



# Blue-Green Infrastructure for Sustainable Resilience: A Systematic Review of Global Practices and Its Recommendations for Urban Flooding and Land Subsidence in Greater Bandung

Saut Sagala<sup>1,2</sup>, Cecilia Nonifili Yuanita<sup>2,3\*</sup>, Dekka Dhiringantara Putra<sup>2,3</sup>, Niken Prilandita<sup>1</sup>, Aria Mariany<sup>2,4</sup>, Naufal Hilmy Pratama<sup>2,3</sup> and Faldi Fakhri<sup>3</sup>

<sup>1</sup> School of Architecture, Planning and Policy Development (SAPPK), Bandung Institute of Technology (ITB), Bandung, Indonesia

<sup>2</sup> Research Center for Disaster Mitigation (PPMB), Bandung Institute of Technology (ITB), Bandung, Indonesia

<sup>3</sup> Resilience Development Initiative (RDI), Bandung, Indonesia

<sup>4</sup>Swadaya Gunung Jati University, Cirebon, Indonesia

cecilianonifily@gmail.com

**Abstract.** Many metropolitan areas face serious challenges from recurring urban flooding, exacerbated by land subsidence, urbanization, high land conversion, and environmental degradation, as seen in Greater Bandung, Indonesia. Conventional flood control infrastructure is inadequate, underscoring the need for sustainable solutions to reduce risk. This study aims to identify the potential for Blue-Green Infrastructure (BGI) interventions in metropolitan areas by synthesizing evidence from global practices. The results provide recommendations for enhancing the resilience of Greater Bandung. A Systematic Literature Review (SLR) was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. After screening 1,574 articles from the Scopus database using predetermined inclusion and exclusion criteria, 192 relevant studies were analysed to identify the types of BGI, associated co-benefits, effectiveness in flood mitigation and land subsidence, suitability for various urban typologies, and implementation challenges. The comprehensive review identified 24 key BGI solutions, taking into account urban characteristics (dense urban centres, riparian, and mountainous areas), land use, slope, and specific hazards. BGI generates many co-benefits, particularly in biophysical aspects, such as water management, biodiversity, and temperature reduction. Socio-economic benefits are mentioned in some literature, although they remain under-explored. Combined BGI strategies are generally more effective than single interventions. The greatest challenges stem from the pressures of urbanisation, regulatory constraints, and difficulties in monetising long-term benefits. A gap that has been identified is the limited studies on BGI solutions addressing land subsidence. Based on these findings, BGI offers a transformative approach to improving urban resilience in Greater Bandung. Recommendations include prioritising hybrid (blue-green-grey) infrastructure systems that provide dual benefits, integrating BGI into cross-border spatial planning, and encouraging community participation to ensure long-term maintenance.

**Keywords:** Blue-Green Infrastructure, Metropolitan Area, Systematic Literature Review, Urban Flooding, Urban Resilience

# 1 Introduction

## 1.1 Background

Increasing risks in urban areas are becoming increasingly inevitable, especially with the tangible impacts of climate change. Current mitigation and adaptation policies are not keeping pace with these increasing risks. Even if current pledges are fulfilled and the national adaptation plans of 195 countries are implemented, temperatures will still rise by 2.4-2.6 degrees Celsius and emissions will still increase by 8.8% by 2030 [1]. Based on climate change projections through 2040, more than 2 billion people living in urban centers could be exposed to temperatures at least 0.5 degrees Celsius higher than today. By 2025, areas vulnerable to river flooding will be home to around 1 billion people, half of whom live in urban centers, 39% in suburban areas, and the remaining 11% in rural areas [1]. This is also in line with a study conducted by CDP, which found that in 2023, more than 83% of the 1,131 cities that reported their environmental data experienced significant climate hazards, an increase of 80% from 2022, and 56% of them experienced substantial impacts from these hazards [2].

The risks faced by these cities are exacerbated by the complexity of urban systems, which increase the frequency and intensity of various hazards, such as urban flooding and the threat of land subsidence. According to the World Cities Report 2024 [1], the report stated that the IPCC [111] noted with high confidence that cities with limited adaptive capacity, such as unplanned and informal settlements in low- and middle-income countries and in small and medium-sized urban centers, tend to have the fastest growing urban vulnerability and exposure. Based on a study conducted by Rentschler et al. [3] on urban growth between 1985 and 2015, settlement expansion in high flood risk zones exceeded growth in safe areas, with 20% of all settlement areas located in moderate or high flood risk zones in 2015 (17.9% in 1985). This may be influenced by greater economic opportunities in these areas and increasingly limited safe land due to urban expansion. A similar study was conducted by Andreadis et al. [4], who found that the highest rates of urbanization occurred in the most vulnerable areas of floodplains. These studies show that many cities were built without comprehensive planning and consideration of their environmental capacity, thereby increasing the risk [3], [5], [6]. On the other hand, land subsidence has emerged as a global environmental problem that has affected more than 150 cities since the 1990s, which is one of the key factors influencing flood risk dynamics [7], [8].

Flood risk reduction efforts in many developing cities are still largely conventional, unintegrated, and inadequate. As has been widely discussed in various studies [9], [10], [11], standard flood risk management, namely flood control measures through traditional approaches and hard infrastructure (levees, dams, etc.) that are useful for retaining water, are insufficient to minimize risk and are unsustainable, especially given the much higher construction and maintenance costs.

Nature-based solutions (NbS) through blue-green infrastructure (BGI) can be a solution to overcome these urban challenges. BGI is a network of natural elements (green spaces such as forests and wetlands) to semi-natural elements (“engineered” systems such as green roofs and bioretention systems) that are interconnected and capable of providing co-benefits and environmental services [12], [13]. However, most of the knowledge and empirical studies related to BGI for flood risk mitigation are still concentrated in the northern hemisphere, while among many cities in Southeast Asia with high flood risks exacerbated by socio-economic vulnerability, this knowledge and studies remain sparse and limited [12], [13], and how this solution can enhance urban resilience is still an ongoing process [14]. Within the various studies using systematic literature reviews (SLR) [15], [16], [17], none specifically identifies the type of BGI that is suitable for metropolitan areas with diverse typologies (urban centers, suburbs, riparian areas, and high lands) while also identifying its co-benefits and effectiveness in minimizing flood and land subsidence risks. A previous study by Yuanita & Sagala [18] conducted similar research in Bekasi City and linked the results to the urgency of cross-administrative collaboration in the Jakarta Metropolitan Area. However, a more comprehensive study with a broader case study coverage and application in other cities is still needed. Therefore, this related research can serve as an innovation and recommendation for developing cities with relevant local characteristics and facing these dual risks, as a basis for determining the appropriate type of BGI.

