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ADVANCED REVIEW

Nature-based solutions for urban pluvial flood risk management

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Abstract

Urban pluvial flooding now occurs more frequently than it has in past decades, mainly due to an increasing number of extreme precipitation events occurring in the context of a changing climate. To limit the evolving risks of urban pluvial flooding in a more environmentally friendly manner, the research community has recently paid increasing attention to Nature-Based Solutions (NBS), which are based on new green technologies. To meet the urgent demand for a comprehensive review of the most recent literature, this review conducts a systematic survey of the literature to characterize various NBS adopted in different regions of the world and to elaborate on the benefits and limitations of such NBS. The review highlights the role of NBS in urban flood risk management under ongoing climate change and rapid urbanization. It shows that NBS could effectively mitigate urban flooding caused by high-frequency precipitation events, with additional economic, ecological, and social benefits. However, NBS are less effective at helping cope with pluvial flooding caused by extreme precipitation events over a short period of time, while gray infrastructures also have limitations as a mitigation measure against extreme pluvial flooding. We thus recommend identifying flood risk management strategies by evaluating the performance of alternative combinations of NBS with gray infrastructures in preventing pluvial flooding in the cities. Finally, recent advances made in the applications of NBS are presented with suggestions (e.g., long-term monitoring) to improve urban flood adaptive management.

This article is categorized under:
Engineering Water > Planning Water
Engineering Water > Sustainable Engineering of Water
Science of Water > Water Extremes

KEYWORDS
extreme precipitation, nature-based solution, risk management, urban pluvial flood

Yijing Huang and Zhan Tian equally contributed to this study.

[Correction added on 27 April 2020, after first online publication: the unit of second affiliation has been updated and funding information has been reordered.]

1 | INTRODUCTION

Urban pluvial flooding is generally caused by heavy rainfall events (Blanc et al., 2012; Rosenzweig et al., 2018; Rözer et al., 2019; Schanze, 2018; Sun & Xu, 2009). It is now widely acknowledged that heavy and/or torrential rainfall events will become more frequent and intensive due to the increasing global surface temperatures (IPCC Work Group I, 2013). The severity of such flood events is fundamentally dependent upon the precipitation intensity (Lin, 2013). Downpours of torrential rain can produce an extreme event, which is characterized as a flood event exerting significant impacts on human society in terms of causing general damage, human casualties and overall social disruption (Kvočka, Falconer, & Bray, 2016). The drainage of stormwater in urban environments with extensive impervious surfaces depends mainly on the structure of sewer systems (Coutts, Tapper, Beringer, Loughnan, & Demuzere, 2013). Once the intensity of rainfall overwhelms the drainage capacity of pipeline networks, the stormwater cannot be discharged in time, usually leading to the serious urban flooding (Cauncil, 2007). In fact, the combined effects of observed climate change and urbanization in last several decades have led to a significant increase in the occurrence of urban flood events, not only in low-lying coastal cities but also in inland cities such as the capital of China, Beijing (Zhang, Podlasly, Feger, Wang, & Kai, 2015). Extreme pluvial flooding occurred in the city of Beijing in July 2012, claiming 77 lives and causing damage valued at US $1.9 billion (Peterson et al., 2013). Additionally, data on the international disasters for 2006–2015 collected and consolidated by the Centre for Research on the Epidemiology of Disasters (CRED, 2011) show that every year of this period urban flooding events affected approximately 140 million people, and claimed about 10,000 human lives around the world (Sanderson & Sharma, 2016). The 2011 flooding event in Thailand caused US $43 billion and $16 billion in economic and insured losses, respectively (Re, 2013). Hence, it is highly likely that insufficient prevention and management measures in the urban areas will become more vulnerable to severe flooding in light of the future changes in extreme precipitation. As 55% of the world's population lives in urban areas (United Nations (UN), Department of Economic and Social Affairs, 2018), potential damages resulting from such urban floods are expected to become more severe.

Traditional urban stormwater management systems (gray infrastructures including gutters, storm sewers, and tunnels; Dietz, 2007) have been widely implemented in cities to quickly drain away stormwater (Yuan, 2016). Such rapid drainages significantly affect the natural hydrological cycle (Wang, Chen, & Zhang, 2016), and are ineffective to drain away flooding water caused by extreme events according to the design standards (Berggren, Olofsson, Viklander, Svensson, & Gustafsson, 2012; Mouritz, 1996). To cope with enhanced urban flooding challenges, the construction of urban drainage systems should be consistent with the rapid pace of rapid urbanization. However, the mismatch between rapid urban development and the lagging infrastructure construction (e.g., sewer system) have been persistent in many parts of the world (Song, 2012). Expansion of traditional gray engineering facilities can also lead to a number of negative effects on the urban environment (Palmer, Liu, Matthews, Mumba, & D'Odorico, 2015). Hence, Nature-Based Solutions (NBS) have been proposed and designed based on ecosystem services considerations (e.g., green infrastructures). NBS aim to improve water availability and quality, and also to enhance overall water security by, for instance, reducing urban flood risks (United Nations World Water Assessment Programme (WWAP)/UN-Water, 2018; Kabisch, 2017; Cohen-Shacham, Walters, Janzen, & Maginnis, 2016). It is expected that NBS will play a critical role in achieving sustainable development goals around the world. In comparison with the construction of reservoirs and water diversion canals, NBS offer the benefits of reforestation, wetland restoration, and rainwater harvesting, which all improve water supply security in an ecological friendly way (Van et al., 2017). Urban green infrastructures such as green walls, roof gardens, and permeable pavements can increase water availability, further purify wastewater, and reduce stormwater runoff. Other NBS, such as wetlands and mangroves, can also reduce the risks of flooding and drought (Narayan et al., 2017). More importantly, green infrastructures require very little energy and are usually cost-efficient (Baig, Rizvi, Josella, & Palanca-Tan, 2016; Palmer et al., 2015). Numerous regions and countries have proposed NBS as the means to address problems related to frequent pluvial flooding and water pollution in urban areas (Schanze, 2017; Zölch, Henze, Keilholz, & Pauleit, 2017). In recent years, researchers worldwide have examined the effectiveness and efficiency of adopting NBS as a means through which societies can enhance urban development and resilience (Lafortezza, Chen, van den Bosch, & Randrup, 2017; Maes & Jacobs, 2015). However, terminologies differ in various regions and countries, resulting in misunderstanding and duplication during the research process (Nesshöver et al., 2016). A number of researches have also questioned the effectiveness and efficiency of applying NBS in areas experiencing high-intensity of precipitation over short period of time (Ahilan et al., 2014; Ellis & Viavattene, 2014). These hindrances have considerably attenuated the interests of urban planners and other authorities in this new solution. To highlight the role of NBS in urban flood risk management during ongoing climate change and rapid urbanization, this paper will (a) review the development of NBS while focusing on their terminologies and applications in different regions of the world; (b) summarize the benefits and limitations of applying NBS for urban flood mitigation; and (c) propose a more efficient solution for reducing urban pluvial flood risk. By doing the above, this study strengthens the foundations for the development of NBS adaptation and for the improvement of urban flood risk management.

