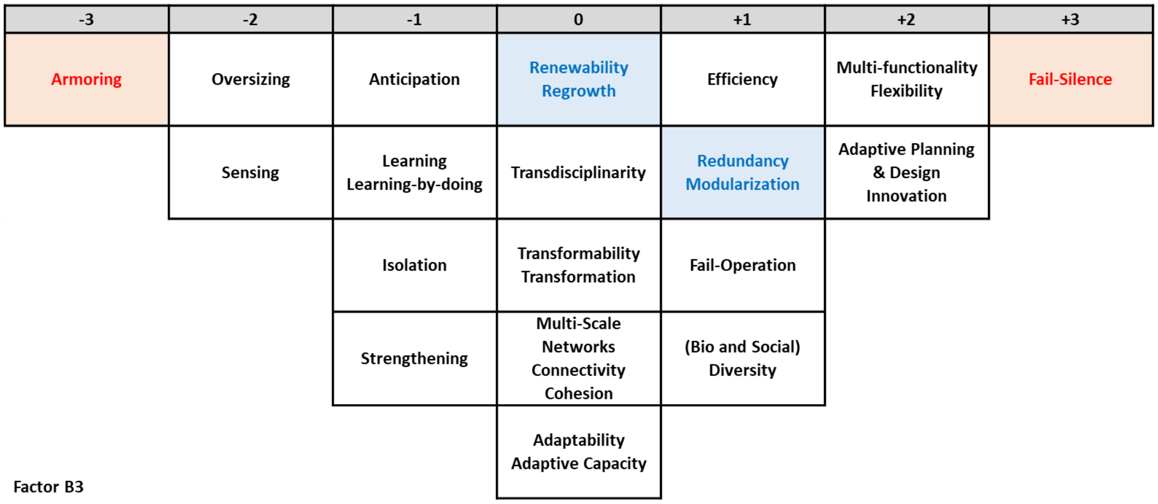
Factor B2

Figure 5.7. The "idealized" Q-sort for Factor B2: "The Transformative Infrastructure Discourse". Strategy in red color presents the distinguishing statements for this factor, and strategy in blue color presents the consensus statements shared with other factors.

In this discourse, the strategy of "oversizing" (#13, 0) receives neutral relevance for safe-to-fail, because it is an unavoidable strategy to deal with the large risks expected with climate projections. This is true even as participants recognized that oversizing and/or strengthening the infrastructure system has minimal capability to control the failure consequences when risk thresholds are exceeded. Interestingly, this discourse is distinct as "multi-scale networks/connectivity/cohesion" (#12, -1) is treated as less relevant for developing safe-to-fail infrastructure in the metro-Phoenix area when compared to other "idealized" factors. This is because large-scale flood infrastructure such as flood storage and open channel conveyance are often built and managed by the a single responsible institution and are managed under strict regulations. Thus, participants argued this makes it difficult to create or harness linkages between systems and managerial institutions.

The Efficient Infrastructure Discourse

This discourse is focuses on developing safe-to-fail infrastructure in with respect to region-wide flooding problems and current financial constraints. The "idealized" Q-sort is displayed in Figure 5.8. Viewpoints on safe-to-fail infrastructure in this discourse emphasize pragmatic solutions to mitigate flooding risks when, in the Phoenix-metro area, there is little or no attention paid to flood management. These practitioners state that there is currently a limited funding to deal with flooding issues, especially since the semi-arid region of Phoenix that experiences only infrequent flash floods. However, precipitation patterns are becoming unpredictable, making flood control a more complicated issue than in the past. Utilizing “multi-functionality/flexibility” (#11, +2) strategy that adopts “the design of systems or components with extensible functionality, capacity for reconfiguration, intertwining/combined functions, and time-shifted functions” is highly valued to prepare for unpredictable, infrequent flooding with limited budget. For example, creating green areas in existing vacant lots can promote multi-functionality, but creating a place for recreation and social cohesion during dry seasons while acting as a bioretention basin to accommodate rainfall during wet season. Notably, “fail-silence” (#8, +3) is emphasized in this discourse by highlighting the need to shut down infrastructure systems when multi-functional solutions do not work and avoid more intricate and problematic damages across various system functions.



