Journal of Environmental Management 344 (2023) 118260

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Assessing the effectiveness of nature-based solutions-strengthened urban planning mechanisms in forming flood-resilient cities

Mahmoud Mabrouk[a,b], Haoying Han[a,*], Chao Fan[c], Karim I. Abdrabo[b,d], Guoqiang Shen[a], Mohamed Saber[d], Sameh A. Kantoush[d], Tetsuya Sumi[d]

[a] *College of Civil Engineering and Architecture, Zhejiang University, Hangzhou, China*
[b] *Faculty of Urban and Regional Planning, Cairo University, Egypt*
[c] *School of Civil and Environmental Engineering and Earth Sciences, Clemson University, Clemson, USA*
[d] *Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, 611-0011, Japan*

ARTICLE INFO

Keywords:
Flood
Urban planning
Sustainable cities
LID
Natural-based solutions
Alexandria

ABSTRACT

Cities have experienced rapid urbanization-induced harsh climatic events, especially flooding, inevitably resulting in negative and irreversible consequences for urban resilience and endangering residents' lives. Numerous studies have analyzed the effects of anthropogenic practices (land use changes and urbanization) on flood forecasting. However, non-structural mitigation's effectiveness, like Nature-Based Solutions (NBS), has yet to receive adequate attention, particularly in the Middle East and North Africa (MENA) region, which have become increasingly significant and indispensable for operationalizing cities efficiently. Therefore, our study investigated the predictive influence of incorporating one of the most common NBS strategies called low-impact development tools (LID) (such as rain gardens, bio-retention cells, green roofs, infiltration trenches, permeable pavement, and vegetative swale) during the urban planning of Alexandria, Egypt, which experiences the harshest rainfall annually and includes various urban patterns. City characteristics-dependent 14 LID scenarios were simulated with recurrence intervals ranging from 2 to 100 years using the LID Treatment Train Tool (LID TTT), depending on calibrated data from 2015 to 2020, by the Nash-Sutcliffe efficiency index and deterministic coefficient, and root-mean-square error with values of 0.97, 0.91, and 0.31, respectively. Our findings confirmed the significant effectiveness of combined LID tools on total flood runoff volume reduction by 73.7%, revealing that different urban patterns can be used in flood-prone cities, provided LID tools are considered in city planning besides grey infrastructure to achieve optimal mitigation. These results, which combined multiple disciplines and were not explicitly mentioned in similar studies in developing countries, may assist municipalities' policymakers in planning flood-resistant, sustainable cities.

1. Introduction

Cities face increasing climate challenges that threaten urban socio-economic development goals (Beier et al., 2022; Silva and Costa, 2018; Mohammed et al., 2023). In November 2022, the Cop-27 summit was held in Sharm el-Sheikh, Egypt (Mabrouk and Haoying, 2023). The conference sought to move beyond slogans and go toward achieving climate justice. Joe Biden said, "Climate disasters wreak the most havoc on the countries and communities with the fewest resources to respond and recover; let's raise our ambition and the speed of our efforts using natural-based solutions (NBS) in our communities (White House Council on Environmental Quality, 2022)." Sustainable development presented by the UN Assembly can conserve natural resources, mitigate environmental degradation, adapt to climate change, address poverty and inequality, and foster diversity and resiliency (Burrichter et al., 2022; Mamani et al., 2022; Zahedi and Golivari, 2022). Urban flooding, one of the harshest natural phenomena threatening cities (Y. Chen et al., 2015), accounts for 46% of natural events between 1994 and 2019, affecting nearly 2.5 billion people and causing economic losses in property damage and loss of lives (B. Dong et al., 2021; Lin et al., 2021; Tingsanchali, 2012).

Most global cities are ill-equipped to reduce unprecedented floods as they still depend on grey infrastructure and structural mitigation measures (anthropogenic interventions) as the best solutions for flood

---

* Corresponding author.
E-mail address: hanhaoying@zju.edu.cn (H. Han).

https://doi.org/10.1016/j.jenvman.2023.118260
Received 15 February 2023; Received in revised form 20 May 2023; Accepted 24 May 2023

mitigation (Ferrari and Viero, 2020; Mustafa et al., 2020; Sörensen et al., 2016). These measures have proven their inability to withstand increased floods annually and have significant weaknesses in flood resilience (H. Huang et al., 2018). For example, solutions such as levees or flood walls can provide temporary relief (Bazilevs et al., 2011; Tomiczek et al., 2016). Still, they may not be effective in the long term, fail during extreme weather events, or be overtopped by rising floodwaters, leading to catastrophic consequences such as levee breaches or structural collapse (Dazzi et al., 2022). Furthermore, these solutions have significant social and environmental impacts, such as altering natural water flow patterns or disrupting habitats, which have long-term consequences for ecosystems and wildlife (Abdrabo et al., 2022; Han et al., 2020; Wing et al., 2020). They may even exacerbate flooding in other areas, affecting society, displacing communities, or altering cultural landscapes (Afata et al., 2022). Regardless, the high costs associated with these solutions can limit their implementation, particularly in developing countries or regions with limited resources (H. Wang et al., 2021).

NBS was defined by Bartesaghi Koc et al. (2017) as an interconnected network of natural and semi-natural elements capable of providing multiple functions for ecosystem services and effectively addressing a range of societal challenges (Monteiro et al., 2020). One of the primary benefits of NBS is its ability to provide multiple co-benefits beyond flood mitigation, such as improving air quality, creating a synergistically interconnected protective tissue, creating attractive green spaces and recreational spaces for residents and visitors, transitioning from self-protection to harmony with nature, reducing urban heat island effects, enhancing socio-economic outcomes (Babí Almenar et al., 2021; Puppim de Oliveira et al., 2022). Regarding flood reduction, integrating NBS can effectively shape flood-resilient cities by considering natural flood management techniques like green roofs, permeable surfaces, rainwater harvesting, rain gardens, and multifunctional green infrastructure such as parks, greenways, urban forests, and wetlands (Ferreira et al., 2022; Y. Huang et al., 2020; Spyrou et al., 2021).

On the other hand, NBS has gained increasing attention as a sustainable approach to address challenges posed by climate change, improve the resilience of cities to natural disasters such as flooding, and enhance the liveability and sustainability of cities (Bartesaghi Koc et al., 2017; F. Wang et al., 2022).

Our study aims to demonstrate the effectiveness of integrating LID solutions as an innovative strategy for NBS into city planning for mitigating flood propagation and illustrate the urban planning mechanisms to integrate these tools. Our methodology relied on previous studies like Fazhi Li et al. (2021) and Chao Mei et al. (2018) for assessing green infrastructure (GI) in sponge cities in China (F. Li et al., 2021; Mei et al., 2018). Therefore, city characteristics-dependent 14 LID scenarios were evaluated using the Low Impact Development Treatment Train Tool (LID TTT), which has been developed by the Lake Simcoe Region Conservation Authority (LSRCA) and the Toronto and Region Conservation Authority (TRCA) (Auger et al., 2017). This tool assists consultants, municipalities, and landowners in implementing more sustainable stormwater management planning in their regions (Leimgruber et al., 2019). We applied our methodology to Alexandria city, Egypt, because it is in a semi-arid region according to the classification of the Kappen Classification Map of the World from 1980 to 2016, which is more dangerous to deal with than wet regions (Barthel et al., 2013; Hemeda, 2021; Soliman and Soliman, 2022; Zevenbergen et al., 2017). Furthermore, Alexandria, one of Egypt's 227 cities, suffers from annual floods and sophisticated urban growth, which may be a good example for similar cities in developing countries (Abdo et al., 2012; Sirry, 2018). Our study is divided into four steps: (1) Describing datasets and presenting the backgrounds of NBS strategies (2) Conducting multiple LID scenarios and ranking the effectiveness of LID tools. (3) Explain how urban planning regulations can integrate LID tools during urban planning. Hopefully, our study will assist municipalities' policymakers in planning flood-resilient cities.

2. Theoretical framework

The MOVE Framework (Methods for the Improvement of Vulnerability Assessment in Europe; www.move-fp7.eu) was developed as part of the research project sponsored by the European Commission within the framework of the FP 7 program; it was adopted in this study. This framework included the risk components (Hazard and vulnerability), dimensions (exposure, susceptibility, and lack of resilience), and the adaptation interventions for reducing the hazard and vulnerability (Arias-Gonzales, 2022). As a part of the interventions that reduced the hazard events (flood in this case), the nature-based solutions including many approaches such as Water-Sensitive Urban Design (WSUD), Sustainable Urban Drainage System (SUDS), Integrated Urban Water Management (IUWM), Sponge Cities (SC), Best Management Practices (BMPs) and Low Impact Development (LID) have been introduced by the early 1990s (G. Dong et al., 2018; Ferreira et al., 2022; Y. Huang et al., 2020; Luo et al., 2021; Yin et al., 2021).

By the early 1990s, the term Best Management Practices BMP had been adopted in almost every jurisdiction's stormwater design manual, and consequently, BMPs were implemented across North America. Low Impact Development (LID) is considered a sub-strategy of BMPs. The LID (Low Impact Development) approach is a set of stormwater management practices that aims to reduce the runoff generated by urban areas, to achieve a natural hydrology system by integrating control measures. Natural hydrology refers to the predevelopment runoff, infiltration, and evapotranspiration volumes that achieve the site's balance through a functionally equivalent landscape (Saber et al., 2023). This approach employs various techniques to capture and treat stormwater runoff as close to its source before it can cause flooding or other damage downstream. The LID layout applies a cascading flow system to minimize the direct connectivity between adjacent impervious areas. LID mainly concerns the spread of runoff flows produced from upper impermeable surfaces onto lower permeable areas, such as absorbent landscaping areas, for additional infiltration benefits and water quality enhancement. LID depends on small-scale stormwater treatment devices such as permeable pavement (PP), green roofs (GRs), bio-retention (BR), swales, infiltration wells/trenches, infiltrating wetlands, and rain barrels located at or near the source of runoff (Fletcher et al., 2015; Hunt et al., 2010).

Implementing the LID-BMP should be coordinated entirely with the local construction plan and incorporated into the site landscaping design. The following is part of the LID-BMP planning strategy: (1) preserving the original terrain, (2) limiting the ratio of impervious surface areas, (3) avoiding direct connection of impervious areas, (4) selecting the most appropriate BMP types in terms of both technical and social/economic factors, and (5) establishing an appropriate goal for LID-BMP implementation (Boutaghane et al., 2022; Fletcher et al., 2015). Atheoretical framework for the LID in a densely populated urban area may need to address issues such as limited space for green infrastructure, competing land uses, and high construction costs. In contrast, a theoretical framework for the LID in a less densely populated area may focus more on optimizing the design and placement of LID techniques to capture the most stormwater runoff. A theoretical framework for the LID in flood risk reduction can be developed by considering the following steps.

I. Identifying the potential sources of stormwater runoff in the urban area, such as rooftops, roads, parking lots, and other impervious surfaces.
II. Implementing various LID techniques to capture and treat stormwater runoff as close to its source. Examples of LID techniques include green roofs, rain gardens, permeable pavement, and bio-retention systems.
III. Monitoring the effectiveness of the LID techniques in reducing stormwater runoff and controlling flooding. This may be

accomplished by combining field observations with computer simulation.

IV. Continuously improving the LID techniques based on the monitoring results and new research findings. This can include optimizing the design of the LID systems, selecting the most appropriate LID techniques for a given site, and integrating LID into larger-scale flood risk management plans.

3. Literature review

3.1. Low Impact Development (LID) tools

LID is a stormwater management strategy that prioritizes using natural systems and techniques to manage stormwater at its source rather than relying on traditional "grey" infrastructure such as pipes and concrete channels (Kumar et al., 2021; F. Li et al., 2021). It originated in the 1990s as a response to the negative environmental impacts of urbanization, including increased stormwater runoff, water pollution, and the loss of natural habitats (Ignatieva and Stewart, 2008; Leimgruber et al., 2019; Rubinato et al., 2018). It also promoted techniques that mimic natural systems and processes, such as infiltration and evapotranspiration, by including a range of practices, such as green roofs, rain gardens, permeable pavement, bioretention cells, and constructed wetlands, as shown in Table 1. These practices work by reducing the volume and velocity of stormwater runoff and promoting the infiltration and storage of rainwater into the ground (Dreiseitl and Wanschura, 2016; Ignatieva and Stewart, 2008; Steve et al., 2023). LID-dependent stormwater can be managed more sustainably, reducing the negative impacts of urbanization on the environment and improving the resilience of communities to flooding and other climate-related hazards (Ferreira et al., 2022; Spyrou et al., 2021). Today, LID principles are widely recognized as a sustainable stormwater management approach and have been incorporated into various environmental policies and regulations in the United States and other countries (F. Li et al., 2021; Nie, Linmei; Jia, 2018). The LID approach is often combined with other sustainable design principles, such as green building and smart growth, to promote sustainable and resilient communities (Rosenberger et al., 2021; Suteerasan, 2020; Zhou et al., 2019). Various software options are available for assessing LID, such as EPA SWMM (Storm Water Management Model), PCSWMM, HydroCAD, Bio-Retention Design Calculator, Hydrological Simulation-FORTRAN (HSPF), Visual OTTHYMO, and finally, Low Impact Development Treatment Train Tool (LID TTT), which were used in our analysis as the easiest for large regions and most modern tool (Auger et al., 2017; Leimgruber et al., 2019; Steve et al., 2023).

3.2. Effectiveness of nature-based solution in mitigating flood propagation

A strategically planned network of natural-based solutions can mimic or complement grey solutions (Ghofrani et al., 2017; Kimic and Ostrysz, 2021). For example, Palla et al. (2015), Liu et al. (2014), Hu et al. (2017), and Kong et al. (2017) investigated LID-based hydrological performance. They confirmed the effectiveness of LID solutions even for the design of storm events (Kumar et al., 2021). Fazhi Li et al. (2020) used Green Infrastructure (GI) practices to measure multiple scenarios in China and found the runoff was reduced by up to 47.01% (F. Li et al., 2021). Chao Mei et al. (2018) also assured the previous conclusion in China, highlighting that the GI could not eliminate total flooding (Mei et al., 2018). Dietz and Clausen (2008) conducted a comparative study between the efficacy of traditional development and LID practices, where the results of investment in conventional development showed increases in surface runoff and pollutant loads in contrast to LID (Afata et al., 2022; Sörensen and Emilsson, 2019). Goncalves et al. (2018) assessed seven LID scenarios in South Brazil and found that the total flood volume decreased by 30%–75% (Dottori et al., 2016; Mignot et al., 2013). Dreelin et al. (2006) investigated the efficacy of permeable pavement and found that it produced 94% less runoff than concrete parking (Y. Huang et al., 2020; Kumar et al., 2021; O'Donnell et al., 2020). Eckart et al. (2017) proposed a coupled optimization-simulation model, and they found that a grassed swale was the most cost-effective LID for flood peak mitigation (Guillén et al., 2017; X. Li et al., 2021). Zhang et al. (2010) conducted a time-series modeling approach for residential districts, revealing that the system mitigates urban waterlogging problems by lowering flood volume by 13.9% (Fan et al., 2020). Abdelkebir et al. (2021) proposed a method to decrease runoff peaks and volumes in northeast Algeria, exploring that LID could reduce peak runoff by 54.7% and total runoff volume by 75.2%. In Malaysia's Johor, the effectiveness of infiltration trenches was investigated, and the findings indicated that the peak flow might be decreased by 17.4%–21.95% (Begoña Arellano Jaimerena, et al, 2021). Schmitter et al. (2016) assessed the intervention effect of a green roof over 100 km^2 in the center of Singapore, where annual runoff volumes were 12.4% lower. Bartens et al. (2008) demonstrated that tree belts could reduce runoff from an agricultural grass slope by 32%–68% (Cea et al., 2010; C. J. Huang et al., 2014). Planting five vegetated vacant lots in northern Philadelphia decreased runoff by 30% and peak runoff by 24%. Gill, Handley, and Pauleit (2007) modeled the potential runoff reduction in Manchester; they indicated that a 10% increase in tree cover in high-density residential areas lowers surface runoff by 5.7% in a 28 mm event (OECD, 2020; Pansare, 2022). Li et al. (2021) illustrated that the

Table 1
Natural-based solutions tools (Management, n.d.; Stagakis, 2020), (Fan et al., 2020; WMO/GWP Associated Programme on Flood Management, 2008).

