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Management of urban floods based on tolerable consequences in an uncertain future

Salar Haghighatafshar(1), Per Becker(2), Steve Moddemeyer(3), Andreas Persson(4), Johanna Sörensen(5), Henrik Aspegren(6), Karin Jönsson(7)

(1,6,7) Water and Environmental Engineering, Department of Chemical Engineering, Lund University, Lund, Sweden
salar.haghighatafshar@chemeng.lth.se, henrik.aspegren@chemeng.lth.se, Karin.jonsson@chemeng.lth.se
(2) Division of Risk Management and Societal Safety, Lund University, Lund, Sweden
(2) Unit for Environmental Sciences and Management, North-West University, Potchefstroom, South Africa
per.becker@risk.lth.se
(3) CollinsWoerman | Seattle Architects, Seattle, USA
smoddemeyer@collinswoerman.com
(4) GIS Centre/Physical Geography and Ecosystem Science, Lund University, Lund, Sweden
andreas.persson@nateko.lu.se
(5) Department of Water Resources Engineering, Lund University, Lund, Sweden
johanna.sorensen@tvrl.lth.se
(6) Sweden Water Research AB, Lund, Sweden
henrik.aspegren@swrab.se

Abstract

Precipitation is intrinsically associated with high uncertainty, which is exacerbated exponentially over time—especially concerning climate change. However, the current design practice in urban drainage infrastructure remains firmly bound to deterministic assumptions regarding the design load. This approach is too simplified—focusing only on the return period of the design event—and ignores the complexity of drainage systems, the potential changes in catchment hydrology and the at-risk valuable assets within. Therefore, the current design approach is inherently an unsustainable practice that cannot deal with extreme uncertainties associated with urban drainage and flood resilience in changing climate and society. This paper examines the current deterministic design practice and encourages a collective discussion on the need for a paradigm shift in the engineering of pluvial floods toward a risk-based design. We believe that adopting a risk-based design will partially address the uncertainty and complexity of climate and urban drainage, respectively, although a method for the new practice in a risk-based design paradigm must be developed.

Keywords: Urban flood risk, Drainage infrastructure, Climate change, Deterministic design, Probabilistic design

1. INTRODUCTION

Pluvial flooding, in which the urban drainage system is overwhelmed, has the characteristics of both design failure—as a result of the classical engineering mindset, i.e., maximum tolerable load on the drainage system—and a disaster that occurs in an urban context. There is an inherent contradiction between the engineering perspective, which stipulates the deterministic maximum load that is used as the design load, and the notion of disaster, which connotes the combination of a range of extraordinary events that cause the flood. Nevertheless, the former view has predominated in determining the current paradigm and its principles and practices of managing pluvial flood risk in urban areas worldwide, largely viewing such risk from the perspective of conventional stormwater management and urban drainage, with piped and centralized systems as the chief solution, routinely expressed in terms of historical recurrence intervals of design rains.

For instance, in the city of Malmö, Sweden, most flood damage is related to basement floods that are linked directly to intensive rainfall (Sörensen and Mobini, 2017). Compensation for such damage can be claimed from the water utility company when the pressure head in a combined sewer exceeds the lowest lying basement floor at a rain intensity with a 10-year recurrence interval for which it was designed (SWWA, 2004)—all of which depend on the definition of the 10-year design rain and local circumstances. Similarly, current Swedish guidelines for separate stormwater network designs (SWWA, 2016) recommend a 30-year design rain and an arbitrary climate factor of at least 1.25. Thus, the pressure head in separate stormwater networks is allowed to reach ground level once in 30 years, even if the rainfall intensity is 25% higher than that with 30-year recurrence intervals historically.

Such climate factors, although they are recommended worldwide due to their practical convenience (Arnbjerg-Nielsen, 2012; Kang *et al.*, 2016; Niemczynowicz, 1989; SWWA, 2016; Watt *et al.*, 2003), are arbitrary and deterministic when the impacts of climate change on rainfall in Sweden or elsewhere are highly uncertain. Further, these approaches largely ignore what happens during rainfalls that are more intense than the design rain, which is especially problematic considering the generally nonlinear relationship between rainfall intensity and the effects of flooding (Leitão *et al.*, 2013; Sörensen and Mobini, 2017; Wilby *et al.*, 2008).