## 1.2 Research Aim and Objectives

Based on the background of the issues and gaps identified, this study aims to identify the appropriate types of BGI interventions according to the varying characteristics of metropolitan areas by synthesizing global evidence through SLR.

- To identify the distribution of BGI studies from global evidence through SLR on existing research.
- To synthesize BGI types classified by their suitability across metropolitan area typologies, effectiveness for flood and land subsidence mitigation, co-benefits, and their challenges and opportunities.
- To provide BGI implementation recommendations for the selected tailored-case metropolitan area (Greater Bandung, Indonesia).

## 2 Literature Review

### 2.1 Urban Flooding and Land Subsidence Risk in Metropolitan Areas: Global, Indonesia, and Greater Bandung Context

Increased carbon dioxide concentrations in the atmosphere, exacerbated by anthropogenic factors, have accelerated climate change, which is now evident in changing weather patterns and an increase in the frequency and intensity of natural hazards in various parts of the world [19]. In 2024, the Emergency Events Database (EM-DAT) recorded 393 disasters that caused 16,753 fatalities, affected 167.2 million people, and

resulted in economic losses of US\$241.95 billion [20]. In the same year, extreme temperatures in Asia killed thousands of people, severe drought in Africa affected more than 25 million people, and devastating tropical storms in the United States caused economic losses of more than US\$100 billion [20].

As the world's largest archipelago with diverse topography and climatic conditions, located in the Pacific Ring of Fire, Indonesia is highly vulnerable to various disasters. These risks are exacerbated by limited access to funding, lack of trust in the government, as well as uneven, unintegrated, and outdated access to technology and infrastructure, given that Indonesia is a developing country [18], [21], [22]. Consideration of local context and knowledge integrated with disaster risk reduction efforts is also often overlooked [23], [24]. Data from the National Disaster Management Agency (BNPB) show that floods are the most frequent disasters and cause significant economic losses due to damage to housing, infrastructure, and business interruption [25]. During the period 2010–2024, floods accounted for 34.46% of all disasters in Indonesia. This high frequency is accompanied by significant impacts, with floods causing 3,516 fatalities, affecting 44,269,188 people, and causing 33.23% damage to homes, 49.05% damage to infrastructure, and up to 63.30% damage to productive land [26].

The Greater Bandung area is a flood-prone region in Indonesia. As one of the third largest metropolitan areas in Indonesia and designated as a national strategic area with priority economic development [27], Greater Bandung has experienced high population growth, even exceeding the national average [28], [29]. This growth has driven rapid urbanization, which has triggered changes in land use, as seen in the period 1983–2015, where built-up land and mixed gardens continued to increase, while rice fields continued to decline [30], to the point where building density became higher than vegetation cover. This condition is exacerbated by low drainage capacity and sloping soil characteristics, which make water flow more easily concentrated in urban areas, especially in the cities of Bandung and Cimahi [27], [31], [32], [33].

The Greater Bandung area as a whole is traversed by a dense network of large rivers flowing southward [32], [34]. During the rainy season, this area often experiences flooding originating from 13 tributaries of the Upper Citarum River, including the Cikapundung River. Over the past two decades, this watershed has developed rapidly, increasing peak flows while reducing base flows, thereby increasing the region's vulnerability to flooding [35]. Research by Harto et al. [36] in the Cikapundung river basin also shows that from 1973 to 2023, there was a conversion of 14.32% to built-up land and 12.89% to agricultural land. Not only that, excessive groundwater extraction, especially in industrial areas, coupled with the natural consolidation effect of the aquifer layer, has caused land subsidence [36]. This phenomenon has expanded the flood-prone areas in the Greater Bandung region.

Research by Agustina et al. [32] showed that the flood risk level in Bandung Regency and West Bandung Regency was high, while Bandung City and Cimahi City were classified as moderate. BNPB data showed that during the 2021–2023 period, flooding in Greater Bandung resulted in 2 fatalities and 464,480 people affected. The physical damage was also significant, with 85 houses severely damaged, 57 moderately damaged, 119 slightly damaged, and 91,747 flooded [37]. Although there is a spatial

plan for the Bandung Basin and the Bandung City Spatial Plan (RTRW) has taken sustainable drainage into account in its policies, implementation in the field to reduce the risk is often still constrained and not integrated [31].

## 2.2 Blue-Green Infrastructure (BGI) as Mitigation Solution

BGI is a form of NbS rooted in physical infrastructure that integrates blue and green spaces within urban landscapes to deliver multiple functions, including environmentally friendly approaches for mitigating urban flood risks [38], [39], [40]. Over the past several years, BGI components have been classified into several key categories, namely by function, position, and scale.

By function, BGI consists of detention and retention interventions. Detention facilities temporarily store stormwater before gradually releasing it into the urban drainage system, whereas retention facilities store and infiltrate water slowly into the ground without direct connection to drainage infrastructure. A notable best practice illustrating detention performance is found in Newcastle, United Kingdom, where detention ponds in Newcastle Great Park effectively reduced peak discharge during major storm events. In contrast, the older residential area of Kingston Park, which lacks detention facilities, experienced a peak discharge of up to 65% [41].

By position, BGI can be located above ground (e.g., green roofs and green facades), on the ground surface (e.g., permeable pavements, parks, and urban forests), and below ground (e.g., subsurface water storage beneath public spaces). A well-documented above-ground best practice is the application of green roofs in Hong Kong, which retained 73–84% of stormwater during light rainfall, 36–47% during moderate rainfall, and 16–19% during heavy rainfall [42], [43].

