The Past, Present, and Future of Design Storms

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Introduction & Background

Design storms, a rainfall standard utilized by engineers to protect infrastructure from extreme events by determining an acceptable level of risk, have come under scrutiny for their assumption of a stationary climate (Adams & Howard, 1986; Harvey & Connor, 2017; Hirabayashi et al., 2013; Koerth-Baker, 2017; Packman & Kidd, 1980; Watt & Marsalek, 2013). Climate change eradicates this assumption by (1) altering historical climate patterns over time (**Figure 1**) and (2) increasing extreme events in both magnitude and frequency. It is time to recognize that the world is a complex system with numerous non-linear relationships (Snowden, 2007), and it is not safe to assume a stationary climate, which could lead to under- or over-designed infrastructure that is built to last decades (Chester & Allenby, 2018).

While design storms have historically only referenced rainfall events; similar logic is used to determine likelihood of various environmental hazards such as extreme heat and wind. Therefore, the authors propose the following definition for design storm:

> *"The acceptable level of probability, from any environmental hazard(s), for the process of the design of hard infrastructure, including transportation, power, water, and buildings."*

Table 1 displays predominant infrastructure design standards for select environmental hazards to demonstrate the application of this definition.

Objectives

By reviewing academic literature and existing design standards regarding extreme weather events across the transportation, power, and water infrastructure sectors, the authors sought to:

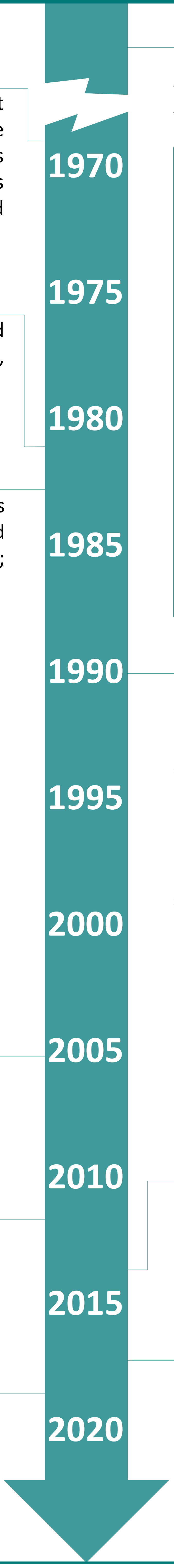
1. expand and evaluate the definition of design storms in the context of all infrastructure systems and all environmental hazards, and
2. propose new ways of considering these environmental hazards to infrastructure that go beyond risk and extend the resiliency of these systems.

Current Infrastructure Design Standards

Table 1. Predominant Design Standards for Select Environmental Hazards

	Transportation: Roads	**Power: Power Poles**	**Water: Pumps**	**Misc.: Buildings**
Flooding	Design Storms	None Identified	Design storms	Design Storms
Extreme Heat	Threshold	Threshold	Threshold	Threshold
Wind	None Identified	Recurrence Interval	None Identified	Threshold

Timeline of Design Storm Methodology



1889

Kuichling developed the rational method, which is used to determine drainage of small watersheds.