Although it is intuitive and correct that intense rainfall is a major underlying factor of urban floods, many other elements are often overlooked when the focus is placed on designing conventional urban drainage systems against design rains with specific recurrence intervals. For instance, the type and hydraulic capacity of the urban drainage system, the extension and distribution of impervious surfaces, soil type, initial soil moisture, and terrain properties (eg, slopes and elevations) are also factors that influence flood location, spatial extent, depth, speed of onset, and duration (Becker, 2014). Moreover, intense rainfall is not always the main cause of flood. In a study in Haarlem, the Netherlands, (ten Veldhuis, Clemens, & van Gelder, 2009) showed that gully pot blockages were nearly 16 times more common as causes of floods than intense rainfall (79% vs 5% of reported claims), demonstrating the importance of maintenance and rehabilitation.

Finally, flood risk is determined by not only the “temporary covering by water of land not normally covered by water” (EU, 2007) but also the exposure of something valuable that is vulnerable to the impact of that water (Becker, 2014). Thus, climate change is not the sole factor that introduces uncertainty—future urban planning, demographic and socioeconomic processes, and citizens’ everyday habits do, as well.

For over a century, engineers have relied on a paradigm of conceptualizing flood risk management in the framework of the deterministic design of conventional urban drainage systems, based on recurrence intervals of specific design rains. A financial advantage of this paradigm is that it tends to limit the liability of the designer to the design threshold. This benefit can complicate changes in the best practice. The existing paradigm provides a clear and measurable definition of a sufficient level of protection. Any protection beyond this threshold can be considered rare enough to obviate the need for devoting additional resources to larger pipes and pumps.

This paper aims to critique the contemporary paradigm of experiential, deterministic, and reductionistic fail-safe engineering and related assumptions and design procedures regarding urban flood risk management. It also suggests a paradigm shift toward risk-based urban design, with flexible urban drainage systems, that takes into account change and uncertainty in pluvial flood hazard and vulnerability and encompasses prevention, mitigation, and preparedness for effective response and recovery.

2. CHALLENGING THE CURRENT PARADIGM

2.1 Historical Recurrence Interval in The Era of Nonstationarity

Historically, designing the capacity of urban drainage and stormwater systems has been based on stationarity—i.e., under the assumption that the stochastic natural systems fluctuate within an unchanging range of variability (Hertig *et al.*, 2015). (Milly *et al.*, 2008) argue that climate change has already eroded this foundation of contemporary engineering practices regarding the management of water resources, because it is not possible to use probabilities to predict the variability and intensity of future rainfall events, based on existing weather records.

To overcome the problem of changing rainfall trends and the nonlinearity of these system changes, researchers have suggested engineering practices that apply climate factors to design rain intensities (Arnbjerg-Nielsen *et al.*, 2013; Kang *et al.*, 2016; Semadeni-Davies, 2004; SWWA, 2016; Watt *et al.*, 2003; Niemczynowicz, 1989) or update local IDF curves to anticipated future climates (Mailhot and Duchesne, 2010; Guo, 2006; Mailhot *et al.*, 2007; Lima *et al.*, 2018; Hailegeorgis *et al.*, 2013). However, the issue is more fundamental, even if the resulting increase in the hydraulic capacity of urban drainage or stormwater systems has reduced flood risk. The management of urban drainage is a problem of complexity.

The contemporary focus on design rains also results in an expert blind spot, meaning that the consequences of preceding rainfall events are completely ignored. This oversight is concerning on its own, considering the uncertainty in any estimation of the probability and intensity of rainfall, wherein even a small increment in rainfall can trigger a significant increase in the effects of flooding.

