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Fail-safe and safe-to-fail adaptation: decision-making for urban flooding under climate change

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Abstract As climate change affects precipitation patterns, urban infrastructure may become more vulnerable to flooding. Flooding mitigation strategies must be developed such that the failure of infrastructure does not compromise people, activities, or other infrastructure. "Safe-to-fail" is an emerging paradigm that broadly describes adaptation scenarios that allow infrastructure to fail but control or minimize the consequences of the failure. Traditionally, infrastructure is designed as "fail-safe" where they provide robust protection when the risks are accurately predicted within a designed safety factor. However, the risks and uncertainties faced by urban infrastructure are becoming so great due to climate change that the "fail-safe" paradigm should be questioned. We propose a framework to assess potential flooding solutions based on multiple infrastructure resilience characteristics using a multi-criteria decision analysis (MCDA) analytic hierarchy process algorithm to prioritize "safe-to-fail" and "fail-safe" strategies depending on stakeholder preferences. Using urban flooding in Phoenix, Arizona, as a case study, we first estimate flooding intensity and evaluate roadway vulnerability using the Storm Water Management Model for a series of downpours that occurred on September 8, 2014. Results show the roadway types and locations that are vulnerable. Next, we identify a suite of adaptation strategies and characteristics of these strategies and attempt to more explicitly categorize flooding solutions as "safe-to-fail" and "fail-safe" with these

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characteristics. Lastly, we use MCDA to show how adaptation strategy rankings change when stakeholders have different preferences for particular adaptation characteristics.

1 Introduction

1.1 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 US cities continue to grow by altering landscapes, increasing impervious areas, and building more civil infrastructure, roadways in particular are becoming increasingly vulnerable to urban flooding (Meyer et al. 2013; Revi et al. 2014). Several climate studies predict that the US Southwest—spanning Arizona, New Mexico, Utah, Nevada, and California—may be hotter and drier in the twenty-first century (e.g., Seager et al. 2007) and that precipitation may occur in more intense bursts (Hunt and Watkiss 2011).

The vast majority of urban growth in the US is asphalt and concrete-based "gray infrastructure," such as roads, buildings, and parking lots (Brown et al. 2014; Wilbanks and 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 infrastructure, and cause service disruptions to communities and businesses (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 et al. 2012).

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 et al. 2012; Garfin et al. 2013; Hawkins et al. 2015; Piras et al. 2016), (ii) estimate the risk of urban flooding (Ashley et al. 2005; Wilbanks and Fernandez 2014), (iii) assess the impact of climate change and flooding on urban infrastructure (Schmitt et al. 2004; Suarez et al. 2005; Kirshen et al. 2008; Semadeni-Davies et al. 2008; Chang et al. 2011; Willems et al. 2012; Sayers et al. 2012; Meyer et al. 2013), (iv) suggest adaptation strategies for urban areas (Arnbjerg-Nielsen and Fleischer 2009; Keath and Brown 2009; Liao 2012; Wilby and Keenan 2012; Fratini et al. 2012; Salinas Rodriguez et al. 2014), and (v) improve infrastructure design (CIRIA 2014; Liu et al. 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 the failure. 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 and Rosenzweig 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-h) resolutions, which are not commensurate for hydrological analysis in small watersheds (Willems et al. 2012; Piras et al. 2016). Downscaling techniques at the regional scale have been developed to improve climate model resolution (Skamarock et al. 2012; Wilby and Dawson 2013) and adopted in impact studies (Piras et al. 2016). Still, these estimates of future changes in precipitation extremes are highly uncertain and provide limited support to future infrastructure design (Hunt and Watkiss 2011). Furthermore, there is the issue of cascading uncertainties introduced with each model, from emissions scenarios to the hydrological models used to determine impacts (Wilby and 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.

1.2 "Safe-to-fail" and "fail-safe" infrastructure

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 and 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 infrastructure with low probability of failure, instantiated for decades, and oversized to handle unforeseen threats. Common examples of these types of infrastructure 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 (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 (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 infrastructure 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 (Park et al. 2013; Eisenberg et al. 2014; Linkov et al. 2014). 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. A "safe-to-fail" design strategy embraces the inevitability of unforeseen extreme weather by centering design decisions on urban resilience—the adaptive capacity of the urban system (Meerow et al. 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 the following:

- Focusing on maintaining system-wide critical services instead of preventing component failure (Möller and Hansson 2008).
- Minimizing the consequences of the extreme event rather than minimizing the probability of damages (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 (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 adaptive capacity of systems than risk-based approaches, including preserving ecosystem services, providing social equity, enabling innovation, and improving catastrophe response processes.

