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# The potential of Blue-Green infrastructure as a climate change adaptation strategy: a systematic literature review

Tamer Almaaitah[a,*], Madison Appleby[b], Howard Rosenblat[b], Jennifer Drake[c] and Darko Joksimovic[a]

[a] Department of Civil Engineering, Ryerson University, 350 Victoria St., Toronto, ON M5B2K3, Canada
[b] John H. Daniels Faculty of Architecture, University of Toronto, 1 Spadina Crescent, Toronto, ON M5S 2J5, Canada
[c] Department of Civil and Mineral Engineering, University of Toronto, 35 St. George Street, Toronto, ON M5S 1A4, Canada
*Corresponding author. E-mail: tamer.almaaitah@ryerson.ca

TA, 0000-0001-7051-8743; MA, 0000-0002-6871-5796; JD, 0000-0001-6235-3918; DJ, 0000-0001-7977-0566

## ABSTRACT

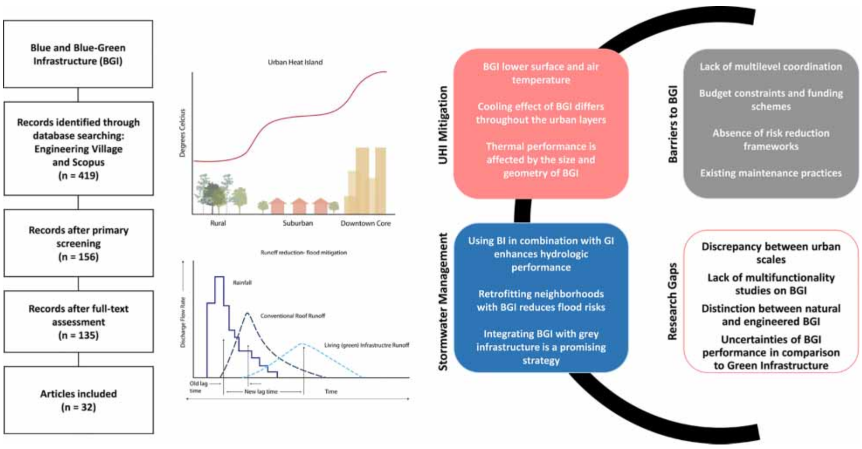
Blue-Green Infrastructure (BGI) consists of natural and semi-natural systems implemented to mitigate climate change impacts in urban areas, including elevated air temperatures and flooding. This study is a state-of-the-art review that presents recent research on BGI by identifying and critically evaluating published studies that considered urban heat island mitigation and stormwater management as potential benefits. Thirty-two records were included in the review, with the majority of studies published after 2015. Findings indicate that BGI effectively controls urban runoff and mitigates urban heat, with the literature being slightly more focused on stormwater management than urban heat island mitigation. Among BGI, the studies on blue- and blue-green roofs focused on one benefit at a time (i.e. thermal or hydrologic performance) and did not consider promoting multiple benefits simultaneously. Two-thirds of the selected studies were performed on a large urban scale, with computer modelling and sensor monitoring being the predominant assessment methods. Compared with typical Green Infrastructure (GI), and from a design perspective, many crucial questions on BGI performance, particularly on smaller urban scales, remain unanswered. Future research will have to continue to explore the performance of BGI, considering the identified gaps.

**Key words:** blue-green infrastructure, blue-green roofs, blue infrastructure, climate change, stormwater management, urban heat island

## HIGHLIGHTS

- Findings on blue-green infrastructure (BGI) are reviewed considering UHI mitigation and stormwater management.
- BGI effectiveness to UHI mitigation is influenced by geographic and climatic conditions.
- BGI can better manage stormwater than green infrastructure.
- Barriers to BGI implementation include lack of multilevel coordination, budget constraints and absence of risk reduction frameworks.

## GRAPHICAL ABSTRACT



## 1. INTRODUCTION

The environmental, economic and social impacts of climate change are accelerating worldwide, resulting in ever-increasing severe adverse effects on ecosystems. Current research indicates that climate change increases air and surface temperature and intensifies rainfall events in both magnitude and duration (Kendon *et al.* 2014; Westra *et al.* 2014). An increasing body of literature, including research on the effects of climate change on air temperatures and precipitation, points out that urbanization (Maheshwari *et al.* 2020) and the loss of green spaces (Govindarajulu 2014; Herslund *et al.* 2015) are magnifying the risks of climate change patterns (Zareian *et al.* 2017; Berardi & Jafarpur 2020). Today almost 25% of the global population is exposed to floods (Tellman *et al.* 2021).