-3	-2	-1	0	+1	+2	+3
Armoring	Oversizing	Anticipation	Renewability Regrowth	Efficiency	Multi-functionality Flexibility	Fail-Silence
	Sensing	Learning Learning-by-doing	Transdisciplinarity	Redundancy Modularization	Adaptive Planning & Design Innovation	
		Isolation	Transformability Transformation	Fail-Operation		
		Strengthening	Multi-Scale Networks Connectivity Cohesion	(Bio and Social) Diversity		
			Adaptability Adaptive Capacity			

Factor B3

Figure 5.8. The “idealized” Q-sort for Factor B2: “The Efficient Infrastructure Discourse”. Strategy in red color presents the distinguishing statements for this factor, and strategy in blue color presents the consensus statements shared with other factors.

Since funding constraints are the highest concern of this discourse, “armoring” (#4, -3) and “oversizing” (#13, -2) are perceived as the least relevant strategies for safe-to-fail infrastructure development. Multiple respondents portray these strategies as expensive solutions for the limited improvement they offer for mitigating failure.

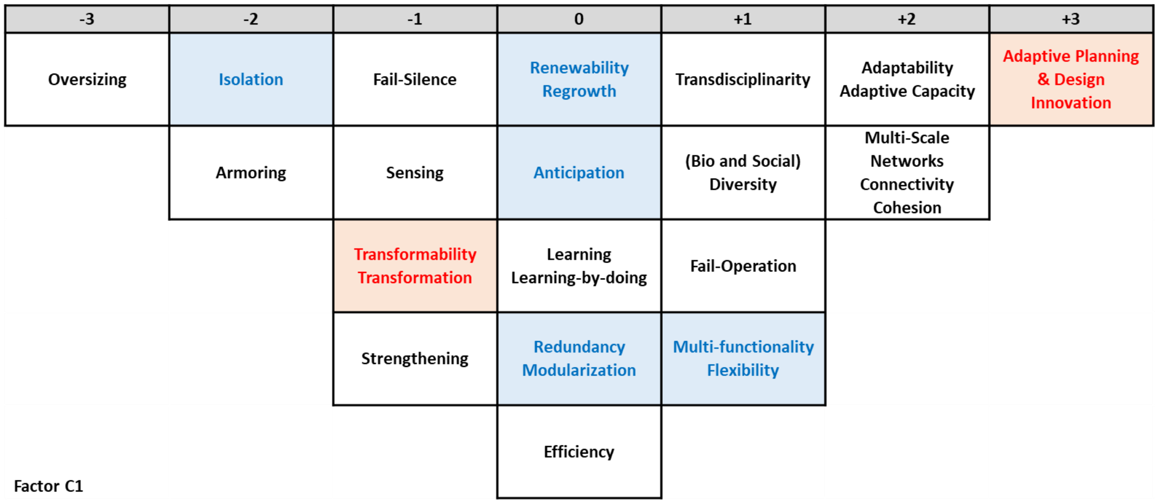
5.3.3. Considering failure consequences in the process of developing resilient infrastructure

Results of the factor analysis for Question C construct two discourses based on "idealized" factors. These discourses are driven by a participant's standpoint on failure consequences and emphasize either soft or hard infrastructure solutions. Soft infrastructure encompasses knowledge systems, humans, institutions, and policies such as communication among institutions, rules and regulations governing the various infrastructure system, design specification, the financing of systems, and professionals managing infrastructure. Hard infrastructure refers to physical systems that are built and engineered. In the case of Hurricane Harvey in Houston, Texas used to form Question C, the failure of infrastructure systems and resulting consequences exemplify problems that can be solved both by soft and hard infrastructure. These include insufficient information on climatic conditions that exacerbate the damage caused by heavy rainfall, infrastructure systems built without considering pre-existing topographical characteristics of city, path-dependent infrastructure management practices, malfunctioning infrastructure, and a lack of funding for upgrading the infrastructure systems, among others.

There is consensus across the two discourses on strategies like "renewability/regrowth" (#15, 0), "redundancy/modularization" (#14, 0), "anticipation" (#3, 0), "multi-functionality/flexibility" (#11, +1), and "isolation" (#9, -2). This is attributed to the broad applicability of these strategies in both in soft and hard infrastructure solutions for #3, #11, #14, and #15. Strategy #9 is perceived as a less promising strategy for the Houston case, as isolated bayous were identified by participants as ineffective for isolating flood retention basins from residential areas.