2.2 Inherited Determinism and Reductionism

“The temporary covering by water of land not normally covered by water” (EU, 2007) is determined by a complex combination of factors. This phenomenon is influenced by the design of urban drainage and stormwater systems and various factors, such as maintenance (ten Veldhuis *et al.*, 2009), the extension and distribution of impervious surfaces (Du *et al.*, 2015), soil type and infiltration capacity (Zhao *et al.*, 2018), initial soil moisture (Schoener and Stone, 2019), rises in sea level, and topography (Butler and Davies, 2011), that can change and are more or less governable over time. These factors affect flood location, spatial extent, depth, speed of onset, and duration (Becker, 2014) but are not adequately accommodated in contemporary engineering practices that focus on designing systems for a specific hydraulic capacity under a set of assumed circumstances. This approach is deterministic, disregarding significant uncertainties in some of these factors, and reductionistic, externalizing the remaining elements.

Reductionism also exists in the current best practice for the design of urban drainage infrastructure using only recurrence interval, which reflects the probability component in the risk definition, omitting consequence. The concept of risk is often mistaken as an interchangeable term for probability. However, risk is the product of probability and consequences, as shown in Eq. 1 below per (Ale, Burnap, & Slater, 2015):

$$R = \sum_{i=1}^{n} p_i \times c_i \qquad [1]$$

where R is the magnitude of risk set; p_i is the range of recurrence probabilities/frequencies of an incident, considering the prevailing uncertainties; and c_i is the range of costs/consequences of the incident within the uncertainty boundaries. Moreover, this reductionism is equally conspicuous as determinism (deterministic design), in that the designs of these systems are considered in isolation from the changing context and value of the urban areas that they are intended to protect—particularly so, because the entire purpose of these systems, during their extended lifespans, is to shield urban areas from experiencing consequences of pluvial floods that cannot be tolerated. Although complete overhauls of urban areas, in which the land use changes significantly, often entail the corresponding reconstruction of their urban drainage and stormwater systems, the change in urban areas that have been developed can appear to be gradual and less dramatic but remained associated with significant potential for changes in hydrology and context, and thus in flood risk, over time.

This deterministic and reductionistic approach is a legacy of the rational method. Although it has proven to be efficient in dealing with a range of simple and complicated contexts worldwide, it seems to have reached an intellectual and practical dead end. Carpenter et al. (2009) suggest that its longevity, based on its current by countless competent engineers, can be explained in part by the tendencies among engineers to work with computable parameters and believe in and persevere with dominant models. Engineers who are inclined to change can be restrained, because existing regulations and legal liability are tied to best practices, which are in turn tied to past practice (Wihlborg *et al.*, 2019).

Conversely, engineers are also suggesting considerable revisions to urban stormwater governance, emphasizing, for instance, a more holistic focus (Sörensen *et al.*, 2016), broader participation and interinstitutional collaboration (Dhakal and Chevalier, 2016; Sörensen *et al.*, 2016), and the potential of blue-green stormwater systems (SuDS) to buffer uncertainty and making current notions of recurrence intervals irrelevant for design (Haghighatafshar *et al.*, 2018).

2.3 Erroneous Notions of Probability

There is another aspect of the use of recurrence intervals as a basis for designing urban drainage and stormwater systems, which is related to the intellectual intricacies of understanding probability. Although the notion of a “10-year rain” can be intuitive and compelling—i.e., a rainfall event with particular attributes that occurs once in 10 years—it is also vulnerable to fundamental misconceptions of probability. Undoubtedly, this intuitiveness has been critical in establishing the use of design rains with particular recurrence intervals as a nearly universal input in designing urban drainage and stormwater systems worldwide.

However, common cognitive biases complicate the understanding of probability, which might undermine flood risk management in practice, especially when public awareness regarding flood management must be promoted. For instance, when lacking or considering historical data, people tend to base their estimations of probability on what they have recently experienced (Tversky and Kahneman, 1973) and on affect (Slovic *et al.*, 2007). Thus, an urban area is likely automatically to be considered safe by many policymakers, practitioners, and the public if it has not been flooded, whereas flood risk is likely to be a top priority among the same stakeholders after a significant flood, even if the risk of being affected has not changed.