2 | TERMINOLOGY AND APPLICATIONS OF NBS

2.1 | Terminology—Similarities and differences

NBS represent a set of new concepts in engineering, economics, and environmental planning and they also provide simultaneous benefits to human and natural systems by maintaining and/or restoring hydrological functions (Albert, Spangenberg, & Schröter, 2017; Zölch et al., 2017). NBS apply green infrastructures to address particular problems (such as urban floods) while maintaining the natural features and hydrological processes of a city (Potschin et al., 2015). NBS can alleviate the adverse impacts of climate change, including urban flooding caused by evolving patterns of precipitations (Kabisch, 2017), and have been widely used as the reference of various alternative terminologies over the world. These alternative terminologies originate from different regions with their own histories and include Low Impact Development (LID), Best Management Practices (BMPs), Water Sensitive Urban Design (WSUD), the Sustainable Urban Drainage System (SUDS), Green Stormwater Infrastructure/Green Infrastructure (GSI/GI; Fletcher et al., 2014), and the Sponge City (MOHURD (Ministry of Housing and Urban-Rural Development of the People's Republic of China), 2014). To the best of our knowledge, LID was first mentioned in a land-use planning report in 1977 (Barlow, Burrill, & Nolfi, 1977). BMPs were first used in research on the influence of agriculture on water quality in 1983 (Bicknell, Donigian, & Barnwell, 1985). WSUD was first used for water balance management, water quality enhancement, water conservation, and social environments in 1996 (Mouritz, 1996). SUDS was first coined to describe stormwater management Technologies in 1997 (Butler & Parkinson, 1997). GI was first defined as an interconnected natural life support system interconnected network in 1999 (Benedict & McMahon, 2002). The Sponge City was standardized for water quality improvement and environmental protection in 2014 (MOHURD (Ministry of Housing and Urban-Rural Development of the People's Republic of China), 2014). All of these terminologies carry the same mission: dealing with the functions of hydrology, water quality, water supply, and landscape planning explicitly or implicitly (e.g., advocating the use of green-roofs and rain barrels for water supply, applying green infrastructures in landscape planners' developments, and so on). Due to the language barriers, this review will mainly cover NBS terminologies widely used in English literature. Table 1 presents a summary of these terminologies, including their application areas, scales, the year each was first introduced and the corresponding references.

Low impact development (LID) was first described by Barlow et al. (1977) in a report on stormwater management published in 1977. To mitigate the adverse effects of urbanization (e.g., impermeability), LID was experimentally conducted as a land planning and design approach in the State of Maryland (Prince George Country, 1999) in the USA, with the aim to achieve low impact of urban development on the soils, vegetation, and aquatic systems in the experimental area (Dietz, 2007). Such approaches are generally used in Canada and the USA to reduce runoff volumes, peak flows, and water pollution levels with micro-scale (site level) control measures. However, the method is inefficient when applied to nitrate-nitrogen and phosphorus reduction (Gilroy & McCuen, 2009). The measures are designed to reduce runoff volumes and delay peak flows by using, for instance, green roofs to slow runoff processes and rain barrels for rainwater collection (Shaver, 2000). In addition to being widely used in the USA and Canada, LID has become a mainstream approach to stormwater management in New Zealand, the UK, and China (Toronto Region Conservation Authority, 2010; US Public Law, 2007). It should be noted that Best Management Practices (BMPs) were widely applied before LID on a large scale (states level) in the USA, and have been incorporated into US regulations (Dorn & Rodgers, 1989), but there are no effectiveness measurement standards for what constitutes a "best" practice (Fletcher et al., 2014). BMPs have been adopted in almost every state of the U.S. through the Rainwater Control Guide (Scholes et al., 2008).

Water sensitive urban design (WSUD) was first proposed as a means to use sustainable and ecologically compatible water management methods for urban planning and design, which integrates the natural water systems in urban areas

TABLE 1 Worldwide NBS terminologies

Terminology	Region/ country	Application scale	The year in which the terminology was first introduced	References
LID	USA CA NZ IT	Small scales	1977	Barlow et al. (1977), Shaver (2000), Dietz (2007), States (2007), Gilroy and McCuen (2009), Toronto Region Conservation Authority (2010)
BMP	USA	Large scales	1983	Bicknell et al. (1985); Dorn and Rodgers (1989), Scholes, Revitt, and Ellis (2008)
WSUD	AU NZ EU	All scales	1996	Mouritz (1996), Barton and Argue (2007), Wong (2006), Burge, Browne, Breen, and Wingad (2012), Ashley et al. (2013), Rodriguez et al. (2014)
SUDS	UK	All scales	1997	Butler & Parkinson (1997); Martin (2000), Martin et al. (2000), Andoh and Iwugo (2002); Tebal (2007), States (2007)
GSI/GI	USA CA UK DE DM	All scales	1999	Benedict and McMahon (2002), Keeley et al. (2013), Rai (2013), Palmer et al. (2015), Strickler (2015), Suppakittpaisarn, Jiang, and Sullivan (2017)
Sponge City	CN	All scales	2014	MOHURD (2014); Kongjian et al., 2015; Zheng, Lei, and Fei (2016), Hua (2016), Xia et al. (2017), Dai, Rijswick, Driessen, and Keessen (2018)

