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OVERVIEW

Pluvial flood risk and opportunities for resilience

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The risk presented by pluvial flooding has emerged as a critical issue in urban water management. Pluvial flooding occurs when precipitation intensity exceeds the capacity of natural and engineered drainage systems, and it is expected to increase in frequency, severity and impact through the 21st century due to the combined effects of climate change and urbanization. Although there have been recent advances in approaches to assess the risk presented pluvial flooding and to enhance the resilience of cities to its impacts, they have not been broadly implemented and there are many opportunities for additional research. We provide case studies of pluvial flooding in six cities in the continental United States, which serve as examples of the current vulnerability of cities that have not developed comprehensive pluvial flood management plans and the challenges in conducting pluvial flood research in light of existing data gaps. We also identify key research challenges that should be prioritized by the interdisciplinary water research community to better support urban resilience practice.

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Engineering Water > Sustainable Engineering of Water
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KEYWORDS
blue green, climate change, infrastructure, pluvial flooding, resilience, urban

1 | INTRODUCTION

As global climate changes and human populations and assets are increasingly concentrated in cities, there is an urgent need for improved understanding of the risk presented by urban flooding and the development of strategies to make cities more resilient to flood events when they occur (Brody, Peacock, & Gunn, 2012; Cheng & AghaKouchak, 2014; Hallegatte, Green, Nicholls, & Corfee-Morlot, 2013). Until recently, most urban flooding research, planning and policy has focused on fluvial (stream/river) or coastal flooding (Guerreiro, Glenis, Dawson, & Kilsby, 2017; Zhou, Mikkelsen, Halsnæs, & Arnbjerg-Nielsen, 2012). However, pluvial flooding—rain-driven ponding or overland flow that results from the exceedance of natural or engineered drainage capacity (Carter et al., 2015; Falconer et al., 2009; Figure 1)—has emerged as a critical issue in urban water management. Many contemporary cities are vulnerable to pluvial flooding and its associated risks are projected to increase as the global climate changes, urban populations grow and existing infrastructure ages (Hossain et al., 2015).

Despite its importance, pluvial flooding has received limited attention in both research and practice compared to other types of flooding for several reasons. First, pluvial flooding was assumed to be a "solved" technical problem. There are well-

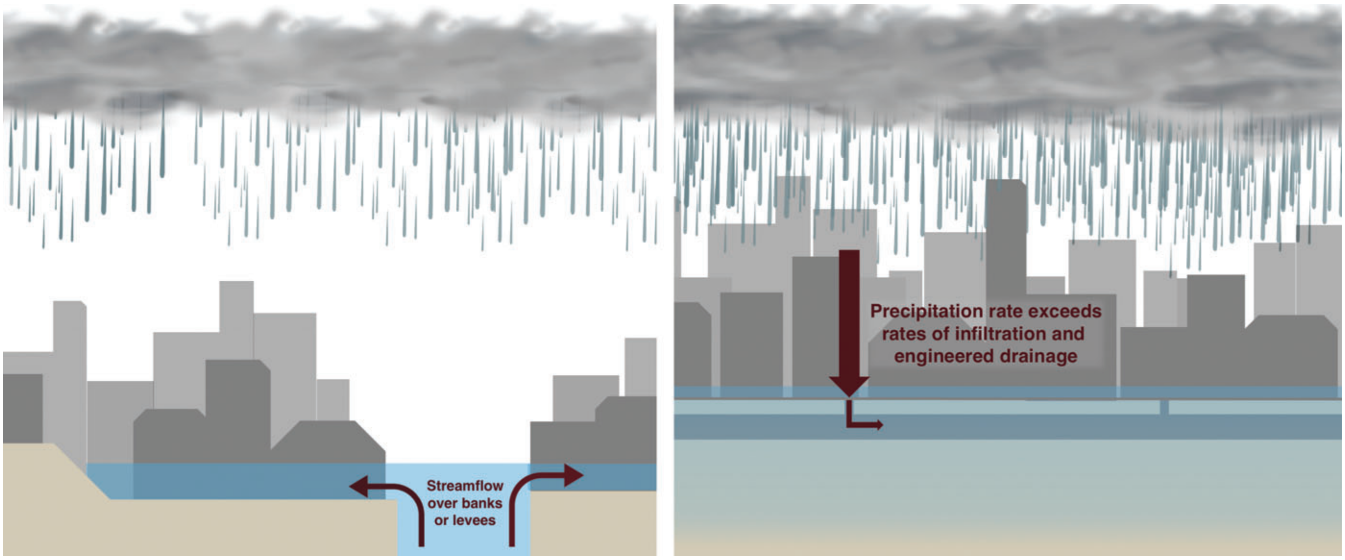

FIGURE 1 Fluvial (left) versus pluvial (right) flooding. Fluvial flooding occurs when water routed by streams, rivers or equivalent water bodies overflows its banks, inundating the adjacent floodplain area. Pluvial flooding occurs when precipitation rates exceed the infiltration capacity of soils and the drainage capacity of stormwater infrastructure, resulting in ponding and overland flow

established methodologies for the design and operation of sewers, culverts, and pumps for flood prevention in cities (American Society of Civil Engineers/Environmental & Water Resources Institute, 2006; J. C. Y. Guo, 2017), and many contemporary pluvial flood events result solely from the failure to adequately implement and maintain these systems (Cherqui, Belmeziti, Granger, Sourdril, & Le Gauffre, 2015; Despotovic, Plavsic, Stefanovic, & Pavlovic, 2005; López-Marrero & Tschakert, 2011). However, conventional engineering approaches for the design of urban flood mitigation infrastructure rely on the assumption of static land cover and climate. Within cities, land cover changes can contribute to flooding when the rate of new development outpaces drainage infrastructure upgrades (Dietz, 2007; Kaźmierczak & Cavan, 2011; Yin, Yu, & Wilby, 2016). In addition, stormwater drainage design is based on past climate trends and is neither adaptive nor sufficient to accommodate more frequent and intense extreme storm events associated with climate change (Mailhot & Duchesne, 2009). As we will discuss later in this review, the performance of urban stormwater infrastructure also needs to be viewed within the context of its interconnections with the broader urban water cycle, of which many components will be altered with changing climate (Grabowski et al., 2017; Koop & van Leeuwen, 2015; Zhou, 2014).

Second, pluvial flooding is often assumed to only present a "nuisance," with minimal impacts. However, there are many examples where it has resulted in direct loss of life, contaminant and pathogen exposure, significant property damage, and widespread disruption of transportation networks or other urban critical systems (Chang et al., 2010; Douglas et al., 2010; Falconer et al., 2009). This "nuisance" designation also misrepresents the cumulative nature of urban flood risk where, over time, the summative costs of relatively minor but frequent events can exceed the costs of less frequent events with severe impacts (Moftakhari, AghaKouchak, Sanders, & Matthew, 2017; ten Veldhuis, 2011).

Third, pluvial flooding is often excluded in flood frequency assessments, which typically rely on time series of in situ observations such as river stage or tidal elevation (Merz et al., 2014). While some local stormwater management agencies monitor the occurrence of surcharging conditions within their drainage networks, these data are rarely made accessible for intercity comparison or climate change impacts assessment. It can also be difficult to monitor precipitation events that result in pluvial flooding, because they are often short duration "cloudburst" events that occur over relatively small urban sewershed areas, requiring quantitative precipitation data at very high temporal and spatial resolution for characterization (Blanc et al., 2012; Carter et al., 2015; Westra et al., 2014). As a result, the historic record of pluvial flood occurrence is often limited to municipal service requests and social media reports, and is affected by the documented biases associated with these data sources (Downton, Barnard Miller, & Pielke, 2005; R.-Q. Wang, Mao, Wang, Rae, & Shaw, 2018). This lack of coherent records creates difficulty in assessing the risk pluvial flooding presents, identifying trends in its occurrence over time, and assessing the effectiveness of mitigation approaches.