In considering even the most accurate historical record of rainfall events, other cognitive biases influence perceptions of probability. The common belief in local representativeness is that “the law of large numbers applies to small numbers as well” (Kahneman & Tversky, 1972). This tendency leads to a very common bias, called “the gambler’s fallacy,” also referred to as “the negative-recency effect,” which is the intuitive but erroneous estimation of a lower probability of a “10-year rain” in the period immediately after one or several such rainfall events.

3. AN ALTERNATVE PARADIGM: THE WAY FORWARD

3.1 Alternative Scaling of Pluvial Floods and Inherent System Characteristics

In a perspective through which urban flood is considered a natural disaster in an uncertain era of nonstationarity, it is no longer reliable to project the intensity of the floods based on their recurrence interval (Vogel *et al.*, 2011). Thus, alternative approaches and methods are needed.

An existing analytical classification, based on consequences, similar to the Mercalli intensity scale, can be used. Giuseppe Mercalli, an Italian volcanologist, suggested a 10-degree seismic intensity scale, based on data from people regarding the extent of damage that they had experienced. A consequence-based approach for classifying floods, similar to the Mercalli intensity scale for earthquakes, has several major advantages. All of the factors, including anthropogenic parameters, that affect the consequences of the flood are inherently reflected in the scale. For example, identical cloudbursts in 2 cities with disparate proportions of impervious surfaces will be classified on 2 levels, because the city with more impervious surfaces might experience more severe consequences. Considering other prevailing local circumstances than only the rain characteristics facilitates a more reliable development of design criteria with easier modification possibilities.

A second advantage is the flexibility with which the scale can be modified. Based on the damage data that are posted on social media platforms, such as Twitter, Facebook, and Instagram, researchers could perform a preliminary and quick evaluation of a flood (Mendoza *et al.*, 2018).

Figure 1 illustrates the simple 7-degree scale that this paper suggests for the classification of floods. However, the nature of the possible consequences also depends on the type of onsite drainage system. As seen in Figure 1, the consequence-threshold for the combined sewer network is low—i.e., for combined sewer networks, even weak rainfalls will have an impact on the wastewater treatment plant. This impact, in the case of weak rainfalls, is primarily economic, due to the increased requirements for aeration and possible dosing of chemicals. However, as the magnitude of rain increases, WWTPs face more severe consequences, such as untreated overflow, dysfunction due to high hydraulic load, and biomass washout.

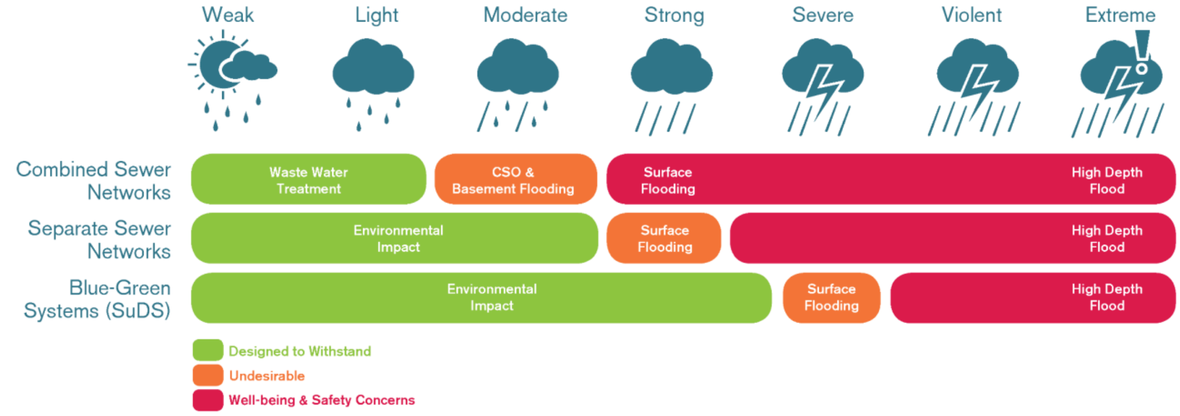

Figure 1. Suggested schematic of the classification of rain magnitude based on faced/expected consequences in various drainage systems. The dashed lines and shapes for blue-green systems indicate the unestablished design criteria and lack of clarity regarding the full-scale effects of such systems.