Abbreviations: CA, Canada; CN, China; DE, Germany; DM, the Dominican Republic; EU, Europe; IT, Italy; NZ, New Zealand; UK, the United Kingdom; USA, the United States.

with two divisions (stormwater management and wastewater management) based on the water-sensitive features of a given area (Barton & Argue, 2007). It focuses on coping with or recovering from floods at all scales (Ashley et al., 2013) and is widely used in Australia and Europe (Barton & Argue, 2007; Rodriguez et al., 2014). In Australia, the University of Melbourne took a lead in urban sustainability projects with the adoption of WSUD (Barton & Argue, 2007). Some European cities have adopted the WSUD to help the urban drainage systems sufficiently manage water quantity under a changing climate (Burge et al., 2012).

With the principle of storing or re-using surface water at the source (Poleto & Tassi, 2012), the Sustainable Urban Drainage System (SUDS) was first proposed by Coventry University in 2001 by considering sustainable development in the drainage system design in urban places (Charlesworth, 2010). SUDS aims to alleviate pluvial flooding while preserving/maintaining waterways (Andoh & Iwugo, 2002) by implementing measures, such as swales in the residential districts (Tebal, 2007). Two SUDS design manuals on Sustainable Drainage Systems for England and global adaptations have been published (Martin, 2000; Martin et al., 2000), which promote the broader application of SUDS globally (Congress of the United States of America, 2007).

Green Stormwater Infrastructure (GSI) or Green Infrastructure (GI) is a universal term (Strickler, 2015), which refers to the suite of LID, SUDS, WSUD and other conceptualizations that control the stormwater in a watershed without destroying its natural functions and enhance its resilience to hazards (Keeley et al., 2013). GI includes a range of measures (e.g., bioswales, rain gardens, permeable pavements, urban wetlands, and green roofs) that manage flooding during a precipitation event by infiltration, storage, and evapotranspiration throughout the entire rainfall-runoff process while using plant or soil systems to reduce pluvial flows (Rai, 2013). This term has been adopted in many countries (including the USA, Canada, the UK, Germany, and the Dominican Republic) and applied at all scales (Strickler, 2015; Suppakittpaisarn et al., 2017).

The term Sponge City, which is widely used in China (Dai et al., 2018), was first proposed as a way to describe the water storage capacity of natural wetlands and rivers to those of a "sponge" (Kongjian et al., 2015). In a period of concentrated precipitation, water infiltration, retention, and accumulation take place in green spaces, such as gardens, in so-called "Sponge Cities" (Zheng et al., 2016). During dry periods, such green infrastructures can release the stored rainwater, combining water recycling with drainage to supply water (Hua, 2016). The concept of

"Sponge City" has been used in 30 pilot cities including Beijing Shenzhen and Shanghai in China since 2015 (Xia et al., 2017).

Other terminologies are also used in different areas, including the Stormwater Control Measure (SCM), which has replaced reference to BMPs in most states of the USA, and which refers to controlling measures such as the structural and nonstructural infrastructures for stormwater (Jones, 2012), and Decentralized Rainwater/Stormwater Management (DRWM) in Germany (Hoyer & Dickhaut, 2006). The essence of these terminologies is the same; mainly to control runoff volumes and reduce peak flows while improving water quality and maintaining waterways in the cities using locally adapted, resource-efficient and systematic interventions. They mainly focus on natural or ecological retention, detention, infiltration, and drainage as the means to build more resilient cities.

2.2 | Mechanisms and examples

NBS effectively and adaptively address water problems through sustainably managing and restoring natural or modified ecosystems, while simultaneously benefiting the inhabitants and biodiversity (Cohen-Shacham et al., 2016). As water in the atmosphere falls as precipitation, some of it is intercepted by vegetation, while some falls to the land and flows through runoff into rivers or infiltrates through the soil-aquifer-rock layers. Transpiration and evaporation then return to the atmosphere. Physical and biological processes related to water in ecosystems can affect hydrological pathways (including evaporation, infiltration, storage, and runoff) in the water cycle (Chen, Wang, Wei, Fu, & Wu, 2010; Wang-Erlandsson, Ent, Gordon, & Savenije, 2014).

After implementation, NBS infrastructures (e.g., green roofs, infiltration trenches, permeable/porous pavement, and vegetable swales/bio-swales) become integrated parts of the ecosystem and can influence the hydrological processes and manage the stormwater through changing ecological elements (e.g., vegetation and soils). Vegetation can intercept precipitation with its leaves and remove water by transpiration (Zhang et al., 2015). Soil surface conditions significantly influence the transformation of water, and the volume of water storage depends on the soil structures and pore sizes (Azoulay, Houngbo, Uhlenbrook, & Connor, 2018). Figure 1 illustrates the intermediation of NBS infrastructures in the hydrological process.