Urbanization replaces natural permeable surfaces with impermeable surfaces leading to an increase in both the surface runoff volume and peak runoff rate and a reduction in response time (Miller *et al.* 2014). These hydrologic disruptions associated with land-use change increase the risks of floods and environmental problems. As the world's urban population continues to grow, urban areas will continue to expand rapidly, typically with the corresponding loss of green, natural areas (United Nations 2019). Urban sprawl and intensification will worsen the consequences of climate change and increase the magnitude and frequency of floods (Westra *et al.* 2014).

The loss of green spaces associated with urbanization is linked to the Urban Heat Island (UHI), which manifests itself by increasing heatwaves in both frequency and intensity (Gunawardena *et al.* 2017). Urban infrastructure absorbs solar radiation and re-radiates it as heat, resulting in elevated demands for energy consumption for cooling, increased air pollutant emissions, and undesired human health impacts (Santamouris & Osmond 2020). In a recent study investigating heat waves in Europe, there were, on average, 5–10 heatwaves per year, with heatwaves ranging between 25 days for Scandinavia and nearly 60 days for western Russia (Zschenderlein *et al.* 2019). In Canada, Toronto's urban climate was found to be significantly warmer than it was a century ago, with a considerable addition in growing degree days (Waffle *et al.* 2017). Cities generally have less vegetation and water bodies, which explains why climate change is more exacerbated in urban environments than in rural surroundings (Gunawardena *et al.* 2017).

Green Infrastructure (GI) refers to the nature-based systems that mimic the natural hydrology and regulate surface energy processes through evaporation, shadowing, and adjusting emissivity, and positively affecting air movement and heat exchange (Oke 1982; Bonan 1997; Shishegar, 2014; Liu *et al.* 2019). Blue Infrastructure (BI) refers to the natural or man-made forms of water implemented in the city that slows runoff by providing temporary storage, emitting longwave radiation to cool surfaces, and effectively absorbing shortwave radiation and releasing it through evaporation (Volker *et al.* 2013; Wu *et al.* 2019). Blue-Green Infrastructure (BGI) is a collective term used when blue and green applications are integrated to mitigate urbanization and adapt to climate change by providing multiple benefits for urban areas affected by unmanaged stormwater and high heat (Versini *et al.* 2018). This utilization delivers various services (e.g. cooling via evapotranspiration, water storage for extreme rainfall events, peak discharge attenuation, and groundwater recharge) (Voskamp & Van de Ven 2015).

Urban Ecological Infrastructure (UEI) is another relatively new term that has been recently introduced to describe blue, green, and grey infrastructures as a combined system aimed to integrate ecosystem services (Li *et al.* 2017). UEI involves networks of natural lands and working landscapes that conserve ecosystems' functions.

Recent research has shown the effectiveness of BGI to reduce floods and urban heat (Žuvela-Aloise *et al.* 2016; Sörensen & Emilsson 2019). BGI can be integrated with the conventional 'grey' urban drainage systems, including conveyance (sewer) systems and storage and treatment facilities to form blue-green-grey infrastructure. To better illustrate what could be considered 'green,' 'blue,' or 'grey,' Figure 1(a) and 1(b) illustrate the most common blue, green and grey infrastructure applications. In contrast, Figure 2 depicts an example of an integrated blue-green infrastructure

BGI will be an integral part of future urban living as cities move towards climate change adaptation strategies. On a city-scale, blue and blue-green roofs are an emerging type of BGI and are beneficial due to the multiple environmental benefits achieved through these systems (i.e. urban water management and microclimate improvement) with the nature of cities (i.e. highly urbanized areas and small-scale spaces) (Campisano *et al.* 2018; Cirkel *et al.* 2018). Green roofs consist of vegetation and soil medium planted over a waterproofing membrane, whereas blue roofs are non-vegetated source control that retains stormwater (Shafique *et al.* 2016). Green roofs have