NBS solutions	Urban scale	General Characteristics	our study
Waterways	CS	Waterways are channels that capture and convey flows from catchments, including streams, creeks, and rivers, and can be natural or modified systems.	SE
Rainwater harvesting	BS/CS	Rainwater is collected from the building's roof and combined in the cistern, interception well, aquifer, or reservoir with percolation.	DE
Infiltration trenches	CS	Linear excavations like wastewater are utilized under a gravel cover.	SE
Green corridors	CS	Green corridors are linear green spaces that can provide connectivity services, including natural habitats and recreational pathways.	DE
vegetated swales	CS	Linear, shallow depressions (pots or surfaces) with sealed bottoms, filled with fertile soil, and densely planted with hydrophilic vegetation	SE
Bioretention basins	CS	linear depressions adjacent to a pavement, planted with multi-species plants resistant to flooding regularly.	SE
Rain gardens	BS/CS	Small depressions and containers planted with flood-resistant vegetation collect stormwater for reuse or infiltration into the soil.	SE
wetland ponds	BS	open water bodies that are designed to hold water permanently. If appropriately managed, it will improve microclimate, enhance groundwater restoration, and add to the aesthetics of recreational areas.	DE
Permeable pavement	CS	Walk on flat, low-sloped surfaces made of porous materials such as gravel, stones, grass, eco-grids filled with grass or gravel, and so on.	SE
Green roofs	BS	a method of developing roof and ceiling coverings made up of numerous substrate layers that allow for the growth of flora	SE
Green walls	BS	Add greenery to walls, fences, and other vertical structures, such as with vines or plants in pots.	DE

Urban scale: CS, city scale; BS, building scale. SE, Selected tools for our study; DE unselected tools in this study.

annual surface runoff decreased by 30% from 1990 to 2005, and the peak flow decreased by over 40% in Shenzhen, China (Qiu et al., 2020). Shafique, Kim, and Kyung-Ho (2018) noted that a green roof in Seoul, South Korea, reduced runoff from storms by 10–60%, depending on the intensity of the rainfall event (Ahmed et al., 2019; Asian Development Bank, 2016a; Y. Huang et al., 2020).

Relevant studies were conducted to predict the effectiveness of NBS practices; however, empirically, studies needed to be more adequately proposed to combine LID practices into urban planning mechanisms, particularly in flood-prone cities. Our research covered this point, which contributes significantly by combining different disciplines. Second, all studies focused on countries with clearly defined strategies, such as sponge cities in China (G. Dong et al., 2018; Kumar et al., 2021; F. Li et al., 2021; Luo et al., 2021; Mei et al., 2018; Nie, Linmei; Jia, 2018; Peng and Reily, 2021; Yin et al., 2021). Still, no study has proposed the most effective flood reduction tool in the MENA region's arid and semi-arid urban areas. Third, most studies reveal that green infrastructure significantly influences urban flood risk management more than grey infrastructure. However, research such as Alves et al.'s (2020) found that LID is likely less efficient than more traditional grey infrastructure, generating a conflict between some studies (Alves et al., 2020). Finally, existing studies are mainly case studies on small regions, which may be difficult in a highly urban, dense city with complicated patterns.

4. Materials and methods

4.1. Description of the study area

Alexandria, the Mediterranean coastal city, is the second largest city in Egypt, spanning over 2390 km^2 with a population of approximately 6.5 million and a fast-growing industrial included logistic city that accounts for 40% of the national industrial output (Hemeda, 2021). The city consists of eight urban districts based on administrative boundaries, characterized by a regular gridiron and irregular street network strongly connected to the seafront and flanked by three-to twenty-three-story buildings. Also, most of Alexandria's districts have a dense, compact urban pattern with mixed land uses (Barthel et al., 2013; Hafez, 2018; Sirry, 2018). Like many North African cities, it has experienced the emergence of unregulated, informal expansion, which has grown almost 47% during the past 20 years with increasing impermeable surfaces and collapsed utility infrastructure (Abdo et al., 2012; Hemeda, 2021). According to geomorphological maps, the city is characterized by an arid Mediterranean climate and is vulnerable to climatic stressors (floods, tsunamis, migratory cyclones, and sea level rise) (MOHUUC & Center, 2020). The city experiences rainy winters, locally called "Nawas," from October to January and warm summer months with no rain (Young, 2018; Young et al., 2021). There is high variability in annual rainfall, between 368 mm in 2004 and 70 mm in 2014, with an average of 195 mm per year (Hafez, 2018).

Regarding drainage infrastructure, recent data from the Alexandria Sanitary Drainage Company (ASDC) indicate that approximately 93.4% of the urban area is connected to the sewer system, which has roughly 1.6 to 1.9 million m^3 per day (Young, 2018). The capacity is estimated at a 2-year return period, indicating the city will be exposed to frequent flooding ahead, as shown in Fig. 1. Because of the city's rapid urbanization over the years, much of the city's aged infrastructure has become ineffective in dealing with flooding (Soliman., 2022; Sumi et al., 2013).

4.2. Methodological framework

Assessing LID tools in regions requires a multidisciplinary approach that involves experts from different fields, such as hydrology, ecology, and urban planning (Alves et al., 2020; Bernello et al., 2022). The methodology should be flexible and adaptive to the specific needs and constraints of the region. Our study consists of three sections, as shown in Fig. 2: First, the data collection; various types of data were collected, such as topographic characteristics (a digital elevation model [DEM]), sub-catchment-dependent automatic extraction of sub-watersheds using Global Mapper 24.1, physical characteristics of the city (building footprints and land use data), and other data such as soil type, slope, and vegetation cover, and hydrological characteristics such as the rainfall intensity, runoff, and infiltration. Second, select appropriate LID tools and consider the specific needs and constraints of the region, such as climate, soil type, land use patterns, and available space. The assessment was conducted for each tool separately, and then all tools were combined into the model. All data was simulated using the LID TTT, which assesses each tool's impacts in terms of the reduction of water depth, volume, and flow peak; additionally, we evaluated the cost-effectiveness of each tool, followed by selecting the appropriate scenario for the case study, identifying areas where LID tools may not be practical, and identifying opportunities for further improvement. Finally, we presented urban planning mechanisms for integrating these LID tools into the city's strategic plan at various scales (city, neighborhood, building) to help stakeholders, such as policymakers, planners, and the public.

4.3. Data availability

Data availability for assessing the effectiveness of LID tools can vary depending on the city. As shown in Table .2, our study relied on data from 2018 to 2023 from multiple sources. Most of the data was obtained from the Ministry of Egyptian Housing, the country's official authority for the most updated data, which are the 2018 and 2020 data. Here are some types of data typically gathered, such as hydrological data on precipitation, runoff, and streamflow. Topographic data (elevation, slope, and drainage areas) to assess the suitability of different LID tools for a particular site; soil data (soil texture, infiltration rates, and soil moisture); and land uses (use type, density, and coverage).

4.4. Data collection

- *Topographic characteristics*

The USGC (the NASA website) and the Shuttle Radar Topography Mission (freely available ASTER GDEM V2) were used to obtain the digital elevation model (DEM) with a high accuracy of 10 m resolution. The map delineates runoff flow and other hydrological and morphometric parameters. The elevation varies between 1 m along the shore of the Mediterranean Sea and 69 m near the city's back and front, as shown in Fig. 3. As the city progresses away from the coast, the topography is characterized by low-lying areas below mean sea level, with a significant portion below 5 m sea level.

-Land use data

Data on anthropogenic uses, such as building coverage ratio (BCR) and classification of Land uses, were obtained through a GIS map in 2020 from the Ministry of Egyptian Housing. For accuracy, we updated GIS MAP and some information until 2023 using Open Street Map (OSM) in GIS 10.7 and aerial photography from Google Earth Pro-2020. Table 3 shows land use in Alexandrina in 2020. As shown in Fig. 4, land use was classified; residential areas have the highest percentage, followed by roads.

- ***Historically observed rainfall and flood data***

Regarding Daily precipitation data from 1957 to 2020 was provided (Fig. 5) by three institutions responsible for flood risk management in the city: the Ministry of Irrigation and Water Resources, the Egyptian Metrological Station (EMA), and the Company for Water and Wastewater (HCWW) of the Ministry of Housing, as well as three stations: the eastern station Ras El Teen (31.29 N and 29.98 E); the western station

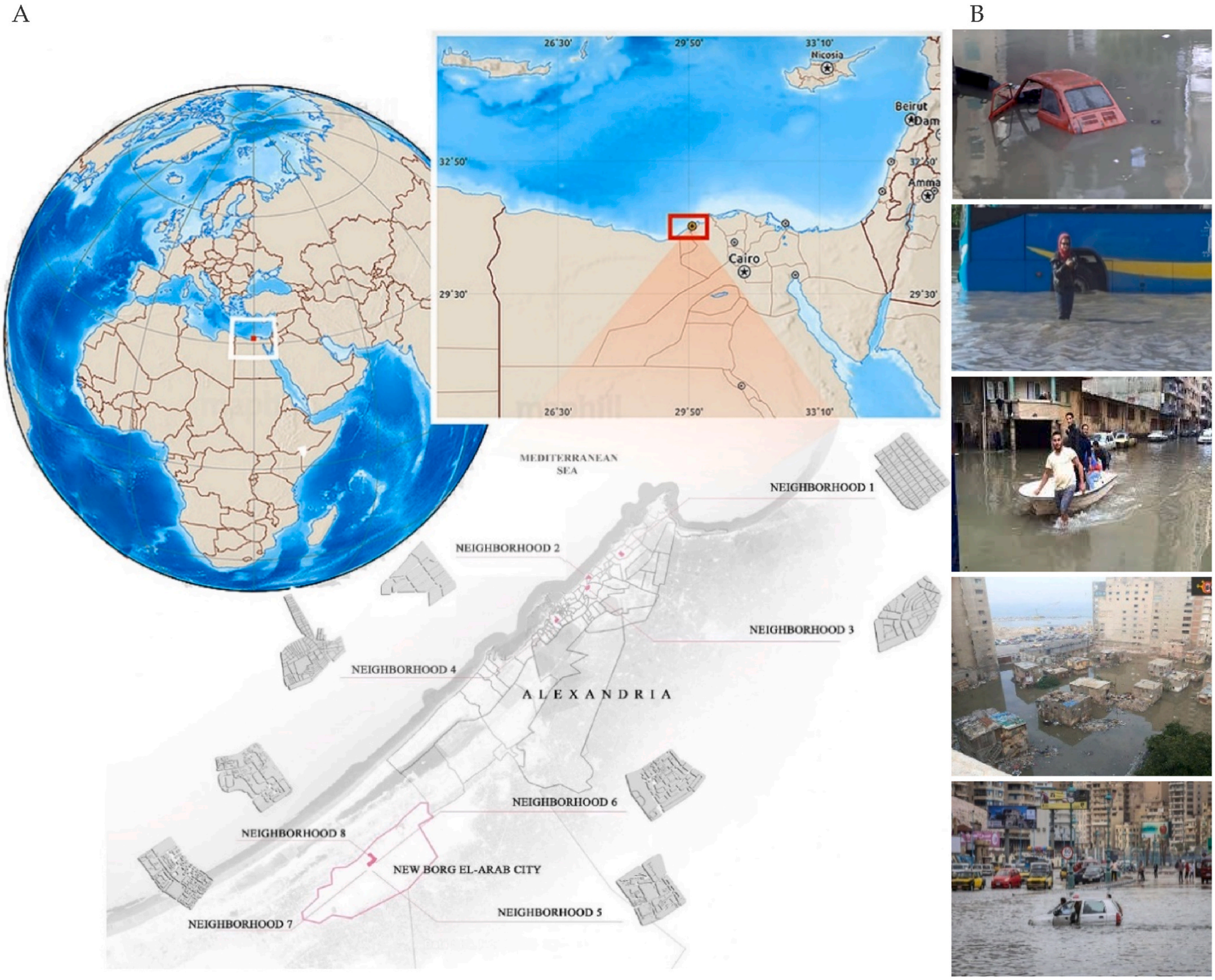


Fig. 1. (A) global and local location of Alexandria City and below image illustrating different urban form characteristics for some areas of eight districts (based on Ibrahim and Masoumi, 2018); (B) images illustrating the impact of runoff on the city streets.

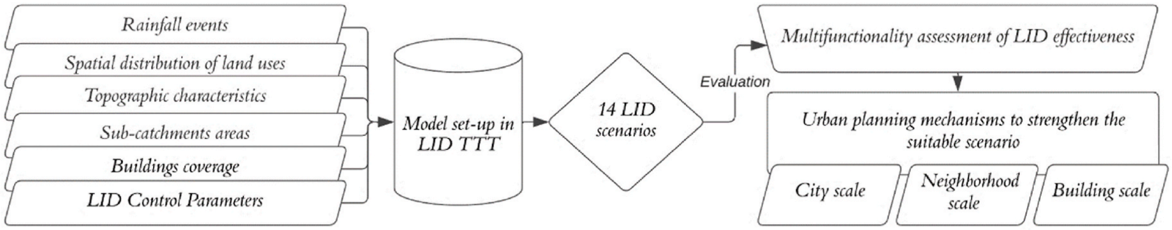


Fig. 2. Research methodology.

Table 2
Data availability and source of data.