Table 2 presents the selected examples of NBS infrastructures with schematic diagrams and functions. It shows five infrastructures, including green roofs, permeable/porous pavement (impervious roofs and pavements account for most of the impervious urban areas), infiltration trenches (replacing cement trenches, the main components of drainage systems), vegetable swales/bioswales (including a rain garden and bio-retention swale) and rain barrels. A green roof is covered by a layer of soil to support vegetation, creating temporary ponding in the roof's drain inlets and gradually releasing stormwater to delay the peak flow retention (Hutchinson et al., 2003; Mohammad et al., 2012); an infiltration

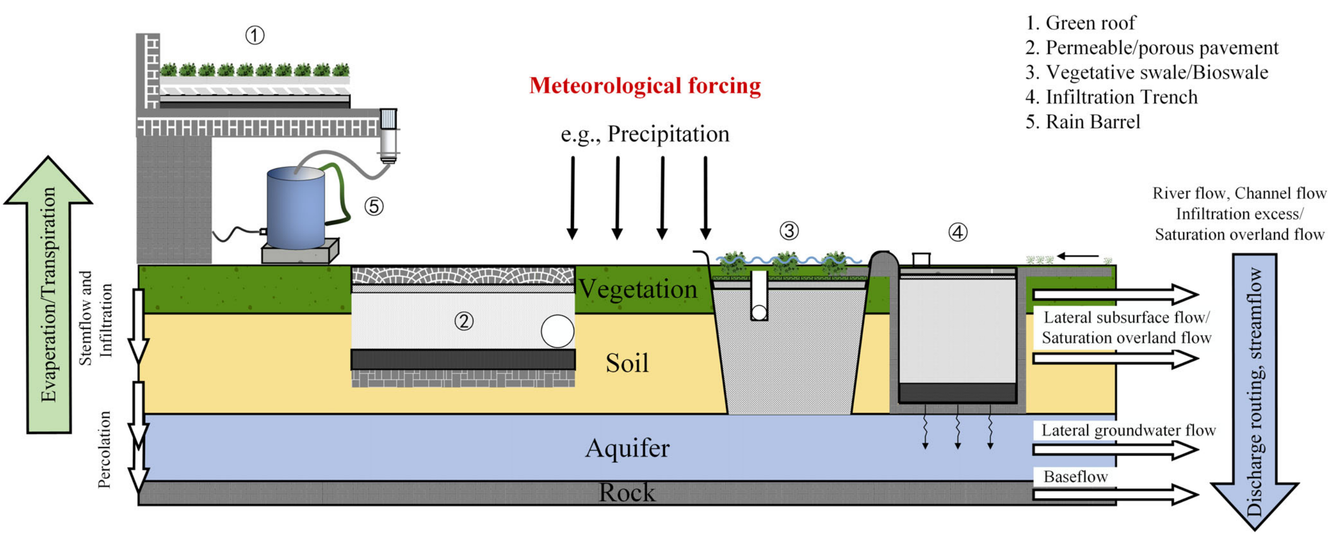
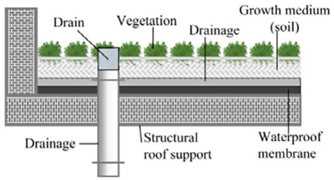
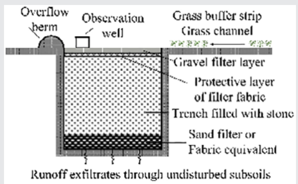
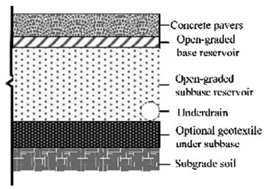
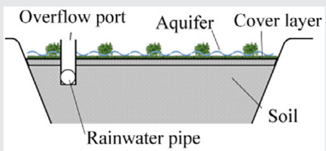
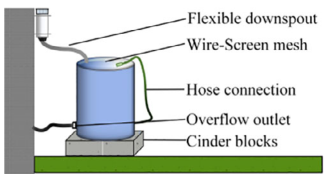


FIGURE 1 Hydrological process with NBS intermediation (Reprinted with permission from United Nations World Water Assessment Programme (WWAP)/UN-Water, 2018)

TABLE 2 Description of NBS infrastructures

Typical NBS measures	Schematic diagram	Example	Functions			Source
			Infiltration	Retention	Detention	
Green roof			×	×		Hutchinson, Abrams, Retzlaff, and Liptan (2003), Mohammad, Rasul, and Khan (2012), Environmental Affairs Department (2007)
Infiltration trench			×			Gabriele, Giorgio, and Gaspare (2009); Fischbach et al., 2017)
Permeable/porous pavement			×			Brears (2018), Sansalone, Kuang, and Ranieri (2008)
Vegetative swale/ bioswale			×	×	×	Barton and Argue (2007), Chui, Liu, and Zhan (2016), Clark and Acomb (2008)
Rain barrel				×	×	Campisano, Catania, and Modica (2016); Ahiablame, Engel, and Chaubey (2013); William et al. (2013)

trench is built as a rapid infiltration system to replace an increasingly impervious surface by capturing the wastewater during a rainfall event and allowing the stormwater to infiltrate into the ground (Gabriele et al., 2009); Permeable/porous pavement replaces traditional impermeable concrete or asphalt to facilitate the infiltration process during a rainfall event and to allow the stormwater to seep in from the permeable materials into the ground (Brears, 2018); a vegetable swale/bioswale is a channel covered with a layer of soil to support a combination of grasses and other vegetation, which increases friction along the flow path to prolong the runoff process and reduce the peak flow (Barton & Argue, 2007; Chui et al., 2016). A rain barrel is a small tank designed to control rainwater through interception at the source in small areas (e.g., rooftops and parking lots; Campisano et al., 2016; Ahiablame et al., 2013). These infrastructures can reduce runoff and peak flows during storm events through infiltration, retention, and detention.