In this study, we review the literature on pluvial flooding as a significant driver of urban flood risk with a focus on potential increases with climate change and emerging approaches for urban resilience practice. Our review is organized as follows: First, we provide an overview of conventional stormwater management in cities and how it greatly increases the likelihood of pluvial flooding in response to extreme rain. We then present examples of pluvial flooding events in several United States cities, which serve as useful case studies of both the potential severity of this type of flooding and the challenges of pluvial flooding research in a nation that does not have targeted policies for pluvial flooding in place. Next, we review the emerging approaches for pluvial flood risk assessment and opportunities for cities to enhance their resilience practices. Finally, we discuss the current state of pluvial flooding research and identify key research challenges that must be addressed to advance urban hydrology research and provide the actionable information needed by practitioners (Box 1).

2 | PLUVIAL FLOODING IN CONTEMPORARY CITIES

In any city, the occurrence of pluvial flooding in response to intense rainfall is primarily determined by its stormwater management practices, along with biophysical characteristics such as climate, topography, and soil type (Westra et al., 2014). Urban stormwater management has typically followed an ordered progression as cities develop and densify (Hale, 2016; Kaushal & Belt, 2012). First, as rural areas begin to urbanize, infrastructure practices such as the channelization of natural streams, culverting of streams under roads and bridges, and the construction of stormwater detention basins are initially utilized to prevent flooding (Whipple, 1979). As urbanization progresses and the fraction of impervious cover increases, subterranean storm sewer systems are usually constructed to further reduce flooding hazards (Delleur, 2003; Leopold, 1968). Along with basements, tunnels and other underground infrastructure, these subterranean storm sewer systems can exchange water to or from the ambient subsurface (Bhaskar, Welty, Maxwell, & Miller, 2015; Bonneau, Fletcher, Costelloe, & Burns, 2017; Lerner, 2002), and thus serve as a secondary form of porosity in the shallow aquifers underlying cities, creating a complex induced permeability that has been described as "urban karst" (Kaushal & Belt, 2012; Sharp, Krothe, Mather, Gracia-Fresca, & Stewart, 2003).

Historically, as cities continued to densify, headwater streams were often buried, with their flow redirected to drainage sewers to create additional land for development (Elmore & Kaushal, 2008; Napieralski & Carvalhaes, 2016). While the practice of stream burial has been largely discontinued, the legacy of its historic use remains today and many older cities are "stream deserts" (Napieralski et al., 2015), with their drainage and rainfall response dominated by subterranean conveyance infrastructure. Although this practice, by definition, eliminated the local occurrence of fluvial flooding, in many cases fluvial flood risk was simply replaced by increased pluvial flood risk in response to intense rain.

The basic strategy behind the conventional approach to urban stormwater management was to collect and convey water as quickly as possible, while maximizing dry land area for urban development (Chocat, Krebs, Marsalek, Rauch, & Schilling, 2001; Keller & Hoffman, 1977; Zhou, 2014). While this approach initially appeared to be effective for flood mitigation, it did not consider the consequences when extreme rainfall rates occur. Stormwater infrastructure is engineered to convey runoff associated with a "design storm," a rain event with the intensity over a duration that can be expected to occur with a threshold frequency. This threshold frequency is usually described using a return interval, the inverse of the probability that the rain event will occur in a given year, based on historical observations. When rainfall intensity exceeds that of the design storm, pluvial flooding can result, even though the drainage system is still performing as intended (Q. Guo & Song, 1990). For local-scale drainage systems in dense cities, the design storm usually corresponds to precipitation events with a 2- to 10-year return interval (American Society of Civil Engineers/Environmental & Water Resources Institute, 2006; Y. Guo, 2006; Mohurd, 2011; ten Veldhuis, 2011). This return interval is much shorter than what is usually used as the basis of floodplain management for fluvial flooding, which is typically the 100–500-year storm (Gersonius et al., 2012; Kundzewicz et al., 2010; Ludy & Kondolf, 2012). As a result, pluvial flooding is a frequently occurring challenge in many cities with conventionally designed stormwater infrastructure (Figure 2).

BOX1. PLUVIAL FLOODING TERMINOLOGY

Pluvial flooding (Figure 1) is described by a variety of terms in the academic and gray literature. The term is meant to designate flooding that results from inadequate drainage and is not meant to include overbank flow from streams or coastal inundation. Alternative terms for pluvial flooding include, "street," "sheet," "surface," or "overland" flooding (de Almeida, Bates, & Ozdemir, n.d.; Jenkins, Surminski, Hall, & Crick, 2017; Leandro, Schumann, & Pfister, 2016; Surminski, Bouwer, & Linnerooth-Bayer, 2016). Since cities are particularly prone to pluvial flooding, it is sometimes referred to simply as "urban" flooding, even though pluvial flooding can occur in undeveloped or agricultural catchments when precipitation rates exceed natural infiltration rates, and flooding in urban areas can result from other mechanisms such as fluvial and coastal flooding.

FIGURE 2 Minor pluvial flooding in Phoenix on September 8, 2014 (top left, image: Devon Christopher Adams), New York City on July 15, 2015 (middle, image: Simone Wilson), Baltimore on July 2017 (right, image: Julie Blum)

2.1 | Pluvial flooding case studies in the United States

As previously discussed, the occurrence of pluvial flooding is difficult to monitor and often inconsistently recorded, with implications for risk assessment and the development of mitigation practices. Cities in the United States present a useful example of the limitations of existing data in spite of the risk presented by this type of flooding. Pluvial flooding is excluded from the US National Flood Insurance Program (NFIP; Burby, 2001) and as a result, from subsidized insurance coverage, inclusion in flood hazard mapping and consideration in national flood management projects.

For this review, we consider the recent pluvial flood history of six cities in the United States (Figure 3): New York City (NY), Syracuse (NY), Baltimore (MD), Miami (FL), Phoenix (AZ), and Portland (OR). These cities are part of the Urban Resilience to Extreme Events Sustainability Research Network (UREx SRN), a partnership between interdisciplinary

