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Re-imagining design storm criteria for the challenges of the 21st century

Samuel A. Markolf[a,*], Mikhail V. Chester[a], Alysha M. Helmrich[a], Kelsey Shannon[b]

[a] School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ, USA
[b] Department of Physics, Florida International University, Miami, FL, USA

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ABSTRACT

Design storm criteria (i.e., the specific intensity and/or frequency to which infrastructure systems are designed to withstand) are a critical part of resilience efforts within urban and infrastructure systems. However, factors like climate change and increasing complexity within our urban systems call into question the viability of current approaches to and implementation of design storm criteria moving forward. This paper seeks to identify design practices and strategies that are well-suited for the increasingly complex and rapidly changing contexts in which our cities and infrastructure are operating. We posit that the advancement of a multi-scalar perspective on resilience will be increasingly necessary in response to the growing challenges our cities and infrastructure face. At the scale of single components/sub-systems, return periods (or similar criteria) will likely remain a necessary element of the design process. At the scale of the entire system(s), approaches like *safe-to-fail*, *robust decision making*, and enhanced sensing and simulation appear well suited for complementing existing approaches by more explicitly considering failure consequences in the design and management processes. Ultimately, this paper seeks to spur continual research and advancement of these topics in order to facilitate the evolution of the design storm process for an increasingly complex and non-stationary world.

1. Introduction

Recent catastrophic events like recurring floods in Houston, Texas and Maryland (Ellicott City and Baltimore), as well as the large-scale levee breaches and over-topping throughout the Midwestern United States (Nebraska, Missouri, South Dakota, Iowa, and Kansas) highlight the continual challenge that extreme precipitation and weather events continue to pose to our urban and infrastructure systems. A key element underlying these perpetual challenges is the design storm criteria (i.e., the specific intensity and/or frequency) to which our infrastructure systems are designed to withstand. In particular, one might call into question whether current design storm criteria are suitable for an era of increasing complexity, uncertainty, and climatic flux. Over the past few decades (and even more so recently), design storm criteria have faced growing inspection and examination related to the efficacy of various approaches and assumptions inherent in the process—especially in regards to the use of sometimes incomplete or inconsistent historical data (Adams et al., 1986; Adams & Howard, 1986; Harvey & Connor, 2017; Hirabayashi et al., 2013; Koerth-Baker, 2017; Packman & Kidd, 1980; Watt & Marsalek, 2013). For example, previous design storm efforts have been built on the implicit or explicit assumption of a stationary climate (i.e., a climate where past trends and data are indicative of future conditions). However, increased variability and intensity of extreme events as a result of climate change directly challenge assumptions of stationarity in design storm criteria (Milly et al., 2008). Despite rising scrutiny and concern over design storm criteria, a clear pathway forward does not appear to have yet emerged. Thus, in an attempt to continue to spur the evolution of design storm thinking and criteria in an age of non-stationary and complexity, this paper explores the history and some of the challenges facing design storm criteria (including climate change, as well as growing complexity and interconnectedness among infrastructure and social systems), and discusses some possible alternatives and complements to the existing approach.

Typically, design storms have been defined almost exclusively in the context of stormwater management or flood control, referring to the "rainfall amount and distribution in space and time, used to determine a design flood or design peak discharge," (American Meteorological Society, 2012). Design storms for extreme precipitation and stormwater (as well as wind and snow on occasion), are often expressed in terms of a return period such as a "10-year" or a "100-year" storm event. However, other terms such as *probable maximum*, *worst case*, *worst likely*, *previous worst experience*, or *extreme storm volume* are also used in the context of infrastructure design for extremes. Under the "return-period" nomenclature, the probability of a specific event (e.g., rainfall or flood)

* Corresponding author at: School of Sustainable Engineering and the Built Environment, Arizona State University, 660 S. College Avenue, Tempe, AZ 85281, USA.
E-mail address: smarkolf@asu.edu (S.A. Markolf).

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occurring in a given year is determined by taking the inverse of the return period: for example, the annual probability of a 10-year storm is 1-in-10 (10% or 0.10), and the probability of a 100-year storm is 1-in-100 (1% or 0.01). Regulations frequently encode the design storm required for stormwater and flood control infrastructure (shortened to *flood control infrastructure* for the duration of the article) in terms of a return period or duration (e.g., U.S. EPA, 2011; Flood Control District of Maricopa County, 2013).

Given that design storm criteria predominantly apply to stormwater infrastructure and flood management, this paper primarily focuses on flood control infrastructure. Focus on these particular infrastructures is based on two criteria. First, the history, implementation, and evolution of design storm criteria for flood control infrastructure are ripe for critical examination and exploration (see Sections 2 and 4). Second, unlike most other infrastructure systems, hazard mitigation is the primary service of flood control infrastructure (see Table 1). Therefore, any critical examination of and improvements to the design and implementation of flood control infrastructure have the potential to translate to substantial improvements to human health and well-being—especially in urban environments where much of these infrastructure systems are located.

Table 1
Summary of key infrastructure sectors and the primary service that each provides.

Infrastructure system	Primary service
Stormwater / Flood Control	Mitigate the impacts of flooding and extreme precipitation events on human well-being and property
Drinking Water	Provide reliable delivery of clean drinking water for consumption and use in homes, businesses, and industry
Waste Water	Transport contaminated water from homes, businesses, and industrial processes and remove contaminants before returning water to watershed
Transportation	Allow for citizens to access key services and activities, as well as allow for businesses to engage in the exchange of goods and services, often expressed as physical mobility
Electric Power	Provide reliable input (in the form of electricity) to many crucial day-to-day functions of households, businesses, and industries
Energy	Provide reliable input (in the form of natural gas, gasoline, or other fuel sources) to many crucial day-to-day functions of households, businesses, and industries
Information Communication Technologies	Allow for fast and reliable communication between citizens and businesses, as well as providing access to information