Source of data	Date	Format	Indicators
GOPP (the Ministry of Egyptian Housing)	2020	Geodatabase	Land uses
Egyptian Metrological Station	2021	PDF	Rainfalls Intensity (RFV)
NASA website	2023	GeoTiff	(DEM) Topographic characteristics
Company for Water and Wastewater (HCWW) (Hafez, 2018)	2018	PDF	Infrastructure network

Abu Kir (west of Alexandria, 32.55 N, and 30.18 E); and the southern station Nozha (31.19 N and 29.95 E) (Liao et al., 2016; Silva and Costa, 2018; Zhou et al., 2019). On November 16, 2015, the maximum observed rainfall was 79 mm, which caused significant flooding (Young, 2018; Zevenbergen et al., 2017). Rainfall frequency analysis shows that 26 mm has a 2-year return period, and 79 mm/day has a 10-year return period. The total rainfall annual volume shows an increasing trend in the previous 20 years. The observed annual precipitation of the region showed that the extreme rainfall events are becoming more recurrent and increasing in intensity, although the total yearly precipitation values have a decreasing trend; this agrees with climate change studies reported by the IPCC (Hemeda, 2021).

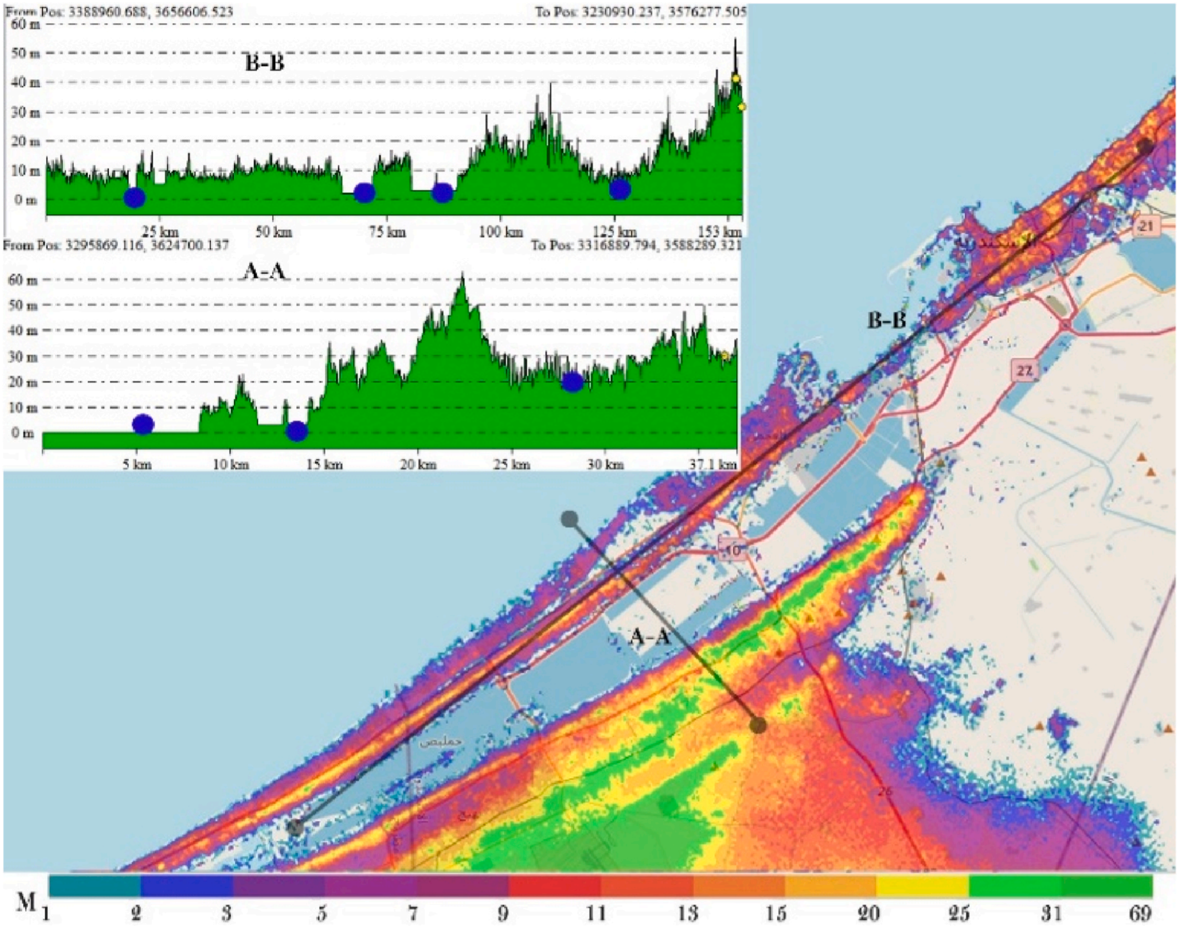


Fig. 3. Topographic characteristics of Alexandria city (unit by meter); the blue circle on sections represents the lowest rainfall sub-catchment points. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Land-use in Alexandria city.

Land use		Area km2	Percentage %
Urban area	Residential	410.49	17.8%
	Residential- Commercial	101.78	4.4%
	Commercial	114.31	5.0%
	Industrial	210.39	9.1%
	Touristic	140.21	6.1%
	Administrative and business	99.12	4.3%
	Roads	324.59	14.1%
	Services	171.83	7.5%
	Green spaces	97.84	4.3%
Waterbody		158	6.9%
Bare soil		347.691	15.1%
Agriculture		123.567	5.4%

5. Methodology of simulation scenarios of LID control

5.1. Methods for setting LID practices of city land use

For doing hydrological simulation pre- and post-integrating LID tools in the flood-prone city, we used the widely used LID TTT. The LID (Permeable pavement PP + green roof GR + rain barrel RB + rain garden RG + infiltration trench IT + bio-retention cells BRC + vegetative swales VS) were simulated based on rainfall intensity, topographic characteristics, land use roughness. The LID tool's location was distributed, as shown in Table 4, based on land use characteristics and built-up coverage. LID was designed mainly as GR and PP in residential, administrative, and commercial areas. Along the sides of roads, LID was marked as IT, PP. Where "area" is used in Table 4 refers to the total size of land use. All vector data were converted to rasters with 20 m resolution for enabling calculations and data processing. Our model provided multiple criteria to select suitable locations for LID tools. I.e., bio-retention cells plus vegetative swales (BRC + VS) should be implemented on the road network to collect road surface runoff. They were executing a green roof, a rain barrel, and a rain garden needed flat regions. At the same time, bio-retention cells and an infiltration trench (IT) could be implemented in areas with sloped drainage. In addition to these tools, others could be added based on actual demands based on best management practices.

5.2. Design LID scenarios

The model incorporated varying combinations and implementation levels of LID practices' performance over six return periods. Using Eq. (1). The storm density over six return periods was defined and calibrated. The reduction rates of peak flow (Rp) and flood volume (FV) were calculated based on comparisons between the results of the scenarios and their effectiveness.

$$\text{Rainfall Intensity} = \frac{1602(1 + 1.02\ \text{design return period})}{(\text{Rainfall duration} + 11.5)^{0.681}} \qquad \text{Eq.1}$$

Combining different analytical methods and tools helps identify potential flood risks and propose solutions precisely (Bruwier et al., 2020; Ferrari and Viero, 2020). If the rainfall exceeded expectations, Using the equation, two independent variables are used to predict the probability of the bivariate dependent variables:

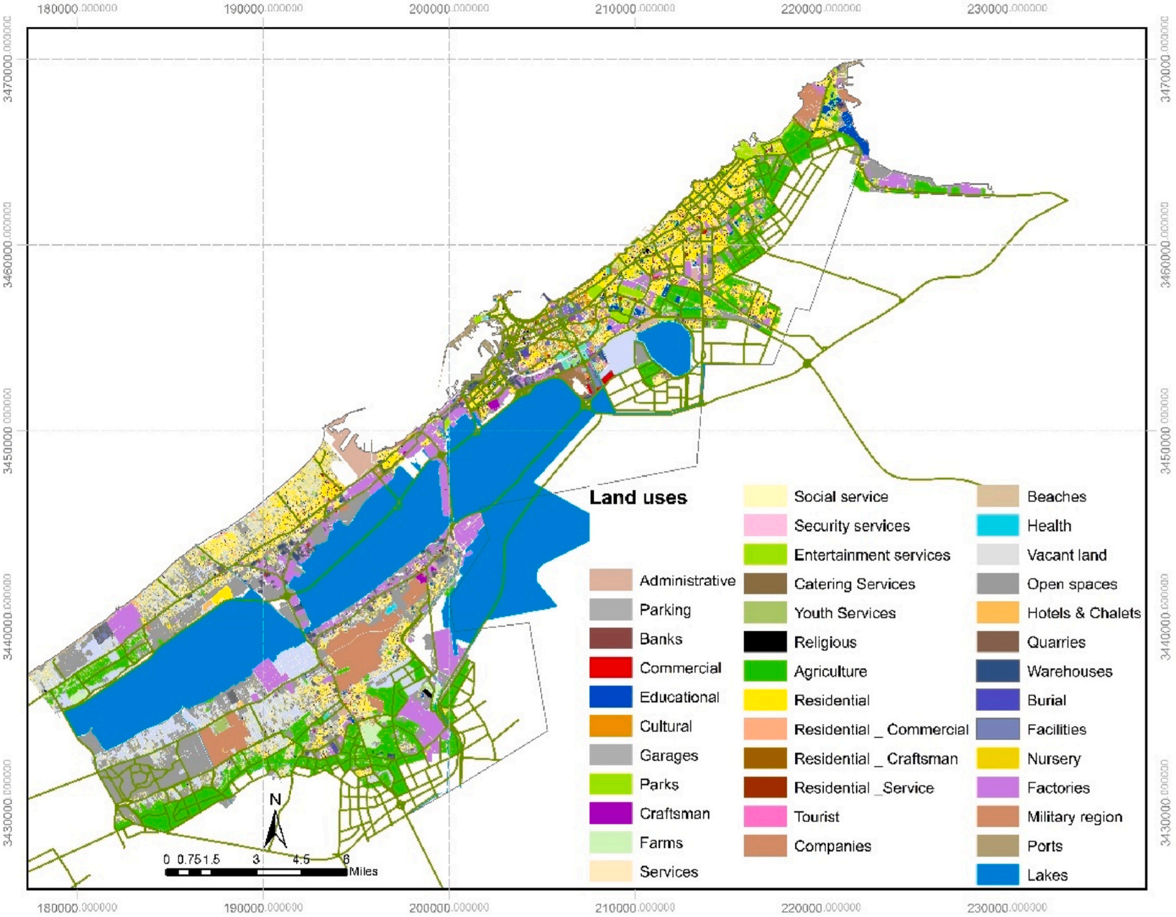


Fig. 4. Spatial distribution of land uses at Alexandria city.

$$p = \frac{1}{1 + e(\beta 0 + B_1\lambda_l + B_2\lambda_2 + \ldots + B_n\lambda_n)} \qquad \text{Eq.2}$$

Where p is the probability of an event occurring, β0 has a constant value, β1… βn are regression coefficients, and λ_l. . . λ_n are independent variables. Maximum daily rainfall data for the region was statistically determined for various return periods. Based on the intensity-duration-frequency chart of Alexandria Sanitary and Drainage Company shown in Fig. 6, the rainfall duration was assumed to be 150 min (2.30 h) (Young, 2018).

In the LID control model, various technical properties were considered, including berm height, hydraulic conductivity, layer thickness, void ratio (voids/solids), porosity, etc., as shown in Table 5.

5.3. Calibration and validation

Assessing the reliability of findings helps determine an analysis's accuracy and applicability. Comparing observed (w_T^{obs}) and simulated (w_T^{sim}) annual runoff volume (ARV) can be gauged using the deterministic coefficient (RC) and Nash-Sutcliffe efficiency (NS) index [54]. RMS provided a general error size, with small values indicating a more accurate model. The NSE, RMS, and RC assess the degree of correlation between the simulated and observed, which are calculated based on Eqs. (3)–(5), respectively (Mei et al., 2018).

$$NS = 1 - \frac{\sum_{T=1}^{n}\left[w_t^{obs} - w_t^{Sim}\right]^2}{\sum_{T=1}^{n}\left[w_t^{obs} - w_t^{-Sim}\right]^2} \qquad \text{Eq.3}$$

$$RC = \left(\frac{\sum_{T=1}^{n}\left[w_t^{Sim} - w_t^{-Sim}\right]\left[w_t^{obs} - w_t^{-obs}\right]}{\sqrt{\sum_{T=1}^{n}\left[w_t^{Sim} - w_t^{-Sim}\right]^2 \sum_{T=1}^{n}\left[w_t^{obs} - w_t^{-obs}\right]^2}}\right) \qquad \text{Eq.4}$$

$$\boldsymbol{RMS} = \left(\frac{\sum_{\boldsymbol{i}=\mathbf{1}}^{\boldsymbol{n}}\left(w_t^{obs} - w_t^{Sim}\right)^{\mathbf{2}}}{\boldsymbol{n}}\right)^{\mathbf{1/2}} \qquad \text{Eq.5}$$

5.4. Criteria for selecting calibration points and LID scenarios

Selecting appropriate LID tools for runoff reduction depends on factors such as site characteristics, soil conditions, climate, available resources, topography, vegetation, and land use. Most of these factors were evaluated to identify the appropriate calibration points and LID tools to reduce runoff effectively. We defined the sub-catchment areas of the city using automatic extraction of subcatchments in Global Mapper, which reached 17 subcatchments classified based on topographic characteristics, as shown in Fig. 7. Regarding the distribution of LID tools, we put them in low-elevation points and areas near the sea, lakes, vacant lands, or brownfield regions. Regarding permeable pavements, we assumed all streets would be converted from concrete to permeable roads and 50%–80% of rooftops to green roofs. All these factors changed, and the values of each parameter were altered, or the so-called combinations and permutations method. We tested each LID tool separately and combined each one with others to generate more than 32 scenarios; only 14 scenarios were presented, which may be appropriate for the case study. In our case study, the criteria for selecting the proper LID tools for runoff reduction depended on many factors, such as site