In Sweden, design rain in a combined sewer network is delimited by the lowest lying basement, above which basement flooding occurs. This threshold is larger for separate stormwater networks, because the decisive factor for flooding is the ground level. Thus, by merely implementing separate sewer networks instead of combined sewer networks, larger magnitudes of rainfall can be managed and certain effects (eg, CSO, basement floods, overloaded WWTPs) are automatically avoided, lowering the risk magnitude.

Yet, even the more desirable separate sewer network has its limitations and drawbacks. Increased hydraulic loads of untreated discharge to receiving waterbodies through separate stormwater networks is a growing concern that must be addressed. Moreover, surface flooding remains a serious consequence that should be managed.

3.2 Tolerable and Recoverable Consequences

Instead of designing urban drainage systems to manage specific design rains with changing recurrence intervals, we suggest designing urban areas that are safe and recover quickly in relation to floods over time. This alternative entails intensification of the work of water and sewage organizations that are increasingly considering blue-green systems and the diversification of the actors (Sörensen *et al.*, 2016). Flood risk does not concern merely climate change and the design of urban drainage systems—other drivers exacerbate urban flood risk and can be managed locally, such as unresponsive engineering, decreasing permeability, densification of people and property, and lack of public awareness (Berndtsson *et al.*, 2019). Beyond preventing floods and mitigating their effects beforehand, although they should be the primary and secondary adaptation choices, flood risk management encompasses preparedness for effective response and recovery (Becker, 2014).

The paradigm shift that we propose thus necessitates a risk-based design of urban areas, which in turn requires mobilizing policymakers and a broader set of practitioners and providing them with the processes, guidelines, and tools to engage in flood risk management and recovery. In the current fundamental shift, according to (Beck, 1992), the past no longer determines the present in the risk society—it is replaced by the future. We should be actively thinking about future consequences and anticipate or project the likely threats and risks to form our actions today (Beck, 1992). These actions should include a consideration of the people/entities that are impacted by urban flooding and strategies that reduce the recovery time—increase resilience— once flooding occurs.