Nonetheless, the concept of frequency-based design (e.g., 100-year storm event) is inherent across nearly all infrastructures and hazards. These hazards include hurricanes (Emanuel & Jagger, 2010; Keim et al., 2007), wind (Della-Marta et al., 2009; Lagomarsino et al., 1992; Naess, 1998), extreme temperatures (Luterbacher et al., 2004; Parey et al., 2010; Zwiers et al., 2011), ice storms (American Society of Civil Engineers, 1994; Irland, 2000), drought (Bonaccorso et al., 2003; Fernández & Salas, 1999), wildfires (Heinselman, 1973; Johnson & Van Wagner, 1984), and several others. Beyond consideration of a single or primary hazard, certain infrastructure systems are exposed to (and thus must account for) multiple hazards and their interactions. For example, roadway bridges are often designed for scouring, stormwater management, deck expansion/contraction due to extreme heat/cold, icing, and wind loads. Therefore, although this paper primarily focuses on flood control infrastructure, where possible, we also look for opportunities to explore design storm criteria and frequency-based design more broadly across different hazards and infrastructure systems. We also explore the applicability of frequency-based approaches from other infrastructures and hazards to the design storm concept in storm water management and flood control. With this broader perspective in mind, we define a design storm criteria as:

The maximum acceptable threshold and/or probability of occurrence to which infrastructure systems (including, but not limited to, stormwater, flood control, transportation, power, and buildings) are designed to endure in the face of hazards.

The remainder of this paper is organized as follows. Section 2 provides background information on the history and evolution of design storm criteria and thinking—especially in the context of extreme precipitation and flooding. Section 3 compares design criteria across different infrastructure systems and hazards, and begins to explore potential complements and additions to existing design storm approaches. Section 4 outlines some of the major challenges facing design storm criteria in the near and long-term. Section 5 concludes the paper by proposing some potential alternatives and complements to current design storm practices that may warrant further exploration and examination. Ultimately, this paper analyzes the use of design storm criteria across multiple hazards and infrastructure systems—especially in the context of flooding and extreme precipitation. We also explore the manner in which concepts like risk and probability are embedded in the design storm process. As discussed in more detail below, design storm criteria (in one form or another) are pervasive across infrastructure types and scales —especially in cities. As a result, vulnerability to extreme weather events within cities is implicitly and explicitly linked to urban infrastructure systems and their inherent design storm criteria. Thus, as cities increasingly assume a leadership role in climate adaptation and resilience efforts (e.g., Rosenzweig et al., 2010; The Rockefeller Foundation, 2020; Tyler & Moench, 2012), design storm criteria likely warrant additional scrutiny and re-imagination as key mechanisms for achieving desirable and equitable outcomes toward these endeavors. By analyzing design storm criteria and risk applications across infrastructures and hazards, the ultimate goal is to identify design practices and strategies (across sectors and hazards) that are particularly well-suited for the increasingly complex and rapidly changing contexts in which our cities and infrastructure are operating.

2. Codifying risk: the history of design criteria in stormwater infrastructure

Given the long-lasting nature of many infrastructure systems, decisions and design practices made several decades ago can influence cities and infrastructure systems in present day (Barnett & O'Neill, 2010; Markolf et al., 2018; White & O'Hare, 2014). Therefore, a historical examination of our infrastructure systems can provide some valuable insights into how current dynamics and performance (or lack thereof) came to be, as well as help us think more critically about where things may be heading in the future. In particular, the remainder of this section synthesizes some of the key moments in the development and evolution of design criteria for stormwater management and flood control infrastructure within the United States. Although much of the examples and discussion throughout the remainder of the article center on the United States, the challenges that non-stationarity and complexity present to the implementation and management of infrastructure systems are widely applicable—especially in countries and regions with infrastructure systems that have been in place for several decades or even centuries. Conversely, locations with relatively new or rapidly developing infrastructure systems can treat the issues discussed in this paper as a 'cautionary tale' about the future challenges that might be expected if concepts like non-stationarity and complexity are not appropriately considered in the earlier stages of system development. In this respect, a direct comparison of the evolution and current state of design storm criteria across different countries and locations would likely be very insightful—albeit outside the scope of this article and thus best left for future efforts.

Starting in the mid 1800's, the use of structures such as levees became the primary approach for flood control. In the 1861 report, *Upon the Physics and Hydraulics of the Mississippi River,* Corps of Topological Engineers members Captain Andrew Humphreys and Lieutenant Henry Abbott advocated support for the completion of the existing levee system and discouraged alternative flood control measures such as land use principles that are more cognizant of flood risk (American Institutes for Research, 2005). Ultimately, this emphasis on levees as core elements of flood control remained the primary focus of U.S. flood policy for several decades. In 1927, the Great Mississippi Flood showed the limits of Humphrey and Abbott's "levees only" approach, and served as a catalyst for rethinking flood management strategies. Shortly after the flooding event, private insurers left the market and decided not to cover flood losses anymore. The creation of the Tennessee Valley Authority (TVA) in 1933, and the subsequent Flood Control Act of 1936, established a two-pronged approach for reducing the impacts of flooding—reducing runoff and retaining more rainfall in conjunction with downstream projects by the Army Corps of Engineers. In the 1950's, President Truman recognized the need for the federal government to step in and offer a "national system of flood disaster insurance" because, at this point, the private insurance market had conducted multiple studies that reinforced their stance that it was not economically feasible to offer flood coverage. In the interim, multiple communities had begun using their own flood control standards and the TVA, along with the Army Corps of Engineers, recognized that there was the need for a uniform standard to be used by all agencies. In 1967, representatives from 26 federal agencies adopted a draft of Proposed Flood Hazard Evaluation Guidelines for Federal Executive Agencies where the use of the 100-year flood as the base standard was first advocated. The National Flood Insurance Act of 1968 created the National Flood Insurance Program (NFIP) and the Federal Insurance Administration (FIA) within the Department of Housing and Urban Development. The NFIP began operation in 1969 and included the 100-year floodplain as the criteria for defining special flood hazard areas for mapping purposes. In 1977, Executive Order 11988 directed federal agencies to assert a leadership role in reducing flood losses and recognizing the value that floodplains can provide. Additionally, Executive Order 11988 included monitoring and enforcement mechanisms to ensure that states complied with the 100-year base flood standard. This executive order was later reviewed by the Federal Emergency Management Agency (FEMA) in 1983, where they concluded that "no alternatives had been identified that are superior to it [the 100-year standard] and there is no evidence to justify the expenditure of funds that would be necessary to convert to another standard" (FEMA, 1983). The FEMA review also concluded "The 100-year flood level was selected because a flood of this magnitude and frequency represented a reasonable probability of occurrence and loss worth protecting against and an immediate level that would alert planners and property owners to the effects of even greater flood levels."