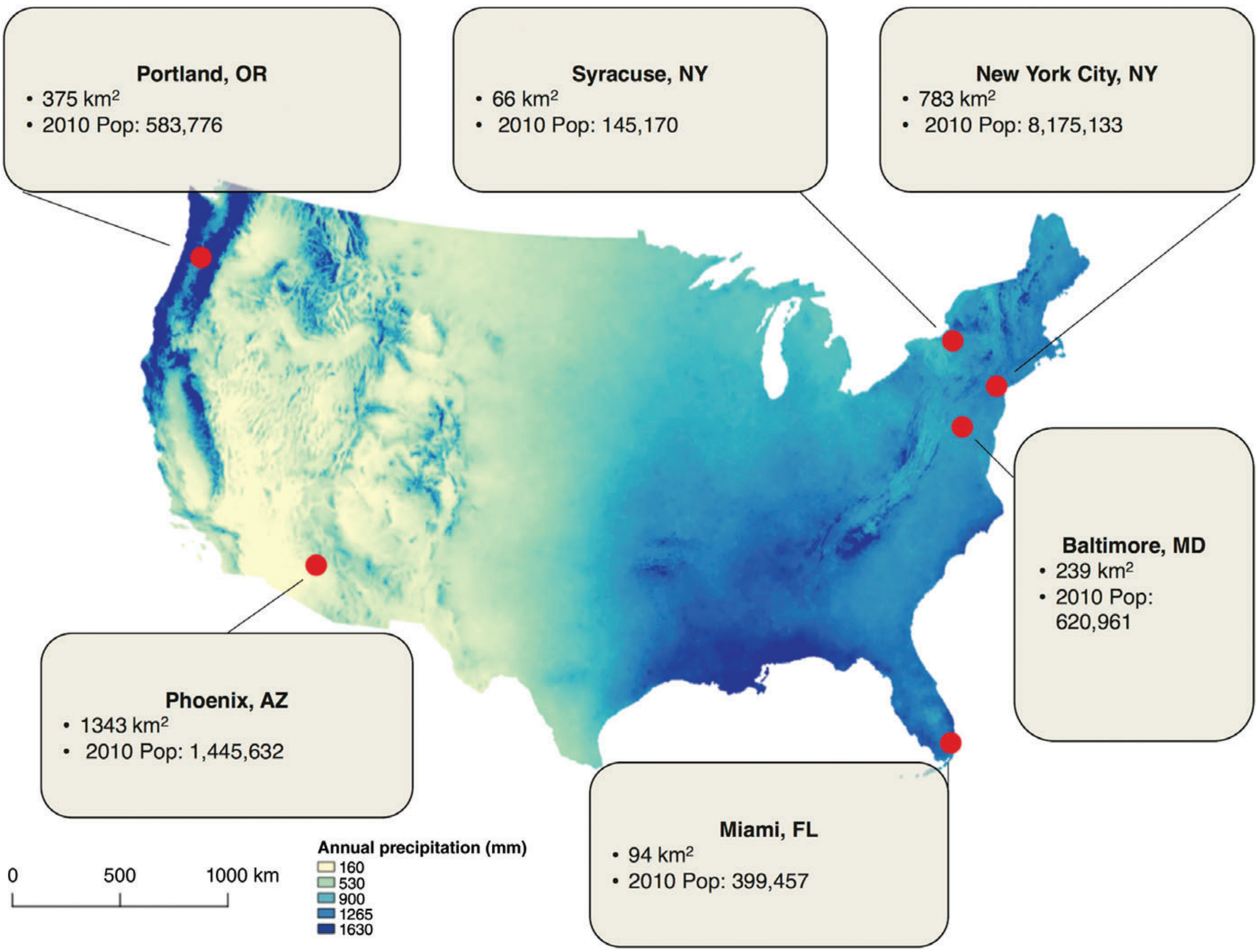

FIGURE 3 Continental US urban resilience to extreme events sustainability research network (UREx SRN) cities. Annual precipitation is from the PRISM climate group, Oregon State University, http://prism.oregonstate.edu, created on February 4, 2004

researchers and practitioners to develop the scientific basis needed to support urban resilience practice. They represent diverse climatic, development and economic settings and are demonstrative of the sociological, ecological and technological (SET; Ernstson et al., 2010; Grabowski et al., 2017) drivers that can influence vulnerability to pluvial flooding. All of these cities are drained by storm sewer systems that are designed to convey runoff associated with precipitation events with return intervals of fewer than 10 years. All six cities also have stormwater management programs that utilize green infrastructure but, with the exception of Phoenix, green infrastructure has been employed primarily to meet water quality regulations and is not designed to mitigate flooding from extreme rain (Chin, 2004; City of Portland, 2016; Center for Watershed Protection/Maryland Department of the Environment, 2009; International Code Council, 2015; Rosenzweig & Fekete, 2018). In Phoenix, large-scale green infrastructure like detention ponds was designed as part of a regional flood control program (City of Phoenix, 2011; McPhillips & Matsler, 2018).

Since there is no dedicated record of pluvial flood occurrence in the United States, we utilize the narrative records of flooding events in the storm events database maintained by the US National Center for Environmental Information (NCEI). This semistructured database includes information on the occurrence of all storms and other significant weather phenomena that cause loss of life, injuries, significant property damage and/or disruptions in commerce from 1996 through the present. Sources for this database include US National Weather Service (NWS) damage surveys, newspaper clipping services, the insurance industry and the general public, among others (US National Weather Service, 2016). There are important limitations to consider in the use of this database even for a first assessment of pluvial flood occurrence and impacts. For example, it may exclude events that impact communities or ecosystems that are less represented in the economy, or in the presence of emergency responders (Gall, Borden, & Cutter, 2009). However, to our knowledge, it is the only cross-city record of significant pluvial flooding impacts for the United States.

Although the storm events database includes structured information on the meteorological driver for listed flooding events, it does not make a distinction between pluvial, fluvial or compound flooding in events resulting from heavy rain. However, the associated narratives often include information that can be used to identify pluvial flooding events. This includes reports of localized flooding in stream deserts, far outside the floodplains of remaining stream channels, descriptions of the flooding resulting from overwhelmed stormwater drainage sewers, or the use of the term "urban poor drainage flooding" within the narrative, which is the term for pluvial flooding used by the US NWS. Using this information in the narratives, we were able to identify pluvial flooding events in five of the six UREx SRN cities considered.

Selected case study events are presented in Table 1. Severe impacts associated with these selected events included the development of conditions that threatened public safety, such as inundated residences and submerged vehicles in fast-moving water. One reported event [NCEI Episode 99,413] resulted in a fatality, when pluvial flooding was compounded by surcharging of the stormwater sewer system. Although monetary damages associated with the NCEI storm events database are incomplete and unreliable (Gall et al., 2009), listed impacts in the narratives included damages to businesses and residences. Though the UREx SRN cities represent diverse climates, the identified events presented in Table 1 were all associated with short-duration, intense (convective) precipitation events. It is also interesting to note that two of the events [Episodes 1,502,938 and 50,267] occurred during cooler seasons since convective precipitation is typically associated with warm summer conditions.

The eight events presented in Table 1 were selected based on their reported significant impacts and provide useful first insight on the current vulnerability of these cities to pluvial flooding with extreme rain. However, there is currently insufficient data to assess the cumulative risk presented by more frequently occurring, minor pluvial flooding events. As an example, along with the two case study events for New York City presented in Table 1, 89 additional pluvial flooding were identified in the database in the period considered (1996–2016). While the impacts associated with most of these events were minor, such as temporary road closures or disruptions in transit service, an increase in the frequency of their occurrence with future climate change may present an intolerable risk in the absence of mitigation efforts.

Other minor events may have actually occurred in New York City and the other UREx SRN cities considered but were not reported in the database. For example, we were not able to identify any pluvial flooding events in Portland for the period of record covered by the NCEI storm events database. However, through conversations with city practitioners, several pluvial flooding events occurred in Portland during the study period of 20 years but were excluded in the database. In collaboration with the Portland State University, the City of Portland is currently actively analyzing pluvial flood risk as it relates to flood reports and neighborhood characteristics (Michelson & Chang, 2018).

3 | CLIMATE CHANGE AND PLUVIAL FLOODING

Climate change is projected to increase the occurrence and magnitude of urban pluvial flooding through alteration in patterns of precipitation. While the local impacts of climate change on annual precipitation totals remain uncertain, there is a general consensus that global climate change will result in more intense short-duration precipitation events in many regions of the