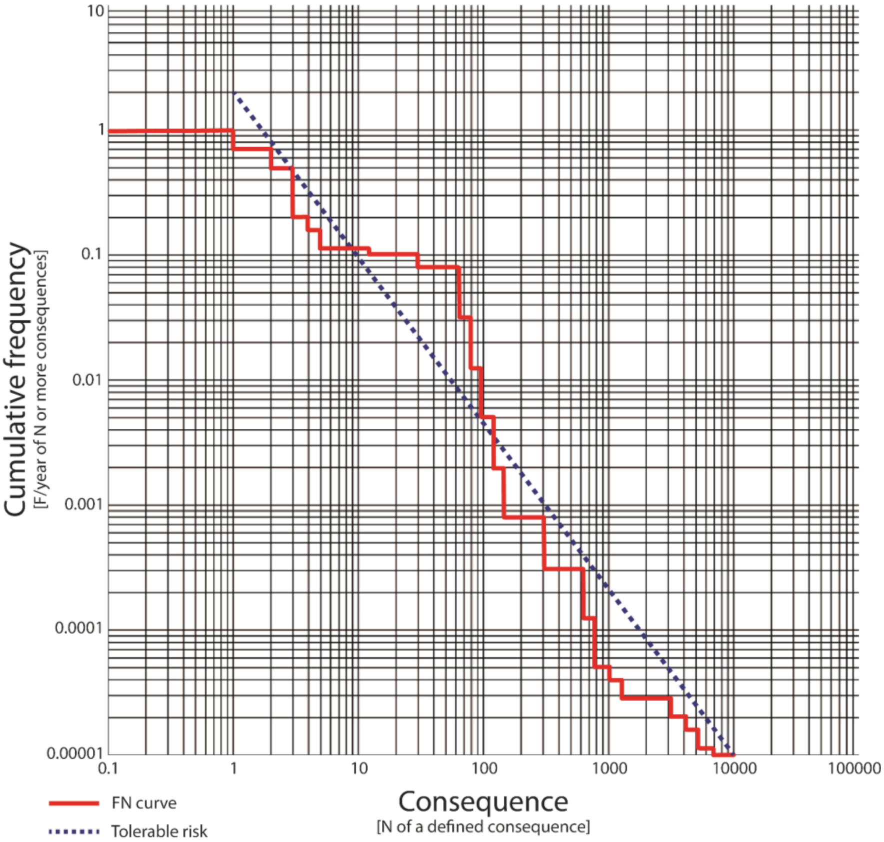

Figure 2. Societal risk represented as an FN curve with tolerable risk criteria.

At its core, the risk of a particular flood event is calculated as a product of the probability of that event occurring and the effects that it will have on whatever is considered valuable but often requires a consideration of the flood hazard (likelihood, location, spatial extent, depth, speed of onset, and duration) and the vulnerability of what is considered valuable to the impact of that particular flood event (Becker, 2014).

Whatever is valuable and vulnerable to the impact of a flood event always has a spatial position, and often has spatial extent. These characteristics of valuable and vulnerable entities facilitate the use of geographical analyses and visualizations, and spatial data infrastructures (SDI) are being built for data that can be used in geographical information systems (GIS) for analyzing flood risk quantitatively. Although flood risk can be analyzed in various ways, quantitative analysis is required to aggregate risk from various scenarios (Stevens, 1946). Also, although traditional flood risk management has considered spatial extent in static flood maps from hydrological models, flood events are dynamic and change in extent and magnitude over time.

Designing safe urban areas requires mobilizing policymakers to define what is sufficiently safe. It is unfeasible to design an urban area that under no circumstances can be affected by flood. It is also impractical for a city to invest its entire budget into flood risk management, ignoring infrastructure, education, social protection, health care, and whatever else cities are responsible for in various countries. Thus, a tolerable level of flood risk must be defined on an administrative level. Although defining what is safe enough is difficult politically, it is possible and has been done across the EU regarding general risk (Trbojevic, 2005). Although tolerable risk criteria are often defined in relation to human life or health, they can focus on whatever is valuable.

Quantitative criteria for tolerable risk can be defined in relation to individual risk or societal risk (Center for Chemical Process Safety, 2009). Individual risk is the probability of harm to an individual entity of what is considered valuable in a specific location and is often expressed as risk contours on a map (Center for Chemical Process Safety, 2009). Societal risk, conversely, is a measure of risk to all such entities within defined boundaries, such as an urban subcatchment area, neighborhood, or city, and is usually expressed as the frequency distribution of multiple flood events and their consequences—often called the FN curve (Center for Chemical Process Safety, 2009). Individual risk criteria thus simply result in a map with areas that are unsafe for that particular valuable entity, and societal risk criteria result in lines representing tolerable risk the FN curve is not allowed to cross (Figure 2).

3.3 System Flexibility, Resilience, And Equity

Astute policymakers are beginning to grapple with the implications of the deep uncertainty in future climate change. They realize that the current "best practice" is risky, because it ignores the new climate situation and context. Thus, regulations must be changed to reflect this new level of complexity and that the university-level training that virtually every practicing professional has been using needs to shift. Further, a new best practice should be centered on adapting to complex change rather than resisting it.