In parallel to the policy developments preceding and related to the NFIP (and continually improving data collection and analysis capabilities), different engineering and hydrologic methods have been applied in the design and implementation of stormwater infrastructure. The Rational Method (Kuichling, 1889) is frequently the basis for designing stormwater control structures in relatively small drainage basins. In particular, this approach estimates runoff rates (in units of volume per time) based on rainfall intensity and watershed characteristics. The rainfall intensity input values for the Rational Method are typically determined from approximating formulas (Texas DOT, 2016) or by using location-specific intensity-duration-frequency (IDF) curves derived from standard meteorological atlases such as TP-40 and HYDRO-35 (Hershfield, 1961; NOAA, 1977; Thompson, 2006). The Natural Resource Conservation Service Technical Release 55 (NRCS TR 55) (USDA, 1986) has served as an updated approach for estimating stormwater runoff, and has increasingly gained popularity and influence in recent years (Harvey & Connor, 2017; USDA, 1986). In contrast to approaches based on the Rational Method, the NRCS TR 55 method specifies 24-hours as the duration of the event, uses inputs and produces outputs in units of runoff depth in inches (as opposed to units of runoff flow rate from the Rational Method), and includes initial approximations of the effect of infiltration, evaporation, and vegetation on overall runoff (Harvey & Connor, 2017). Ultimately, the NRCS TR 55 approach offers advantages over the Rational Method by more comprehensively accounting for losses in runoff (due to infiltration, evaporation, etc.) and by enabling analysis over larger design areas (Harvey & Connor, 2017).

Regardless of their similarities or differences, each of the described approaches can be classified as "Frequency-based design", where consequences are not explicitly considered. Lewis (1992) further explains the implication of "Frequency-based design," as opposed to "Risk-based design":

> "In risk-based design, the recommended size is that with the least total expected costs, wherein risk costs are included along with traditional costs of the installation and maintenance of a structure. The recurrence interval of the largest storm that the culvert will safely pass without damage is an outcome rather than a prescription as in frequency-based methods. It is often argued that risk-based methods incorporate greater consideration of risk because they force the designer to evaluate a wider range of floods and alternatives."

Ultimately, the NFIP (and its use of the 100-year storm designation) and the Rational Method for calculating runoff served as strong foundations for subsequent design codes and standards, and continue to have a strong influence on contemporary stormwater management and flood control practices. Nonetheless, updates and revisions to infrastructure design standards and practices (i.e., a shift from frequency-based methods to risk-based methods) appear to be warranted—especially given the increasing quality and quantity of weather/climate data and analysis techniques, an expanding knowledge of the dynamics between flood control systems and their surroundings, and the growing reliance on well-functioning flood control infrastructure within cities. In doing so, it will be important to first address certain challenges facing the current paradigm of frequency-based design, and confront the difficulties of moving toward risk-based design (see Sections 3 and 4).

Similar histories likely exist for other infrastructure systems (e.g., the evolution of heat thresholds for asphalt over time or the establishment of ice-loading thresholds for power lines). However, descriptions of these histories at the same level of detail as the histories of flood control infrastructure were difficult to come by. One possible explanation for the disparity in information between flood control infrastructure and other infrastructure systems might be due to the fact that a major federal policy (the National Flood Insurance Program) appears to have played a predominate role in the thinking and design of stormwater infrastructure through the years. However, similar pieces of foundational federal legislation do not appear to exist for other infrastructure systems. Further examination of these discrepancies appears warranted, but is outside the scope of this paper. Nonetheless, it is important to be cognizant of the fact that for nearly all infrastructure systems, humans and institutions make decisions that codify risk into our infrastructure (and thus our cities) in some way (either implicitly or explicitly). In turn, this codification has substantial influence on how big and strong we design our infrastructure, and the level of service/protection (or lack thereof) it ultimately provides. To the extent possible, the following section explores design criteria and risk in non-flood related infrastructure and examines approaches that might be applicable across infrastructure systems.

3. Environmental hazards and design approaches expressed in other infrastructure

Although the majority of the focus of this article has been on flood control systems, those infrastructures are not unique in their exposure to climate change, extreme events, or other hazards. For example, rising temperatures and decreased availability of cooling water are expected to increase vulnerability within the electrical power sector (Bartos & Chester, 2015; Burillo et al., 2016; van Vliet et al., 2012), varying temperatures are expected to result in increased pavement costs and failure rates within the transportation sector (Underwood et al., 2017), and sea level rise may disrupt broadband and communication systems (Durairajan et al., 2018). Therefore, prior to discussing challenges and potential strategies for managing different systems under different hazards, we first briefly examine design principles and strategies in other infrastructure sectors, and across multiple hazards, in an attempt to explore whether any approaches or techniques might be applicable and transferrable to flood control systems.

For infrastructures other than flood control, and for hazards other than precipitation, design criteria often appear to be based on intensity thresholds rather than on return periods. For example, pavements are designed to operate between specific temperature thresholds (e.g., 14 °F–157 °F) (Underwood et al., 2017; Virginia DOT, 2018). Similarly, buildings and structures are designed to withstand specific wind levels associated with hurricanes categorized by the Saffir-Simpson Scale (e.g., Category 5 translates to wind intensities over 156 miles per hour) (FEMA, 2013; Institute for Business and Home Safety, 2012). Design for hazards like snow, ice, non-hurricane wind, and storm surge can also exhibit this threshold/intensity approach (ASCE, 2010).