TABLE 1 Selected pluvial flooding events between 1996 and 2016

Event date	Location	Meteorological driver	Reported impacts
January 3, 1999	New York City: Eastern Brooklyn and queens with most severe impacts in the Springfield gardens neighborhood	With cold air in place along the surface, as a strong low-pressure system moved northeast across the Great Lakes, a second low moved northeast across New York City. A period of freezing rain was followed immediately by rapid warming from −4 °C to 12 °C. A narrow band of torrential rain embedded in a large area of steady rain resulted in rates as high as 76 mm/hr falling on frozen ground. [Episode 1,502,938]	Widespread serious flooding of low-lying and poor drainage areas. Life-threatening flash flooding occurred in a 30-block residential area where people required rescue from their flooded basement apartments, where water rose to within 152.4 mm of the ceilings. Many primary roadways were closed due to serious flooding [Event 5,696,065]
June 13, 2003	Baltimore: Northeast neighborhoods of the city	Thunderstorms with very heavy downpours moved through the area for the third straight day [Episode 1,156,704]	Severe flash flooding was reported in the northeast part of Baltimore. Two streets became "rushing rapids," washing several cars hundreds of yards away. Several motorists had to be rescued from their cars or had to swim to safety. "Wall[s] of water" reached a height of 3 m near the intersection of Hillen road and 35th street and 1.8 m at the intersection of Aisquith street and 25th street. Numerous homes were damaged and one woman was injured after flooding weakened the floor of her home and she fell through when it collapsed [Event 5,370,066]
August 8, 2007	New York City: Citywide	An approaching cold front, interacting with energy aloft, produced numerous thunderstorms that generated intense rainfall [Episode 10,328]	Widespread, significant flash flooding closed roads and many subway lines. Numerous cars were submerged [Events 57,570; 57,542; 57,544; 57,556; 57,566]
April 26, 2011	Syracuse: Citywide	Showers and thunderstorms with areas of heavy rain developed due to instability along a slow-moving, warm frontal boundary, where breaks in the cloud cover allowed temperatures to rise to near 21 °C [Episode 50,267]	Officials from the city of Syracuse described the urban flash flooding as major. Most roads in the county experienced degrees of flooding from ponding to major flooding and roadway breakdown. Standing water remained and closed several road intersections for several days afterward [Event 303,330]
September 8, 2014	Phoenix	Showers and embedded thunderstorms developed across the region. In part due to an infusion of tropical moisture from former hurricane Norbert, the storms produced intense rainfall with rainfall rates commonly in excess of 50.8 mm/hr and in some cases, in excess of 152.4 mm/hr for short periods of time [Episode 88,413]	The rainfall caused widespread flash flooding and numerous roads and freeways were closed as pumping stations failed and "lakes" near a meter deep formed across portions of the freeways. Hundreds of cars were stranded across the greater Phoenix area, many buried to the top of their hoods in flood waters. Hundreds of homes and apartment complexes across the greater Phoenix area were flooded [Events 537,722; 537,942]
February 28, 2015	Miami: Omni, Edgewater and midtown areas	A quasi-stationary front was located across South Florida with a surface trough along the southeast coast of the peninsula caused strong thunderstorms to form	Significant flooding occurred in the City of Miami, mainly along the Biscayne Boulevard and North Miami avenue corridors. Multiple cars stalled and flowing water was up to 0.3 m deep. Media reported minor inundation of businesses on the north edge of downtown
June 30, 2015	Syracuse: Citywide	An unseasonably strong storm system tapping into above normal moisture sources across the northeast United States triggered multiple heavy rain producing thunderstorms across the region with localized torrential rainfall [Episode 99,413]	Serious urban flash flooding was reported in the city of Syracuse. Numerous vehicles were stranded in deep, ponded water throughout the city. A man was swept to his death through an open manhole cover [Events 596,768; 596,769]
August 2, 2016	Phoenix	Numerous thunderstorms developed across the greater Phoenix metropolitan area during the afternoon hours and they persisted into the evening; the stronger storms produced intense rain with peak rain rates in excess of 101.6 mm/hr [Episode 646,611]	The heavy rain led to episodes of flash flooding which impacted the central portion of the Phoenix area with road closures and flooded underpasses. Swift water rescues were required but no injuries were reported [Event 107,928]

Narratives of reported impacts are abridged from the storm events descriptions and converted to SI units.

world (Donat, Lowry, Alexander, O'Gorman, & Maher, 2017; Fischer & Knutti, 2016; Loriaux, Lenderink, & Siebesma, 2016). This projected increase arises from two basic mechanisms: First, as described by the Clausius–Clapeyron equation, under the temperature and pressure conditions found at the earth's surface, the maximum atmospheric moisture content will increase at an approximate rate of ~7%/°C (Westra et al., 2014). If moisture is not limiting, this would lead to a similar scaling of the local moisture available to produce precipitation and, in turn, rainfall rates (Trenberth, Dai, Rasmussen, & Parsons, 2003; Figure 4). Second, rainfall generating mechanisms can also vary with temperature. Rainfall generated through convective processes (e.g., during thunderstorm or cloudburst events) is generally more intense and of shorter duration than rain generated through the stratiform processes associated with frontal systems (Ahrens, 2012). The proportion of heavy rainfall that is generated through convective, rather than stratiform processes increases with temperature under many conditions (Haerter & Berg, 2009). Since convective rainfall is associated with more intense precipitation, rainfall rates would increase even faster than predicted by the Clausius–Clapeyron equation (at scaling rates greater than 7%/°C), an occurrence described as "super-CC" scaling, when observed (Berg, Moseley, & Haerter, 2013).

Along with direct changes in the frequency of intense precipitation, climate change may also indirectly affect pluvial flood risk through interactive changes in relative sea level, groundwater levels and the conveyance capacity of stormwater drainage infrastructure (Figure 5). For example, in coastal cities, elevated sea levels can reduce the conveyance capacity of urban drainage infrastructure through backwater effects at coastal outfalls (Wilby, 2007). As a result, as sea levels rise, many coastal cities will be required to implement expensive upgrades on their drainage systems to mitigate direct inflow effects that would otherwise increase their vulnerability to extreme rain and pluvial flooding (Sperotto et al., 2016). In cities with high water tables, groundwater infiltration into storm sewers can result in reduced stormwater conveyance capacity and exacerbate flooding in response to intense rain (Cahoon & Hanke, 2017). Coastal aquifers are hydraulically bound by adjacent marine waters and, as sea levels rise, groundwater flow fields can be altered resulting in increases in the elevation of coastal water tables with resulting increased infiltration into urban subterranean infrastructure (Bear, 2012; Bjerklie, Mullaney, Stone, Skinner, & Ramlow, 2012; Flood & Cahoon, 2011). Thus, in assessing the increased pluvial flood risk presented by climate change, it will be essential to consider the interconnections between the changing urban water cycle and the performance of stormwater infrastructure.

4 | EMERGING APPROACHES FOR PLUVIAL FLOOD RISK ASSESSMENT

The risk from any type of flooding is determined by three parameters:

1. *Hazard*: the probability of occurrence of a driving event.
2. *Exposure*: the amount of people and assets that would be directly impacted by the event.
3. *Vulnerability*: the severity of impacts experienced by the exposed population and assets.