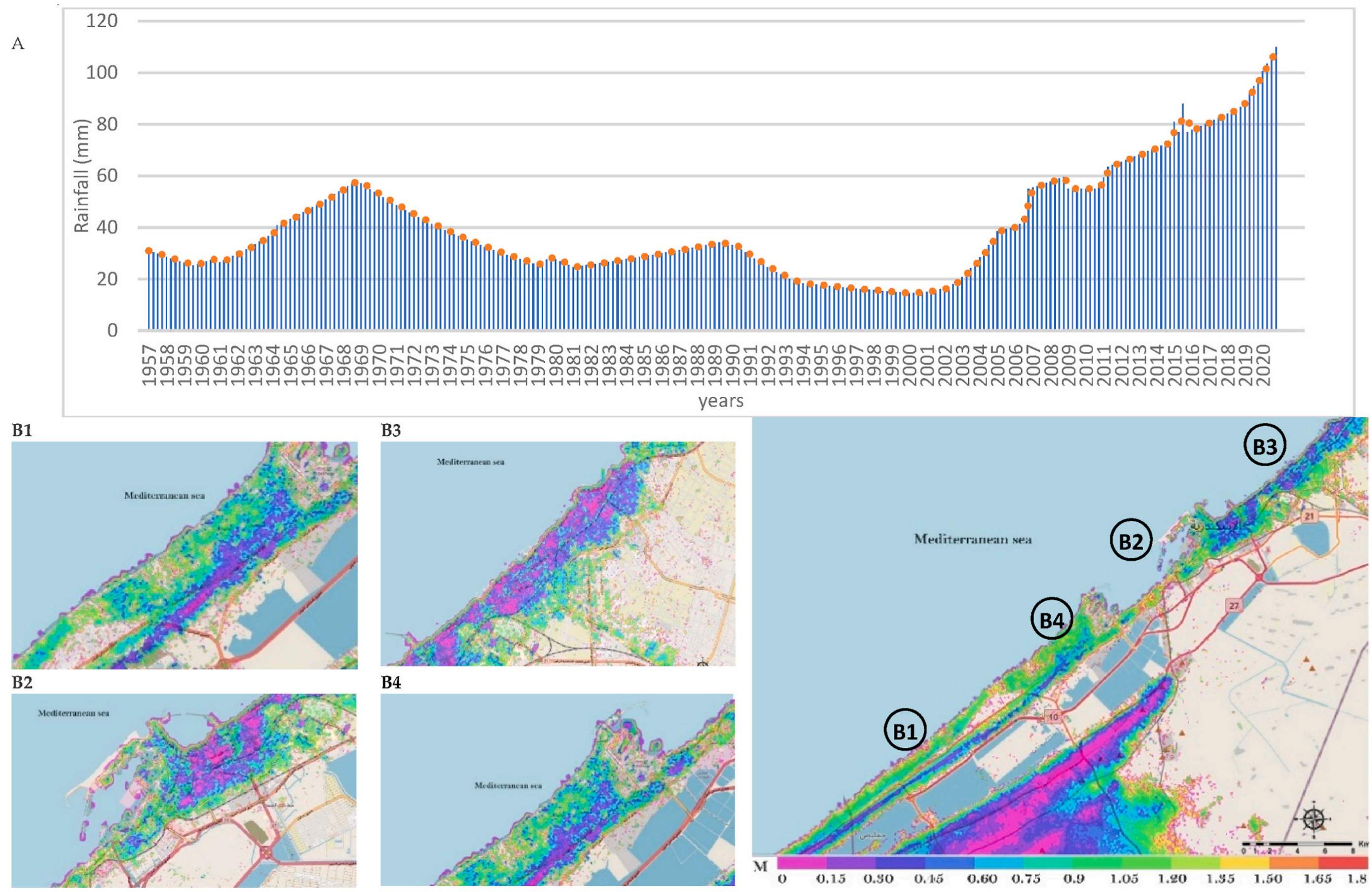


Fig. 5. Historically observed rainfall variability: (A) the vacillation in rainfall intensity for 1957–2020; (B) the spatial distribution of the Flood Map in the city in 2020.

Table 4
Methods for setting NBS practices for city land use (F. Li et al., 2021; Mei et al., 2018).

Land use	Set-up method
Residential	Area × building density (0.30) × potential GR + RB rate (0.50) Area × [1 − greening rate (0.20) − building density (0.35)] × potential PP rate (0.50)
Residential-Commercial	Area × building density (0.35) × potential GR + RB rate (0.40) Area × [1 − greening rate (0.25) − building density (0.35)] × potential PP rate (0.50)
Administrative and business	Area × building density (0.50) × potential GR rate (0.60) Area × [1 − greening rate (0.25) − building density (0.50)] × potential PP rate (0.30)
Touristic	Area × potential RG rate (0.25) Area × building density (0.30) × potential GR rate (0.75)
Industrial	Area × potential RG rate (0.20) Area × building density (0.35) × potential GR + RB rate (0.40) Area × [1 − greening rate (0.25) − building density (0.50)] × potential PP rate (0.30)
Commercial and Services	Area × building density (0.60) × potential GR rate (0.80) Area × [1 − greening rate (0.20) − building density (0.60)] × potential PP rate (0.50)
Roads	Area × potential BRC + VS rate (0.20) Area (length*width) × potential IT rate (0.75) Area × potential PP rate (0.10)
Green spaces	Area × potential RG rate (0.15) Area × potential BRC + VS rate (0.35) Area × potential PP rate (0.10)
Vacant Land	Area × possible BRC + VS rate (0.20) Area × potential RG rate (0.75)

suitability, managing stormwater effectively, cost-effectiveness, longevity and durability, aesthetics and public acceptance, and local regulations and policies.

6. Results and discussion

6.1. Calibration and validation of the selected rainfall model

For our city data, direct calibration and validation were conducted. The scenarios were used for runoff simulations based on a series of modeling conditions, parameter specifications, and data quality. Thus, the model was calibrated based on several events, and we extrapolated the model beyond the calibration runs. Four rainfall timings (December 25, 2020, November 12, 2019, January 11, 2017, and December 30, 2015) and five timings (November 31, 2020, December 23, 2019, January 1, 2017, and December 1, 2015) were used to simulate annual runoff volumes (see Table 6 and Fig. 8). Secondly, land-use data and rainfall data from 2015 to 2020 were used to simulate ARVs from 2010 to 2005. The RC and NS were calculated to be 0.91 and 0.82 after the calibration. Then, ARVs from 2015 to 2020 were simulated to verify the model's accuracy, as indicated by the NSE index and R2 values of 0.97 and 0.91, respectively, for the three calibration events. Thus, the calibration results verified that the model performed well and could be used in further analyses.

6.2. Assessment of LID scenarios' effectiveness in flood mitigation

Table 7 and Figs. 9 and 10 show peak flow reduction water, total volume, and depth reduction under the different scenarios (PP, GR, RB,

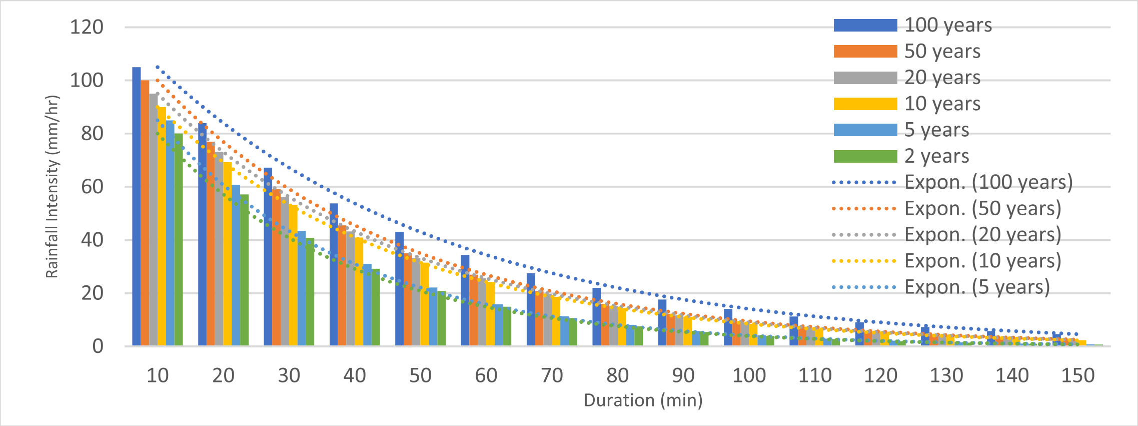


Fig. 6. Intensity–duration– frequency curves in various return periods (2, 5, 10, 20, 50, and 100 years) of Alexandria.

Table 5
LID controlling parameters.

LID Control Parameters		bio-retention cell	Rain Garden	Green Roof	Infiltration trench	Permeable Pavement	rain barrel	vegetative swale
Surface	Storage Depth/Berm Height/Barrel Height (mm or in)	300	300	300	300	300		300
	Vegetation Volume (fraction)	0.05	0.05	0.05	0.05	0.05		0.05
	Surface Roughness (Manning's n)	0.2	0.2	0.2	0.2	0.2		0.2
	Surface Slope (percent)	1	1	1	1	1		1
Pavement	Thickness (mm or in)	100–150				100–150		
	Void ratio (voids/solids)	0.12–0.21				0.12–0.21		
	Impervious Surface (fraction)	0				0		
	Permeability (mm/hr or in/hr)	1000–2000				1000–2000		
	Clogging Factor	360				360		
	Regeneration Interval (days)	2				2		
Soil	Thickness (mm or in)	450–900	450–900	75–150				
	Porosity (volume fraction)	0.437	0.437	0.437				
	Field Capacity (volume fraction)	0.062	‘0.062	0.062				
	Wilting point (volume fraction)	0.024	0.024	0.024				
	Conductivity (mm/hr or in/hr)	120.34 (Sand)						
	Conductivity slope	5 for sand to 15 for silty clay						
	Suction Head (mm or in)	49.02	49.02	49.02				
Storage	Height	150–450			150–450	150–450	600–900	
	Void Ratio	0.5 to 0.75			0.5 to 0.75	0.5 to 0.75		
	Seepage Rate	0			0	0	0	
	Clogging Factor	360			360	360	360	

RG, IT, BRC, VS). It is worth noting that implementing the combination of LID practices resulted in a 58.5% reduction in peak flow. Therefore, combinations of green and grey infrastructure will improve flood mitigation effects. In scenario one, PP plays a significant role, with an average 26.2% reduction in ARV. This result may be like the research of Hu et al. which showed that region-wide surface runoff could be reduced by 22.25% using permeable pavements. The bio-retention cells plus vegetative swale scenario (BRC + VS) was implemented, resulting in a 20.91% ARV reduction. Compared to BMPs, the BRC + VS system performed well and was more effective at controlling runoff in low areas.

In the Green Roof GR scenario, results showed that the ARV reduction would be 16.21%. GR was proven to be the six most cost-effective practices due to their low runoff velocities and lack of discernible influence on ARV reduction. Our findings were consistent with those of Hu et al. and we concluded that GR had the potential to reduce high flood hazards in high-risk areas by 6–15% and promote rainwater harvesting recycling. In Rain Garden (RG), the ARV decreased by 56.4%. Additionally, it was shown that RG had the least detrimental effects on the environment, aside from its potential for landscape and for creating eco-friendly cities. ARV reduction was high in infiltration tracts (IT) (by 40.3% compared to PP and others), but it may not be effective in cases of increased rainfall, and it also requires a large area with a high cost for implementation. Because of the high urban density in our city, this method may not be effective.

ARV was significantly reduced when multiple LID tools were combined. For example, PP + BRC + VS + RG, IT + GR + RB, and PP + BRC + VS + RG + IT + GR + RB reduced ARV by 55.4%, 57.7%, and 73.7%, respectively. This reduction percentage can treat flooding risk and other eco-environmental problems, which many studies have assured. For instance, Gong et al. concluded that 30.8%–85.4% of peak runoff reduction in Beijing, China, can be mitigated. Talebi et al. concluded that runoff reduction varied from 17% to 50% in six cities with various Canadian climates (F. Li et al., 2021).

6.3. *Multifunctionality assessment of LID effectiveness*

Assessing the multifunctionality of LID effectiveness requires a comprehensive approach that considers the local context and quantifies the benefits of each function, such as the volume of stormwater runoff reduced and interactions between LID functions, as they can be complementary or trade-offs. For instance, a green roof can reduce stormwater runoff, improve air quality, and provide aesthetic benefits; however, it may not support biodiversity. Also, considering the local context and stakeholder priorities to determine the importance of each

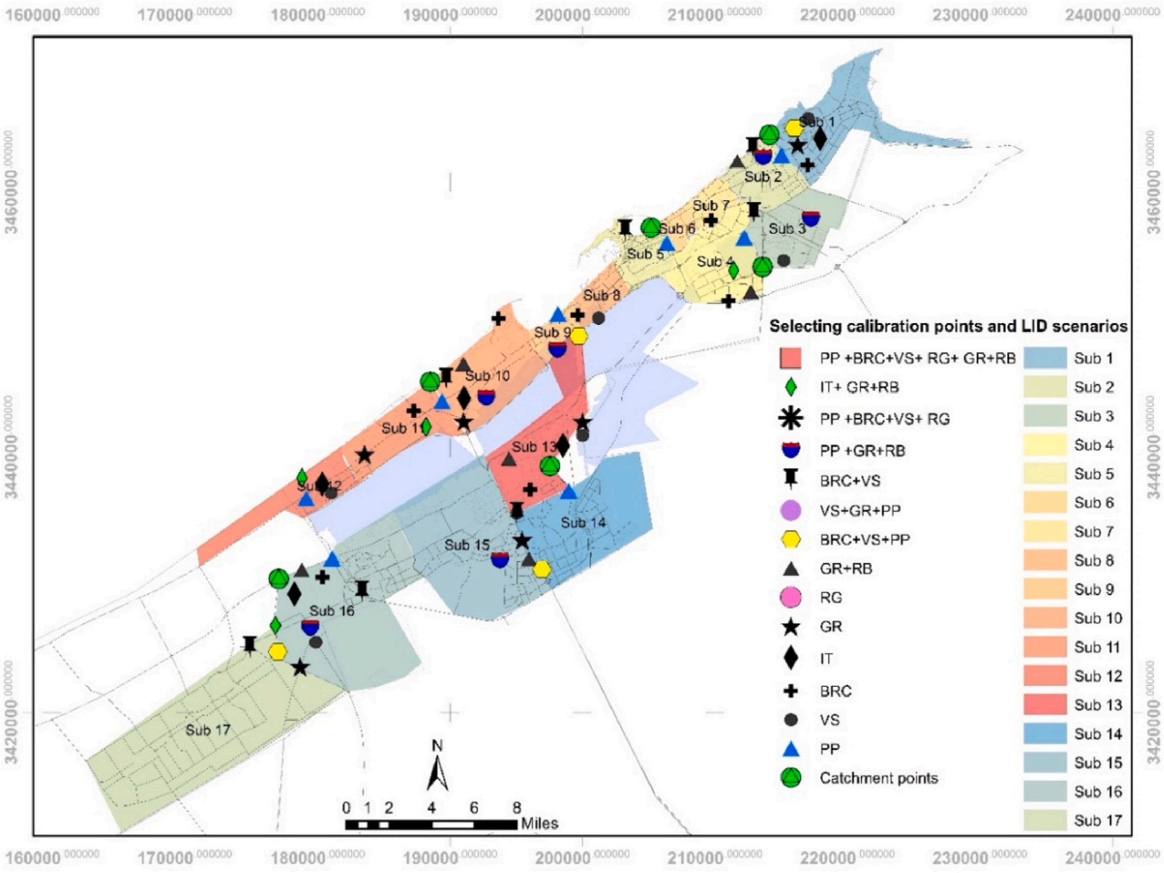


Fig. 7. Define sub-catchment based on the automatic extraction of sub-watersheds using Global Mapper 24.1 and selecting calibration points and LID scenarios.