Similar outcomes were observed across hazards and infrastructures in a case examination of the Phoenix metropolitan area. Table 2 summarizes some of the specific design criteria held by various city and state government entities and infrastructure managers. In particular, the table includes three infrastructure sectors (flood control, electrical power, and on-road transportation) and three hazards (precipitation, temperature, and wind). For each combination of infrastructure and hazard, we examine whether design criteria appears to exist, the specific values of the design criteria, and whether the criteria aligns more with the return-period approach or the threshold approach. Generally, wind was the hazard with the fewest related design criteria, precipitation-related design criteria were based on return periods, and temperature and wind-based design criteria were based on intensity thresholds.

Ultimately, the comparison across infrastructure systems and hazards appears to indicate that design criteria for precipitation and/or related to flood management infrastructure systems adopt a return period approach, while design critieria related to wind and temperature adopt a threshold approach. Fundamentally, both of these approaches are rooted in determining or selecting a specific intensity – the return period approach does so implicitly while the threshold approach does so explicitly. Thus, a fundamental question arises: why does precipation-based design critieria entail the consideration of the probability of the hazard occuring (via specification of a return period), and does this consideration of probability provide any distinct advantages or disadvantages over a threshold-based approach? The differences in purpose and service provision of each infrastructure system potentially contribute to some of the differences in design approaches (Table 1). Stormwater management and flood control systems are somewhat unique in that their primary purpose is to 'control' or mitigate hazards (specifically flooding and extreme precipitation). In contrast, other infrastructure systems (e.g., power, transportation, etc.) are responsible for deliverying a variety of services and may only consider risk and hazard management as a secondary service, or a necessary function of fulfilling their primary objectives. The positioning of hazard mitigation as the primary service of stormwater and flood management systems perhaps factors in to the thinking that design criteria warrant the establishment and explicit treatment of probabilities (i.e., return periods) as opposed to the more straightforward approach of 'simply' designing to agreed upon intensity values or thresholds (regardless of the

Table 2
Summary of design criteria across different hazards and infrastructure systems for the Phoenix Metropolitan Area.

Infrastructure Type		Hazard Type: Precipitation	Temperature	Wind
Water	Design Criteria? (Y/N)	Y	N	N
	Design Criteria Values	2-year/100-year*	N/A	N/A
	Return Period vs. Threshold Values	Return Period	N/A	N/A
Power	Design Criteria? (Y/N)	N	Y	Y
	Design Criteria Values	N/A	35 - 50 C**	40 mph - 125mph
	Return Period vs. Threshold Values	N/A	Threshold	Threshold
Transportion	Design Criteria? (Y/N)	Y	Y	N
	Design Criteria Values	2-Year/50-Year*	14F - 157F	N/A
	Return Period vs. Threshold Values	Return Period	Threshold	N/A

*Depends on type of infrastructure and geographic scale/location

**Depends on type of infrastructure and geographic scale/location; Power system also includes thresholds for ice (0''-0.6'')

* Depends on type of infrastructure and geographic scale/location.
** Depends on type of infrastructure and geographic scale/location; Power system also includes thresholds for ice (0″–0.6″).

likelihood of those thresholds being exceeded in a given time period). A deep examination of these issues, the genesis of the difference in approaches across hazards and infrastructure, as well as the potential significance of these differences appear worthy of further exploration in future work.

4. Challenges with current design storm standards

The expected increase in the intensity and variability of climate hazards (e.g., heat waves and extreme precipitation events) is likely to create substantial challenges and incongruences with current design storm standards. Nonstationarity, the idea that systems fluctuate within an ever-changing envelope of variability (Koutsoyiannis, 2011; Lins, 2012; Milly et al., 2008), seems poised to be a prominent feature of the expected climate variability and uncertainty, as well as a key factor in the difficulties that design storm standards and infrastructure may encounter. In essence, the past may no longer be a reliable predictor or indicator of the future, and infrastructure systems may be entering a period where they are designed for conditions that no longer persist. For example, Lopez-Cantu and Samaras (2018) found that by year 2050, projected changes in precipitation patterns due to climate change will stress stormwater infrastructure beyond their design capacity in at least 43 U.S. states. Similarly, Underwood et al. (2017) estimate that projected temperature increases will add roughly $22 to $36 billion in pavement maintenance and construction costs in the U.S. by the year 2070. Although it frequently appears to be the case, climate nonstationarity does not necessarily mean that infrastructure will be underdesigned for future conditions—there may be cases where infrastructure gradually becomes 'over-designed' as extreme events become less intense or less frequent as a result of climate change (Chester et al., 2020; Salas & Obeysekera, 2014; Underwood et al., 2020). Ultimately, the nonstationarity conditions presented by climate change may undermine the data upon which much of the quantitative understanding and management of infrastructure risk is based. Similarly, the increasing variability associated with the frequency and intensity of various climate hazards is likely to obfuscate infrastructure services and design (Harvey & Connor, 2017; Katz & Brown, 1992; Read & Vogel, 2015; Salas & Obeysekera, 2014). Therefore, design criteria based on historical return periods and past data (e.g., the Rational Method) will likely become decreasingly reliable. In their stead, efforts should be made to develop and implement design standards that are increasingly forward looking and capable of handling conditions of nonstationarity (Chester et al., 2020; Cook et al., 2017; Salas & Obeysekera, 2014; Underwood et al., 2020).