By scale, BGI consists of micro, meso, and macro interventions. At the micro scale, BGI is implemented at the household or neighborhood level, such as through green roofs and permeable pavements. At the meso scale, interventions cover broader areas, for example, the green street project in Portland, featuring rain gardens and vegetated swales, successfully reduced peak discharge by up to 95% [44], [45]. At the macro scale, the implementation of the Sponge City concept in Wuhan, which involves rain gardens, vegetated swales, permeable pavements, and bioretention, proved effective in reducing flood-prone locations from 162 to 32 points within four years [46].

In this study, using a SLR approach, BGI classifications will be further examined in relation to variations in metropolitan area typologies, particularly concerning levels or urban flood hazards, proximity to blue spaces (water bodies), green spaces (vegetated areas), and the extent of built-up areas.

## 3 Methodology

### 3.1 Systematic Literature Review Design

The SLR in this study was used to identify types of BGI that can be implemented as solutions in the Greater Bandung Area. The literature review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) method [47],

[48], which provides a structured approach for systematically collecting and analyzing data to develop evidence-based recommendations for flood risk mitigation.

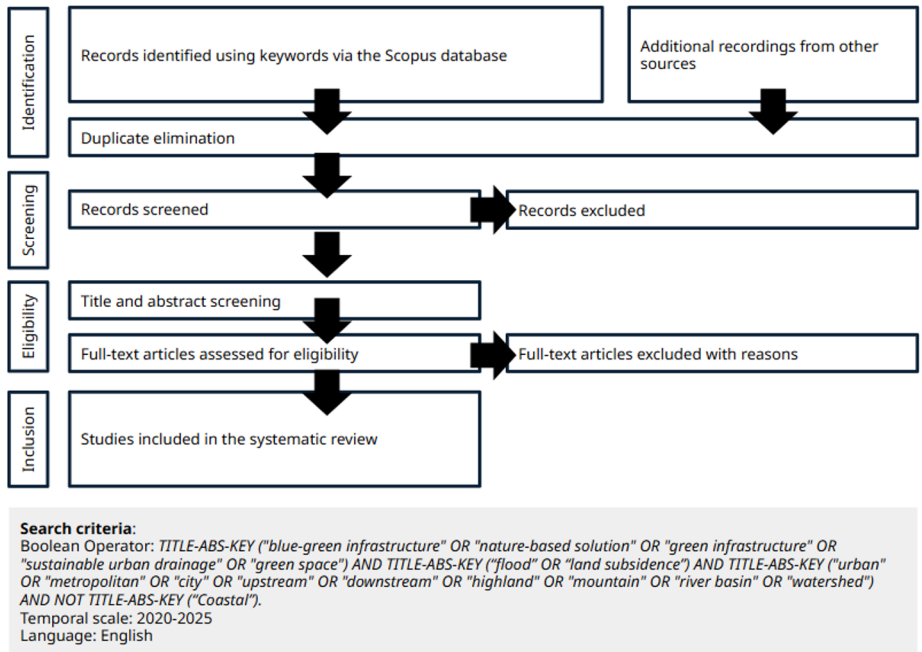


Fig. 1. PRISMA framework for this study

### 3.2 Data Search and Screening Process

A search for publications discussing NbS in urban contexts, from upstream to downstream areas, to address flooding and land subsidence in Greater Bandung was conducted using the Scopus search engine. The literature search also considered the typology of cities in Greater Bandung, which are predominantly located in highland areas. Scopus was selected due to its broader coverage compared to other academic search engines and its strong academic credibility.

A combination of keywords was used with Boolean operators as follows:

TITLE-ABS-KEY ("blue-green infrastructure" OR "nature-based solution" OR "green infrastructure" OR "sustainable urban drainage" OR "green space") AND TITLE-ABS-KEY ("flood" OR "land subsidence") AND TITLE-ABS-KEY ("urban" OR "metropolitan" OR "city" OR "upstream" OR "downstream" OR "highland" OR "mountain" OR "river basin" OR "watershed") AND NOT TITLE-ABS-KEY ("Coastal").

The initial search on Scopus resulted in 1,574 articles. A total of 1,101 articles were excluded based on publication year, access, language, and document type, leaving

473 articles for further screening. This study focused exclusively on journal articles to ensure the inclusion of high-quality empirical studies validated through academic peer review. The publication period was restricted to 2020–2025 to ensure the novelty of the selected BGI interventions. Only English-language and open-access articles were included to ensure full-text availability. The excluded publications were removed according to predefined exclusion criteria.

Explicit inclusion and exclusion were established prior to and during the abstract and full-text screening process. **Fig. 1.** presents the PRISMA flow diagram illustrating the selection process. From the initial screening, only 237 articles had accessible full texts. Subsequent exclusion steps were then conducted (as further described in Section 4 of this study). Initial exclusion criteria included BGI interventions that were not relevant to urban flood risk reduction and/or land subsidence mitigation, studies focusing on coastal BGI interventions, and studies conducted outside downstream areas and/or highland contexts.

### 3.3 Data Synthesis

The synthesis of SLR results for the analysis of the Greater Bandung area was carried out by considering the following components, including (1) title, (2) authors, (3) year, (4) location, (5) BGI types, (6) typology, (7) co-benefit, (8) effectiveness, and (9) challenges and opportunities.