Table 6
Calibration and validation of the model.

Period	Date	Total rainfall (mm)	RMS	RC	NEC
Calibration	December 25, 2020	109.3	0.31	0.91	0.97
	Nov 12, 2019	97.6	0.18	0.93	0.77
	Jan 11, 2017	83.7	0.03	0.88	0.89
	December 30, 2015	87.3	0.12	0.88	0.91
Validation	November 31, 2020	100.8	0.19	0.88	0.84
	December 23, 2019	88.4	0.06	0.85	0.81
	Jan 01, 2017	80.3	0.15	0.90	0.87
	December 1, 2015	78.1	0.19	0.73	0.78
	Jan 19, 2015	75.7	0.24	0.88	0.89

function; for example, reducing stormwater runoff may be a priority over enhancing biodiversity in an area with frequent flooding. Use a holistic approach to assess the overall effectiveness of LID practices rather than focusing on individual functions. This can help capture the synergies and trade-offs between functions and determine the robustness of LID practices for future changes.

Regarding our case study, our analysis shows that PP + BRC + VS + RG is the optimal LID combination for our city. In Table 8, a multifunctionality assessment of LID effectiveness for all scenarios was analyzed. The chosen scenario has a low implementation cost because few buildings will be affected, and more LID tools will be implemented in road networks and open spaces. LID may also provide socio-economic and environmental benefits such as promoting livable and healthy places, purifying the air, supporting natural resource productivity, improving the landscape, and protecting and enhancing biodiversity. IT (infiltration trenches) may effectively reduce floods, but the trade-off with other benefits is minimal because of their underground location. As a result, while social benefits may be reduced, keeping rainwater for reuse in garden irrigation is more economically practical. The roof garden may be less effective at flood reduction. Still, it provides numerous benefits, such as lowering building temperatures, harvesting productive crops, creating an aesthetic appearance, lowering CO2, and so on, implying that trading off the benefits of LID tools is a never-ending process. It may achieve multiple benefits post-implementation, resolve many climate threats and social issues, and create livable cities with high productivity and competitiveness globally by creating attractive cities for tourism like Hangzhou, China (O'Donnell et al., 2020).

7. Discussions and recommendations for NBS-enhanced cities

7.1. Administrative mechanisms

Several administrative mechanisms and regulatory frameworks can provide a legal basis to strengthen NBS in city planning processes and create more sustainable and resilient communities, as follows: (1) Zoning laws can be updated to prioritize the development of green spaces, or building codes can be updated to require green roofs or walls (Qin, 2020). (2) Cities can create a dedicated office or department to oversee the implementation of NBS and coordinate with other stakeholders, residents, and community groups to ensure that they meet the community's needs, which allows NBS to be tailored to local needs and priorities and designed and implemented in a way that is socially acceptable and culturally appropriate (Devore and Millar, 2021; Dreiseitl and Wanschura, 2016). (3) Public-private partnerships can help leverage private sector resources and expertise to support the development and maintenance of NBS. (4) Cities can also incentivize developers and property owners through tax credits or other financial incentives offered to those who incorporate green infrastructure into their development plans. (5) Governments can explore various financing

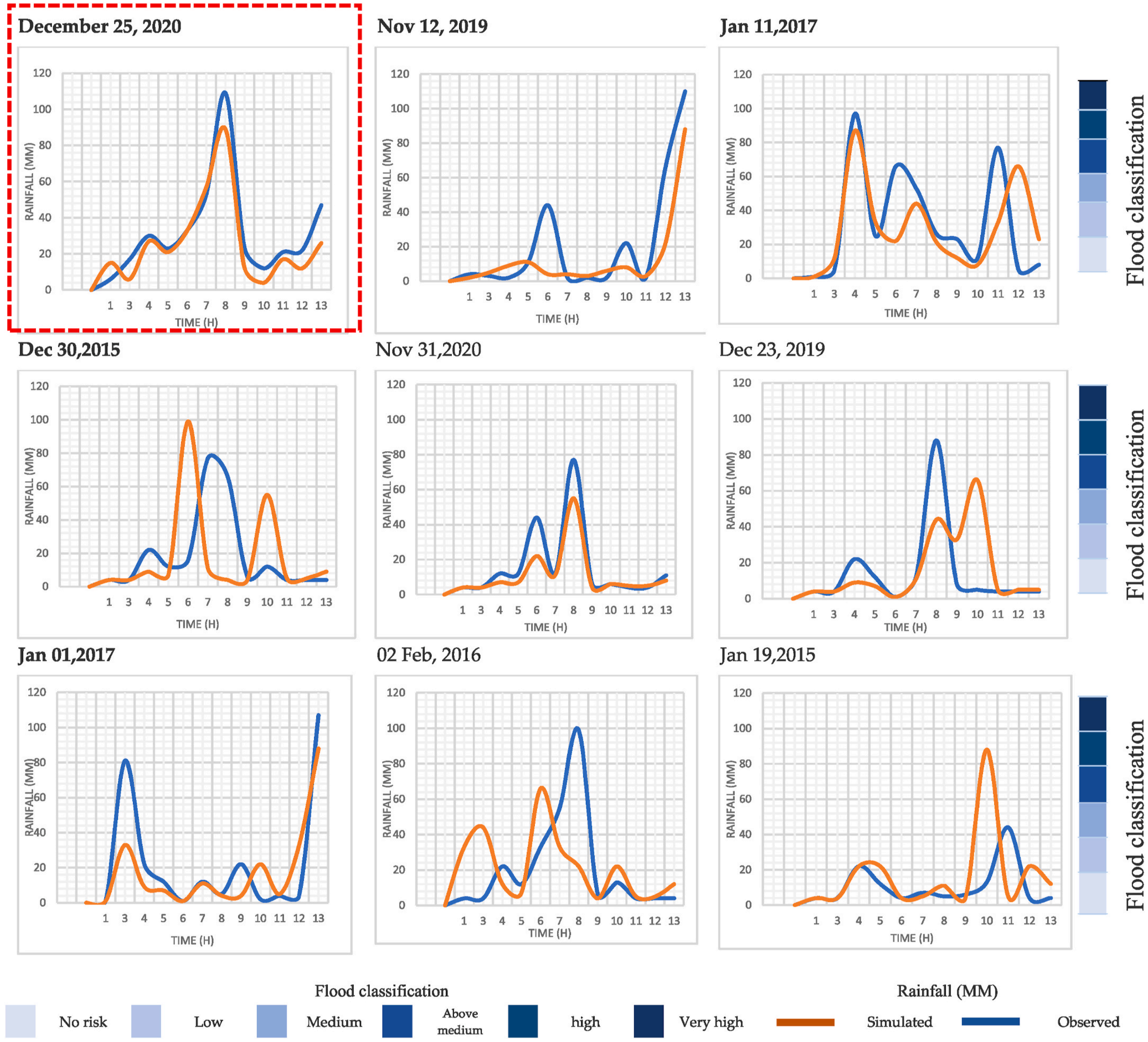


Fig. 8. Calibration and validation of the model Flood classification risk are ranked from "rainfall 0" to "rainfall 120" based on a published paper regarding floods in Alexandria (Young et al., 2021; Zevenbergen et al., 2017). The red rectangle represents the measured model (December 25, 2020), which is appropriate for scenario building because the observed and simulated curves may be the same. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

mechanisms, such as green bonds, climate finance, and public-private partnerships, to fund NBS projects. (6) Building the capacity of local governments and communities for the successful implementation of NBS in cities, which includes training programs for local government officials, education programs for communities, and knowledge-sharing platforms (Afata et al., 2022; Sörensen and Emilsson, 2019).

7.2. Urban planning mechanisms

NBS has long been recognized as essential for city dwellers and mitigating climate risk. Therefore, to enhance urban resilience, planners' new relationships and partnerships need to extend to include urban ecologists, horticulturalists, and landscape planners. According to the floods, integrating structural and non-structural mitigation measures in physical planning may be more effective than using one tool alone. Additionally, they provide opportunities for flood-protective smart urbanization and an attractive aesthetic appearance for wildlife habitats. Urban planning would draw together various decision-making processes and provide a broader perspective that crosses land ownership boundaries so that land use decisions explicitly consider spatial trade-offs. However, trade-offs or jurisdictional conflicts may persist when jurisdictional and biophysical boundaries are inconsistent. So new strategies should be proposed to integrate disaster prevention with urban planning. Our study suggests five recommendations, as follows.

- **First,** strengthen sustainable urban intensification, which plays a vital role in defining urban density characteristics through rational enacting long-term building control legislation such as control over setbacks, potential land use, heights, and building coverage ratio (see Table 9).

Table 7
Runoff reduction of simulating LID scenarios (more details in supplementary data (Appendix. 1)).

	Scenario	Volume total reduction %	Peak flow reduction %
S1	PP	48.0	44.2
S2	VS	28.7	26.5
S3	BRC	26.8	24.8
S4	IT	33.6	31.0
S5	GR	19.0	17.5
S6	RG	45.8	42.3
S7	GR + RB	47.1	43.5
S8	BRC + VS + PP	49.4	45.1
S9	VS + GR + PP	53.0	47.6
S10	BRC + VS	55.1	46.3
S11	PP + GR + RB	59.2	51.1
S12	PP + BRC + VS + RG	55.4	51.0
S13	IT + GR + RB	57.7	53.8
S14	PP + BRC + VS + RG + GR + RB	73.7	58.5

- **Second**, embracing the NBS tools for reconfiguring flood-prone communities alongside grey infrastructure may create resilient communities. For example, the Prairie Crossing and Serenbe communities in the USA achieved an innovative solution for stormwater disposal and simultaneously created an attractive habitat for wildlife and humans. The stormwater collection system uses long-rooted native prairie plants to slow and purify rainwater and snowmelt on their way to the large, centrally located Lake Aldo Leopold. This lake serves as a detention basin and is a popular amenity for swimming, boating, fishing, hydroponically growing plants, and skating among the community's residents. This plan creates civic space for community interaction, local sources of healthy food, and higher status and property values outside the development (Ghofrani et al., 2017).
- **Third,** re-planning brownfields such as fragile land, marshes, graveyards, and urban farming areas for flood contingency and other climate threats. Policymakers should encourage acquisition and investment in brownfield reuse and reinforce investments in "adaptive, multifunctional, water-sensitive infrastructure and urban design" incorporated into existing urban configurations.
- **Four,** enhance prudent land use planning in the long and medium runs to develop proactive policies and support land acquisition for emergencies. Support participatory approaches to public policy analysis as well, which aid in developing a common ground for meaningful policy discourse (Bozovic et al., 2017; D'Ascanio et al., 2016; Golz et al., 2013; Van Long et al., 2020).
- **Finally**, establishing a comprehensive strategic plan and citywide vision to incorporate the NBS into urban planning regulations is critical, as piecemeal implementation may result in poor outcomes. Instead of high investments in upgrading the current infrastructure, the LID tools would be cheap and effective in flooding reduction. Our findings emphasize the influential role of urban planning policies in merging NBS tools into land uses. As a result, future planning in areas prone to similar conditions should primarily account for the long-term and unpredictable effects of climate fluctuations.

8. Conclusion

Flooding, the highest climatic threat, poses considerable urban vulnerabilities. Alexandria, one of the most flood-prone Egyptian cities, has high rainfall variability, insufficient drainage capacity, and low flood preparedness. Our research investigated the predictive influence of incorporating low-impact development control (LIDc) (Rain Garden (RG), Bio-Retention Cell (BRC), Green Roof (GR), Infiltration Trench (IT), Permeable Pavement (PP), and Vegetative Swale (VS)) during urban planning. LID scenarios were simulated with return periods ranging from 2 to 100 years using the LID Treatment Train Tool (LID TTT), depending on calibrated data from 2015 to 2020, by the Nash-Sutcliffe efficiency (NSE) index and deterministic coefficient R2, with values of 0.97 and 0.91, respectively. Our findings indicated that annual rainfall volume (ARV) was significantly reduced when multiple LID tools were combined. For example, PP + BRC + VS + RG, IT + GR + RB, and PP + BRC + VS + RG + IT + GR + RB reduced ARV by 55.4%, 57.7%, and 73.7%, respectively. These findings remain acceptable when compared to LID-related topics. For instance, Goncalves et al. (2018) found that LID could decrease runoff by 30%–75%, and Abdelkebir et al. (2021) demonstrated that LID could reduce peak runoff by 54.7% and total runoff volume by 75.2%. As a result, the PP + BRC + VS + RG practice was determined to be the most appropriate for the study area under high urban densification. No scenario could eliminate flooding, indicating that NBS should be combined with grey infrastructure to achieve optimal mitigation.

In summary, decision-makers should work reasonably by extending well beyond structural approaches. So, assessing the effectiveness of integrating NBS into city planning requires a comprehensive and context-dependent approach that considers the co-benefits and