In addition to the issues presented by climate non-stationarity, increasing complexity within and among urban and infrastructure systems is another major challenge confronting current design and implementation paradigms (Chester & Allenby, 2019). Not only are urban and infrastructure systems comprised of many integrated components, users, and managers, they are also interconnected to other social-ecological-technological systems (Markolf et al., 2018). This integration and interconnection within and between systems often results in higher degrees of complexity, where distinctive causal relationships between system elements are difficult to discern or influence, and the behavior and performance of the system(s) manifest as emergent properties. The opacity of the causal relationships within the system(s) inhibit the probabilistic and risk-based approaches that underpin much of the design criteria used in cities and infrastructure systems. Thus, growing complexity within our infrastructures and the systems with which they interact is difficult to take into account during the design process, and is likely to impact the effectiveness of infrastructure systems in delivering the services for which they are designed. Ultimately, the conditions and context in which infrastructures exist begin changing as soon as they are installed, and continue to change and evolve throughout their lifespan. For example, in addition to extreme weather and climate conditions, recent flooding issues in Houston, Texas were likely exacerbated by the lack of strict zoning laws in the area, rapid population growth, and urban sprawl over the past several decades (Blessing et al., 2017; Boburg & Reinhard, 2017; Bogost, 2017; Fessenden et al., 2017; Ingraham, 2017; McGuire, 2016; Pinter et al., 2017). In particular, since the construction of two of the region's primary flood control mechanisms (the Addicks and Baker Reservoirs) in the 1940s, much of the population growth and development (and related decrease in permeability) has occurred in the suburban areas upstream of the reservoirs—drastically altering the hydrologic conditions for which the reservoirs were initially designed.

Increasing complexity within and across urban and infrastructure systems (coupled with non-stationarity), makes it exceedingly challenging to fully implement any form of risk analysis/management. As distinct causal relationships become increasingly opaque, the likelihood and potential consequences of a disruption become increasingly unknowable and unpredictable. At their core, design storm criteria are mechanisms for understanding and managing risk. However, further examination of the fundamentals of risk analysis reveal that design storm criteria result in an incomplete assessment of risk. According to the "Risk Triplet" definition from Kaplan and Garrick (1981), *risk* is composed of the product of *hazard*, *probability*, and *consequences*, where *hazard* refers to the type of threat or storm (heat, flooding, wind, etc.), *probability* refers to the likelihood that a hazard of a certain magnitude will occur, and *consequences* refer to the impacts and disruptions that the hazard may cause. Frequency-based designs are fairly adept at accounting for the hazard and probability elements of risk, but appear to only account for consequences in an implicit manner (if at all). For example, Phoenix, Arizona designs its street storm drains to a 2-year storm standard but its stormwater detention facilities to a 100-year storm standard (Flood Control District of Maricopa County, 2013). This is a common practice seen in other municipalities across the United States (U.S. EPA, 2011). Here, the higher standard for stormwater detention is likely because these systems protect buildings from flooding, whereas the street drains 'only' protect the road, and roadway flooding is perceived to have fewer impacts. Structural engineering practices include higher standards for structures generally deemed of higher importance, but similar approaches in other infrastructure sectors do not appear to be as common (ASCE, 2010). Difficulty in more explicitly incorporating the consequence element of risk into design standards/criteria may be due in part to obscured causal relationships within complex systems. Therefore, it appears that grappling with complexity will become increasingly necessary if we are to eventually move from frequency-based design toward a truly risk-based design.

Another challenge worth discussing is the fact that infrastructure systems are increasingly subjected to concurrent hazards and the propagation of failures due to interconnectedness with other systems. However, the emphasis on specific "design storms" may result in the unwitting under-appreciation of these conditions. For example, in 2014, major flooding on Interstate 10 in Phoenix occurred not as a result of under-design or failure in the stormwater infrastructure, but as a result of power outages in some of the pumping stations along the highway. Understanding which hazards may occur simultaneously or propagate from other systems can be difficult and is highly location-dependent. In the context of risk-based design, these circumstances increase uncertainty in all three elements of the "Risk Triplet." Similarly, as climate change influences the probabilities and intensities of different hazards, our understanding and calculation of the risks of combined and/or propagating hazards will become even more difficult. Nonetheless, other (non-flood related) infrastructure systems can provide some insights into addressing multiple hazards. For example, building design often accounts for several different hazards (e.g., snow, wind, dead load, live load, etc.) by combining them into different load factors (Ellingwood, 1994; Ellingwood & Bruce, 1980). Similarly, power lines and distribution systems are often designed to account for both ice and wind. Although there is a fairly large and well-established body of literature related to multi-hazard risk and propagating failures in critical infrastructure systems (e.g., Clarke & Obrien, 2016; Gardoni & LaFave, 2016; Korkali et al., 2017; Laugé et al., 2015; Markolf et al., 2019; Rinaldi et al., 2001; Wang et al., 2012; Winkler et al., 2012; Zhang et al., 2016), additional work appears warranted to fully integrate and embed the results and lessons from this body of literature into infrastructure design standards and practices.

Finally, and perhaps most fundamentally, design storm criteria can have important effects on broader urban resilience, governance, and equity objectives. In particular, design storm criteria can contribute to various forms of maladaptation – actions taken to reduce vulnerability in one context that ultimately increase vulnerability (or adverse effects) in other contexts or among other groups (Adger et al., 2005; Adger & Barnett, 2009; Adger et al., 2013; Barnett & O'Neill, 2010; Torabi et al., 2018). For example, in the context of resilience thinking, design storm criteria appear to mostly align with the "resistance to disturbance" portion of Holling's (1996) definition of engineering resilience. However, engineering resilience (and resilience thinking writ large) has evolved beyond this definition. Woods (2015) outlines engineering resilience as a system's ability to dynamically move between the mutually-exclusive regimes of *rebound* (return to pre-disruption conditions), *robustness* (prevent/minimize disruptions), *graceful extensibility* (mitigate the consequences of surprise events), and *sustained adaptability* (transformation in response to evolving system conditions). Likewise, Park et al. (2013) position engineering resilience as an iterative process of *Sensing*, *Anticipating*, *Adapting*, and *Learning* (SAAL). Beyond engineering, contemporary resilience thinking is marked by a growing convergence among engineering, ecology, and the social sciences (Flynn & Davidson, 2018; Grimm et al., 2008; Grimm et al., 2015; Grimm et al., 2017; Gunderson & Holling, 2002; Holling, 1973; Holling, 1986; Holling, 1996; Markolf et al., 2018; McPhearson et al., 2016; Meerow et al., 2016; Meerow & Newell, 2016), including the emergence of the concept of *evolutionary resilience*—the ability to transform, change, and adapt in the face of strains and stresses, rather than 'simply' returning to 'normalcy' (Davoudi et al., 2012). Similarly, Adger et al. (2005) posits *flexibility* and *robustness* to uncertainty as two crucial indicators of adaptation action – neither of which are currently strong characteristics of design storm standards. Thus, design storm criteria (in their current and historical form) appear to be increasingly divergent from (and even potentially maladaptive to) developments in engineering resilience, and resilience thinking writ large.