The Soft Infrastructure Discourse

This discourse focuses on addressing failure consequences by enhancing soft infrastructure solutions in the infrastructure development process. The "idealized" Q-sort is displayed in Figure 5.9. These participants emphasize that the major problem in Harvey appeared to be a lack of planning and a poor understanding of what the actual flooding risks were. In Houston, the actual risks were damages experienced by overflow from the bayous and waterways in nearby neighborhoods. While the same physical infrastructure such as bayous and waterways were constructed and widened as the flood hazard zone expanded, when the capacity of these structures was exceeded during Hurricane Harvey, nearby neighborhoods were flooded. This discourse recognizes a stagnant flood mitigation strategy focused on built systems was ineffective for minimizing consequences, and suggests resilience requires practitioners to come up with new solutions by promoting "adaptive planning and design innovation" (#2, +3). This is primarily achieved with soft infrastructure solutions that create greater recognition of flooding risks with sufficient climate data and past experiences, e.g., by working with community members to inform about risks of living in flood hazard zones or by allocating funds in various attributes of infrastructure.



-3	-2	-1	0	+1	+2	+3
Oversizing	Isolation	Fail-Silence	Renewability Regrowth	Transdisciplinarity	Adaptability Adaptive Capacity	Adaptive Planning & Design Innovation
	Armoring	Sensing	Anticipation	(Bio and Social) Diversity	Multi-Scale Networks Connectivity Cohesion	
		Transformability Transformation	Learning Learning-by-doing	Fail-Operation		
		Strengthening	Redundancy Modularization	Multi-functionality Flexibility		
			Efficiency			

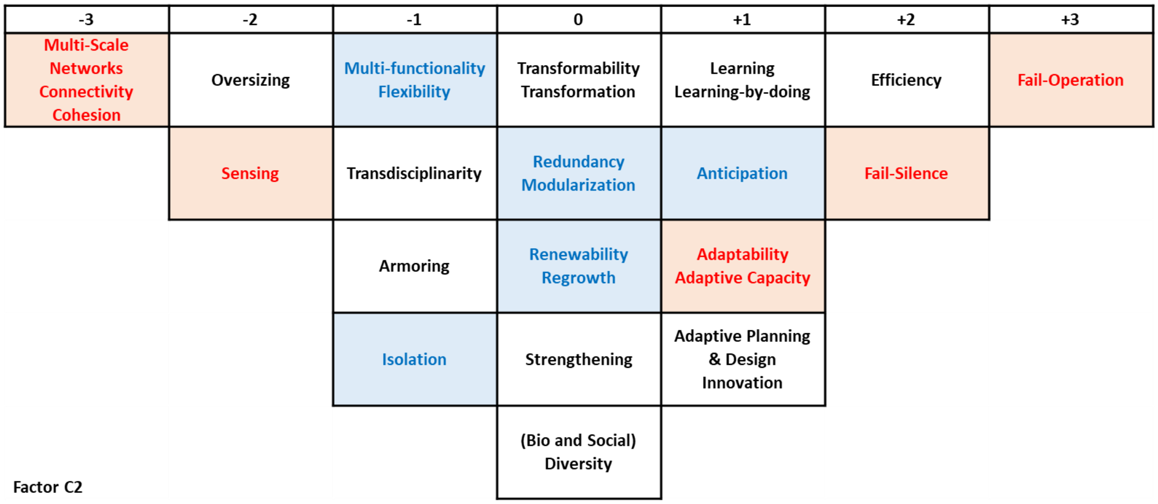
Factor C1

Figure 5.9. The "idealized" Q-sort for Factor C1: "The Soft Infrastructure Discourse". Strategy in red color presents the distinguishing statements for this factor, and strategy in blue color presents the consensus statements shared with other factors.

This discourse considers "transformability/transformation" (#19, -1) as particularly less relevant for dealing with failure consequences, since changes in knowledge systems institutions, regulations, and policy usually take a longer time to be implemented to lead to changes in physical systems.

The Hard Infrastructure Discourse

This discourse focuses on addressing failure consequences by remedying past failures and improving existing hard infrastructure solutions during the infrastructure development processes. The "idealized" Q-sort is displayed in Figure 5.10. Respondents in this discourse focus on how to better design and manage physical infrastructure systems to avoid the catastrophic failure of system. Participants in this group highlight "fail-operation" (#7, +3) and "fail-silence" (#8, +2) as the most relevant strategies in developing hard infrastructure system that would not forfeit nearby neighborhoods nor other connected infrastructure systems by shutting down physical systems and maintaining their critical function despite component failures.