## 4 Results and Discussion

To identify the appropriate type of BGI intervention in metropolitan areas with varying metropolitan typologies, an SLR was conducted on various BGI literature globally. Given that the pilot case would ultimately be in Greater Bandung, the SLR was adjusted based on the characteristics of the region. Of the 237 pieces of literature screened based on the initial exclusion criteria (in the Methodology section), the abstracts and substantial content will be reviewed further to exclude literature that is insufficient or irrelevant. Additional exclusions include:

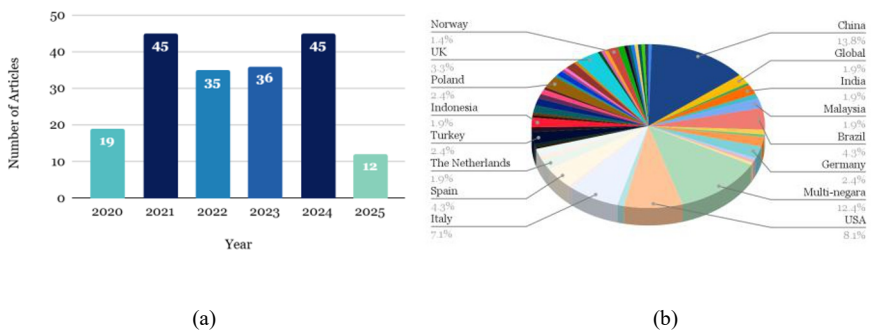
- (1) The literature is opinion-based or conceptual [49].
- (2) The literature does not discuss specific BGI solutions. For example, it only touches on general issues or concepts without any specific and technical evaluation, review, and/or implementation [50], research is only in the form of risk mapping [51], and is limited to a discussion of green space typology [52].
- (3) The literature does not focus on the issues of urban flooding and/or land subsidence. For example, there is still some literature that is limited in scope to coastal areas [53], rural areas [54], and literature that discusses other irrelevant hazards (such as extreme heat, mental and public health, and fires) [55], [56], [57], [58].
- (4) The literature only discusses social and/or economic impacts, such as examining eco-gentrification [59] and the settlement location preferences of flood-prone communities [60].

- (5) Limitations of the study due to language and access. There is literature with English titles but with study content in other languages, such as [61]. In addition, some literature is unavailable (not open access and/or the full text cannot be found).
- (6) Regional contexts that are less relevant to the Greater Bandung Area, such as Canberra (a planned city in the highlands with a dry climate and low rainfall), Serbia (a rural area), Puerto Rico (focusing on coastal tropical storm management), Galena Park (an industrial urban area in Texas), and Amazon (forest conservation with potential as carbon storage) [52], [54], [62], [63], [64].

Based on these considerations, 192 scientific papers were selected as the basis for determining appropriate BGI in metropolitan areas such as Greater Bandung. Several dimensions were analyzed, including (1) year, (2) study location, (3) types, (4) effectiveness, (5) co-benefits, and (6) implementation challenges and opportunities.

#### 4.1 Overview of Reviewed Literatures

This section provides an overview of the literature that has been successfully conducted and reviewed further. Based on the results of SLR over the past five years (**Fig. 2(a)**), interest in conducting BGI-related research shows a global upward trend. BGI research results in metropolitan areas for flood mitigation and land subsidence reduction were most dominant in 2021 and 2024.



**Fig. 2.** Year (a) and location (b) of BGI research studies resulting from SLR

The SLR results (**Fig. 2(b)**) show that most of the BGI research locations are in China (29 publications or 13.8%), followed by multinational case studies or those involving more than one country (26 publications or 12.4%), the United States (17 publications or 8.1%), Italy (15 publications or 7.1%), Spain (9 publications or 4.3%), and the United Kingdom (7 publications or 3.3%).

The Sponge City concept originated in China and has since become a model for other locations around the world. Sponge City is an infrastructure concept with a drainage system that functions like a sponge, absorbing as much water as possible when heavy

rains hit the city [65]. On the other hand, the United States is known for its Low Impact Development (LID) concept, which was first implemented in Maryland to address the negative impacts of urbanization and increased impervious surfaces that can cause water management problems, such as high water runoff and decreased water quality [66]. Several pieces of literature with research locations in Italy discuss green infrastructure, a concept that arose from the need to harmonize development and the environment [67]. Spain and the United Kingdom have discussed the Sustainable Urban Drainage System (SUDS) in depth, a concept that emerged in response to the need to shift from conventional drainage approaches to more sustainable approaches to stormwater management [68]. These concepts are interrelated and form part of NbS that can be used for urban flood mitigation.

### 4.2 Suitable BGI Types for Metropolitan Areas from Global Studies

From the results of the SLR conducted (Figure X), there were a total of 24 types of BGI identified, with most studies conducting research related to green roofs (80 literature or 41.67%), followed by rain gardens (65 literature or 33.85%), permeable pavement (63 literature or 32.81%), urban parks and other related green open spaces (59 publications or 30.73%), and bioretention basins (cells) (52 publications or 27.08%).

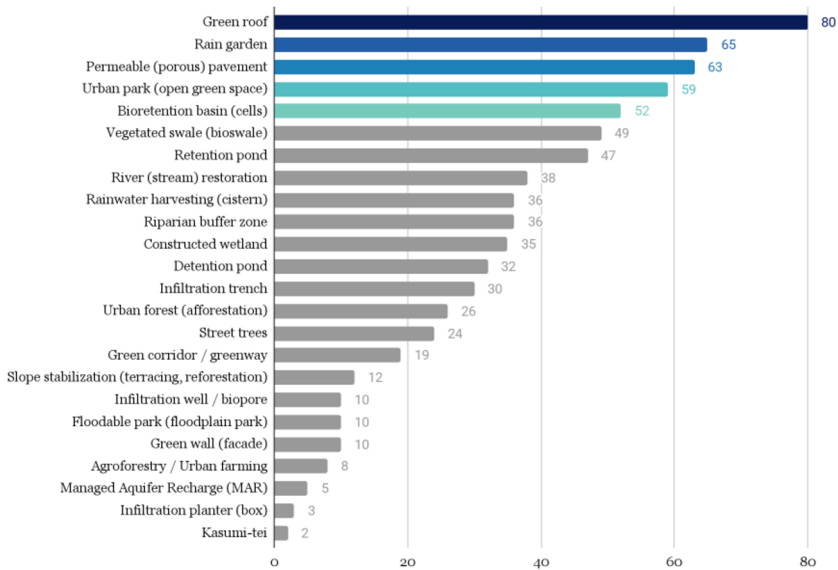


Fig. 3. BGI types resulting from SLR





The types of BGI that have been successfully identified are applied to areas with varying typologies, as summarized in **Table 1**. Based on the SLR results, there are several

things that need to be considered when applying BGI, including general regional characteristics, slope criteria, the need for proximity to water bodies, and land cover (vegetation or built-up land). An explanation of the colors used in this table can be found below **Table 1**.