Related to the above issues, design storm criteria can contribute to maladaptive outcomes in governance and equity. In particular, design storm criteria are a clear example of the increasing role that "calculative practices" play in urban planning and resilience. Although calculative practices are necessary and helpful in many contexts, there are certain tradeoffs that can emerge that appear to warrant deeper acknowledgement and consideration. First, design storm criteria (and other calculative practices) can contribute to the mischaracterization or overestimation of the level of certainty and stability present in increasingly complex and uncertain environments—especially as nuance and uncertainty from the original analysis tend to get masked or 'smoothed-over' as information moves up the institutional/decision-making hierarchy (Miller, 2001, 2008; White, 2019). In cases where certainty and reductionism are pushed to the extreme, calculative practices may provide maladaptive evidence and support for which they were not originally designed or intended (White, 2019; White & O'Hare, 2014). Similarly, the (actual or perceived) certainty derived from calculative practices may contribute to the perception that innovative ideas, policies, strategies, and transformations may introduce 'unnecessary' uncertainty or avoidable risk to the system (Davoudi, 2014; White, 2019). Thus, behavior, actions, and policies tend to crystallize and lock-in over time (Markolf et al., 2018; White, 2019). For example, despite growing awareness of flood risks and recognition of emerging flood resilience technologies/approaches, practitioners and community members expressed reluctance to implement (or even test) novel technologies/approaches due to (real and perceived) concerns about uncertainty associated with their compatibility, cost, and performance (Hedger et al., 2000; Tippett & Griffiths, 2007; White et al., 2018). Thus, there appears to be a critical role for standard-setting organizations (e.g., International Organization for Standardization < ISO > , British Standards Institution < BSI > , National Institute of Standards and Technology < NIST > , American Society of Civil Engineers < ASCE > , etc.) to take the lead on providing clear and consistent guidance for implementing novel and innovative policies and standards related to design storm criteria and broader urban resilience efforts. Otherwise, although there may be wide acknowledgement of the value and need for innovation, individual companies, cities, and infrastructure managers may remain reluctant to take on the 'risk' (perceived or otherwise) of being early adopters and first-movers.

Additionally, due to their nature, design storm criteria (and other calculative practices) tend to emphasize actions/impacts/traits that are more readily quantifiable (e.g., economic metrics). While this is not an inherently problematic characteristic, if left unacknowledged and unaccounted for, maladaptive outcomes such as the "securitization of nature" (i.e., construing nature as a risk and something to be secured or protected against, rather than a resource) and the privileging of some groups/sectors/systems over others can potentially occur (Davoudi, 2014; White & O'Hare, 2014). For example, by placing risks in terms of a "storm event," design storm criteria may implicitly be contributing to the securitization of nature or the privileging of some groups over others by overlooking critical underlying conditions, actions, and decisions that contribute to vulnerability and risk (e.g., poverty, demographics, system interactions, distribution of resources, infrastructure age and condition, etc.). Similarly, the knowledge, skillsets, data, information, and financial resources required to conduct and interpret calculative practices can result in inequitable power dynamics and outcomes among different groups, systems, and perspectives (Davoudi, 2016; Davoudi, 2018; White, 2019). For example, community members who are not well funded or not well versed in calculative practices may have difficulty engaging in productive discourse, discussion, and negotiation of specific resilience policies and practices (White, 2019). Likewise, more qualitative objectives (e.g., quality of life, walkability, etc.) or novel but uncertain approaches (e.g., nature-based solutions) may be overlooked or de-emphasized because they do not align as well with the parameters of a particular calculative practice or viewpoint of the institution(s) conducting the analysis (Bush & Doyon, 2019; White, 2019). Thus, as design storm criteria and infrastructure resilience practices continue to evolve, it is increasingly important to weigh the broad impacts of actions (or inactions) across all members of society, as well as ensure that the process for establishing design storm and resilience standards is as open, transparent, and inclusive as possible.

5. Toward resilience-based design standards

5.1. Takeaways for practice and future research

In addition to incorporating an interdisciplinary, multi-hazard, and inclusive perspective, there appear to be opportunities and pathways for continuing to evolve design storm criteria for stormwater (and other) infrastructure systems in response to rising challenges from forces like climate change and increasing complexity. Following are some specific takeaways for practice—each of which are discussed in greater detail throughout the remainder of this section:

- Work toward better incorporation of uncertainty, complexity, and flexibility within urban infrastructure design storm criteria and risk thinking.
  - o Return-period and threshold-based approaches are likely to remain suitable and appropriate for individual components/subsystems (albeit they will likely need to be revised and updated more frequently). Where possible and appropriate, incorporate additional safety factors and expand thresholds/return periods to

which infrastructure are designed and constructed (particularly with additional consideration for climate change and climate non-stationarity).
 o However, modified and alternative approaches are needed at the systems-scale. In particular, more explicit consideration of equity and failure consequences appears to be warranted. Current (infrastructure-centric) design approaches could be complemented by the addition or expansion of green infrastructure and nature-based solutions within cities. Similarly, risk assessment and thinking could strike a balance between "fail-safe" (i.e., emphasis on avoiding disruptions) and "safe-to-fail" (i.e., acknowledging that some degree of disruption is likely inevitable, while placing emphasis on minimizing the impact of said disruptions).
- Place more emphasis on communities and individuals (including the services they receive and the impacts they experience) rather than specific infrastructure components or hazards.
- Instead of relying on design criteria that are relatively static and long-lasting, strive to incorporate capabilities for experimentation, continuous performance evaluation, and continual refinement of standards and approaches.
- Develop a broader consideration of the urban/design space as inclusive of environmental, social, and technical factors in order to cultivate multi-faceted solution spaces rather than rigid technical ones.