3 | BENEFITS AND LIMITATIONS OF NBS

3.1 | The development of a dual-drainage model for the evaluation of NBS

For the physical and biological processes related to water within an NBS (including evaporation, infiltration, storage, and runoff), the evaluation of the effectiveness of NBS measures can be tested with dual-drainage models (which can simulate overland flow and the sewer drainage flow simultaneously; Rossman, 2010). When the volume of rainfall is beyond the capacity of a drainage system, the water will flow over the curbs instead of remaining in the profile, and a combined 1D (line) and 2D (surface) model is required for the simulation (Mark, Weesakul, Apirumanekul, Aroonnet, & Djordjević, 2004). Numerous researchers have compared 1D and 2D models, including 1D model REM^{2}U with the 2D model RUBAR 20 (Paquier, Tanguy, Haider, & Zhang, 2003), HEC-RAS (1D) with 2D models LISFLOOD-FP and TELEMAC-2D (Horritt & Bates, 2002), and the development of coupled 1D–2D models has been suggested (Paquier et al., 2003). Sewer and surface flow coupled models (a 1D sewer model coupled with a 1D surface network model or with a 2D surface flow model) have been developed by Leandro, Chen, Djordjević, and Savić (2009) to simulate flooding in the region of West Yorkshire, UK, that can accurately simulate the surface flow propagation and the time of peak water levels. Since the Personal Computer Stormwater Management Model (PCSWMM[1]) was updated (James, Finney, Perera, James, & Peyron, 2012), several researchers have used it to simulate the effectiveness of NBS in their case studies (Akhter & Hewa, 2016; Bloorchian, Ahiablame, Zhou, & Osouli, 2016; Carvalho, Costa, Conserva, Andrade, & Koide, 2019; Talbot, McGuire, Olivier, & Fleming, 2016). The PCSWMM integrates urban storm/combined sewers and watershed models with dynamic interaction. By using this model, researchers can create comprehensive models that include complex water systems and hydrological processes. In addition, in the planning or renovation of sites/cities (e.g., Illinois in the USA, Foshan in China, and Colle Ometti in Italy), researchers have developed other dual-drainage models for flooding simulation, such as Infoworks ICM[2] for assessing hydraulic performance of drainage systems, HYSTEM-EXTRAN[3] for rainwater management and hydraulic process modeling, MIKE Flood[4] for combined river, urban systems and 2D surface flow modeling, Model of Urban Sewers (MOUSE; Semadeni-Davies, Hernebring, Svensson, & Gustafsson, 2008) and Rainwater (Chen, Samuelson, & Tong, 2016).

3.2 | Benefits

3.2.1 | Effectiveness of flood reduction

Bloorchian et al. (2016) used the PCSWMM to evaluate the performance of NBS in reducing the stormwater runoff volumes of highways and roads in Illinois, USA. They reported that NBS could reduce runoff by between 89 and 100% for half of the selected highways across the urban and suburban areas, thus beneficial for the department to develop NBS for the management of stormwater generated from roads and highways. Mao, Jia, and Yu (2017) proposed that in Foshan, China, the combination of different NBS structures (e.g., rain barrels, green roofs, and swales) had achieved a reduction of flow volumes by 31–42%, and peak flow rate by 5–15%. Ahilan et al. (2014) found that NBS can reduce the runoff and downstream flood hazard in three selected flood events (15-, 50-, and 100-year), and has the most effective impact on the 15-year event while with only very limited volumetric reductions for storm events exceeding this return period. Gilroy and McCuen (2009) found that NBS could reduce runoff volume by 46% for a single-family lot in a selected scenario (2-year) with a spatiotemporal model. Palla and Gnecco (2015) selected the urban catchment of Colle Ometti, Italy, as the study area, and demonstrated that NBS are effective in stormwater control and can reduce peak flows by 14–45% and runoff volumes by 9–23% during precipitation events with different return periods (2.5- and 10-year). Ahiablame, Engel, and Chaubey (2012) found that NBS can reduce 23–100% of runoff by summarizing 13 studies conducted on 12 different areas of five countries. Eckart, Mcphee, and Bolisetti (2018) coupled the stormwater management model (SWMM) with the Borg multi-objective evolutionary algorithm (MOEA) and found that in precipitation events of different return periods (5–100 years), a combination of NBS infrastructures could reduce storm sewer peak flow (by up to 29%) and total runoff (by up to 13%) in Windsor, Ontario, Canada. Stewart and Hytiris (2008) designed an infiltration basin that can not only store a 200-year flood event (under a 17 mm/hr precipitation) but also can control the pollution in Middle Mause Farm in Scotland. In 1998, the permeable pavement system installed in Wheatley, near Oxford, was found to let only 22.5% of runoff leave the system during a storm on average (Abbott & Comino-Mateos, 2003). In the Iguaçu-Sarapuí River Basin, located in the western portion of Rio de Janeiro, the Brazilian government planted more than 200,000 trees along local riverbanks, and built a fluvial urban park along the river, four flooding urban parks in low elevation areas, and an environmental urban park to dampen flood peaks and minimize runoff generation (Miguez, 2012). The combined use of different NBS structures (green roof, permeable pavement, bioretention and three other types of NBS infrastructures) in the City of London, Ontario, Canada was found to reduce runoff by 48–96%. Joksimovic and Alam (2014) used the USEPA's SWMM to simulate the long-term performance of NBS in a mixed-land use of residential and commercial lots in Toronto, Canada, showing that NBS could reduce runoff and peak flows by 32.8–52.8% and 13.8–65.5%, respectively. Modeling results obtained under precipitations of similar intensities may show disparities for different rainfall processes (Reinhart, 2016). Zahmatkesh, Burian, Karamouz, Tavakol-Davani, and Goharian (2014) used the EPA's SWMM5 to study NBS's impacts on urban flood risk management in the Bronx River watershed in New York City, USA, concluding that NBS could respectively reduce runoff and peak flows by 30% and 11% under a 4.9 mm/hr precipitation. Jia, Lu, Yu, and Chen (2012) coupled the SWMM and BMPDSS model to analyze the implementation of NBS for load management of the Beijing Olympic Village, China. The results showed that NBS could make 27% runoff reduction and 21% peak flow reduction using local 2008 rainfall data. Table 3 provides an overview of flood effectiveness in terms of runoff reduction and peak flow reduction as a function of precipitation intensity. For the same study area and implementation scale, NBS infrastructures with the same settings would have more significant effects on stormwater management (runoff reduction and peak flow reduction) under shorter return periods of rainfall events.