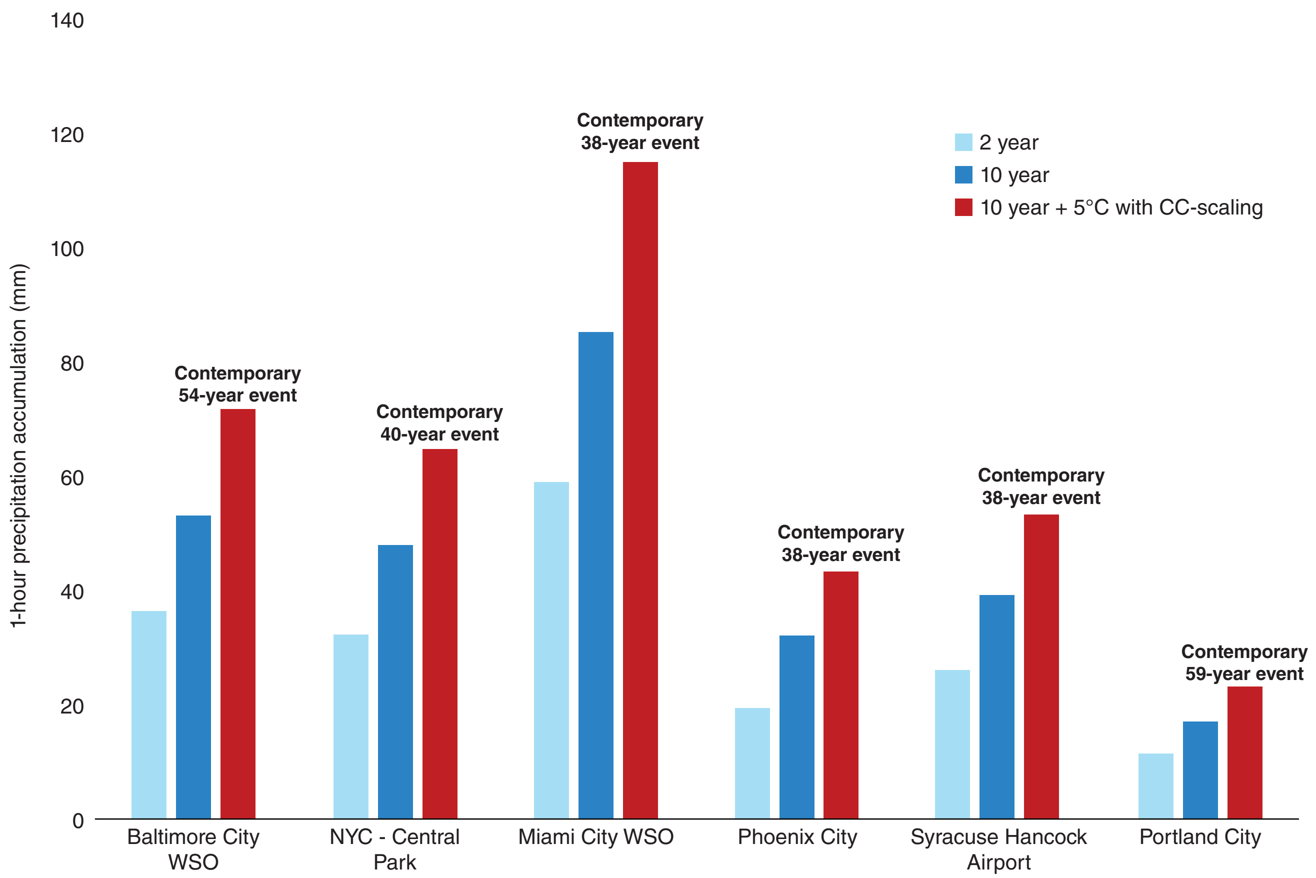

FIGURE 4 The contemporary 50% (2-year) and 10% (10-year) probability hourly precipitation events in six urban resilience to extreme events sustainability research network (UREx SRN) cities, with the equivalent 10-year storm with a hypothetical *local* temperature increase of 5 °C, assuming scaling rates based on the Clausius–Clapeyron relation. Parts of the stormwater drainage system in older cities (e.g., Syracuse, New York City and Baltimore) are designed to convey runoff generated only from storms with a 2-year return interval

Since all three of these risk parameters are expected to increase through the 21st century (Hossain et al., 2015), a comprehensive approach to pluvial flood risk assessment must be representative of nonstationary hazard occurrence, exposure, and vulnerability (Sperotto et al., 2016). Over the past decade, research to develop improved assessment methods for all three of these parameters of pluvial flood risk has been initiated. A summary of many of these studies is presented in Table 2.

For example, research has begun to better characterize the probability of pluvial flood occurrence (hazard) in light of climate change. While thermodynamic scaling approaches based on the Clausius–Clapeyron equation provide useful first insight on how climate change may amplify the hazard presented by intense rainfall (Ban, Schmidli, & Schär, 2015), they are unable to capture the regionally variable changes in large-scale circulation that will drive local precipitation dynamics with climate change (Fildier, Parishani, & Collins, 2017). The recent development of regional climate models that represent the dynamics of convective rainfall will allow for improved representation of changes in the frequency and magnitude of cloudburst rainstorms under alternative scenarios of global climate change (Prein et al., 2015). However, our predictive understanding of the changes in intense precipitation with climate change will remain limited until more of these types of modeling studies are conducted and until our understanding of the mechanisms that drive intense precipitation is improved. In addition, as previously discussed, one of the challenges in investigation of pluvial flooding is the lack of a quantitative record of its occurrence and magnitude in response to extreme rainfall. Several studies have taken advantage of recently available data sources, such as environmental sensors or crowd-sourced information, to construct records of local pluvial flood occurrence and impacts (Assumpção, Popescu, Jonoski, & Solomatine, 2018; de Vitry et al., 2017; Griesbaum et al., 2017).

For other types of flooding, the delineation of flood hazard areas, such as the "100-year floodplain" for river flooding or the storm surge "maximum envelope of water" is a common practice to support flooding exposure and vulnerability assessment. Recent studies have used geographic information systems (GISs) to delineate analogous high-risk areas for pluvial flooding, taking advantage of newly available, highly resolved geospatial datasets. Beyond the use of simple GIS-based approaches for pluvial flood hazard delineation, several studies have investigated the use of numerical modeling that better represents the dynamic effects of spatially varying rainfall, runoff generation processes and features of the built environment (Löwe et al., 2017; Obermayer et al., 2010; Zellner, Massey, Minor, & Gonzalez-Meler, 2016). Recent reviews of available urban drainage models are provided by Bach, Rauch, Mikkelsen, Mccarthy, and Deletic (2014) and Salvadore, Bronders, and Batelaan (2015).

Along with the delineation of flood hazard areas, the assessment of urban flood vulnerability once flooding occurs is an active area of research, as there are critical shortcomings associated with standard flood vulnerability approaches when applied in cities (Cho & Chang, 2017; Hammond, Chen, Djordjević, Butler, & Mark, 2015). These standard approaches overlay geospatial data of flooding extent and depth over data on buildings and critical infrastructure, and then use site-specific depth-cost

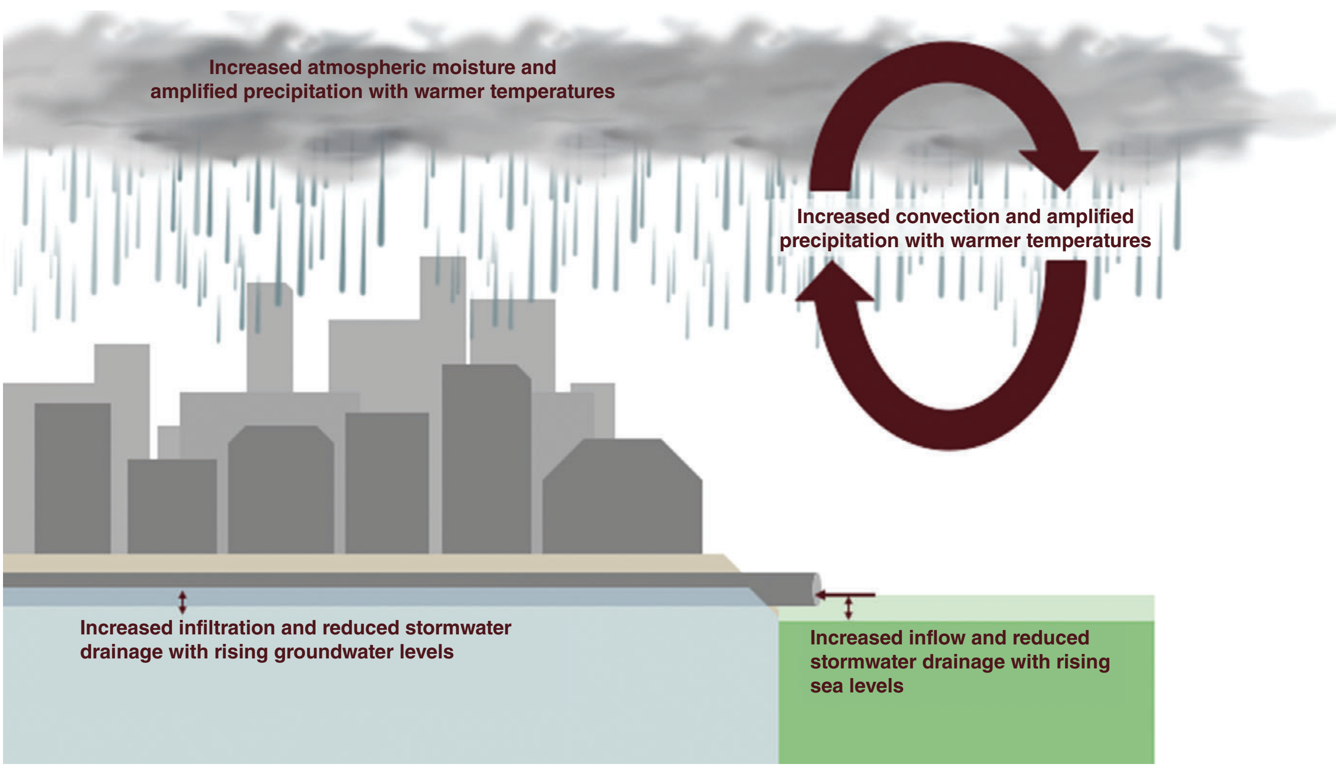

FIGURE 5 Potential mechanisms by which climate change can increase pluvial flood hazard in cities. Climate change can directly increase the frequency, spatial extent and magnitude of intense rain, which can result in exceedance of designed drainage capacity