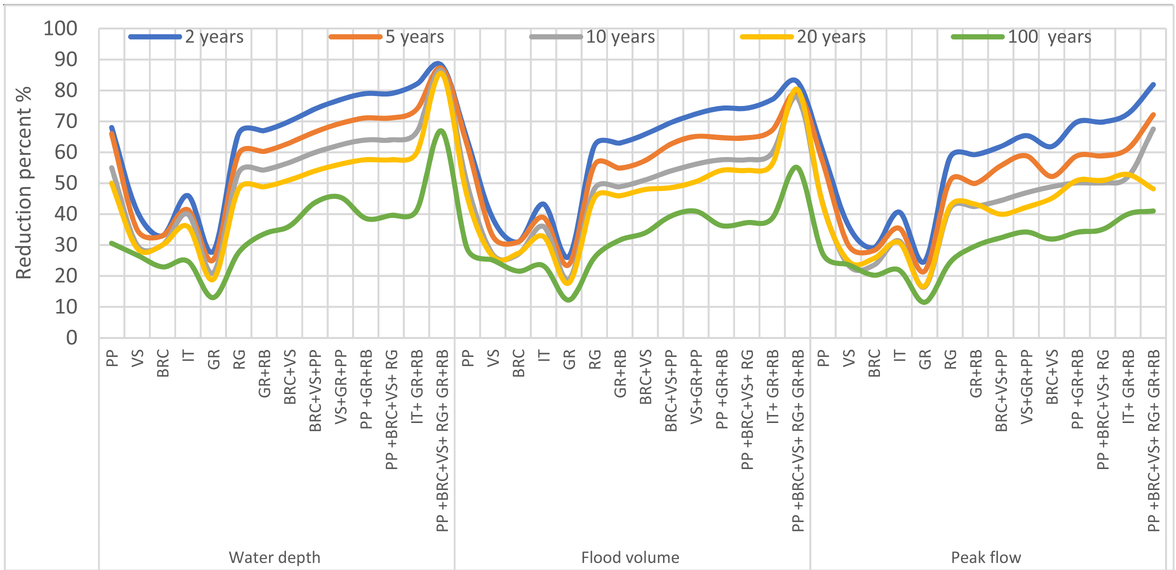
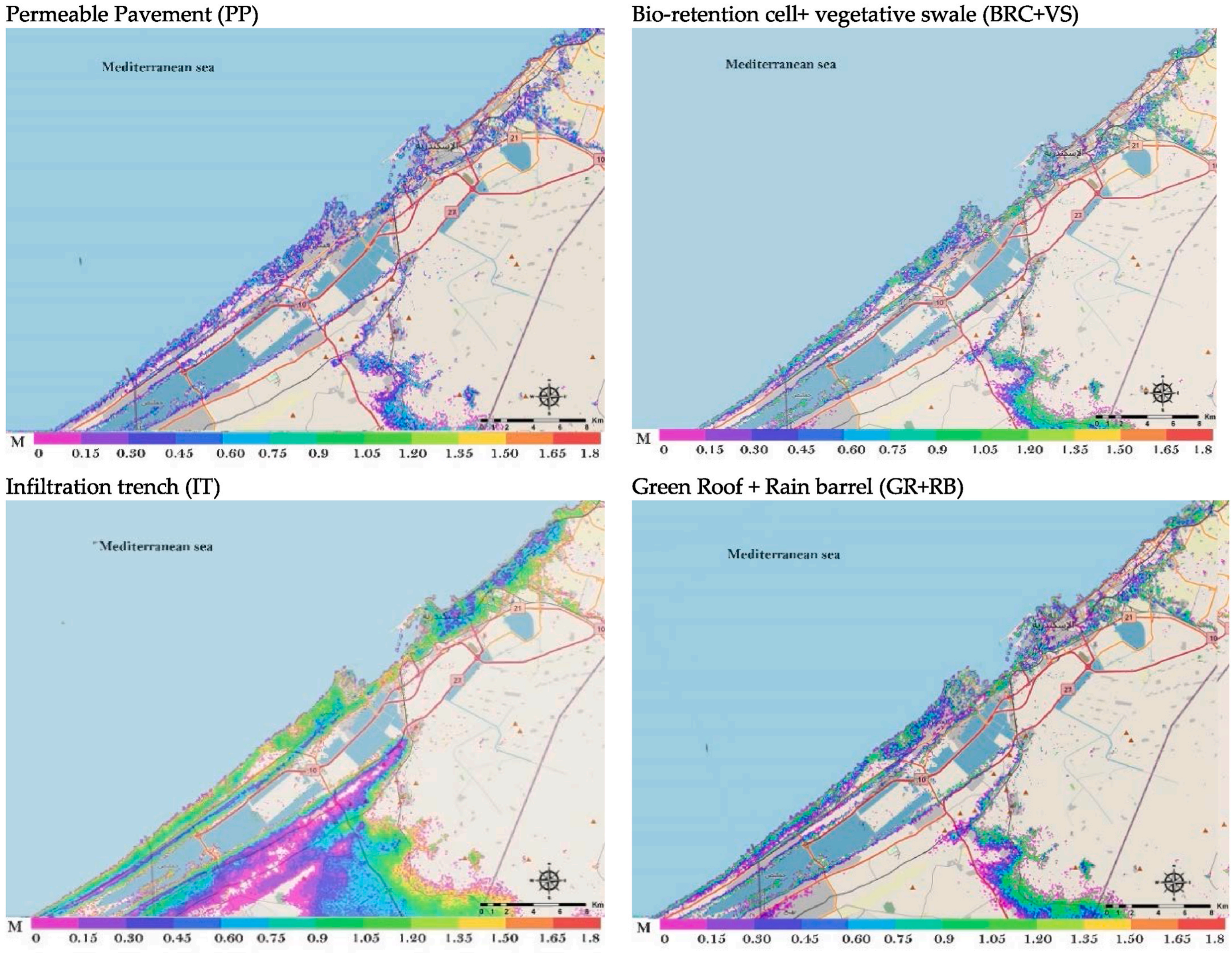


Fig. 9. Assessment of LID scenarios' effectiveness in flood mitigation during six rainfall events.


Permeable Pavement (PP)

Bio-retention cell+ vegetative swale (BRC+VS)

Infiltration trench (IT)

Green Roof + Rain barrel (GR+RB)

Fig. 10. Simulation findings indicting depth reduction for the implementation effect of LID tools.

challenges of NBS implementation and effective stakeholder engagement. Multi-criteria decision analysis should also be considered, including urban land demand, city regulations, direct and indirect investments, socio-economic factors, and land-use planning, besides evaluating these solutions' long-term impacts and NBS-prioritized alternatives.

Some limitations need to be covered in further studies. Simulation findings are simply generalizations; therefore, decision-makers must consider the specific circumstances of each district during the implementation of LID practice. Our study tested 14 scenarios; future research must adequately study the complex grey infrastructure to look at it all together. Also, the study proposed the appropriate scenarios and the advantages of each one. Still, we need to find out the potential obstacles during implementation, especially if it is an existing city, so more studies and interviews with policymakers are required. Finally, because our study focused on the LID's role in flooding, we recommend looking into the socio-economic benefits of its implementation in detail.

Supplementary data (Appendix. 1)

The following link includes all analyses of pre- and post-LID scenarios and data about the cost-effectiveness based on a lot of studies conducted before in China about sponge cities: https://drive.google.com/file/d/1rqnGPJGVCIHlyx37wO9iVY2CuXV957_q/view?usp=share_link.

Author contribution statement

Conceptualization, M.M., H.H., C.F.; G.S.; TS. ; KA.; M.S., and SAK; methodology, M.M., H.H.; C.F.; and KA. ; software, M.M., and KA.; formal analysis, M.M., H.H, and KA.; resources, M.M.; data curation, M.M., H.H., SAK., M.S., TS., and KA.; writing—original draft preparation, M.M, H.H., KA., C.F., and G.S; writing—review and editing, M.M., H.H., and KA.; visualization, M.M., and H.H.; supervision, M.M., H.H.; and G.S; project administration, M.M., H.H, C.F., and G.S.

Funding

Funding: This research is supported by the Center for Balance Architecture of Zhejiang University (Project No: K Heng 20203512-02B, Index and planning methods of resilient cities).

Declaration of competing interest

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

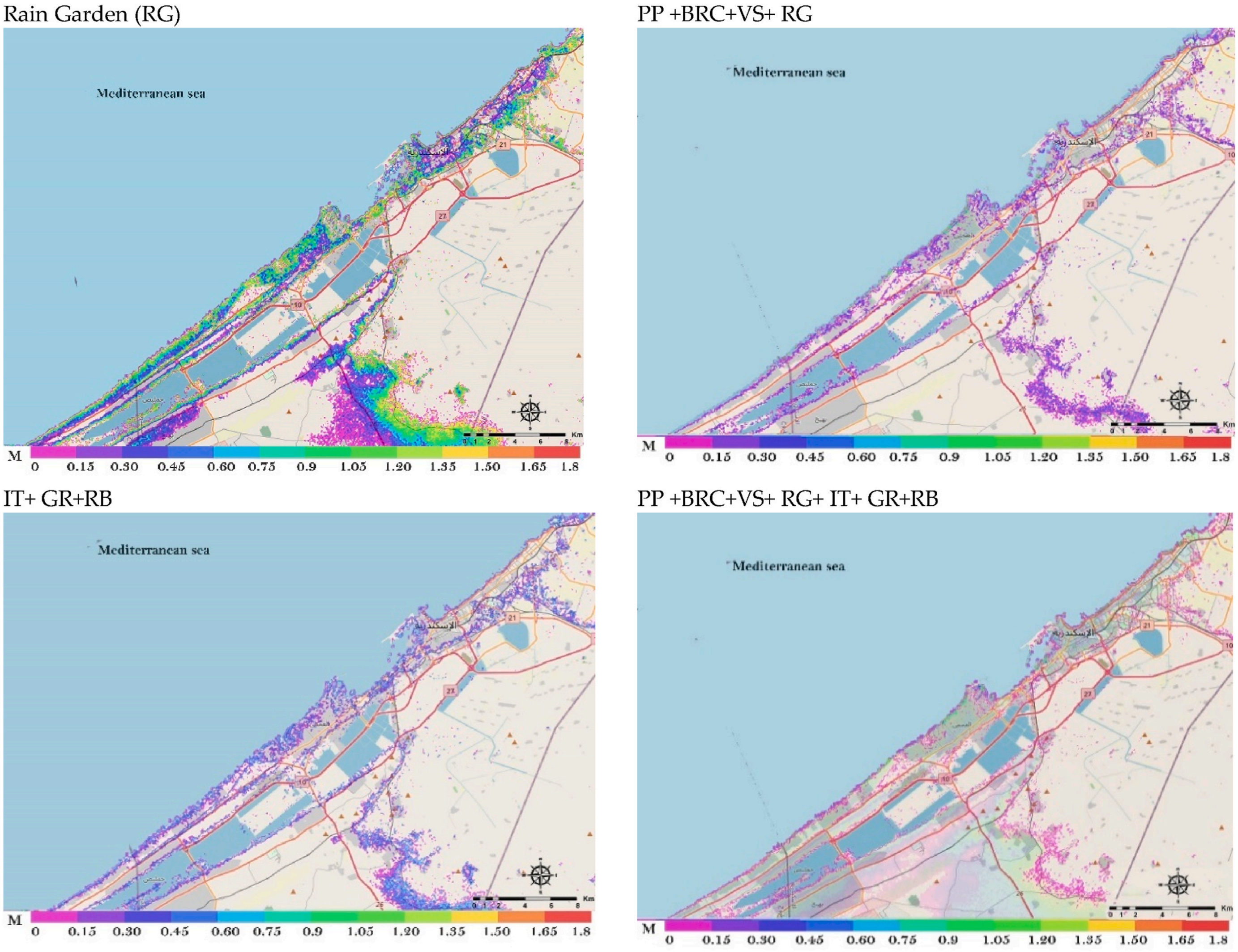


Fig. 10. (*continued*).

Table 8
Multifunctionality assessment of LID effectiveness, regarding cost-effectiveness evaluation and less affected buildings, is available in supplementary data (Appendix. 1). For socio-economic and environmental benefits, we relied on data from previous articles that assessed LID tools in terms of their effectiveness (Lafortezza and Sanesi, 2019; Panno et al., 2017; Raymond et al., 2017; Wild et al., 2017).

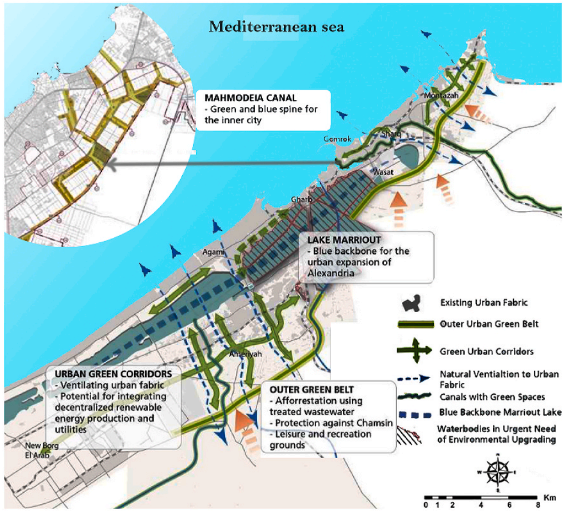
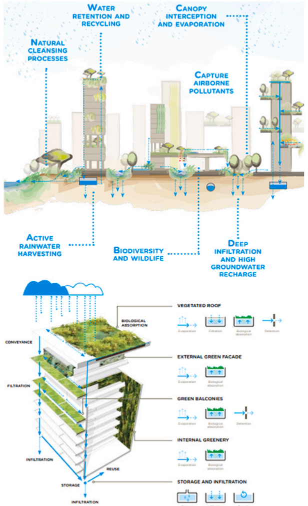
	% less affected buildings	% Cost-effectiveness evaluation	% Volume total reduction	% Peak flow reduction	Socio-economic benefits	Environmental benefits
PP	█	░	█	█	▓	▓
VS	░	█	░	░	▓	▓
BRC	▓	░	▓	░	▓	░
IT	░	█	░	█	▒	▒
GR	█	░	▒	▒	▓	▓
RG	░	▒	░	▓	█	█
GR+RB	█	░	▓	░	▓	▓
BRC+VS	█	░	▓	▒	░	█
BRC+VS+PP	░	▒	▓	▓	█	░
VS+GR+PP	░	█	▓	▒	░	▒
PP +GR+RB	▓	░	▓	▓	█	█
PP +BRC+VS+ RG	█	█	█	█	▒	▒
IT+ GR+RB	▓	█	▓	▓	░	▓
PP +BRC+VS+ RG+ GR+RB	█	█	█	█	█	█

Influence degree

░	Low	▒	Medium	▓	High	█	Very high

Table 9

Urban planning tools for integrating NBS in Alexandria city (Bölen and Kaya, 2017; M. Chen and Ye, 2014; Norris, 2002; Su et al., 2014; Asian Development Bank, 2016b; Ferreira et al., 2022; Hemmati et al., 2020; Song et al., 2021).

	City scale	Neighborhood scale	Building scale
Urban planning Mechanisms	- Creating an interconnected blue-green network at a city scale linked to the Mediterranean Sea - Land-use planning controls reduce flood risk by allocating recreational areas in flood-prone areas and increasing densification in risk-free areas. - Restricted regulations, institutionalized standards, and legislation will be needed for land use and unplanned urban sprawl. - Integrate inhabitants into the city plan to illustrate NBS' benefits, as there are compensations for demolishing some buildings.	- Increasing setbacks between buildings (built-up ratio does not exceed 75% of total land area) - Increasing building floors in the large parcels (exceeding 1000 m^2) as compensation for significant setbacks (economic factor) - Space between the buildings shall be used to provide detention and retention services for stormwater by implementing vegetated water bodies, urban gardens, and tree-lined avenues.	- Support vertical gardens, external green facades, plants on balconies, and vegetated roofs in new and existing buildings. - Design new buildings with roofs able to support loads. - Support urban agriculture at the building scale for flood mitigation, city health, and productivity.
			