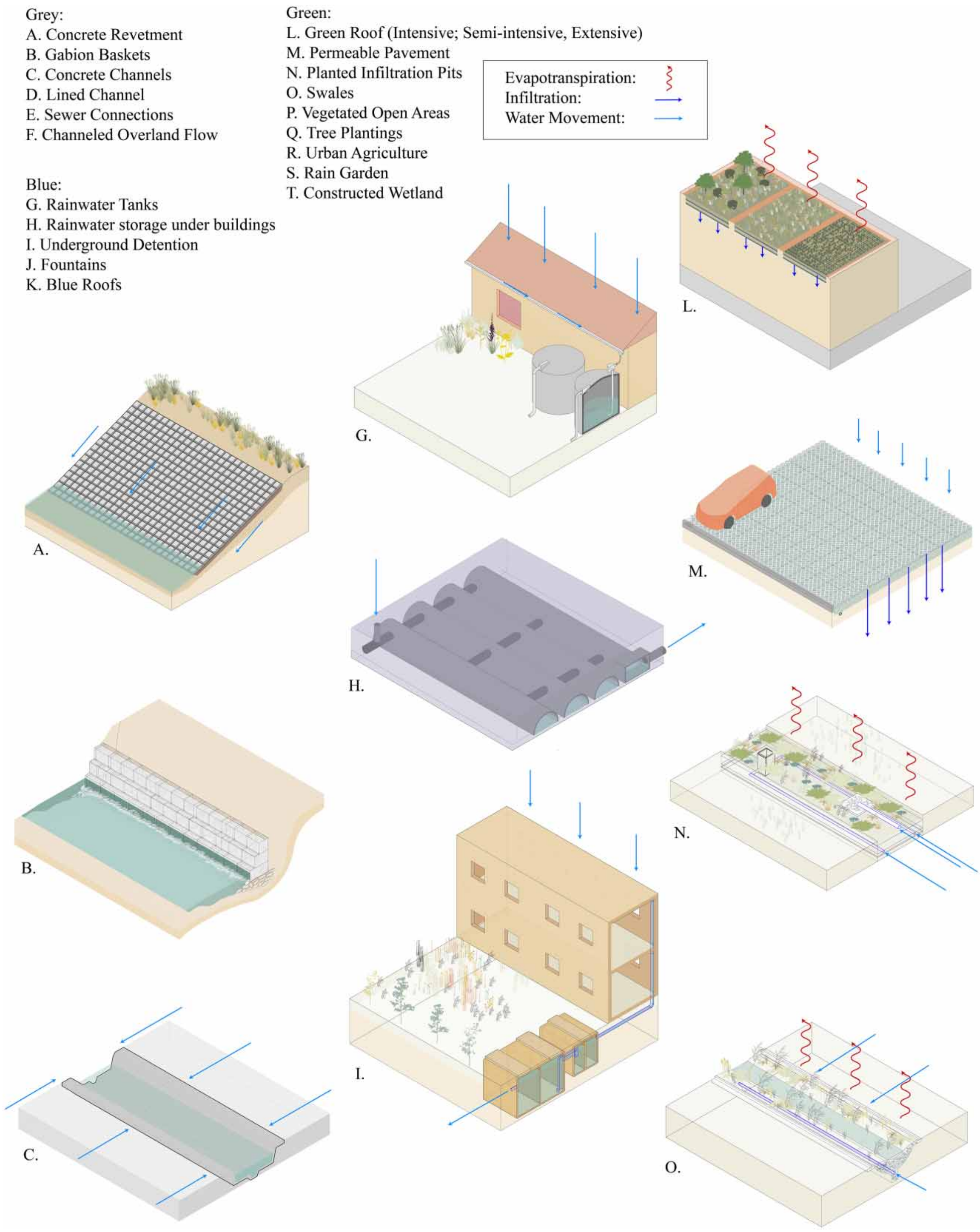



**Figure 1** | (a) Common applications of blue-green-grey infrastructure, developed based on (Voskamp & Van de Ven 2015; Mulligan *et al.* 2019). (b) Common applications of blue-green-grey infrastructure, developed based on (Voskamp & Van de Ven 2015; Mulligan *et al.* 2019). *(continued.).*

similar layers to blue-green roofs. However, the latter has an expanded drainage layer that allows for a more significant amount of rainwater to be stored and gradually released through pre-designed drains (Skjeldrum & Kvande 2017; Campisano *et al.* 2018). This attenuation helps manage stormwater and reduces the stress on sewer systems, consequently reducing flooding risks (Shafique *et al.* 2016). In addition to their stormwater management role, blue-green roofs are promoted as a climate change adaptation strategy due to their capability to reduce air and surface temperature providing thermal comfort for residents (Cirkel *et al.* 2018). Figure 3 presents the common drainage layers of blue-green roofs compared to the typical green roof.