3.2.2 | Economic, ecological, and social benefits

In addition to mitigating urban flooding, NBS can have economic, ecological, and social benefits. These benefits range from climate mitigation to improving recreation opportunities, provisioning of sociocultural and socioeconomic systems, and enhancing biodiversity and ecosystem conservation (Christopher & Razvan, 2017; Geneletti, Zardo, & Cortinovis, 2016). NBS also enables cities to reach their economic development goals (Lafortezza et al., 2017) and offers a transition path with ecology-friendly steps toward a sustainable economy (Maes & Jacobs, 2015).

NBS reduce runoff discharge, relieves the drainage system pressure, and reduces system long-term maintenance and operation costs (Clark, Adriaens, & Talbot, 2008; Palla, Gnecco, & Lanza, 2009). In storm events, the roof runoff and sewage discharge will potentially cause systems to exceed their capacity and lead to premature aging of the pipelines. In addition, NBS can also intercept sewage and improve the quality of stagnant rainwater, which can reduce the cost of sewage treatment (Berndtsson, Emilsson, & Bengtsson, 2006; Duan et al., 2013). For instance, permeable pavement can reduce the entry of toxic pollutants into natural water systems and carry out toxic substances, degrade them, and decrease the cost of treatment of polluted water (Roon, 2007). Niu, Clark, Zhou and Adriaens (2010) found that a green roof in the city of Washington DC could decrease the cost of discharge system maintenance by between 0.12 and 0.17 USD per m^2, potentially generating profits of roughly $1,195–6,277 to the 2,000 m^2 study area per year.

Through its detention and storage functions, NBS can reduce the cost of water intake for a large number of residents and provide water supply in dry periods (Liu, 1998). NBS can alleviate the heat island effect. Compared to the high temperature of 48–67°C for impervious pavement, permeable pavements can have decreased surface temperatures down to 37°C through the evaporation process (Mao, Ge, & Chen, 2008), and effectively alleviate the effect of the urban heat island.

In terms of social benefit, NBS promote local tourism and other forms of economic development, greatly increasing the city's ornament and improving the quality of residents' living environment. NBS improve residents' quality of life because of their key role in the provision of ecosystem services (Eggermont et al., 2015). NBS can also promote human well-being by improving mental health (Cariñanos et al., 2017; Vujcic et al., 2017) and by mediating the effects seen on

TABLE 3 An overview of the effectiveness of NBS in terms of runoff reduction and peak flow reduction as a function of precipitation intensity worldwide (updated from Eckart, Mcphee, & Bolisetti, 2017)

Study area		Storm events			Stormwater management		
		Rainfall intensity (mm/hr)	Duration (hr/days/ years)	Return period [−]	Runoff reduction	Peak flow reduction	Source
Baltimore, Maryland, the USA	Single-family	22	1 hr	1 year	92%	31–92%	Gilroy and McCuen (2009)
		36		2 years	30%	25%	
	Townhome lots	22		1 year	86%	27–87%	
		36		2 years	28%	31%	
	Commercial lots	22		1 year	5%	38%	
		36		2 years	1%	14%	
Santo Domingo, The Dominican Republic		7.3 (max)	1 hr	5 years	20%	54%	Strickler (2015)
		9.2 (max)		20 years	–	33%	
Windsor, Ontario, Canada		40 (max)	24 hr	5 years	0.67–12.84%	1.17–27.31%	Eckart et al. (2018)
		–		25 years	0.63–10.53%	1.27–26.43%	
		–		100 years	0.53–9.01%	1.23–29.33%	
Birmingham, UK		22.4(max)	8 hr	200 years	30%	36%	Viavattene and Ellis (2013)
Foshan, China		10 (max)	1 day	–	49%	32%	Mao et al. (2017)
		8 (max)			33%	19%	
		13 (max)			26%	15%	
		53 (max)			14%	15%	
Toronto, Canada		2.1 (max)	22 hr	–	52.8%	57.2%	Reinhart (2016)
		2.5 (max)	16 hr		52.1%	43.5%	
		2.9 (max)	18 hr		44%	65.5%	
		7.0 (max)	16 hr		32.8%	13.8%	

cardiovascular disease-related mortality (Van & Sang, 2017). The enhancement of the environment by NBS through pollution removal has accounted for €161.78 million of air pollution removal value for the city center of Rome (Marando, Salvatori, Fusaro, & Manes, 2016).

NBS enhance the cities' resilience ability in dealing with flooding, which means that NBS benefit the cities' capacity to withstand the damages and losses caused by flooding events and help urban systems quickly recover after flooding events (Chen & Leandro, 2019). The effectiveness of NBS on cities' resilience can be evaluated by Flood Resilience Index (FRI), with aggregate weighted mean index (AWMI) method through five dimensions (social, economic, institutional, physical and natural), based on the evaluation matrix with 91 indicators, (Batica & Gourbesville, 2016), or assessed by City Resilience Index (CRI[5]) for stakeholders and decision-makers via a qualitative and quantitative assessment system.

3.3 | Limitations

Several researchers have found that NBS to be less effective at reducing urban flooding risks under extreme rainstorms. However, when enough measures are implemented, NBS have significant impacts on small-scale rainstorms. Ahilan et al. (2014) integrated 1D and 2D hydrodynamic modeling to simulate stormwater runoff in the Wortley Beck catchment in the UK, and indicated that NBS have a great impact on precipitation events with low return period (15-year), but exhibited very limited volumetric reductions for a 100-year storm event. Likewise, Ellis and Viavattene (2014) reported that NBS have a significant impact on runoff volumes reduction for short return period storms (smaller than 30-year) in the two urban basins of Birmingham and Coventry in the UK. While exceeding this return period, NBS can make only very limited volumetric runoff reductions. In addition, it has been found that various NBS implementations in the watershed of central Illinois resulted in 3–47% runoff reduction and 0–40% flood flow reduction (Ahiablame & Shakya, 2016). Research conducted in Los Platanitos of the Dominican Republic also shows that decentralized NBS infrastructures (combining rain gardens and rain barrels) could lead to up to 20% total reduction in runoff volume under a 5-year designed precipitation with "Chicago Method" (Strickler, 2015).