5.2. Discussion and conclusions

Incorporating additional safety factors and/or expanding the return period to which infrastructure are designed can be effective strategies in the face of large uncertainty, and are perhaps most congruent with existing design paradigms. However, there are limits (and even potential downsides) to this approach. In the context of existing urban infrastructure systems, funding availability, space, interdependence with other systems, and public approval can all inhibit expansion or strengthening of infrastructure systems. Even if cost and space are not initial constraints on expanding the system, current climate trends appear likely to eventually push the system to (or beyond) its limit. For example, Salas and Obeysekera (2014) present a case where a 435-year storm event under 'normal' (stationary) conditions is estimated to become as frequent as a 50-year storm event under conditions of non-stationarity. This drastic difference in scale is likely to be accompanied by substantial cost and space implications (and limitations), or even technological limits. Given expected variability in climate, expanding infrastructure may even result in substantial over-capacity (and an inefficient use of money and resources) in locations where rainfall intensities may decrease over time (Lopez-Cantu & Samaras, 2018). Additionally, continual expansion and hardening of infrastructure systems can contribute to counter-productive outcomes like *lock-in* (in which prior design decisions restrict future ones) or even the *levee effect* (where infrastructure protections encourage development and population growth in vulnerable areas, thereby increasing the consequences if and when the infrastructure protections ever fail) (Corvellec et al., 2013; Di Baldassarre et al., 2009; Markolf et al., 2018).

Despite the challenges and issues described throughout this article, design storm criteria (whether in the form of return periods or something different) are still needed and are likely to remain a fundamental component of infrastructure development and implementation for many years to come. However, considering that there are limits to how much infrastructure systems can be expanded or enhanced, we posit that fundamental shifts may be warranted in how we think about risk in the design and implementation of our infrastructure systems. In particular, the adoption and advancement of a multi-scalar perspective on risk and system functioning may be an increasingly necessary response to the growing uncertainty and challenges that climate change and complexity present our systems. At the scale of single components or sub-systems, return periods (or other similar criteria, thresholds, and rules of thumb) will likely still play a necessary role in decisions related to sizing, material selection, maintenance requirements, and replacement schedules. These efforts may be complemented or supplemented by green infrastructure and/or low impact development (LID) approaches that help reduce or eliminate exacerbating features such as impervious surfaces that increase runoff generation, or surfaces that exacerbate urban heat island (e.g., Waters et al., 2002). In fact, nature-based solutions and ecosystem-based adaptations have shown the potential for more cost-effectively mitigating the effects of extreme events (i.e., heatwaves, floods, storms) compared to traditional large, centralized infrastructure systems (Brink et al., 2016; Bush & Doyon, 2019; Depietri & McPhearson, 2017; Kabisch et al., 2016; Temmerman et al., 2013). As an example of the shift toward nature-based solutions, the city of St. Paul, Minnesota is currently researching how to implement a "fee-in-lieu" program that will allow developers to pay into the city's green infrastructure fund rather than constructing onsite stormwater facilities (Levine, 2018).

At the scale of the entire system(s), there appears to be an opportunity (and need) for more explicitly considering and incorporating failure consequences into infrastructure design and management processes (Kim et al., 2019). In structural engineering, more important buildings (e.g., hospitals) are often designed more robustly than less important structures (e.g., warehouses). Emulating the codes and practices from structural engineering could serve as a good starting point for more effectively incorporating failure consequences into infrastructure design across all sectors. The “safe-to-fail” approach (where consideration of infrastructure failure consequences is reflected in design) is a promising alternative to the traditional “fail-safe” approach that sometimes underestimates the possibility of an eventual system failure (and thus does not fully consider the consequences and implications of said failures) (Kim et al., 2017; Kim et al., 2019). Perhaps existing design storm criteria would benefit from shifting to, or being complemented by, more pluralistic, holistic, and flexible approaches. These approaches would still include some level of large scale engineered systems, but would also incorporate resilience measures at the property or community scale (e.g., mobile perimeter barriers and door guards for flooding) and would acknowledge that water (or other hazards) cannot be held at bay at all times and under all scenarios (i.e., “make space for the water,” “Room for the River,” “live with rivers, etc.) (Fleming, 2002; Johnson & Priest, 2008; White, 2010; Zevenbergen et al., 2010; Butler & Pidgeon, 2011; U.K. DEFRA, 2014; Jha et al., 2012; Scott et al., 2013; Warner et al., 2012; O'Hare et al., 2016; White et al., 2018). However, it will also be important to be mindful that an emphasis on such communty-scale measures may eventually result in an over-reliance on self-sufficiency, and thus further disadvantage those who are already disadvantaged (Davoudi, 2014; Davoudi, 2016; Davoudi, 2018; Davoudi et al., 2012; White, 2019; White & O'Hare, 2014). Acknowledgement and avoidance of such outcomes will be key to ensuring that novel design storm criteria avoid the neoliberal and regressive versions of resilience described by Davoudi (2016, 2018) and White and O'Hare (2014), and instead move toward the more transformative, active, and dynamic version of resilience described by DeVerteuil and Golubchikov (2016).