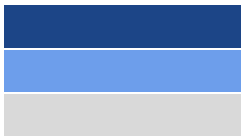
**Table 1.** Suitability of area typology for the implementation of each type of BGI identified from the SLR results

BGI Types	Area typology				Slope	Blue space	Green space
	Urban Centers	Sub-urbs	Riparian	Mountainous			
Green roof	✓				Tidak berlaku		
Rain garden	✓	✓			1-12%		
Permeable (porous) pavement	✓	✓			0-2%		
Urban park (open green space)	✓	✓	✓		Tidak berlaku		
Bioretention basin (cells)	✓	✓			1-5%		
Vegetated swale (bioswale)		✓	✓	✓	1-5%		
Retention pond	✓	✓	✓	✓	2-20%		
River (stream) restoration	✓	✓	✓	✓	Tidak berlaku		
Rainwater harvesting (cistern)	✓	✓			Tidak berlaku		
Riparian buffer zone	✓	✓	✓	✓	<5%		

BGI Types	Area typology				Slope	Blue space	Green space
	Urban Centers	Suburbs	Riparian	Mountainous			
Constructed wetland	✓	✓			0-5%		
Detention pond	✓	✓	✓	✓	2-20%		
Infiltration trench	✓	✓	✓	✓	0% (harus datar)		
Urban forest (afforestation)	✓	✓	✓	✓	Tidak berlaku		
Street trees	✓	✓			0-33%		
Green corridor/ greenway	✓		✓		0-10%		
Slope stabilization (terracing, reforestation)			✓	✓	15-60%		
Infiltration well/ biopore	✓				Tidak berlaku		
Floodable park (floodplain park)	✓				0-20%		
Green wall (facade)	✓				Tidak berlaku		
Agroforestry / Urban farming	✓	✓			6-12%		
Managed Aquifer Recharge (MAR)	✓	✓	✓		0-5%		

BGI Types	Area typology				Slope	Blue space	Green space
	Urban Centers	Sub-urbs	Riparian	Mountainous			
Infiltration planter (box)	✓	✓			0-0.5%		
Kasumi-tei		✓	✓		0-10%		

Blue space (water body)



- Must be located on or near a water body
- Can be applied regardless of the presence of a water body
- Not applicable

Green space (vegetation)



- Must be located on vegetated land cover
- Must be applied to buildings or built-up land
- Can be applied to both vegetated land cover and built-up land

The results of this synthesis can be used as a basis for determining the type of BGI in accordance with the local typology of the area.

**4.3 Effectiveness of BGI for Mitigation**

Qualitative analysis of SLR findings shows that almost all BGI solutions focus on mitigating flooding and most have been proven effective in minimizing the risks. On the other hand, studies that directly assess the benefits and effectiveness of BGI in relation to the risk of land subsidence are still limited. To discuss the effectiveness of BGI, it can be classified based on its location of application, including buildings or limited spaces on private land, city centers and residential areas, open urban areas, riparian areas, as well as mountainous areas and steep slopes. In addition, the combination of two or more types of BGI and BGI specifically designed to address land subsidence can also be discussed.

**Buildings and/or Limited Space on Private Land.** Green roofs, green walls, rainwater harvesting, infiltration planters (boxes), infiltration wells, and biopores are effective in densely built-up areas with limited land.

A green roof is a roof covered with specific vegetation (sedum roof, extensive) or in the form of a garden (intensive). A study by Ismael & Mustafa [69] shows that green roofs can reduce runoff by up to 79% for average rainfall.

Based on the Regulation of the Minister of Agrarian Affairs and Spatial Planning No. 14 of 2022 (Permen ATR 14/2022), green walls can be applied to walls, columns, and/or fences. From the study by Palermo et al. [70], the green roof studied had an average retention capacity of 42% with a 1-minute delay in outflow, making it effective in reducing the risk of urban flooding.

Rainwater harvesting (cistern) is useful for collecting and storing rainwater (in individual barrels) which can be applied both on the surface and below ground, to store flowing water [71], [72]. Rainwater harvesting has been proven effective in reducing flooding by 53.9% to 85.7%, depending on building density [73].

Infiltration planters (boxes), infiltration wells, and biopores can also contribute significantly at the household level by increasing infiltration and reducing flooding.

**City Center and Residential Areas.** Permeable pavement, rain gardens, infiltration trenches, and bioretention basins are interventions that, based on SLR studies, have been extensively tested for their effectiveness in urban areas and densely populated settlements.

Permeable pavement is a porous surface designed to allow rainwater to seep into the underlying layers or be temporarily retained [71]. The results of a study by Radu et al. [74] show that the water impermeability of parking lots with porous pavements can be reduced from 85% to 60%.

Rain gardens are small gardens used for water storage and infiltration into the ground, which can include several components, such as small stagnation basins, artificial wetlands, and vegetation [71]. According to a study by Glick et al. [75], rain gardens have the highest runoff reduction rate, namely 77%, when fully implemented.

An infiltration trench is a shallow trench filled with debris or stones designed to capture and temporarily store rainwater runoff, which then allows the water to seep into the surrounding soil [71]. Based on the results of a study by Espinal-Giron et al. [76], this infrastructure can reduce runoff by up to 7.5%.

A bioretention basin is a type of bioretention system in the form of a vegetated basin that retains runoff from impervious surfaces, allowing for the sedimentation of sediments and pollutants, and allowing water to infiltrate into the soil [71]. Bioretention systems, such as bioretention basins, can reduce peak flow rates by up to 60% [74].

**Open Urban Space.** Urban forests, urban parks, vegetated swales, street trees, and green corridors are vegetation and trees that are effective in mitigating urban flooding, while also providing co-benefits as public spaces.