This challenge can be perplexing. To avoid this complexity, complicated workarounds have been developed, in which global climate models (GCMs) are downscaled, based on scenarios of how local conditions might change. Yet, these models contain several assumptions that might or might not reflect future conditions. Uncertainties and assumptions in the GCMs are compounded by the downscale models themselves. These localized models must make additional assumptions of conditions outside of the bounds of the downscaled model. "Large uncertainties attached to climate model scenarios cascade into even larger uncertainties in downscaled regional climate change scenarios and impacts." (Asong *et al.*, 2017). Another concern is that neither global nor downscaled models account for thresholds or tipping points at which runaway positive feedback loops can be triggered (or might have already been triggered) when earth systems suddenly tip into alternate semisteady states. The uncertainty in intensity, frequency, and tipping point thresholds for urban stormwater and wastewater systems from climate change calls for a new paradigm of flexibility and adaptability.

Fortunately, decision-making in times of deep uncertainty is not a new art. Building on work by Snowden and Boone in the Leader's Guide to Decision-Making, the recommendation is to increase a community's adaptive capacity.

The current "best practice" has been to design infrastructure to resist impacts up to a certain threshold—eg, 20-year rainfall. Although it was not intended as such, this approach is consistent with other examples of institutional bias and inequities in racial and social justice. When rainfall events exceed their design capacity, the families in flooded homes bear the burden. They are the ones who must deal with the damage to homes and businesses, even if compensation is received at a future date. When systems are designed without consideration of recovery time for those who are affected, it is the damaged small business owners who bear the burden of weeks of lost revenues while their rent and debt never cease. When baseline conditions change and infrastructure is no longer reliable, poor and marginalized communities in vulnerable places are often disproportionately impacted (WESS, 2016).

Taking a risk-based approach to systems design, we establish recovery time as a fundamental metric of a new best practice, engendering new solutions and opportunities and increased equity (McAllister, Moddemeyer, 2019). This metric would change the request for qualifications, requests for proposals, and the questions that governmental authorities ask themselves and consultants when contracting, specifying, and designing infrastructure. Focusing on a risk-based metric broadens the range of options for solutions and might prove to be less expensive than relying solely on current approaches. This broader range of alternatives provides policymakers with more choices and strategies and greater ability to achieve the same or better levels of service for the same or less cost (Center for Sustainable Infrastructure, 2014).

The focus of the flood mitigation discourse must address the effects of and recovery from floods. Tackling extreme rainstorms means dealing with the consequences of these events. This management of consequences can be reflected with structural systems, qualitative measures/choices, and nonstructural strategies for accelerating the capacity of society at large to reduce vulnerability and accelerate recovery beyond current and future problems.

The large uncertainty of the noncomputable—i.e., extreme events (Carpenter *et al.*, 2009; Milly *et al.*, 2008)—and the deficiency in dominant models and methods mandate a serious shift in the paradigm of flood management from an engineering perspective, as well.

4. CONCLUSIONS

This article encourages society to redefine the engineering of urban drainage within a framework of uncertainty, wherein a changing climate, increased urbanization, and transforming land use now place severe stress on the fundamental basis of the drainage practices that have evolved over the last 100 years. The subsurface urban drainage system will always have a specific hydraulic limitation at some point. The realization that the statistical recurrence intervals for rainfall and the assumption that everything else remains constant in the urban catchment are functionally obsolete require a new best practice to be developed—one that can better manage the overall dynamic conditions of urban drainage systems. Shifting from a probabilities-based system that focuses solely on the recurrence intervals of deterministic design loads to a risk-based system that includes probabilistic estimations of the likelihood and consequences of a range of flood scenarios is an invaluable step toward addressing the uncertain future of climate change, continued urbanization, and population growth.

This article is a call to the water engineering and urban planning communities to consider the limitations and vulnerabilities that are inherited in the current design paradigm. A new paradigm is suggested that is based on risk-based design criteria through a holistic perspective for urban spaces. The paradigm encompasses adaptive capacity, socioecological resilience, and preparedness for a changing future. We hope to spur greater dialog and interest in contributing to the development of a new method for risk-based design of urban drainage and stormwater management systems that take complexity and uncertainty better into account and mobilize a wider group of stakeholders.

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