One could also envision design criteria that focuses on the people and property 'served' by the infrastructure systems rather than focusing on specific return periods. This type of approach echos elements of *Collaborative Planning* discussed by Healey (1998) and Bush and Doyon (2019), as well as the idea of the *Relational City* (where there is a connectedness between people on the ground and sources of knowledge) proposed by Lejano (2019). For example, standards could be put in place that require a doubling of the level of adaptation efforts (whether through infrastructure changes or other means) whenever the population and/or property value within a specified area doubles—though care should be given to ensure this approach does not contribute to unfavorable outcomes like *lock-in* or the *levee effect*. Advancement and intergration of computing technologies with traditional infrastructure systems also show promise for leading to more informed design decisions. For example, with ever-increasing sensing and computing capabilities, the development of *digital twin cities* (i.e., digital reproductions of physical infrastructure, assests, and systems within a city) has the potential to radically improve how we model and analyze infrastructure systems before and after an extreme event, as well as gain a stronger understanding of the consequences of potential system failures (DesRoches & Taylor, 2018; Mohammadi & Taylor, 2017). Additional support and advancement can also likely be achieved by incorporating elements of *robust decision making (RDM)*. Under this approach, a large suite of probable and possible future scenarios are examined in order to illuminate the conditions and decisions that typically lead to positive and negative outcomes—with an ultimate goal of encouraging the former and avoiding the later (Hall et al., 2012; Lempert et al., 2004; Lempert et al., 2010; Lempert & Groves, 2010; Shortridge & Camp, 2019). Ultimately, the combination of these different efforts and approaches can result in more impactful, meaningful, and equitable cost-benefit analyses of infrastructure systems, where avoided impacts and damages from effective infrastructure systems are more holistically captured and considered.

As climate change, emerging technologies, and population growth contribute to increased complexity and uncertainty within our urban and infrastructure systems, a critical examination and re-imagination of the design storm concept appears to be crucial for ensuring the continued performance of infrastructure systems (and the cities they support) at acceptable levels. By focusing our design efforts around specific storms (or at least representative storm conditions), we are potentially overlooking or underestimating the inherent and growing complexity within our infrastructure and social systems. This simplification of storm events can result in chaotic responses to and inadequate management of events that occur outside the design storm parameters. Thus, the impetus exists for us to reshape our thinking and design principles for the *complex* (i.e., systems and situations characterized by constant flux and ambiguity where emergent patterns lead to unpredictability) rather than the *complicated* (i.e., systems and situations characterized by relatively well understood cause and effect relationships where optimization and efficiency are often core operating principles) (Chester & Allenby, 2019; Helmrich & Chester, 2020; Snowden & Boone, 2007). In order to better account and design for the complex domain (as opposed to the complicated domain), incorporating capabilities for experimentation and continuous performance evaluation (i.e., "probing") of various options will become increasingly valuable (Chester & Allenby, 2019; Snowden & Boone, 2007)—further highlighting the promise of approaches like *digital twin cities* and *robust decision making*. The integration of "probing" into the design process has the added benefit of helping to move our thinking and understanding of resilience away from a static outcome and toward a more dynamic and active process that involves sensing, anticipating, adapting, and learning (Park et al., 2013; Seager et al., 2017).

By applying the assumption of complexity and uncertainty to our infrastructures, system managers may begin incorporating aspects of sustained adaptability and resiliency across entire infrastructure systems, rather than overly emphasizing the development and maintenance of robust, fail-safe structures (Helmrich & Chester, 2020). For instance, design storm criteria often appear to serve as the end-point for much of the resilience thinking and effort that occurs in our infrastructure systems and cities. A more stringent design storm parameter (e.g., designing and building to a 300-year storm criteria instead of a 100-year storm criteria) could be utilized to strengthen the infrastructure and prepare it for climate change. However, this choice of a more stringent parameter is still (at least partially) arbitrary due to uncertainty in climate predictions and system complexities. Therefore, even highly stringent frequency-based design storm criteria still embody a fail-safe approach that assumes a *complicated* and certain context by determining a stationary system boundary. This assessment additionally applies beyond design storms for precipitation events, and may also be applied to thresholds for temperature and wind. Without the incorporation of anticipating and learning, design storm criteria will remain fail-safe. In the complex world in which we are currently living (and moving toward), design storm criteria should be considered the starting point for resilience thinking and efforts, rather than the end point. Under this paradigm, design storm criteria would not be synonymous with resilience, but instead serve as a crucial element of more dynamic, holistic, and multi-faceted resilience thinking and implementation.

Finally, an increased focus on resilience thinking over purely risk-based thinking and practice can help transform urban planning and development, as well as enhance decision-making under uncertainty and complexity. Put bluntly, the days of 'simply' looking up a number in a table (and basing design decisions accordingly) appear to be over. As a result, engineering/planning/policy training and education will need to adjust accordingly. Engineering education often emphasizes the approach of "reiterating upon the design," where the mentality is that the first design will not likely be the final design. However, once infrastructure is built and installed, this mentality appears to subside. Therefore, moving forward, it will be critical for education, training, and institutional knowledge to seek ways to emphasize a mentality of "reiterating upon the design *and implementation*" of infrastructure systems in the face of a dynamic and complex world. An improvement within engineering, infrastructure management, policy and planning, and the public-at-large with respect to understanding uncertainty and design storms will start to push these issues to the forefront where they can be given due consideration. A broader consideration of the design space as inclusive of environmental, social, and technical factors can also improve urban infrastructure resilience and allow designers to draw from multiple solution spaces rather than rigid technological ones (Markolf et al., 2018). Continual research and advancement of this topic is essential for making the design storm process (and urban/infrastructure resilience writ large) equitable and effective in an increasingly complex and non-stationary world.

CRediT authorship contribution statement

Samuel A. Markolf: Conceptualization, Writing- Original Draft, Writing – Review & Editing, Revisions, Supervision.

Mikhail V. Chester: Conceptualization, Writing – Review & Editing, Supervision, Funding Acquisition.

Alysha Helmrich: Investigation, Writing- Original Draft, Writing – Review & Editing.

Kelsey Shannon: Investigation, Data Curation, Writing- Original Draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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