relations to estimate flooding damages. While this can provide important estimates on the direct effects of flooding, it excludes many indirect impacts that are particularly important in urban settings, such as health effects, disruption in transportation and business, and loss of recreational resources (Ahern, Kovats, Wilkinson, Few, & Matthies, 2005; Hajat et al., 2005; ten Veldhuis, 2011). Several of the studies presented in Table 2 have attempted to better quantify the indirect impacts of pluvial flooding in cities to support a more representative risk assessment.

5 | OPPORTUNITIES TO ENHANCE PLUVIAL FLOOD RESILIENCE

5.1 | Resilience theory and pluvial flooding

Along with improved quantification of the risk presented by pluvial flooding, there is also great interest in developing robust strategies for its management. The concept of resilience has been widely adopted by flood management policymakers, but has also been broadly interpreted and its precise definition remains a topic of discussion (de Bruijn, Buurman, Mens, Dahm, &

TABLE 2 Overview of recent advances in pluvial flood risk assessment

	Risk assessment advance	Source
Hazard	Developed a generalized framework for calculating nonstationary intensity–duration–frequency (IDF) curves using Bayesian inference	Cheng and AghaKouchak (2014)
	Conducted continuous, multiyear climate change experiments using a high-resolution regional climate model (RCM) that directly represented convective dynamics, showing future intensification in summer precipitation beyond what had been projected by previous coarse-resolution modeling	Kendon et al. (2014)
	Modeled the impacts of alternative scenarios of climate change using a convection-resolving RCM and found that extreme precipitation increases with temperature in moist, energy-limited environments and decreases with temperature under large-scale moisture-limited conditions	Prein et al. (2017)
	Developed a trend-analysis framework for calculating nonstationary IDF curves using regional observation data	Ganguli and Coulibaly (2017), Sarhadi, Ausín, and Wiper (2016)
	Used the Gumbel distribution function and daily observation data to temporally downscale 6-hourly RCM outputs	Vu, Raghavan, and Liong (2017)
Exposure	Developed a novel approach for pluvial flood monitoring using sensors and surveillance video cameras	de Vitry, Dicht, and Leitão (2017)
	Developed a modeling framework using information posted by the general public on Twitter to map flooding extent during two extreme rainstorms in a community in the United Kingdom	Smith, Liang, James, and Lin (2017)
	Developed an approach to use digital images, such as those typically captured using mobile phone cameras, to assess building flood inundation	Griesbaum, Marx, and Höfle (2017)
	Used light detection and ranging-derived digital elevation models to identify topographic depressions or “bluespots” that can accumulate overland runoff to impactful depths	Di Salvo, Ciotoli, Pennica, and Cavinato (2017)
	Developed areal flood risk regressions based on multiple geospatial parameters, such as stream, sewer or infrastructure density, topography and land cover, or the presence of informal settlements	Sperotto et al. (2016), C. Wang et al. (2017)
	Used the MIKE hydraulic software suite (DHI group) to delineate flood hazard areas	Olsen, Zhou, Linde, and Arnbjerg-Nielsen (2015)
	Used the InfoWorks CS model [Innovyze], driven by a 100-year time series of stochastically generated, hourly rainfall data, to assess flood risk zones	Blanc et al. (2012)
	Used FLURB-2D, a dynamic overland flow model to delineate flood hazard areas	Palla, Colli, Candela, Aronica, and Lanza (2018)
	Used a cellular automata model as an alternative to hydrodynamic modeling to investigate pluvial flooding extent in response to hypothetical rainfall	Ghimire et al. (2013)
Vulnerability	Developed an enhancement of this standard vulnerability assessment approach for pluvial flooding, which allowed for the consideration of both direct and indirect flooding impacts in calculation of expected annual damages	Olsen et al. (2015)
	Used radar-based quantitative precipitation estimates and/or flood insurance claim data available for the Netherlands and Sweden to investigate vulnerability to pluvial flooding	Grahn and Nyberg (2017), Spekkers, Kok, Clemens, and Ten Veldhuis (2013)
	Developed a novel approach for the assessment of roadway vulnerability to pluvial flooding, using a GIS-based road failure analysis	Yin, Yu, Yin, Liu, and He (2016)
	Assessed roadway vulnerability to pluvial flooding using the SWMM hydrodynamic model	Kim et al. (2017)
	Assessed the effects of relatively frequent, low-magnitude pluvial flooding events on intra-urban traffic patterns, using a function relating roadway water depth to vehicle speed	Pregnolato, Ford, Glenis, Wilkinson, and Dawson (2017)
	Used a hydrodynamic model to perform a continental-scale pluvial flood vulnerability assessment for 571 cities across the Europe	Guerreiro et al. (2017)

Klijn, 2017). For this overview, we use the definition of resilience proposed specifically for urban systems by Meerow, Newell, and Stults (2016):

> The ability of an urban system—and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales—to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity.

With this definition, the relevant "disturbance" is the occurrence of an intense rain event. A city that is resilient to this hazard may not experience pluvial flooding in response to an intense rain event or, if pluvial flooding does occur, is able to maintain or quickly restore its essential systems (e.g., transportation, housing, economic, and ecological). The resilient city would also have knowledge systems (Munoz-Erickson, 2014) in place that allow stakeholders to learn from their experiences with extreme rain and pluvial flooding and adapt their essential systems for the future.

In assessing and developing strategies to enhance pluvial flood resilience, it is important to consider the magnitude, timing, and frequency of intense rain event disturbances (Rykiel, 1985; White & Pickett, 1985). For example, cities with conventional stormwater drainage systems are typically resilient to rainstorms that do not exceed their design storms but may not be resilient to an extreme rain event that causes significant uninsured damage to residences and businesses. Also, cities may be resilient to a single rain event that results in minor pluvial flooding and short disruption of essential systems but may not be able to quickly recover from events of comparable magnitude that occur frequently or in close succession.

5.2 | Pluvial flooding resilience practices

Targeted approaches to enhance the resilience of cities to pluvial flooding have only been investigated in the past decade. Sörensen et al. (2016) suggested that a "regime shift" in urban water management is necessary, where integrated water management is favored over large-scale, single-purpose sewerage projects to mitigate flooding in sensitive areas, areas where controlled flooding can be tolerated are designated, and plans are made for reorganization in case damage occurs. To an extent, this regime shift is already in progress—many cities have begun adopting a "blue-green" infrastructure (BGI) approach to stormwater management, using multifunctional green infrastructure to try to restore predevelopment hydrologic function (Novotny, Ahern, & Brown, 2010). Examples of commonly employed BGI include rain gardens, bioretention basins, bioswales, green roofs, and porous pavement.

However, the extension of this approach to mitigate the impacts of pluvial flooding—particularly during extreme rain events—is in the earliest stages of development (Lawson et al., 2014). Although flood regulation is often listed as an important service provided by BGI, quantitative information on its actual effectiveness and optimal utilization remains limited. While numerous studies have considered the general runoff retention provided by BGI (Eckart, McPhee, & Bolisetti, 2017), few published studies have actually quantified the catchment-scale effectiveness of BGI in mitigating pluvial flooding and, of these, only two consider extreme (>20 years recurrence) precipitation events (Table 3). In practice, many types of BGI rely primarily on the infiltration of stormwater to mitigate flooding and would be limited in their effectiveness when rainfall rates greatly exceed the maximum infiltration rates of their soils. Some types of BGI are designed to detain water, temporarily storing stormwater runoff during rain events and releasing it slowly to prevent exceeding the conveyance capacity of water infrastructure. However, as with other types of urban water infrastructure, BGI is designed for the management of a design storm and may provide limited detention capacity during events that exceed the design storm intensity.