Urban forests are systems that combine trees with other biotic and abiotic components, which can be equipped with limited socio-cultural facilities that can increase

infiltration and absorb carbon (Permen ATR 14/2021; Permen ATR 14/2022). A study by Shiferaw et al. [77] shows that an increase in urban green space, such as broad-leaved forests in the Gap-Cheon watershed, which increased by almost 50% in 2022, has reduced surface runoff by up to 21% in several sub-watersheds.

Urban parks are open spaces that have social and aesthetic functions intended to serve city residents and are equipped with blue spaces (such as retention ponds, bioswales, rain gardens, and biopores) (ATR Regulation 14/2022). Of the 15 NbS studied by Biasin et al. [71], forested green areas (urban forests, city parks, and other green spaces) scored 1.9 for effectiveness in flood risk (second highest after floodplains and riparian forests).

A bioswale is a long, natural drainage channel planted with dense vegetation to filter, slow down, and absorb rainwater runoff [72]. Bioswales can retain and manage 11% of rainfall [69].

Green corridors can take the form of tree or vegetation corridors found on various scales, capable of assisting in rainwater management and mitigating flooding through rainwater interception, evapotranspiration, root absorption, and soil infiltration. Green corridors are effective for flood mitigation, as evidenced by a study by Hunter et al. [78] estimating that green corridors will prevent 1,741 properties from flooding in the future, with a total avoided damage value of £54.7 million.

**Riparian Areas.** Riparian areas or areas close to river bodies can apply riparian buffer zones, river restoration, floodable parks, constructed wetlands, retention and detention ponds, and kasumi-tei.

Riparian buffer zones serve to restore or create connections and transitions between terrestrial and aquatic ecosystems, including adjacent alluvial lowlands and terraces [71]. They can be divided into three zones (from inner to outer), namely undisturbed forest, managed forest, and grass and cropland. Riparian forest restoration has been proven effective for flood mitigation by increasing the volume of retained runoff by 2,689 m<sup>3</sup> (15% higher) compared to the business-as-usual scenario, as well as increasing the runoff retention index from 0.45 to 0.52 [79].

River (stream) restoration is a series of efforts to restore the natural conditions and functions of degraded river ecosystems, such as renaturalizing the shape and base material of rivers [71]. River and wetland restoration has the potential to reduce flood risk by increasing water retention capacity [80].

Floodable parks are multifunctional parks designed to store and manage temporary stormwater runoff during extreme rainfall and may include other BGI components, such as rain gardens and vertical gardens [81]. The BGI master plan for the Acari watershed (including floodable parks and detention basins) shows a 40.75% reduction in flood depth compared to conventional gray infrastructure [82].

Constructed wetlands are engineered systems designed to adapt the hydro-ecology of natural wetlands with retention and detention functions, involving wetland vegetation, soil, and associated microbial communities to aid in wastewater treatment and provide additional functions (Permen ATR 14/2022). This BGI is effective in controlling surface runoff, with case studies showing that 20 potential constructed wetland

sites can collect more than 50% of the runoff volume from 2- and 10-year return period rainfall [83].

Retention ponds and detention ponds are also important. Retention ponds are permanent ponds with natural embankments that have additional storage capacity to reduce runoff, which is then slowly released into the drainage system. The ponds also serve to manage water quality by filtering sediments and pollutants and replenishing groundwater (Permen ATR 14/2021). Of the 15 NbS selected by Biasin et al. [71], retention ponds scored 1.6 for effectiveness in flood risk (third highest, along with rain gardens, roadside trees and green paths, and infiltration basins) [71]. On the other hand, detention ponds are depressions in the ground that form reservoirs and serve to temporarily store rainwater in an area (Permen ATR 14/2022). Detention ponds have proven to be highly effective for flood mitigation, with a case study by Gokcekus et al. [72] showing a Benefit-Cost Ratio (BCR) approximately twice as high as other NbS options, making them a highly efficient and economically viable intervention.

Finally, there are *kasumi-tei* (discontinuous levees), a traditional Japanese flood control measure that allows floodwater to flow into surrounding areas (such as rice fields), which then serve as temporary flood retention basins. In this way, *kasumi-tei* can reduce river water levels and mitigate downstream flooding [84], [85]. This BGI is quite effective in reducing the impact of floods with a medium return period (5–25 years) from the study by Lo et al. [86], although its protective power is not as strong as large embankments built with stronger materials.

**Mountainous Areas and Steep Slopes.** For hilly and mountainous areas, slope stabilization and agroforestry can be key. Slope stabilization involves the construction and revegetation of slopes, such as sills and terraces, to reduce surface runoff, retain sediment, increase water infiltration, and improve groundwater recharge, thereby regulating river flow and reducing flood peaks [87].

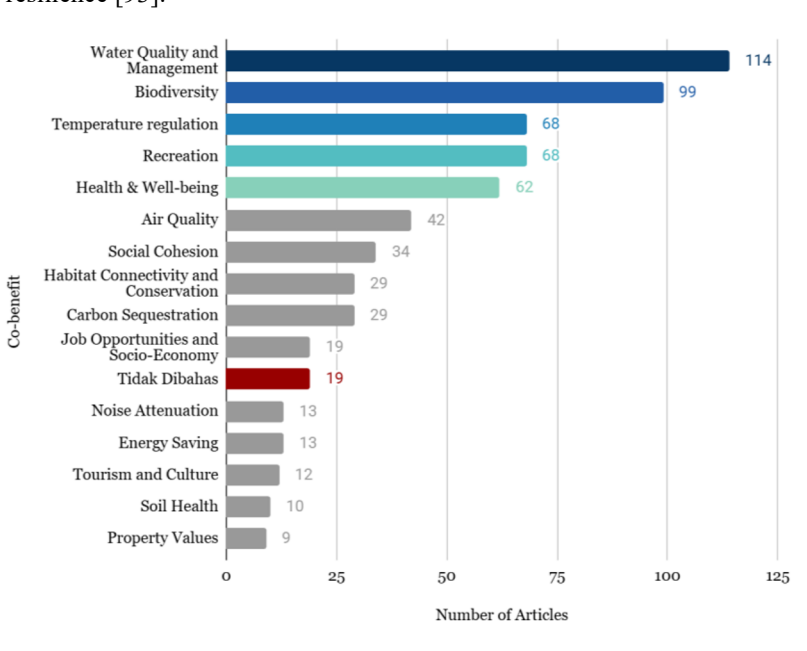
On the other hand, agroforestry is a dynamic, ecology-based natural resource management system that integrates trees and woodlands into agricultural land and productive landscapes, diversifying and increasing agricultural production. According to a study by Janzen et al. [88], agroforestry can reduce surface runoff by up to 22.5%, increase infiltration by 31.1%, and increase evapotranspiration by 56.25%.