-3	-2	-1	0	+1	+2	+3
Multi-Scale Networks Connectivity Cohesion	Oversizing	Multi-functionality Flexibility	Transformability Transformation	Learning Learning-by-doing	Efficiency	Fail-Operation
	Sensing	Transdisciplinarity	Redundancy Modularization	Anticipation	Fail-Silence	
		Armoring	Renewability Regrowth	Adaptability Adaptive Capacity		
		Isolation	Strengthening	Adaptive Planning & Design Innovation		
			(Bio and Social) Diversity			

Factor C2

Figure 5.10. The "idealized" Q-sort for Factor C2: "The Hard Infrastructure Discourse". Strategy in red color presents the distinguishing statements for this factor, and strategy in blue color presents the consensus statements shared with other factors.

Notably, this discourse considers on "multi-scale networks/connectivity/cohesion" (#12, -3) and "sensing" (#16, -2) as less relevant than other factors. Creating more connected and interdependent system would inherently make the management of a system more difficult, especially in situations that requires shutting down failing systems. Also, hard infrastructure is often built in accordance with design specification and regulations to last for a long time with less flexibility, thus improving the capacity to sense new stresses and incorporate new risk information in infrastructure design decisions is challenging.

5.4. Conclusion

By engaging with practitioners at state, regional, and municipal governments, this study demonstrates how practitioners view resilience and its associated strategies as important means to develop safe-to-fail infrastructure and tackle climate risks. More importantly by using the Q-methodology, we can understand how they arrive at their conclusions. A certain definition of resilience does not neatly describe the importance or relevance of practical regimes nor there is a standalone perspective that fits in all contexts. From the diverse perspectives on resilience observed in this study, practitioners' interpretation of resilience adds value to the literature for understanding why different resilience strategies may be preferred in different decision contexts. Practitioner perspectives further reveal that decision considerations such as intensity of the event, identified system vulnerability, and the extent of institutional, social, physical and financial capacity to withstand infrastructure failure all affect infrastructure development and management decisions. They put different importance on various resilience strategies, even when considering the same city for the same weather risk (i.e., flooding).

This study also confirms several benefits of using Q-methodology to engage with stakeholders for developing safe-to-fail infrastructure. Firstly, there are a limited number of practitioners at city, regional, and state governments who directly influence decisions for infrastructure development. Where R-methodology (e.g., surveys and questionnaires) usually requires a large sample size to make statistically meaningful results, Q-methodology only requires few respondents who are of most associated to the topic. Also, Q-methodology shows the variety of perspectives among participants through the valuation of all statements presented, rather than focusing on few, isolated statements in R-methodology. This facilitates incorporating multiple resilience strategies in infrastructure development by observing valuable expert knowledge held in few, critical perspectives, instead of identifying popular resilience strategies among many respondents. Secondly, Q-methodology can support safe-to-fail infrastructure development where a diversity of infrastructure failure consequences must be prioritized by decision-makers. Q-methodology is designed in a way that respondents must evaluate all the given statements in relation to each other and force making trade-offs in prioritizing one statement over the other. While this study uses Q-methodology to prioritize resilience strategies, it can also be used to prioritize various types of failure consequences and costs in development. This may reveal how stakeholders consider both tangible and intangible costs experienced when infrastructure fails, and provide a means to achieve safe-to-fail development.

CHAPTER 6

CONCLUSION

This dissertation contributes to identifying ways to overcome significant limitations in current infrastructure development practices for establishing a decision context; identifying, analyzing, and evaluating risks; choosing a risk management solution; and guiding a system design that acknowledges infrastructure failure caused by non-stationary climate risks. In current infrastructure development, there is no working definition of safe-to-fail that guides decision-makers to establish a decision context for risk management considering both climate hazards and infrastructure failure consequences. Risks are only evaluated with frequency and intensity of a weather event itself, without considering possible failure consequences that can be experienced in various forms. Also, infrastructure hazards and risks are often identified early in the development process based on historical observations to make the most accurate estimation of necessary risk threshold for creating fail-safe infrastructure systems. The adaptive capacity of infrastructure systems to mitigate risks is often ignored when choosing infrastructure solutions, since current development decisions only focus on choosing systems that reliably operate within a calculated risk threshold. Once the type of infrastructure solution is chosen, the system is designed to satisfy design codes and regulations and to persist for a long time. However, infrastructure risk models, solutions, design codes, and regulations rarely update and often do not reflect the rich knowledge of diverse and regional infrastructure experts, including engineers, planners, policymakers, and climate risk scientists. Incorporating a diversity of expert knowledge in infrastructure development may provide new and useful information about how different adaptive capacities of infrastructure need be emphasized in tackling risks to complement existing infrastructure systems, responsible institutions, vulnerable populations, and funding availability among other considerations.