However, it has been found that the adoption of NBS cannot protect the safety of residences or their property during larger storm events. It has been acknowledged that the extent of the NBS implementation in the study is critical. The larger the area NBS are implemented, the more effectively they can reduce flooding. For example, it has been found that the effectiveness of the reduction of runoff volume is limited when NBS are applied to less than 10% of a study area (Ahilan et al., 2014). NBS measures largely function based on natural mechanisms such as infiltration, retention, and detention. High-intensity rainfall can easily exceed the absorption capacity of these green measures. For instance, green roofs quickly become saturated and the runoff from permeable pavement can quickly overwhelms a drainage system rapidly under a 200-year storm event in Birmingham, UK (Viavattene & Ellis, 2013). When the rainfall rate per area-unit surpasses the infiltration rate per area-unit, surface runoff can quickly form during storms; when a drainage system is clogged (e.g., by debris or leaves; Catalano de Sousa, Montalto, & Gurian, 2016), pluvial flooding is inevitable. Strickler (2015) questioned the effectiveness of NBS to mitigate pluvial flooding during events with large runoff volume and rates (16,344 m^3 and 12.7 m^3/s). This brought up a desire for combining gray infrastructures with NBS to meet the flooding mitigation and comprehensive beneficial goals, especially for high-intensity precipitation (Denjean et al., 2017; Jongman, 2018).

With the recognition that not all floods can be prevented (such as extreme floods), the focus of flood risk management has turned to flood abatement, flood control, and flood alleviation. In this connection, NBS can prevent waves and reduce flood impacts (De Bruijn, Green, Johnson, & McFadden, 2007), whereas gray infrastructures can quickly reduce runoff (Dietz, 2007). The combination of NBS and gray infrastructures as an urban flood risk management measure can not only manage the stormwater effectively under extreme precipitation but also can mitigate the impacts of gray infrastructures on both ecological and societal systems (Palmer et al., 2015). Strickler (2015) reported that the expansion of gray infrastructures (including pipes and channels) enlarges the impervious areas and ever-expanding runoff volumes, and this increases the intensity of flooding events downstream, which in turn becomes more vulnerable to increasing drainage pressures on the conveyance of expanding water volumes from upstream (Armitage, 2011). A combination of gray infrastructures and NBS is needed to protect residents and their property. For example, Strickler (2015) observed a flood volume reduction of up to 19% during a 5-year rainstorm in the city of Santo Domingo in the Dominican Republic by using NBS infrastructures such as rain gardens and rain barrels alongside larger-scale gray infrastructure. This solution immediately reduced damage and highly contaminated water. Joyce, Chang, Harji, and Ruppert (2018) found that NBS combined with gray infrastructures (NBS, Dredging & Wall) reduced 31.8% (a reduction of 0% was achieved by each NBS alone) of flood risk under an extreme event (Annual peak 24-hr rainfall) in 2012 in the Cross Bayou Watershed of Pinellas County, Florida, USA. Gray infrastructure is essential if there is a rapid demand for discharge rainwater (Liu, 1998). Green infrastructures can reduce the costs of upgrading a gray system. Such combined measures have been found to protect the residences from moderate storms in the neighborhood of Brentwood, in Austin, USA, and to significantly reduced the damage to structures exposed to flooding in extreme precipitations while ensuring lower project costs (Jarden, Jefferson, & Grieser, 2016). In the USA, (e.g., Philadelphia, North Carolina, Pennsylvania, Colombia, and southern Los Angeles), researchers have used hydrological models to simulate the stormwater management capacities of NBS, concluding that the combination of NBS with traditional stormwater drainage systems can address the inefficiencies of stormwater management under extreme precipitation. This approach can have a significant effect on runoff reduction and reduce the construction costs of the upgrades of the drainage system upgrades (Albright, Traver, & Wadzuk, 2016; Ávila, Amaris, & Buelvas, 2016; Garcia-Cuerva, Berglund, & Rivers, 2016; Hess, DelVecchio, Welker, & Wadzuk, 2016; Klenzendorf, Kelly, Poresky, & Christman, 2016; Sadeghi, Kharaghani, Tam, Gaerlan, & Loáiciga, 2016). Considering the added value that NBS offer to economic, ecological, and societal systems, the implementation of the combined measures in cities is highly recommended. However, because of the evaluation criteria of NBS in different cities, the allocation of gray and NBS measures must be simulated based on different urban scenarios to make the best decisions and to meet the demands of a sustainable and resilient society.

4 | DISCUSSION

This review shows that NBS can effectively mitigate the effects of urban flooding under certain circumstances and bring additional benefits. However, NBS operated under different natural conditions have several variable characteristics,