We use the city of Phoenix and its roadways as our case study location (Fig. 1). 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

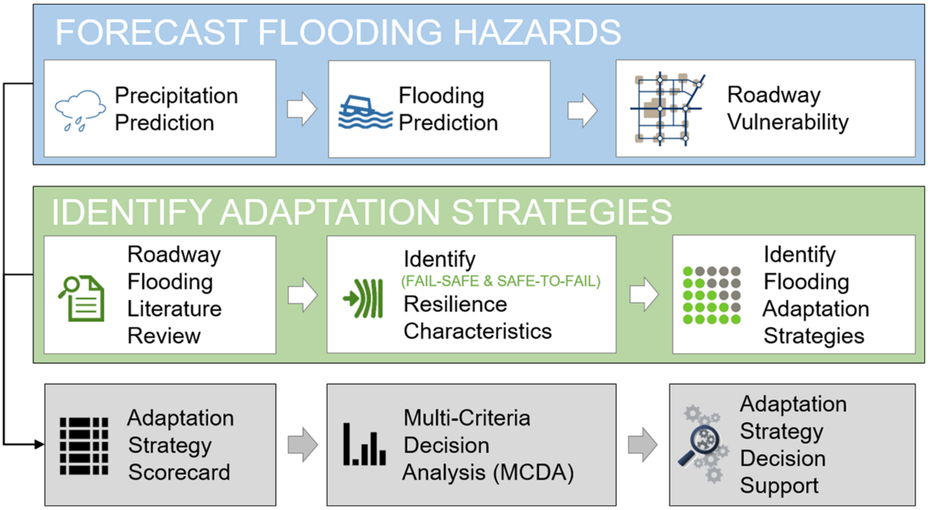

Fig. 1 A schematic diagram of the integrated "safe-to-fail" infrastructure adaptation framework. The framework combines multiple assessments, including flooding simulation, infrastructure vulnerability assessment, and multi-criteria decision analysis (MCDA) supporting adaptation strategy decision-making

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? 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.

2 Methodology

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" (Seager 2008; Park et al. 2013) 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.

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. 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 (Supplementary Material Fig. 1). 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 83.8 mm over 24 h (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.

2.2 Flood estimation and roadway vulnerability evaluation

2.2.1 Climate change and stormwater drainage modeling

We performed a flood estimation 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 conditions (blue box in Fig. 1). The aforementioned 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-h storm events, was used as a test case (FCDMC 2014). We collected hourly rainfall observations over 24-h 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 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 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-h 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. The detailed description of the methodology adopted to apply SWMM-CAT and SWMM can be found in the Supplementary Material.

2.2.2 Roadway 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.

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 (Rossman 2015). From this information, we identified roadway segments that were connected within 1-km 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, US 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 risk and flooding consequences (i.e., level of service), respectively.

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. In total, we reviewed 26 climate change case studies and 10 articles on "fail-safe" and "safe-to-fail" concepts. From the articles reviewed, we found a total of 19 unique "fail-safe" and "safe-to-fail" 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 (see the Supplementary Material).

2.4 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 Fig. 1). AHP is a MCDA method that compares 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 et al. 2005). 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 (see also the Supplementary Material).

Weighting factors introduced represent Phoenix roadway vulnerability and “safe-to-fail” preferences for solution comparison. 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 et al. (2014) and Park et al. (2011, 2013) to demonstrate how differing “safe-to-fail” perspectives may change recommended solutions. Both Ahern et al. and Park et al. offer multiple contrasting “safe-to-fail” perspectives that emphasize different design strategies and solution characteristics. For example, the work developed by 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. (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 as follows:

- 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., multi-functionality, 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 et al. 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 (see also the Supplementary Material for resilience characteristics associated with each perspective). 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; thus, we weighted these five characteristics equally (0.20). Using the AHP algorithm, we calculated the score of each roadway flooding solution for a given characteristic (e.g., multi-functionality) 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.

3 Roadway flooding and vulnerability results

3.1 Flooding intensity and impacts on road infrastructure

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 (see the Supplementary Material). 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 infrastructure 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.

3.2 Roadway flooding vulnerability

The roadway segment-specific vulnerabilities for the event of September 8, 2014, are mapped for the city of Phoenix in Fig. 2. 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.

4 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 1 presents the top five solutions for Phoenix roadway flooding for the seven adaptation perspectives based on MCDA.