Obstacles	- A district with high urban density may necessitate a large amount of money for impacted asset compensation. - Steep roads and a linear urban form parallel to the sea are required (Tutorials et al., 2009). - Because of the high densities of buildings, implementing the NBS involves many stakeholders.	- The presence of a small land area not exceeding 100 m^2 reduces the size of setbacks. - Conflict of interest between the population and decision-makers and attempt to impede the proposed city scheme's policies.	- Weight overloading is a problem for green roof construction, especially in buildings that weren't designed to carry the weight of a saturated green roof in the first place.
Other Recommendations	- Locating green-blue infrastructure in key gateway areas to the city and core business areas, and pedestrian routes - Enhance waterway corridors and riparian planting. - Re-connect floodplains to the waterway and lakes - Enhance anticipatory water management by using the water bodies at the city's border (i.e., Lake Maryot and Airport Lak) to store flood water. - Integrate green-blue infrastructure with crucial walking and cycling routes to provide shaded connections. - Deal with water appropriately and synergistically within urban environments, including ecosystems, and across urban services, design, and planning processes. - Putting in place a flexible strategy (3 PP P) (Flood Preparedness, Flood Protection, and Flood Prevention)	- Provide a variety of natural systems, such as gardens, trees, and building-integrated vegetation within all residential areas. - Using permeable pavement in parking lots, low-traffic roads, sidewalks, and driveways during landscape construction using materials such as open-joint bricks, grass-concrete pavers, open-cell concrete blocks, wood chips, and gravel - Enhance the performance of the urban infrastructure, such as pedestrian pathways, roads, parking areas, buildings, and drainage systems. - Diversion or dualling of flood flows away from affected areas.	- Speeding up recovery to increase resilience by improving building design and construction – so-called "building back better (Ferreira et al., 2022). - Use alternative water from buildings to support green walls and green roofs. - Make the walls of the building and the opening resistant to water. - Housing Codes, like building codes, set minimum standards for construction, but they also set minimum standards for the maintenance of structures.
Potential stakeholder engagement	- Academia and research institutions, local and regional administrations - Financial suppliers/investors, energy suppliers, citizens, government, property developers, non-profit organizations, planners, policymakers, experts and scientists, political institutions, and media - ICT sector representatives - Ministry of Irrigation and the Company for Water and Wastewater	- Landscape consultants and urban planners - Governmental organizations (GOs) - Administrative departments, utilities - Agriculture specialists - enterprises, and civil society representatives - Ministry of Irrigation and the Company for Water and Wastewater - Financial suppliers/investors	- Urban designer (architecture and civil engineers) - Urban landscape engineers - Agriculture specialists - Real estate owners and insurance companies - Non-governmental organizations (NGOs) - Financial suppliers/investors

Data availability

Data will be made available on request.

References

Abdo, M., Ayad, H., Taha, D., 2012. The "open cities" approach: a prospect for improving the quality of life in Alexandria city, Egypt. Proceedings REAL CORP Conference (May), 899–909, 0. http://corp.at/archive/CORP2012_108.pdf.

Abdrabo, K.I., Kantosh, S.A., Saber, M., Sumi, T., Elleithy, D., Habiba, O.M., Alboshy, B., 2022. The role of urban planning and landscape tools concerning flash flood risk reduction within arid and semiarid regions. September 283–316. https://doi.org/10.1007/978-981-16-2904-4_11.

Afata, T.N., Derib, S., Nemo, R., 2022. Review of blue-green infrastructure in some selected countries. Am. J. Environ. Sci. 18 (4), 81–88. https://doi.org/10.3844/ajessp.2022.81.88.

Ahmed, S., Meenar, M., Alam, A., 2019. Planning in dhaka , Bangladesh. Land 8 (138).

Alves, A., Vojinovic, Z., Kapelan, Z., Sanchez, A., Gersonius, B., 2020. Exploring trade-offs among the multiple benefits of green-blue-grey infrastructure for urban flood mitigation. Sci. Total Environ. 703, 134980 https://doi.org/10.1016/j.scitotenv.2019.134980.

Arellano Jaimerena, Begoña, Bergstra, Esther, Pearson, Rene, Wielenga, Rutger, Ranaivoson, Socrate, Ravolatsara, Arlette, Brolsma, Reinder, Driessen, Tjeerd, Rakotondramboa, Mialy, Rakotoarindriana, Tahirintsoa, Nathalie Asselman, S.V., 2021. Antananarivo: strengthening resilience through nature-based solutions and disaster-informed urban planning ACP-EU natural disaster risk reduction program. Mar 1–166.

Arias-Gonzales, J., 2022. The Role of Entrepreneurship and Green Innovation Intention on Sustainable Development: Moderating Impact of Inclusive Leadership 24, 134–143.

Asian Development Bank, 2016a. Nature-based Solutions for Building Resilience in Towns and Cities : Case Studies from the Greater Mekong Region.

Asian Development Bank, 2016b. Reducing Disaster Risk by Managing Urban Land Use : Guidance Notes for Planners.

Auger, S., David, Y., Ho, W., Sani, S., Singh, A., Van Seters, T., Davidson, C., Kennedy, M., MacKenzie, K., 2017. Development of a Low Impact Development and Urban Water Balance Modeling Tool. https://doi.org/10.1061/9780784480540.005.

Babí Almenar, J., Elliot, T., Rugani, B., Philippe, B., Navarrete Gutierrez, T., Sonnemann, G., Geneletti, D., 2021. Nexus between nature-based solutions, ecosystem services and urban challenges. Land Use Pol. 100, 104898 https://doi.org/10.1016/j.landusepol.2020.104898.

Bartesaghi Koc, C., Osmond, P., Peters, A., 2017. Towards a comprehensive green infrastructure typology: a systematic review of approaches, methods and typologies. Urban Ecosyst. 20 (1), 15–35. https://doi.org/10.1007/s11252-016-0578-5.

Barthel, P.-A., Davidson, L., Sudarskis, M., 2013. Alexandria : Regenerating the City, vols. 1–42. https://inta-aivn.org/images/cc/Transmed/AlexandriaContribution.pdf.

Bazilevs, Y., Hsu, M., Kiendl, J., Wüchner, R., Bletzinger, K., 2011. 3D simulation of wind turbine rotors at full scale. Part II: fluid – structure interaction modeling with composite blades. Int. J. Numer. Methods Fluid. 65 (October 2010), 236–253. https://doi.org/10.1002/fld.

Beier, M., Gerstendörfer, J., Mendzigall, K., Pavlik, D., Trute, P., von Tils, R., 2022. Climate impact and model approaches of blue-green infrastructure measures for neighborhood planning. Sustainability 14 (11). https://doi.org/10.3390/su14116861.

Bernello, G., Mondino, E., Bortolini, L., 2022. People's perception of nature-based solutions for flood mitigation: the case of veneto region (Italy). Sustainability 14 (8), 1–13. https://doi.org/10.3390/su14084621.

Bölen, F., Kaya, H.S., 2017. Urban DNA: morphogenetic analysis of urban pattern. Iconarp International J. of Architecture and Planning 5 (1), 10–41. https://doi.org/10.15320/iconarp.2017.15.

Boutaghane, H., Boulmaiz, T., Lameche, E.K., Lefkir, A., Hasbaia, M., Abdelbaki, C., Moulahoum, A.W., Keblouti, M., Bermad, A., 2022. Flood Analysis and Mitigation Strategies in Algeria. https://doi.org/10.1007/978-981-16-2904-4_3.

Bozovic, R., Maksimovic, C., Mijic, A., Suter, I., Reeuwijk, M. Van, 2017. Blue Green Solutions. *A Systems Approach To Sustainable, Resilient And Cost-Efficient Urban Development*. Imperial College London. https://www.climate-kic.org/success-stories/blue-green-solutions-bgs/.

Bruwier, M., Maravat, C., Mustafa, A., Teller, J., Pirotton, M., Erpicum, S., Archambeau, P., Dewals, B., 2020. Influence of urban forms on surface flow in urban pluvial flooding. J. Hydrol. 582 (December 2019) https://doi.org/10.1016/j.jhydrol.2019.124493.

Burrichter, K., Chen, B., Marco, G., 2022. Evaluation of modern technology on human resources management and sustainable development in Pharma industries. J. Commerc. Biotechnol. 27 (2), 119–130. https://doi.org/10.5912/jcb1296.

Cea, L., Garrido, M., Puertas, J., 2010. Experimental validation of two-dimensional depth-averaged models for forecasting rainfall-runoff from precipitation data in urban areas. J. Hydrol. 382 (1–4), 88–102. https://doi.org/10.1016/j.jhydrol.2009.12.020.

Chen, M., Ye, C., 2014. Differences in pattern and driving forces between urban and rural settlements in the coastal region of Ningbo, China. Sustainability 6 (4), 1848–1867. https://doi.org/10.3390/su6041848.

Chen, Y., Zhou, H., Zhang, H., Du, G., Zhou, J., 2015. Urban flood risk warning under rapid urbanization. Environ. Res. 139, 3–10. https://doi.org/10.1016/j.envres.2015.02.028.

Dazzi, S., Vacondio, R., Mignosa, P., Aureli, F., 2022. Assessment of pre-simulated scenarios as a non-structural measure for flood management in case of levee-breach inundations. Int. J. Disaster Risk Reduc. 74, 102926 https://doi.org/10.1016/j.ijdrr.2022.102926.

Devore, E., Millar, S., 2021. Green Building Incentive Programs : Progress in Selected Cities.

Dong, G., Weng, B., Qin, T., Yan, D., Wang, H., Gong, B., Bi, W., Xing, Z., 2018. The impact of the construction of sponge cities on the surface runoff in watersheds, China. Adv. Meteorol. 2018, 1–9. https://doi.org/10.1155/2018/6241892.

Dong, B., Xia, J., Zhou, M., Deng, S., Ahmadian, R., Falconer, R.A., 2021. Experimental and numerical model studies on flash flood inundation processes over a typical urban street. Adv. Water Resour. 147 (August 2020), 103824 https://doi.org/10.1016/j.advwatres.2020.103824.

Dottori, F., Figueiredo, R., Martina, M.L.V., Molinari, D., Scorzini, A.R., 2016. INSYDE: a synthetic, probabilistic flood damage model based on explicit cost analysis. Nat. Hazards Earth Syst. Sci. 16 (12), 2577–2591. https://doi.org/10.5194/nhess-16-2577-2016.

Dreiseitl, H., Wanschura, B., 2016. Strengthening Blue-Green Infrastructure in Our Cities, vol. 174. Livable City Lab. www.ramboll.com/LCL.

D'Ascanio, F., Di Ludovico, D., Di Lodovico, L., 2016. Design and urban shape for a resilient city. Procedia - Social and Behavioral Sciences 223, 764–769. https://doi.org/10.1016/j.sbspro.2016.05.265.

Fan, C., Jiang, X., Mostafavi, A., 2020. A network percolation-based contagion model of flood propagation and recession in urban road networks. Sci. Rep. 10 (1), 1–12. https://doi.org/10.1038/s41598-020-70524-x.

Ferrari, A., Viero, D.P., 2020. Floodwater pathways in urban areas: a method to compute porosity fields for anisotropic subgrid models in differential form. J. Hydrol. 589 (June), 125193 https://doi.org/10.1016/j.jhydrol.2020.125193.

Ferreira, C.S.S., Potočki, K., Kapović-Solomun, M., Kalantari, Z., 2022. Nature-based solutions for flood mitigation and resilience in urban areas. Handb. Environ. Chem. 107 (May), 59–78. https://doi.org/10.1007/698_2021_758.

Fletcher, T.D., Shuster, W., Hunt, W.F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.L., Mikkelsen, P.S., Rivard, G., Uhl, M., Dagenais, D., Viklander, M., 2015. SUDS, LID, BMPs, WSUD and more – the evolution and application of terminology surrounding urban drainage. Urban Water J. 12 (7), 525–542. https://doi.org/10.1080/1573062X.2014.916314.

Ghofrani, Z., Sposito, V., Faggian, R., 2017. A Comprehensive Review of Blue-Green Infrastructure Concepts A Comprehensive Review of Blue-Green Infrastructure Concepts. https://doi.org/10.24102/ijes.v6i1.728. May.

Golz, S., Schinke, R., Naumann, T., Garvin, S., White, I., 2013. Assessing the effects of flood resilient technologies. In: Proceedings of the International Conference on Flood Resilience: Experiences in Asia and Europe. University of Exeter, United Kingdom, September, 5–7.

Guillén, N.F., Patalano, A., García, C.M., Bertoni, J.C., 2017. Use of LSPIV in assessing urban flash flood vulnerability. Nat. Hazards 87 (1), 383–394. https://doi.org/10.1007/s11069-017-2768-8.

Hafez, M.E., 2018. Assessment of Climate Change Impact on Urban Heavy Rainfall Extremes Alexandria , Egypt Case Study, vols. 1–33.

Han, Y., Huang, Q., He, C., Fang, Y., Wen, J., Gao, J., Du, S., 2020. The growth mode of built-up land in floodplains and its impacts on flood vulnerability. Sci. Total Environ. 700, 134462 https://doi.org/10.1016/j.scitotenv.2019.134462.

Hemeda, S., 2021. Geotechnical modelling of the climate change impact on world heritage properties in Alexandria, Egypt. Heritage Science 9 (1), 1–32. https://doi.org/10.1186/s40494-021-00547-8.

Hemmati, M., Ellingwood, B.R., Mahmoud, H.N., 2020. The role of urban growth in resilience of communities under flood risk. Earth's Future 8 (3), 1–14. https://doi.org/10.1029/2019EF001382.

Huang, C.J., Hsu, M.H., Teng, W.H., Wang, Y.H., 2014. The impact of building coverage in the metropolitan area on the flow calculation. Water (Switzerland) 6 (8), 2449–2466. https://doi.org/10.3390/w6082449.

Huang, H., Chen, X., Zhu, Z., Xie, Y., Liu, L., Wang, X., Wang, X., Liu, K., 2018. The changing pattern of urban flooding in Guangzhou, China. Sci. Total Environ. 622–623, 394–401. https://doi.org/10.1016/j.scitotenv.2017.11.358.

Huang, Y., Tian, Z., Ke, Q., Liu, J., Irannezhad, M., Fan, D., Hou, M., Sun, L., 2020. Nature-based solutions for urban pluvial flood risk management. Wiley Interdisciplinary Reviews: Water 7 (3). https://doi.org/10.1002/WAT2.1421.

Hunt, W., Traver, R., Davis, A., Emerson, C., Collins, K., Stagge, J., 2010. Low impact development practices: designing to infiltrate in urban environments. Effects of Urbanization on Groundwater 308–343. https://doi.org/10.1061/9780784410783.ch12.

Ibrahim, M.R., Masoumi, H.E., 2018. The nuances of the supplied urban fabric in the MENA Region: evidence from Alexandria, Egypt. Land Use Pol. 73, 385–399. https://doi.org/10.1016/j.landusepol.2018.01.044.

Ignatieva, M., Stewart, G.H., 2008. Low Impact Urban Design and Development (LIUDD): matching urban design and urban ecology. Landsc. Rev. 12 (2), 61–73.

Kimic, K., Ostrysz, K., 2021. Assessment of blue and green infrastructure solutions in shaping urban public spaces—spatial and functional, environmental, and social aspects. Sustainability 13 (19). https://doi.org/10.3390/su131911041.

Kumar, N., Liu, X., Narayanasamydamodaran, S., Pandey, K.K., 2021. A systematic review comparing urban flood management practices in India to China's sponge city program. Sustainability 13 (11). https://doi.org/10.3390/su13116346.

Lafortezza, R., Sanesi, G., 2019. Nature-based solutions: settling the issue of sustainable urbanization. Environ. Res. 172, 394–398. https://doi.org/10.1016/j.envres.2018.12.063.