**Effectiveness of BGI Combinations.** There are many studies showing that a combination of BGI is consistently more effective than a single intervention. Research by Nazari et al. [89] shows that a combination of rain barrels, porous pavements, and vegetated swales is considered to have the best performance, capable of reducing volume by 20.77% and peak discharge by 19.2% at a much lower cost (\$7.68 million) and requiring almost no space to build. Méndez et al. [90] showed that the best scenario is a combination of bioretention, rain gardens, permeable pavement, and infiltration trenches, which can reduce surface runoff volume by 22–24%.

**Managed Aquifer Recharge (MAR) for Land Subsidence.** BGI solutions based on SLR results that can reduce the risk of land subsidence are still limited. Most discussions focus on indirect impacts. However, there are specific solutions or approaches identified to increase groundwater availability through aquifer recharge, known as Managed Aquifer Recharge (MAR). MAR is a BGI strategy that aims to increase groundwater availability through aquifer recharge. Its functions include restoring or preventing groundwater level decline, controlling seawater intrusion, preventing land subsidence, improving water quality, supporting water recycling, and protecting ecosystems that depend on groundwater [91]. The types include river channel modification, riverbank filtration, water spreading (e.g., infiltration ponds), recharge wells (e.g., aquifer storage and recovery and dry wells), and small-scale recharge (e.g., rainwater harvesting and infiltration wells). A study by Zakir-Hassan et al. [92] shows that MAR significantly contributed to reducing flood intensity with a floodwater storage capacity of 1.88 km<sup>3</sup> in 2020.

#### 4.4 Co-benefits of BGI

Not only is it capable of mitigating flood disasters and minimizing runoff in urban areas, but BGI, which is an NbS and includes a series of interconnected water management practices, is also capable of providing various co-benefits to achieve socio-ecological resilience [93].



**Fig. 4.** BGI co-benefits resulting from SLR

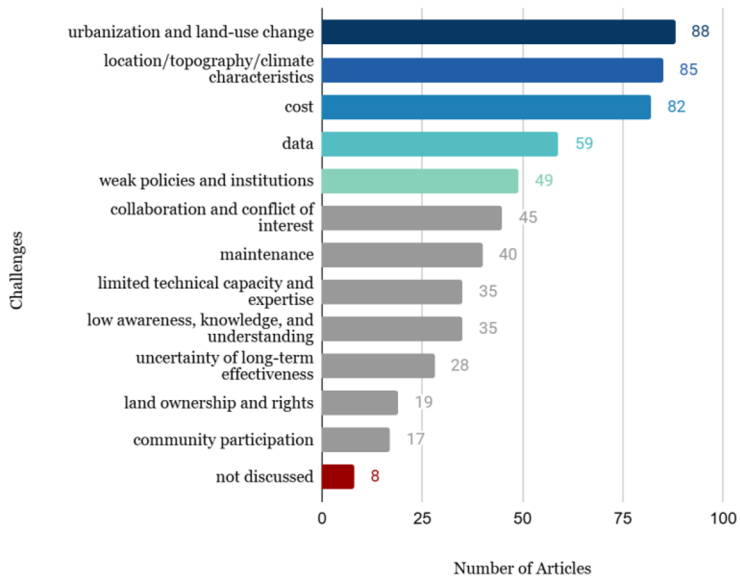
The results of the SLR analysis (**Fig. 4.**) show that most studies highlight additional benefits related to biophysical aspects, such as water management and water quality (114 publications), biodiversity (99 publications), and temperature regulation (68 publications). An example of the benefits for water management can be seen in a study by Zhou & Ghuo [94], in which rain gardens with a drainage-free design were able to retain and distribute rainwater, as evidenced by the study's findings showing an 89% reduction in surface runoff, mostly through infiltration. In addition, floodplain restoration can increase habitat diversity and species richness by reconnecting rivers with their natural floodplains and creating more suitable ecosystem conditions [95]. BGI also provides temperature regulation by reducing the urban heat island effect through increased vegetation and permeable surfaces, which enhance evaporative cooling and reduce ambient temperatures [96].

Socio-economic aspects tend to be given less consideration in studies related to BGI from SLR results, with public health and welfare ranked 5th, social cohesion ranked 7th, and employment opportunities, including related socio-economic benefits, ranked 10th. Previous studies [12], [16] also highlight issues related to socio-cultural aspects whose benefits are not fully taken into account in the implementation of BGI, possibly due to their complex and broad dimensions. Not only ecological benefits, if social and economic benefits can be considered early on in the planning process, then synergies in providing various green space functions can be more optimal, which can also have an impact on reducing the risk of urban flooding [97], [98]. A study by İnançoğlu et al. [99] found that green corridors along the Pedieos River can provide health and welfare benefits by improving water quality, providing recreational areas, improving mental well-being, and promoting social cohesion through the creation of shared public spaces. Green infrastructure can also create job opportunities in the green investment sector and increase property values [100], [101].