This dissertation addresses these limitations by promoting safe-to-fail infrastructure development. Chapter 2 provides a new definition of safe-to-fail and demonstrates what decisions are needed and how to address the infrastructure failure in identifying and analyzing risk. It further reveals the decision dilemma of the "infrastructure trolley problem" that requires decisions made by prioritizing the various failure costs infrastructure systems may experience and/or cause. Chapter 3 presents a method to evaluate the risk of infrastructure failure with consideration of climate change impacts, which helps the prioritization of future failure costs. Chapter 4 identifies resilience strategies that characterize and compare the adaptive capacity of diverse infrastructure solutions and applies multi-criteria decision analysis to prioritize infrastructure solutions for managing roadway flooding in Phoenix, Arizona. Chapter 5 proposes to engage with regional practitioners to identify how they interpret resilience strategies and apply them in safe-to-fail infrastructure development based on their professional experience. It further identifies how a practitioners' perspective of safe-to-fail varies when reflecting upon current capacity of their expert region to adapt to non-stationary climate and associated risks. Practitioner perspectives are distinguished from and more nuanced than dominant safe-to-fail perspectives proposed in research literature. The findings of each chapter articulate additional decision considerations, tools, and strategies for safe-to-fail infrastructure development in the following ways:

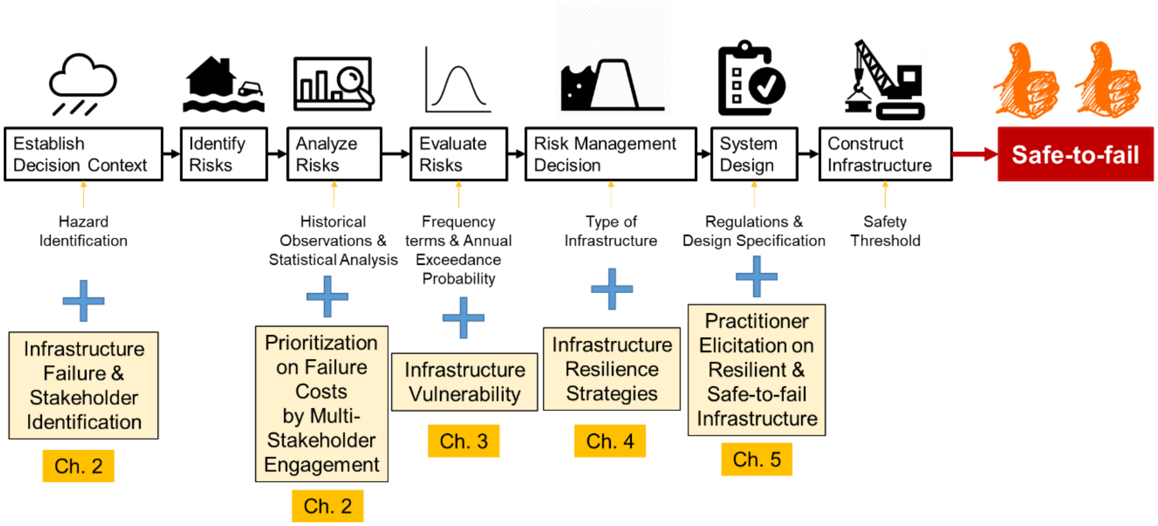


Figure 6.1. Novel safe-to-fail infrastructure development with the highlighted key contributions of this dissertation