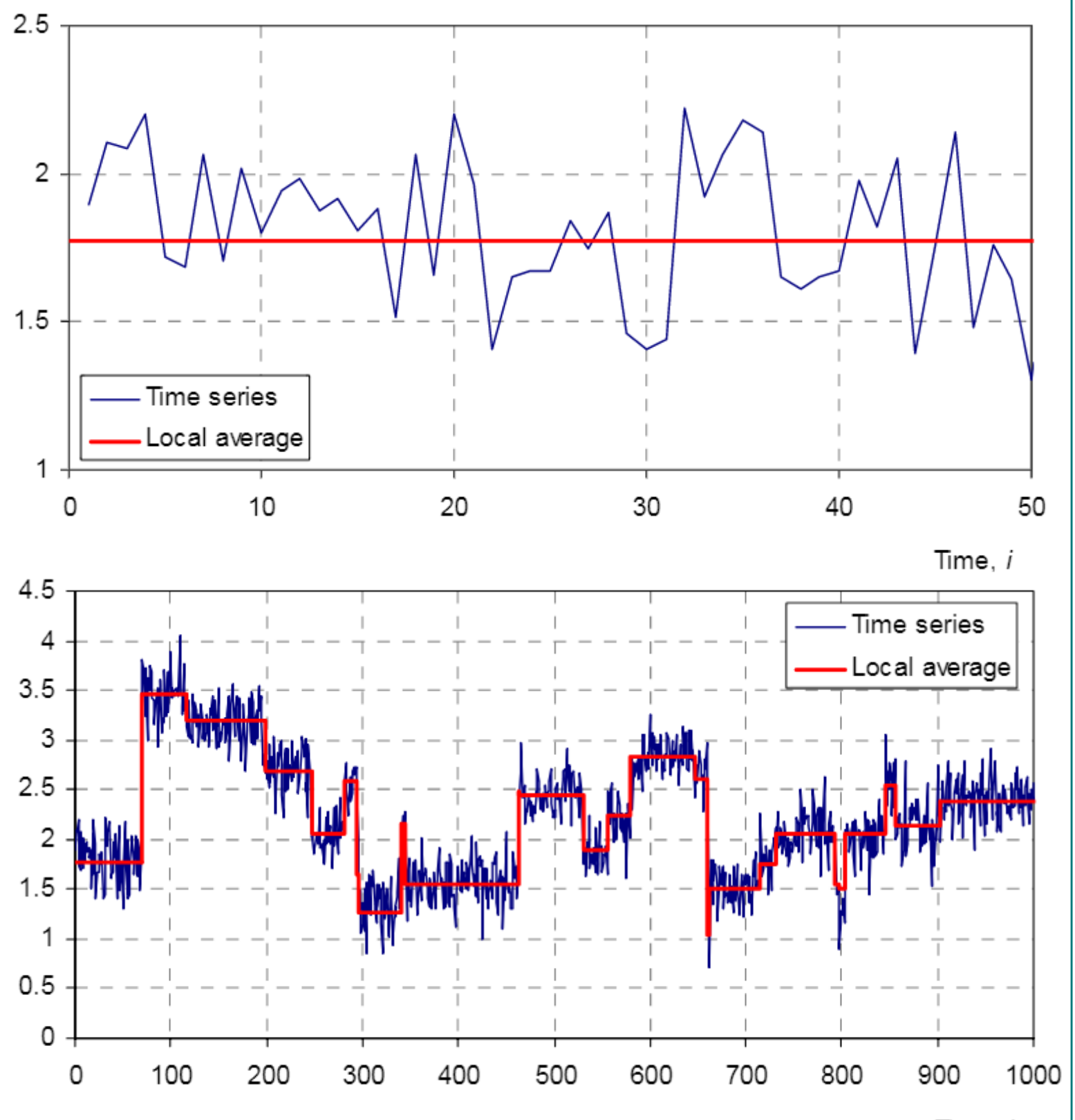


Figure 1. Synthetic datum representation of how patterns may alter with time (Koutsoyiannis, 2011).

1969

100-yr design flood accepted as a default standard for infrastructure design by the National Flood Insurance Program. This approach often utilizes precipitation inputs derived from methods dating to 1957 and 1961.

1981

The risk triplet is defined by Kaplan and Garrick as a composition of hazard, probability, and consequence.