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 (Table 1). This suggests that these nine are the most relevant in regions like Phoenix, where future flooding

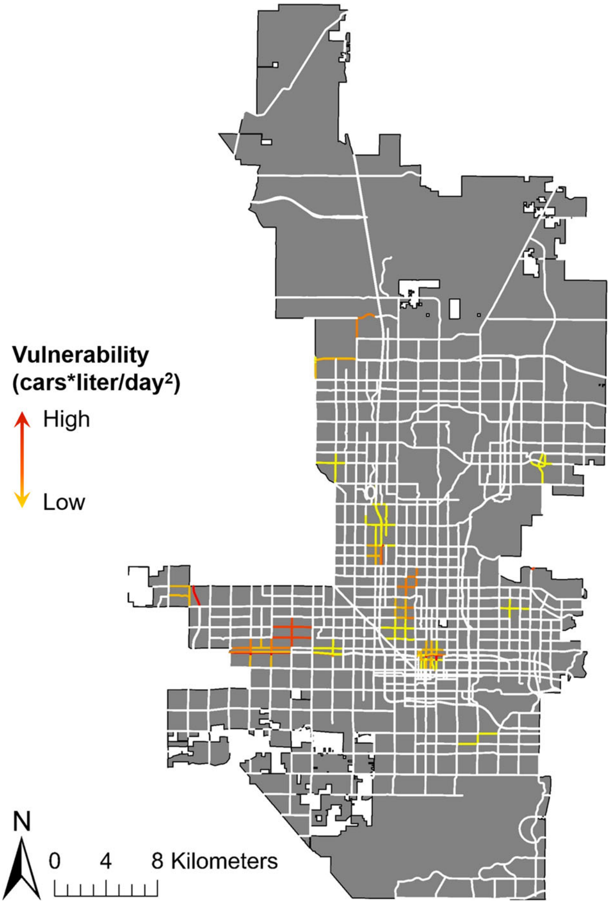

Fig. 2 Map of Phoenix roadways vulnerability to flooding for the event of September 8, 2014. Red networks are the most vulnerable roads in terms of daily traffic loads and flooding volume. White coded roads are identified as being unlikely affected by drainage flooding

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

Table 1 Top five roadway flooding solutions for Phoenix, Arizona

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 conveyence	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 conveyence	Flood storage	Vegetation management	Flood storage	Vegetation management
5	Discouraging subsidence	RWIS	Discouraging subsidence	Vegetation management	Discouraging subsidence	Activated floodway	Relocate service buildings

RWIS: Modernized roadway weather information system 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.

5 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 are easily interpreted as "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). We propose that "safe-to-fail" infrastructure is 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 (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

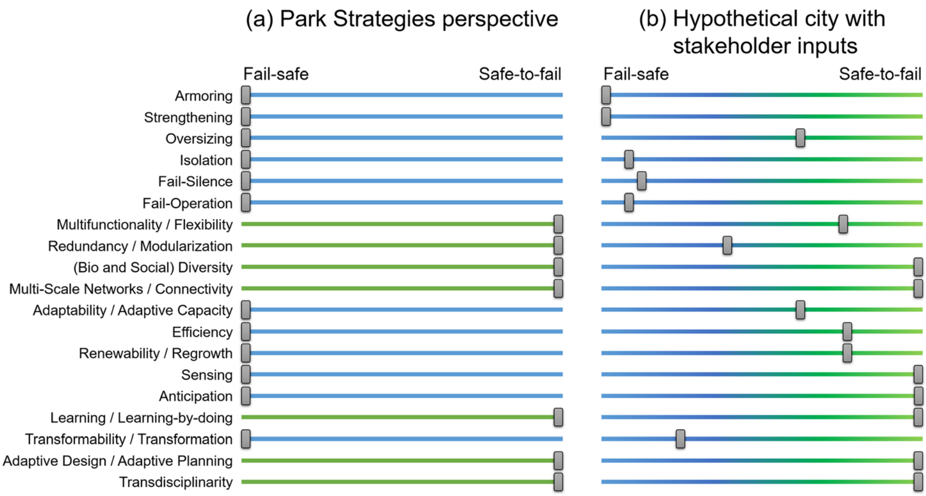

Fig. 3 The infrastructure resilience strategies and their sliding scales from "safe-to-fail" to "fail-safe." **a** The sliders representing the Park strategies perspective for Phoenix evaluated in this study considers "safe-to-fail" and "fail-safe" as binary categories (blue and green in colors). **b** 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

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 (Park et al. 2011).

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 (Fig. 3). For instance, "oversizing" is described as a "fail-safe" infrastructure characteristic based on the Park strategies perspective (Fig. 3a), 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 (Fig. 3b), 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 infrastructure 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.

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