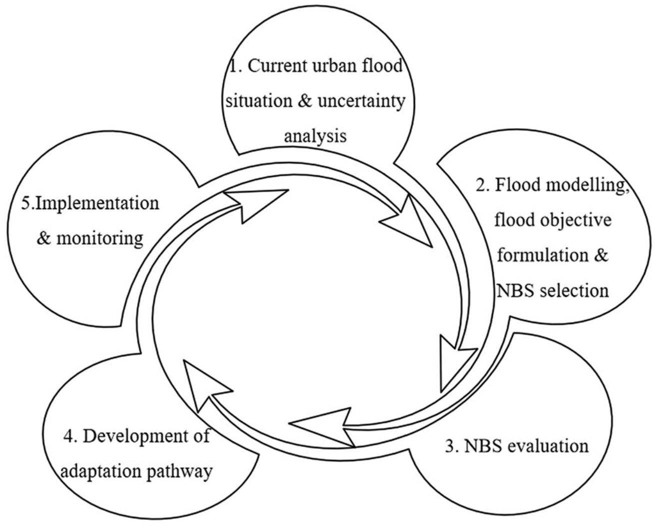


FIGURE 2 Proposed adaptive cycle for the long-term planning of NBS implementation (Reprinted with permission from Haasnoot, Kwakkel, Walker, & Maat, 2013)

meaning that their abilities to manage stormwater might change with the natural systems. This means that NBS can mitigate floods under normal circumstances, while under other circumstances, they may contribute to the natural processes that exacerbate flood hazards. For example, when water levels in rivers are low during the dry periods, the wetlands play the role of attenuating pluvial flows; but during the rainy season, it may generate runoff and contribute to flooding flows when the rivers are saturated (McCartney, Neal, & Neal, 1998). The lack of a clear understanding of the regulating functions of NBS may cause a misunderstanding of which functions (such as rainwater storage and runoff reduction) influence the water system and how these functions change with a dynamic natural system (Bullock & Acreman, 2003). Therefore, natural changes will lead to uncertainty in the impact of NBS on urban flooding after large-scale implementation. Sharma, Cook, Tjandraatmadja, and Gregory (2012) found that the performances of NBS on stormwater management require long-term monitoring to validate the efficiency of NBS measures in flood mitigation.

Adaptive management, an approach that facilitates decision-making with long-term monitoring under uncertainty conditions (Xing, Jones, & Donnison, 2017), can provide guidance on long-term NBS monitoring to maintain flood mitigation efficiency. Figure 2 presents the adaptive management steps of NBS implementation as a loop. The first step involves examining the current state of flooding in the study area and the corresponding uncertainties (e.g., the characteristics of the drainage system, the flood prevention objectives and other potential constraints) over the long-term under a changing climate; the second step is to compare the current and future scenarios with flood mitigation objectives and implementing suitable NBS infrastructures to meet the objectives; the third step is the evaluation of the NBS infrastructures by modeling to identify promising infrastructures and identify sell-by dates for these infrastructures; the fourth step involves developing preferred pathways, through which adequate and promising NBS infrastructures can meet flood mitigation objectives in different periods; the final step is to implement NBS infrastructures through the chosen pathway and monitoring the results of the implementation. Via long-term monitoring by adaptive management, the implementation of NBS can be sufficiently considered for the long-term planning of flood risk management (Haasnoot, Kwakkel, Walker, & Maat, 2013; Schanze, 2017).

5 | CONCLUSIONS

Urban flooding caused by extreme precipitations has occurred more frequently under a changing climate. In many cities, the existing urban drainage systems are insufficient to mitigate pluvial floods for the expansion of impervious areas. In recent years, Nature-Based Solutions (NBS) have been widely applied, which can effectively mitigate urban flooding in combination with gray infrastructures as flood management measures, while there are still limitations for the mitigation of the extreme rainfall events. This study highlighted the role of NBS in urban flood risk management. The following major conclusions were accordingly drawn.

1. NBS have been used worldwide with different terminologies developed based on local conditions and histories of flood risk management history. While no uniform terminology has been developed for the approach, the essence of

these terminologies is homologous with each other. The hydrological mechanisms of all NBS terms discussed in this review intended to reduce runoff volumes, attenuate flood peaks, and improve water environment; while other additional functions like ensuring water supply and beautifying urban landscape were also emphasized by the Sponge City, LID, and GI.

2. NBS can mitigate urban flooding under certain circumstances, while they are less effective at managing more severe flood events. Although the effectiveness of the flood reduction during the high-intensity precipitation has been questioned, when NBS are combined with gray infrastructures as flood risk management measures, they can mitigate urban flooding caused by low/moderate intensity of precipitations more effectively. Apart from flood mitigation and control, NBS confer additional economic, ecological, and social benefits in terms of reducing sewage treatment costs, recycling water, reducing water withdrawal costs, embellishing the environment and promoting the development of local tourism, and so on. However, their innate connection to nature influences their effectiveness to mitigate urban flooding over the long term. Despite the numerous gray infrastructures (e.g., drainage and sewer systems) that have been established in urban areas, the adoption of NBS has often been postponed owing to that their short-term economic benefits (a major concern among decision-makers) are limited. Relevant frameworks mandate or consider NBS, but final decisions must be supported by a more comprehensive analysis of the costs and benefits of all options and a detailed systematic regulatory review prior to decision-making.

NBS have been adopted worldwide to promote sustainable development. Adapting NBS in decision making for flood emergency responses needs the local socioeconomic, environmental, and institutional conditions analysis along with the assessment of risk reduction, their benefits to vulnerable populations, and associated facilities and environmental effects. Implementation of the combination of NBS and gray infrastructures should abide by the basic principles of local environmental protection and restoration, and needs long-term monitoring with adaptive management to ensure its sustainability.

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CONFLICT OF INTEREST

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

AUTHOR CONTRIBUTIONS

Yijing Huang: Data curation; investigation; methodology; writing-original draft. **Zhan Tian:** Investigation; methodology; supervision; writing-review and editing. **Qian Ke:** Data curation; methodology; visualization; writing-review and editing. **Junguo Liu:** Conceptualization; writing-review and editing. **Masoud Irannezhad:** Writing-review and editing. **Meifang Hou:** Investigation. **Laixiang Sun:** Investigation; supervision; writing-review and editing.

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ENDNOTES

[1] https://www.pcswmm.com/application/72313/integrated-catchment-watershed-modeling

[2] http://www.hrwallingford.com/expertise/sustainable-drainage

[3] https://itwh.de/de/softwareprodukte/desktop/hystem-extran

[4] https://www.mikepoweredbydhi.com/products/new-features

[5] http://www.100resilientcities.org/tools/city-resilience-index/

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