In addition to building resilience through land management and infrastructure planning, there are also opportunities to enhance resilience to pluvial flooding through nonstructural policies and practices. Providing advanced warning that pluvial flooding is likely to occur can be an important means to prevent loss of life or property damage by providing the time necessary to evacuate vulnerable areas, clear drainage infrastructure of debris to optimize conveyance capacity, relocate parked vehicles to higher ground and move furniture to higher floors (Despotovic et al., 2005; McNarie, Quist, Lewinger, & Haimann, 2017; Rözer et al., 2016). However, providing early warning for pluvial flooding remains challenging, since it is often driven by highly localized and fast moving cloudburst events that are difficult to forecast (Falconer et al., 2009). At present, the ability to provide warning of intense rainfall is often limited to the use of radar-based observations of approaching storms, however, numerical modeling packages to support near-term forecasting and warning are currently being tested (Clark, Roberts, Lean, Ballard, & Charlton-Perez, 2016; Gallo et al., 2017; Stensrud et al., 2009). Along with near-term forecasting of the occurrence of intense rainfall rates, identification of rainfall thresholds that indicate that pluvial flooding will likely occur is critical to support flood warning systems. Rainfall threshold approaches used to support fluvial flood warning systems, such as the US NWS's Flash Flood Guidance, are based on the use of antecedent soil moisture conditions and less relevant to highly urbanized settings or extreme rainfall intensities (Ntelekos, Georgakakos, & Krajewski, 2006). In response,

TABLE 3 Published studies on the effectiveness of blue-green infrastructure (BGI) in pluvial flood mitigation

Author	Location	BGI considered	Precipitation peak intensity/duration/ frequency	Results
Liu et al. (2014)	Urban community in Beijing, China	Expanding green space, concave green space, retention ponds, porous pavement and combinations	2.8 mm/min (peak)/24 hr/10 years	While the reduction capacity of individual BGI projects is limited, BGI integrated throughout the community was highly effective in preventing flooding from precipitation events with 10-year recurrence interval
Qin et al. (2013)	Guang-Ming New District, Shenzhen, China	Swales, porous pavement and green roofs	4.3 mm/min (peak)/1–4 hr/100 years	Effectiveness of BGI was dependent on the percent coverage and storage capacity. Porous pavement was most effective at the study site since it provided the greatest area of coverage
Hu et al. (2014)	Hexi watershed, Nanjing, China	Rainwater harvesting cisterns, porous pavement and combinations	*Not specified*/20 min/5 years	Porous pavement reduced inundation area by 50%–75% in high hazard areas. Rainwater harvesting was able to provide limited additional mitigation benefits
Zellner et al. (2016)	Hypothetical, based on Cook County, IL, USA	Detention basins	0.25 mm/min (peak)/24 hr/100 years	BGI dispersed throughout the landscape at high levels of coverage (>20%) effectively mitigated flooding
Zhu et al. (2017)	Residential area of Guangzhou, China	Bioretention, porous pavement, infiltration trench, rain barrel, vegetative swale, rain garden and green roofs	Not specified/2 hr/10 years	For the scenarios modeled, BGI was effective for lower intensity storms (2 years), but less effective for the 10-year storm
Chen et al. (2017)	Xingshi Village, Taiwan	Infiltration trench and basin, detention ponds, vegetated filter strip and swale, sand filter, constructed wetlands, green roof, rain barrel, porous pavement, and bioretention	94.7 mm/hr/1 hr/5 years*1.5 to account for climate change	BGI deployment throughout the watershed can be optimized to mitigate pluvial flooding

an enhanced pluvial flood warning system using a distributed hydrologic model that better represents urban land cover has recently been developed (Ochoa-Rodríguez, Wang, Thraves, Johnston, & Onof, 2015; Speight et al., 2016).

Insurance is another example of a nonstructural practice that can play an important role in flood resilience as part of a broad strategy to both reduce flooding exposure and vulnerability and to provide the finance needed to support quick recovery when flooding damages occur (Surminski, Bouwer, & Linnerooth-Bayer, 2016). However, the extent to which pluvial flooding is covered by insurance currently varies among countries (Lamond & Penning-Rowsell, 2014; Spekkers et al., 2013). For example, in the United States, while property owners may privately purchase insurance to cover the damages caused by pluvial flooding, it is currently excluded from the US NFIP and the associated mandates and subsidies that incentivize insurance coverage (Burby, 2001). Since pluvial flooding often occurs outside the floodplain hazard areas designated through the US NFIP, many affected property owners are not aware of their potential exposure and do not purchase insurance even when they have the means to afford the unsubsidized rates (Douglas et al., 2010). The development of policies to incentivize insurance coverage for pluvial flooding presents an important opportunity for resilience practice in the United States and the majority of other countries where pluvial flooding is not widely covered by insurance policies.

5.3 | A "3 Points Approach" for resilience practice

To support the use of BGI and other concepts of integrated water management for pluvial flood resilience, there is great potential in the adoption of a "3 Points Approach" (3PA) to urban water management, as proposed by Fratini, Geldof, Kluck, and Mikkelsen (2012) (Figure 6). This approach considers three distinct frequency domains, delineated by threshold "points" of management: (1) medium recurrence (e.g., 2–10 years) rain events, (2) extreme rain events, and (3) day-to-day function. 3PA Point 1 is already covered by the design of most urban gray infrastructure and BGI. Pluvial flood resilience practices in this domain can involve adapting the determined design standard to account for projected climate change and then constructing or retrofitting infrastructure to meet updated design standards. However, this approach alone is limited in its ability to account for uncertainties in climate projections as well as to manage precipitation events that are more extreme than considered in design standards (Sørup, Lerer, Arnbjerg-Nielsen, Mikkelsen, & Rygaard, 2016).

3PA Point 2 addresses the need to build resilience to extreme precipitation events by taking a broader view of the urban water landscape, designating areas for water to be stored when the conveyance capacity of traditional stormwater conveyance infrastructure is exceeded. To date, this has most often involved the use of centralized "gray" infrastructure such as underground water storage tunnels (Fratini et al., 2012; Liu & Jensen, 2017). However, these are limited by the availability of

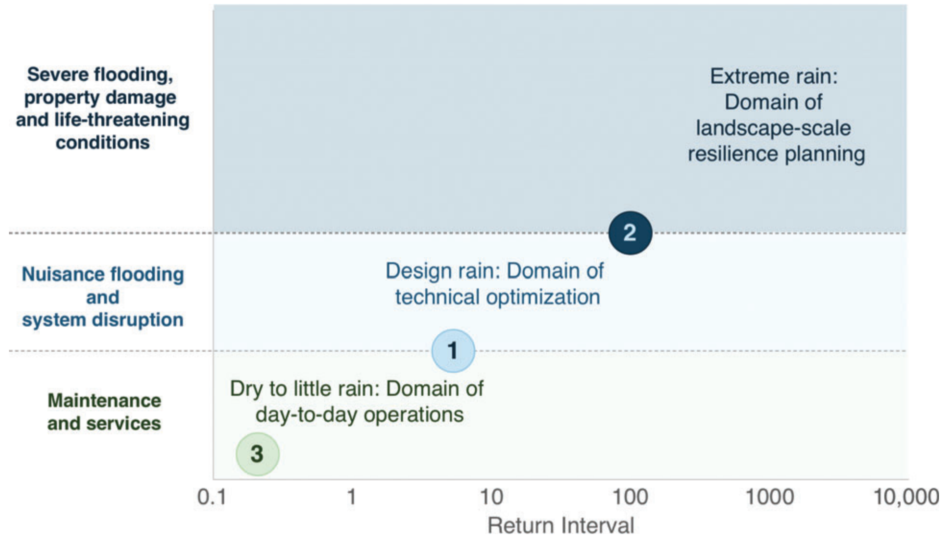

FIGURE 6 Three points approach scheme for pluvial flood management. The horizontal axis represents the rain event return interval and the vertical axis represents the magnitude of impacts. Both axes are on a logarithmic scale. The three "points" represent thresholds for each management domain. (Modified from Fratini et al. (2012))

suitable subterranean space in dense urban environments and can be extremely costly and disruptive to construct (Mottaghi, Aspegren, & Jönsson, 2016; Voskamp & Van de Ven, 2015). As an alternative, some cities are incorporating surface areas for water to flow and pond during extreme events into their landscape planning (Hvilshøj, Lund, Goring, & Lv, 2016; Jiang, Zevenbergen, & Ma, 2018).