- Summary of Chapter 2: Safe-to-fail infrastructure development requires a broader scope of knowledge to address the decision dilemma called the *infrastructure trolley problem* than current fail-safe practice. The development process needs to consider context specific information including existing infrastructure services, social vulnerability, different types of failure cost, and institutional adaptation capacities among others. One approach to address the decision dilemma in safe-to-fail infrastructure development is to engage multiple stakeholders, including decision makers and community members to determine the prioritization for the acceptable consequences of infrastructure failure and their associated costs.
- Summary of Chapter 3: The consequences of infrastructure failure are demonstrated by evaluating the impact of storm drainage failure on interconnected roadway systems. Infrastructure vulnerability assessment provides useful information to identify and estimate infrastructure failure consequences

when both infrastructure system services (e.g., mobility for roads) and the intensity of extreme weather events are considered together. Furthermore, assessment of infrastructure failure impacts provides useful information for prioritizing various failure costs.

- Summary of Chapter 4: Safe-to-fail adaptation offers one approach to develop infrastructure systems based on their adaptive capacity, by focusing attention on specific resilience strategies for managing the consequences of infrastructure failure. Diverse perspectives on safe-to-fail lead to discrete infrastructure solution recommendations. Multi-criteria decision analysis (MCDA) is an effective way to guide safe-to-fail infrastructure development decisions by systematically organizing decision criteria and providing a means to combine disparate information, including resilience strategies, infrastructure vulnerability assessments, and decision-maker preference on different safe-to-fail approaches.
- Summary of Chapter 5: Current definitions of resilience and safe-to-fail do not neatly conform to regional needs for practical implementation in infrastructure development. Instead, incorporating stakeholders’ knowledge in determining what constitutes safe-to-fail infrastructure is critical in evaluating a region’s capacity to endure infrastructure failure consequences. Practitioner perspectives reflect the extent of institutional, social, physical, and financial capacities within a region and highlight nuanced resilience and safe-to-fail strategies for managing infrastructure failure not considered in the literature. This contributes to broad understanding of how practitioners apply the theoretical concept of resilience in climate change adaptation practices.

This dissertation introduces new decision-making issues that change infrastructure development practices and suggest limitations to the implementation of safe-to-fail theory. Safe-to-fail infrastructure systems are now defined as those designed to lose function in controlled ways, such that infrastructure failure consequences are experienced based on prioritized decisions even when risk thresholds are exceeded in unpredictable hazards. New definition of safe-to-fail brings with it decision dilemmas associated, infrastructure vulnerabilities, resilience strategies, and multi-stakeholder engagement needs. Several questions for constructing and operating safe-to-fail infrastructure still need to be answered with future studies, including (but not limited to): 1) who is responsible for the decisions made for prioritizing failure consequences?; 2) who needs to be included in stakeholder engagement for prioritizing failure consequences and determine the appropriate extent of stakeholders in addressing the infrastructure trolley problem?; and 3) what regulations are needed to implement safe-to-fail infrastructure approach in practice and how will the role of institutions change to adapt to the new infrastructure development practice?

Who is responsible for the decisions made for prioritizing failure consequences? With the necessity for considering failure consequences in safe-to-fail infrastructure development, practitioners will need to make decisions that determine whom, where, and why people and infrastructure systems experience certain failure outcomes. Current infrastructure development decisions are made to protect a city against predicted climate risks, rather than to experience the outcomes of failures. In a sense, these decisions allow decision-makers and practitioners to transfer the responsibility of failing infrastructure systems to those that own, operate, or use them. Safe-to-fail infrastructure development, instead, limits this transfer of risk, raising questions regarding to what extent practitioners should bear the infrastructure failure consequences. The amount responsibility that practitioners and decision-makers have for infrastructure failure outcomes is unclear. Do decision-makers take full responsibility or the stakeholders also take the responsibility for infrastructure failures if they were informed during development and knew of possible consequences? An example from the Mississippi river floods in 2011 shows that this transfer of risk attributes to longer decision-maker involvement and legal issues post-infrastructure failure.

Heavy rainfall in 2011 jeopardized thousands of homes in the populated area of Cairo, Illinois and with the risk of flooding. The U.S. Army Corps of Engineers (USACE) was granted a permission from the U.S. Supreme Court to blow up a part of levee and direct flood water into New Madrid Flood Plain (USACE, 2011). This decision made by USACE saved the city of Cairo and nearby areas from catastrophic flood damages, but it damaged farmlands located within the flood plain. Even though this decision is considered “safe-to-fail” operation of the levee system by prioritizing the human and property loss in a populated area over the economic loss of the flooded farmland, USACE was subjected in legal charges by farmers with the claim that the decision of levee breach violated the farmers' rights by taking their land without adequate compensation. This example demonstrates that safe-to-fail infrastructure decisions will challenge decision-makers and practitioners to have the extended responsibility for managing infrastructure failure consequences.