Leimgruber, J., Krebs, G., Camhy, D., Muschalla, D., 2019. Model-based selection of cost-effective low impact development strategies to control water balance. Sustainability 11 (8). https://doi.org/10.3390/su11082440.

Li, F., Chen, J., Engel, B.A., Liu, Y., Wang, S., Sun, H., 2021. Assessing the effectiveness and cost efficiency of green infrastructure practices on surface runoff reduction at an urban watershed in China. Water (Switzerland) 13 (1). https://doi.org/10.3390/w13010024.

Li, X., Erpicum, S., Mignot, E., Archambeau, P., Pirotton, M., Dewals, B., 2021. Influence of urban forms on long-duration urban flooding: laboratory experiments and computational analysis. J. Hydrol. 603 (June) https://doi.org/10.1016/j.jhydrol.2021.127034.

Liao, K.H., Le, T.A., Nguyen, K. Van, 2016. Urban design principles for flood resilience: learning from the ecological wisdom of living with floods in the Vietnamese Mekong Delta. Landsc. Urban Plann. 155 (December 2017), 69–78. https://doi.org/10.1016/j.landurbplan.2016.01.014.

Lin, J., He, X., Lu, S., Liu, D., He, P., 2021. Investigating the influence of three-dimensional building configuration on urban pluvial flooding using random forest algorithm. Environ. Res. 196 (October 2020), 110438 https://doi.org/10.1016/j.envres.2020.110438.

Luo, K., Wang, Z., Sha, W., Wu, J., Wang, H., Zhu, Q., 2021. Integrating sponge city concept and neural network into land suitability assessment: evidence from a satellite town of shenzhen metropolitan area. Land 10 (8). https://doi.org/10.3390/land10080872.

Mabrouk, M., Haoying, H., 2023. International Journal of Disaster Risk Reduction Urban resilience assessment : A m ulticriteria approach for identifying urban flood-exposed risky districts using 91 (February).

Mamani, W.C., Manrique, G.M.L., Madrid, S., del, P.C., Herrera, E.E., Acosta, D.B., Rivas-Diaz, R.R., Arias-Gonzáles, J.L., Maquera, Y.M., Ramos, F.S.S., 2022. The role of entrepreneurship and green innovation intention on sustainable development: moderating impact of inclusive leadership. AgBioforum 24 (1), 134–143.

Mei, C., Liu, J., Wang, H., Yang, Z., Ding, X., Shao, W., 2018. Integrated assessments of green infrastructure for flood mitigation to support robust decision-making for sponge city construction in an urbanized watershed. Sci. Total Environ. 639, 1394–1407. https://doi.org/10.1016/j.scitotenv.2018.05.199.

Mignot, E., Zeng, C., Dominguez, G., Li, C.W., Rivière, N., Bazin, P.H., 2013. Impact of topographic obstacles on the discharge distribution in open-channel bifurcations. J. Hydrol. 494, 10–19. https://doi.org/10.1016/j.jhydrol.2013.04.023.

Mohammed, G.A., Mabrouk, M., He, G., 2023. Towards Sustainable Cities : A Review of Zero Energy Buildings Techniques and Global Activities in Residential Buildings, vols. 1–26.

Mohuuc, Center, A.R.P., 2020. General Strategic Plan for Alexandria Governorate 2032, p. 80.

Monteiro, R., Ferreira, J.C., Antunes, P., 2020. Green infrastructure planning principles: an integrated literature review. Land 9 (12), 1–19. https://doi.org/10.3390/land9120525.

Mustafa, A., Wei Zhang, X., Aliaga, D.G., Bruwier, M., Nishida, G., Dewals, B., Erpicum, S., Archambeau, P., Pirotton, M., Teller, J., 2020. Procedural generation of flood-sensitive urban layouts. Environ. Plan. B Urban Anal. City Sci. 47 (5), 889–911. https://doi.org/10.1177/2399808318812458.

Nie, Linmei, Jia, H., 2018. China's sponge city construction: ambition and challenges – vannforeningen. Vann 2, 159–167.

Norris, F.H., 2002. Disasters in urban context. [Review] [19 refs]. J. Urban Health 79 (3), 308–314. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3456788/pdf/11524_2006_Article_129.pdf.

OECD, 2020. Nature-based solutions for adapting to water-related climate risks, 21, 32. https://www.oecd-ilibrary.org/environment/nature-based-solutions-for-adapting-to-water-related-climate-risks_2257873d-en.

O'Donnell, E., Thorne, C., Ahilan, S., Arthur, S., Birkinshaw, S., Butler, D., Dawson, D., Everett, G., Fenner, R., Glenis, V., Kapetas, L., Kilsby, C., Krivtsov, V., Lamond, J., Maskrey, S., O'Donnell, G., Potter, K., Vercruysse, K., Vilcan, T., Wright, N., 2020. The blue-green path to urban flood resilience. Blue-Green Systems, 2(1) 28–45. https://doi.org/10.2166/bgs.2019.199.

Panno, A., Carrus, G., Lafortezza, R., Mariani, L., Sanesi, G., 2017. Nature-based solutions to promote human resilience and wellbeing in cities during increasingly hot summers. Environ. Res. 159, 249–256. https://doi.org/10.1016/j.envres.2017.08.016.

Pansare, S.S., 2022. URBAN RESILIENCE AND INVOLVEMENT OF NATURE BASED SOLUTIONS. May.

Peng, Y., Reily, K., 2021. Using nature to reshape cities and live with water: an overview of the Chinese sponge city Programme and its implementation in wuhan. January 1–43.

Puppim de Oliveira, J.A., Bellezoni, R.A., Shih, W., Bayulken, B., 2022. Innovations in urban green and blue infrastructure: tackling local and global challenges in cities. J. Clean. Prod. 362, 132355 https://doi.org/10.1016/j.jclepro.2022.132355.

Qin, Y., 2020. Urban flooding mitigation techniques: a systematic review and future studies. Water (Switzerland) 12 (12). https://doi.org/10.3390/w12123579.

Qiu, S., Yin, H., Deng, J., Li, M., 2020. Cost-effectiveness analysis of green–gray stormwater control measures for non-point source pollution. Int. J. Environ. Res. Publ. Health 17 (3). https://doi.org/10.3390/ijerph17030998.

Raymond, C.M., Frantzeskaki, N., Kabisch, N., Berry, P., Breil, M., Nita, M.R., Geneletti, D., Calfapietra, C., 2017. A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. Environ. Sci. Pol. 77, 15–24. https://doi.org/10.1016/j.envsci.2017.07.008.

Rosenberger, L., Leandro, J., Pauleit, S., Erlwein, S., 2021. Sustainable stormwater management under the impact of climate change and urban densification. J. Hydrol. 596 (March), 126137 https://doi.org/10.1016/j.jhydrol.2021.126137.

Rubinato, M., Lee, S., Martins, R., Shucksmith, J.D., 2018. Surface to sewer flow exchange through circular inlets during urban flood conditions. J. Hydroinf. 20 (3), 564–576. https://doi.org/10.2166/hydro.2018.127.

Saber, M., Boulmaiz, T., Guermoui, M., Abdrabo, K.I., Kantoush, S.A., Sumi, T., Boutaghane, H., Hori, T., Binh, D. Van, Nguyen, B.Q., Bui, T.T.P., Vo, N.D., Mabrouk, E., 2023. Enhancing flood risk assessment through integration of ensemble learning approaches and physical-based hydrological modeling. Geomatics, Nat. Hazards Risk 14 (1). https://doi.org/10.1080/19475705.2023.2203798.

Silva, M.M., Costa, J.P., 2018. Urban floods and climate change adaptation: the potential of public space design when accommodating natural processes. Water (Switzerland) 10 (2). https://doi.org/10.3390/w10020180.

Sirry, A., 2018. Alexandria : development challenges of a coastal second city. Colección Monografías CIDOB 145–158.

Soliman, A.M., Soliman, Y.A., 2022. Exposing urban sustainability transitions: urban expansion in Alexandria, Egypt. Int. J. Urban Sustain. Dev. 14 (1), 33–55. https://doi.org/10.1080/19463138.2022.2056894.

Song, X., Cao, M., Zhai, K., Gao, X., Wu, M., Yang, T., 2021. The effects of spatial planning, well-being, and behavioural changes during and after the COVID-19 pandemic. Frontiers in Sustainable Cities 3 (June), 1–15. https://doi.org/10.3389/frsc.2021.686706.

Sörensen, J., Emilsson, T., 2019. Evaluating flood risk reduction by urban blue-green infrastructure using insurance data. J. Water Resour. Plann. Manag. 145 (2) https://doi.org/10.1061/(asce)wr.1943-5452.0001037.

Sörensen, J., Persson, A., Sternudd, C., Aspegren, H., Nilsson, J., Nordström, J., Jönsson, K., Mottaghi, M., Becker, P., Pilesjö, P., Larsson, R., Berndtsson, R., Mobini, S., 2016. Re-thinking urban flood management-time for a regime shift. Water (Switzerland) 8 (8). https://doi.org/10.3390/w8080332.

Spyrou, C., Loupis, M., Charizopoulos, N., Apostolidou, I., Mentzafou, A., Varlas, G., Papadopoulos, A., Dimitriou, E., Panga, D., Gkeka, L., Bowyer, P., Pfeifer, S., Debele, S.E., Kumar, P., 2021. Evaluating nature-based solution for flood reduction in spercheios river basin under current and future climate conditions. Sustainability 13 (7), 1–20. https://doi.org/10.3390/su13073885.

Stagakis, S., 2020. NATURE-BASED SOLUTIONS, 730338.

Steve, A., Yuestas, D., Wilfred, H., Sakshi, S., Amanjot, S., Tim, V.S., Chris, D., Melanie, K., Kevin, M., 2023. Development of a low impact development and urban water balance modeling tool. In: International Low Impact Development Conference 2016, pp. 29–42. https://doi.org/10.1061/9780784480540.005.

Su, W., Ye, G., Yao, S., Yang, G., 2014. Urban land pattern impacts on floods in a new district of China. Sustainability 6 (10), 6488–6508. https://doi.org/10.3390/su6106488.

Sumi, T., Saber, M., Kantoush, S.A., 2013. Japan-Egypt hydro network: science and technology collaborative research for flash flood management. J. Disaster Res. 8 (1), 28–36. https://doi.org/10.20965/jdr.2013.p0028.

Suteerasan, S., 2020. Blue-Green Infrastructure on the Move: How Resilience Concepts Travel between Cities Blå-Grön Infrastruktur I Farten: Hur Motståndskraftskonceptet Färdas Mellan Städer ENVIRONMENTAL ENGINEERING and SUSTAINABLE INFRASTRUCTURE.

Tingsanchali, T., 2012. Urban flood disaster management. Procedia Eng. 32, 25–37. https://doi.org/10.1016/j.proeng.2012.01.1233.

Tomiczek, T., Prasetyo, A., Mori, N., Yasuda, T., Kennedy, A., 2016. Physical modelling of tsunami onshore propagation, peak pressures, and shielding effects in an urban building array. Coast Eng. 117, 97–112. https://doi.org/10.1016/j.coastaleng.2016.07.003.

Tutorials, D., Valley, S., Box, S., Green, U.S., Council, B., Design, E., States, U., Building, U.K., Method, E.A., Araby, E., 2009. Urban Form , Patterns , and Impacts (the Role of Urban Land in Climate Change).

Van Long, N., Cheng, Y., Le, T.D.N., 2020. Flood-resilient urban design based on the indigenous landscape in the city of Can Tho, Vietnam. Urban Ecosyst. 23 (3), 675–687. https://doi.org/10.1007/s11252-020-00941-3.

Wang, H., Zhou, J., Tang, Y., Liu, Z., Kang, A., Chen, B., 2021. Flood economic assessment of structural measure based on integrated flood risk management: a case study in Beijing. J. Environ. Manag. 280 (November 2020), 111701 https://doi.org/10.1016/j.jenvman.2020.111701.

Wang, F., Yuan, X., Zhou, L., Zhang, M., 2022. Integrating ecosystem services and landscape connectivity to construct and optimize ecological security patterns: a case study in the central urban area Chongqing municipality, China. Environ. Sci. Pollut. Control Ser. 29 (28), 43138–43154. https://doi.org/10.1007/s11356-021-16281-4.

White House Council on Environmental Quality, et al., 2022. Opportunities to Accelerate Nature-Based Solutions. White House Council on Environmental Quality, United States of America. https://www.whitehouse.gov/wp-content/uploads/2022/11/Nature-Based-Solutions-Roadmap.pdf.

Wild, T.C., Henneberry, J., Gill, L., 2017. Comprehending the multiple 'values' of green infrastructure – valuing nature-based solutions for urban water management from multiple perspectives. Environ. Res. 158, 179–187. https://doi.org/10.1016/j.envres.2017.05.043.

Wing, O.E.J., Pinter, N., Bates, P.D., Kousky, C., 2020. New insights into US flood vulnerability revealed from flood insurance big data. Nat. Commun. 11 (1), 1–10. https://doi.org/10.1038/s41467-020-15264-2.

WMO/GWP Associated Programme on Flood Management, 2008. A Tool for Integrated Flood Management. Risk Management, March 2008.

Yin, D., Chen, Y., Jia, H., Wang, Q., Chen, Z., Xu, C., Li, Q., Wang, W., Yang, Y., Fu, G., Chen, A.S., 2021. Sponge city practice in China: a review of construction, assessment, operational and maintenance. J. Clean. Prod. 280, 124963 https://doi.org/10.1016/j.jclepro.2020.124963.

Young, A., 2018. Hydro-meteorological Data Analysis for the Characterisation of Urban Floods in Alexandria , Egypt. April.

Young, A., Bhattacharya, B., Zevenbergen, C., 2021. A rainfall threshold-based approach to early warnings in urban data-scarce regions: a case study of pluvial flooding in Alexandria, Egypt. Journal of Flood Risk Management 14 (2). https://doi.org/10.1111/jfr3.12702.

Zahedi, R., Golivari, S., 2022. Investigating threats to power plants using a carver matrix and providing solutions: a case study of Iran. Int. J. Sustain. Energy Environ. Res. 11 (1), 23–36. https://doi.org/10.18488/13.v11i1.2965.

Zevenbergen, C., Bhattacharya, B., Wahaab, R.A., Elbarki, W.A.I., Busker, T., Salinas Rodriguez, C.N.A., 2017. In the aftermath of the October 2015 Alexandria Flood Challenges of an Arab city to deal with extreme rainfall storms. Nat. Hazards 86 (2), 901–917. https://doi.org/10.1007/s11069-016-2724-z.

Zhou, Q., Leng, G., Su, J., Ren, Y., 2019. Comparison of urbanization and climate change impacts on urban flood volumes: importance of urban planning and drainage adaptation. Sci. Total Environ. 658, 24–33. https://doi.org/10.1016/j.scitotenv.2018.12.184.