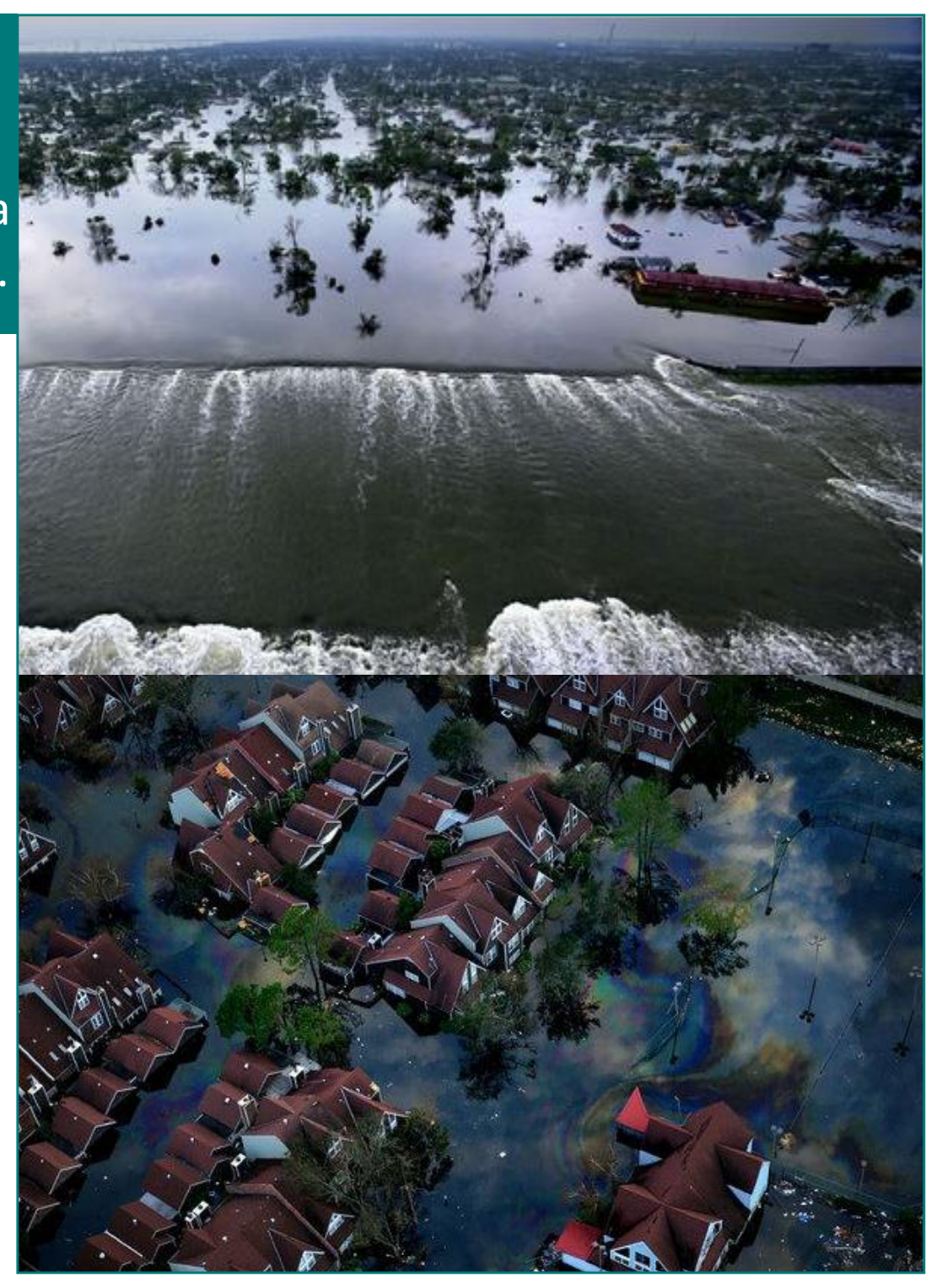
1983

The validity of the 100-yr design flood is questioned by numerous individuals and organizations, including the government; however, the standard is retained.

1990s

Frequency- and risk-based design methodologies became popular in the 1990s. Frequency-based design is a common method to select a standard based upon return interval; however, this choice may be arbitrary. Risk-based design takes into consideration a return interval as well, but also utilizes a frequency that will meet safety standards at the minimum costs.

Image 1. Aftermath of Hurricane Katrina (Vincent Laforet).



2005

Hurricane Katrina had catastrophic consequences due to under-designed infrastructure (**Image 1**).

2012

Hurricane Sandy emphasizes the consequences of interdependencies between critical infrastructures such as power, transportation, and water.

Image 2. I-10 failure in Phoenix, AZ (Michael Chow).

2014

Interstate-10 was impassable after a pump failure when 3.30 inches of rain fell in approximately 7 hours, demonstrating dependencies of critical infrastructure (**Image 2**).

2017

Houston, TX experiences three 500-yr floods in two years, emphasizing the need for resilient infrastructure. Furthermore, Hurricane Maria strikes Puerto Rico. It took approximately one year for full power to be restored on the island.

Today

Design storm methodology is still being used to determine infrastructure design by utilizing historic datum. For example, pavement design is based upon climate records between 1966 to 1995.

Conclusion & Discussion

Why do design standards appear to be vastly arbitrary across the literature?

The review of academic literature and design standards showed inconsistencies with how existing design standards are defined for various infrastructure installations. First, there are disparities of available information across the infrastructure. Information was more readily-available for public sector services (i.e. water) than private sector services (i.e. power). Second, there are disparities between standards within infrastructure sectors regarding which methodologies should be utilized to determine an acceptable level of risk (i.e. largest historic storm, probable maximum flood, etc.). **These disparities within design standards to identify what qualifies as an extreme event combined with the intricacies of a complex system create a diverse response of infrastructure designs** to climate change as developers decide whether or not to climate-proof new developments, and, if so, whether to climate-proof all-at-once or with installments over time. This is a difficult decision when the climate scenarios are surrounded by deep uncertainty.

What infrastructure design methods may be used to unify design storm methodology when assuming a non-stationary climate?

Recognizing that (1) design storm methodology is not consistent and (2) historical data are not reliable to predict future circumstance, infrastructure must be designed to flourish in a complex rather than complicated (engineered) world. This requires a shift in infrastructure design practices, where infrastructure can no longer be designed to a single parameter when that parameter is essentially unknown. This fail-safe method will lead to under- and over-designed infrastructure that may experience catastrophic failures and/or exorbitant expenditures. However, developers cannot simply ignore climate change as a potential threat of the future, but instead, they should **approach infrastructure design with agility and flexibility** in mind as seen with emerging design methods such as low impact development, safe-to-fail infrastructure, and low-regret/adaptive strategies. **Therefore, the next question is, which of these methods best manages the deep uncertainty concepts of climate change?**

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