Who needs to be included in stakeholder engagement for prioritizing failure consequences and determine the appropriate extent of stakeholders in addressing the *infrastructure trolley problem?* The work of this dissertation emphasizes the importance of engaging with multiple levels of stakeholders for making safe-to-fail infrastructure decisions. While tangible costs of infrastructure failure like property loss can be easily assumed in absolute economic terms, additional cost categories considered in safe-to-fail infrastructure development are not easily captured without the inclusion of broad stakeholder opinion. Infrastructure failure consequences such as people displaced, homelessness, livelihood damaged, increased unemployment, environmental losses, and health impacts may be experienced in relative ways depending on the affected stakeholders' different capacity to respond and adjust to each adverse impact. Thus, another challenge for addressing the infrastructure trolley problem is social equity in risk mitigation. People affected by development decisions must be represented and informed in the decision-making process to prioritize "safe" infrastructure failure consequences. The extent of stakeholder engagement dictates the extent that infrastructure failures are understood and planned for. For example, if stakeholder engagement is not effective at including vulnerable populations who have a lower capacity to respond to health issues or unemployment caused by infrastructure failures, then cost prioritization decisions may make the same people more vulnerable to planned failures. In contrast, complete stakeholder engagement is untenable in most cities with large, diverse populations. Thus, an exhaustive study of how to engage and involve various stakeholders in safe-to-fail infrastructure development is necessary to address the infrastructure trolley problem.

What regulations are needed to implement safe-to-fail infrastructure approach in practice and how will the role of institutions change to adapt to the new infrastructure development practice? Regulations that govern infrastructure systems may need to change to reflect this new safe-to-fail design and development. Whereas current infrastructure regulations focus on system construction and maintenance, safe-to-fail regulations may also require additional rules for sharing generally proprietary information with broader stakeholders. For example, safe-to-fail development may require sharing of data on infrastructure performance, decision criteria for prioritizing the failure costs, protocols for emergency system operation, and compensation of failure consequences. Furthermore, these changes in regulation will require changes in the role of institutions like governmental organizations, utilities, and insurance companies perform in infrastructure development, operation, and regulation. For example, one regulatory shift that promotes safe-to-fail development is for city governments to require insurance companies to provide accumulated information on infrastructure risks and damages experienced in the region. This information can be shared with the city government and the affected stakeholders to assess the current adaptive capacity based on the empirical data.

Each of these questions represent limitations in the current work that must be overcome with future evidence-based case studies to advance safe-to-fail infrastructure development. Real-world case studies are particularly valuable for identifying the transfer of risk, the extent of stakeholder engagement, and the changes to existing institutions necessary to promote a safe-to-fail approach. Moreover, future case studies offer a way to compare and categorize the regional, institutional, social, infrastructural, ecological capacity achieved by resilience strategies identified in this dissertation and relate them to various types of consequences experienced by infrastructure failure. Linking this prospective approach with current retrospective practices may offer a systematic and comprehensive decision protocol for fail-safe and safe-to-fail infrastructure development.

In conclusion, this dissertation represents important first steps towards safe-to-fail infrastructure development. The literature now has an operational definition of safe-to-fail infrastructure that acknowledges infrastructure failures in the development process and requires prioritization of infrastructure failure consequences. This urges decision-makers to address infrastructure trolley problem of whom is affected by failure consequences and explicitly embed their resilience concepts and strategies in decision-making process with their context-specific knowledge. Thus, multi-stakeholder engagement is a key element to encourage stakeholders to identify regional, institutional, financial, physical, and social capacity to withstand infrastructure failure. Future work should identify to what extent decision-makers bear infrastructure failure risks, stakeholders should be engaged, and regulations and institutions must change to accommodate this new theory and perspective.

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APPENDIX A

CO-AUTHOR AUTHOR PERMISSION FOR PUBLISHED MATERIAL

Each chapter based on published, in review, or in preparation material lists the order of co-authors and proper citation. All co-authors have granted permission for use the material in this dissertation.