#### 4.5 Challenges and Opportunities in BGI Implementation

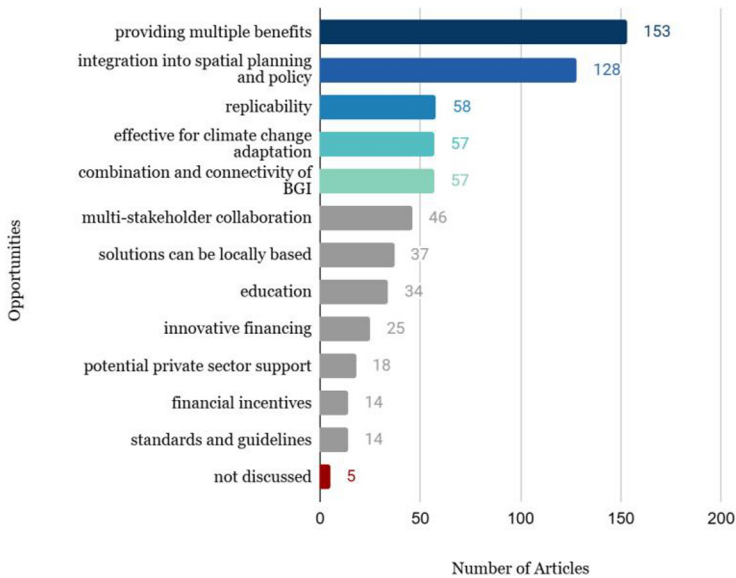
In its implementation, there are challenges and opportunities that can be identified. The results of this identification can be used as a basis for making appropriate decisions and policies to address existing issues.

**Challenges.** The SLR results show that urbanization and land use change (88 publications or 45.83%) are the most common challenges, followed by location characteristics, topography, and climate (85 publications or 44.27%), costs (82 publications or 42.71%), data (59 publications or 30.73%), and weak policies and institutions (49 publications or 25.52%).



**Fig. 5.** BGI implementation challenges resulting from SLR

**Opportunities.** The SLR results show that the provision of multiple benefits (153 publications or 79.69%) is the main opportunity for BGI implementation, followed by integration into spatial planning and policy (128 publications or 66.67%), replicability (58 publications or 30.21%), and effectiveness for climate change adaptation and BGI combination and connectivity (57 publications or 29.69% each).



**Fig. 6.** BGI implementation opportunities resulting from SLR

#### 4.6 Recommendation for Pilot Case: Greater Bandung, Indonesia

Based on the comprehensive SLR results, recommendations can be formulated in this section for the selected pilot case, namely Greater Bandung. Greater Bandung is an urban area in the Greater Bandung consisting of an agglomeration of five regencies/cities.

This region often faces various threats, especially hydrometeorological disasters, which are often an annual problem. Factors such as changes in land use in the Citarum River Basin due to mass urbanization and population density, waste management and drainage problems [102], [103], as well as infrastructure that is not resilient, poorly maintained, and not well integrated into spatial planning, are the main triggers [102], [104], [105]. Flooding in downstream metropolitan areas can also be influenced by poor management of areas and watersheds and unsuccessful policy implementation, as demonstrated by changes in the function of green-blue spaces in the North Bandung Area [102], [106]. On the other hand, the capacity of local governments, especially in terms of budgets for mitigation, is still inadequate, even though there are already several policies and programs for this [31]. Indirect impacts, such as land subsidence, also expand the flood area [105].

Given the characteristics of the region and its hazards, appropriate BGI solutions can be determined. This typology can be divided into areas that include dense urban centers and lowlands (Bandung City and Bandung Regency), suburban areas that include transitional areas on the outskirts of cities (Cimahi City and West Bandung Regency),

riverbank areas, and mountainous areas (Bandung Regency and West Bandung Regency). For areas in Bandung City, such as Braga Village, which is located in a high-density commercial area with moderate flood risk and moderate slopes, BGI solutions such as infiltration wells, permeable road surfaces, and rainwater harvesting can be implemented. Flood-prone areas near the Oxbow Mekar Rahayu landfill in Bandung Regency, which are close to rivers and have extensive green spaces, can implement artificial wetlands, bioretention ponds, urban agriculture, and riverbank buffer zones. For areas with moderate elevation and slopes but with residential land cover, such as Cikande Village in West Bandung Regency, urban forests, terraces, and biopores can be implemented. On the other hand, for Cimahi City, such as in residential areas near Ciuyan Road, which has high slopes, is close to water bodies, and has extensive green spaces, roadside trees and slope stabilization can be implemented.

To address issues in the implementation of BGI, several recommendations can be made. First, a combination of more than one BGI solution or a combination of BGI with gray infrastructure. The results of the SLR show that a combination of solutions is more effective than relying on just one solution [107]. Second, cross-border spatial planning and policy integration are key to strengthening infrastructure integration and flood risk mitigation efforts in Greater Bandung, which can be done through the Bandung Basin Spatial Plan and strengthening collaborative governance [106]. Third, community participation and education to raise public awareness can be strengthened to increase resilience, especially among those most at risk in flood-prone areas [108]. Fourth, innovative financing instruments (e.g., environmental impact bonds, public-private partnerships, green bonds) to strengthen local government capacity in implementing BGI [109]. Finally, to ensure the long-term impact of BGI, regular and sustainable maintenance of infrastructure and/or related projects is needed to maximize its benefits [110].

## 5 Conclusion

Urban flooding and land subsidence pose major challenges for metropolitan areas such as Greater Bandung. This study reviewed 192 publications using the SLR method to identify relevant BGI interventions, evaluate their effectiveness, and formulate recommendations based on the spatial characteristics and risks of metropolitan areas.

A total of 24 types of BGI were identified and classified based on spatial characteristics, including dense urban centers, suburbs, river basins, and mountainous areas. Most studies show that BGI is effective in mitigating urban flooding and provides multiple benefits, especially in biophysical aspects such as water management, increased biodiversity, and heat reduction. Integrated BGI strategies consistently demonstrate higher effectiveness than single interventions.

Implementation challenges include rapid urbanization, limited financing, fragmented regulatory frameworks, and inadequate spatial data. Nevertheless, opportunities for BGI implementation remain through cross-border spatial planning, innovative financing schemes, policy integration, and increased community participation. Recommendations for the Greater Bandung Area include implementing BGI based on local

typologies, applying a combination of BGI types or blue-green-gray interventions, integrating BGI into spatial and cross-jurisdictional planning, collaborative governance, strengthening innovative financing, strengthening the role of the community, and sustainable maintenance for long-term impact. Further research is needed to evaluate the effectiveness of BGI in reducing land subsidence and to explore its socio-economic benefits in greater depth.

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