3PA Point 3 focuses on the day-to-day management of urban land and water when it is not raining heavily. As storage of the great volumes of stormwater associated with extreme rain—even from short duration events—requires large amounts of safe-to-submerse space that can be in short supply in dense cities (Voskamp & Van de Ven, 2015), it is usually essential that these spaces are multifunctional. There are many opportunities for these designated stormwater storage areas to provide engineered or ecosystem services under the normal precipitation conditions of 3PA Point 3, supporting broader urban revitalization goals (de Graaf & van der Brugge, 2010; Lawson et al., 2014; Mguni, Herslund, & Jensen, 2015; Salinas Rodriguez Carlos et al., 2014). In recently piloted projects, these have included BGI, playgrounds and plazas that are submersible and can be safely inundated during extreme rain, along with BGI corridors along roadways that can convey floodwaters and prevent deep inundation of property (Matos Silva & Costa, 2016).

The implementation of a 3PA approach for pluvial and fluvial flood resilience can be supported by broader strategies for decision making under uncertainty available in the climate adaptation literature. Although there have been recent advances in our ability to represent pluvial flood hazards under different global climate scenarios, deep uncertainty remains as a result of limitations in our understanding of climate and hydrologic systems, current modeling capacity and our inability to forecast future emissions pathways. As a result, it is inadvisable to develop pluvial flood resilience strategies based on a "predict-then-adapt" approach, that is reliant on having robust predictions of the future (Dessai, Hulme, Lempert, & Pielke, 2009; Lempert, Nakicenovic, Sarewitz, & Schlesinger, 2004). Alternative adaptation approaches have been developed that are primarily centered on effects, rather than predictions. These approaches consider the function of infrastructure systems and policies in response to a range of plausible extreme events, including those that may not have been predicted by a given climate change pathway (Gersonius et al., 2012; Haasnoot, Kwakkel, Walker, & ter Maat, 2013; Thorne, Lawson, Ozawa, Hamlin, & Smith, 2018; Walker, Haasnoot, & Kwakkel, 2013).

6 | PLUVIAL FLOODING RESEARCH OPPORTUNITIES

Along with the recent advances in pluvial flood risk assessment and resilience practice discussed in this review, there are many opportunities for additional research. We have identified three interrelated research areas that are particularly important in support of the development of resilient cities:

1. *Identification of pluvial flooding "tipping points"*: From our review of the literature and the United States case studies, it is evident that pluvial flooding already presents a significant risk for many cities, which will be amplified by climate change in the coming decades in the absence of adaptation. This risk is currently tolerated in many cities, while this risk is

currently tolerated in many cities, it is unclear whether this is because it is actually deemed acceptable or due to a lack of information about the risk presented. In the United States and many other parts of the world, there is currently an inconsistency between the level of risk that is viewed as acceptable from fluvial and coastal flooding (usually from events with return intervals >100 years) and that from pluvial flooding (>10 years for most local drainage systems).

There is a need for additional research to determine what is the actual level of risk from pluvial flooding that urban stakeholders view as acceptable. To support the development of resilient cities, it is essential that this assessment goes beyond simply identifying acceptable return intervals, but also considers the impacts of potential extreme events (Lempert et al., 2004). Many of the recently developed approaches for adaptation under uncertainty are centered around the identification of adaptation tipping points, thresholds beyond which the magnitude of impacts from climate change (or other drivers) is such that management practices cannot fulfill their stated objectives (Gersonius et al., 2012; Haasnoot et al., 2013; Kwadijk et al., 2010). Tipping points can be delineated based on the magnitude of impacts, such as a pluvial flood event that results in inundation levels above a defined threshold or, alternatively, by frequency such as disruption in transit service due to flooding above a threshold number of occurrences each year.

2. *Enhancing our understanding of the water cycle of ultra-urban areas*: There is a clear need for improved understanding of the dynamic interactions between engineered infrastructure and surface, ground and coastal waters that influence the occurrence and magnitude of pluvial flooding in dense urban environments. Recently, available numerical models that integrate multiple components of the urban hydrologic system will play an important role in this emerging research, but many opportunities remain to improve the computational efficiency and representation of urban hydrologic processes within these models (Salvadore et al., 2015). Also, the utilization of these numerical models is currently limited by the availability of hydrologic process studies and observational data to support their parameterization, calibration and validation. In addition, in many cities, accurate data on as-built subterranean drainage infrastructure is currently unavailable, presenting opportunities for both the development of novel sensing techniques and statistical methods for probabilistic mapping of sewer networks (Bilal et al., 2018; Hopkins & Bain, 2018; Sărăcin, 2017).
3. *Optimization and implementation of a 3PA for urban stormwater management*: Approaches for urban flood mitigation and, more broadly, the management of urban water systems have become increasingly sophisticated over the past 20 years, moving beyond an exclusive focus on drainage to consider multifunctionality and the provision of ecosystem services through the use of BGI (Fletcher et al., 2015; Rozos, Makropoulos, & Maksimović, 2013). These approaches enhance the value of green and gray infrastructure designed to provide drainage during design storm events (3PA Point 1) by also providing services and functionality during dry conditions (3PA Point 3). However, it is critical that performance under extreme precipitation conditions (3PA Point 2) is also considered as an essential design criteria (Voskamp & Van de Ven, 2015), particularly in light of the uncertainty surrounding future climate change impacts. There are many research opportunities presented by the design of multifunctional infrastructure and landscapes that can store water during extreme rain events and the development of the frameworks necessary to institutionalize these strategies into urban planning and policy-making.

7 | CONCLUSION

As 21st century cities plan for billions of dollars in investment in flood resilience, there is an urgent need for a more comprehensive approach to urban that better represents the risks presented by pluvial flooding (Merz et al., 2014; Patrick, Solecki, Jacob, Kunreuther, & Nordenson, 2015). While pluvial flood mitigation is now being incorporated into urban resilience planning in many parts of the world (Dai, Wörner, & van Rijswick, 2017; Hall, Meadowcroft, Sayers, & Bramley, 2003; Jia, Shaw, & Qin, 2017), many cities in other regions have not yet begun this type of work. For example, although five of the six UREx Network Cities profiled in this review have experienced at least one recent, significant pluvial flooding event, only New York City has begun pilot studies on local pluvial flood risk mitigation and this work has not yet been fully institutionalized into city operations or planning (New York City Department of Environmental Protection/Ramboll, 2017). These cities are representative of the majority of global cities that remain vulnerable to pluvial flooding and will face increased risk with climate change if resilience practices are not implemented.

Over the past decade, there have been advances in the development of methods to assess pluvial flood risk and enhance resilience in existing and developing cities. There are also many opportunities for additional research to support broad and effective adoption of these practices. We have identified three key research challenges: the identification of pluvial flood risk tipping points, enhancing our understanding of the water cycle of ultra-urban areas, and implementation of a 3PA approach for urban stormwater management, which should be prioritized in future work.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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