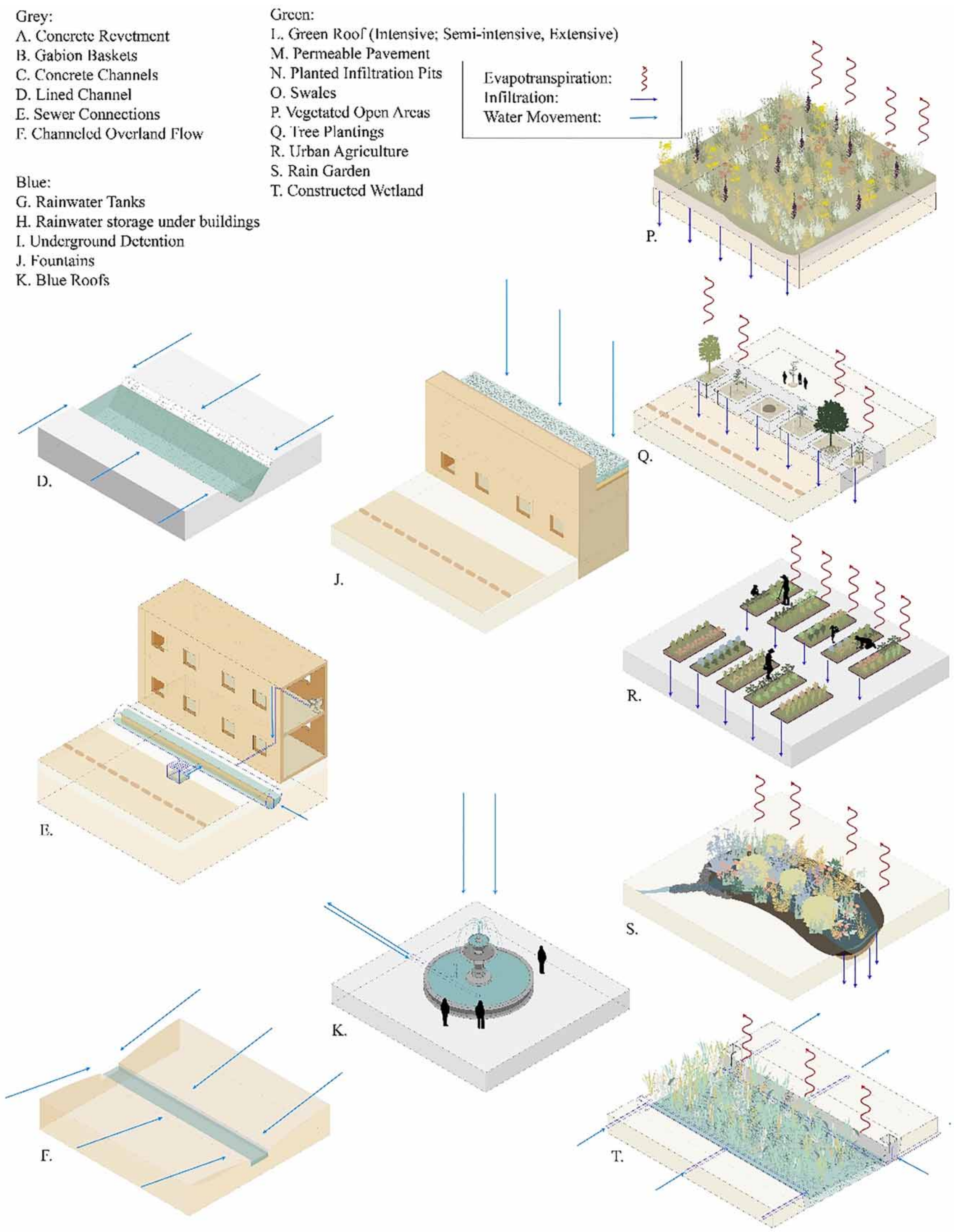



**Figure 1** | Continued.

Despite the growing interests of BGI among researchers, engineers and landscape designers, their widespread implementation is still limited, possibly due to their multidisciplinary design requirements, lack of confidence and knowledge by practitioners, and uncertainties regarding their ecological, financial and hydrologic performance (Fenner 2017; Campisano *et al.* 2018; Thorne *et al.* 2018). Furthermore, to account for climate change-oriented BGI, understanding the operational characteristics over various urban scales is essential (Voskamp & Van de Ven 2015). However, it is unclear whether the current literature has considered different scales or focused on one particular scale.

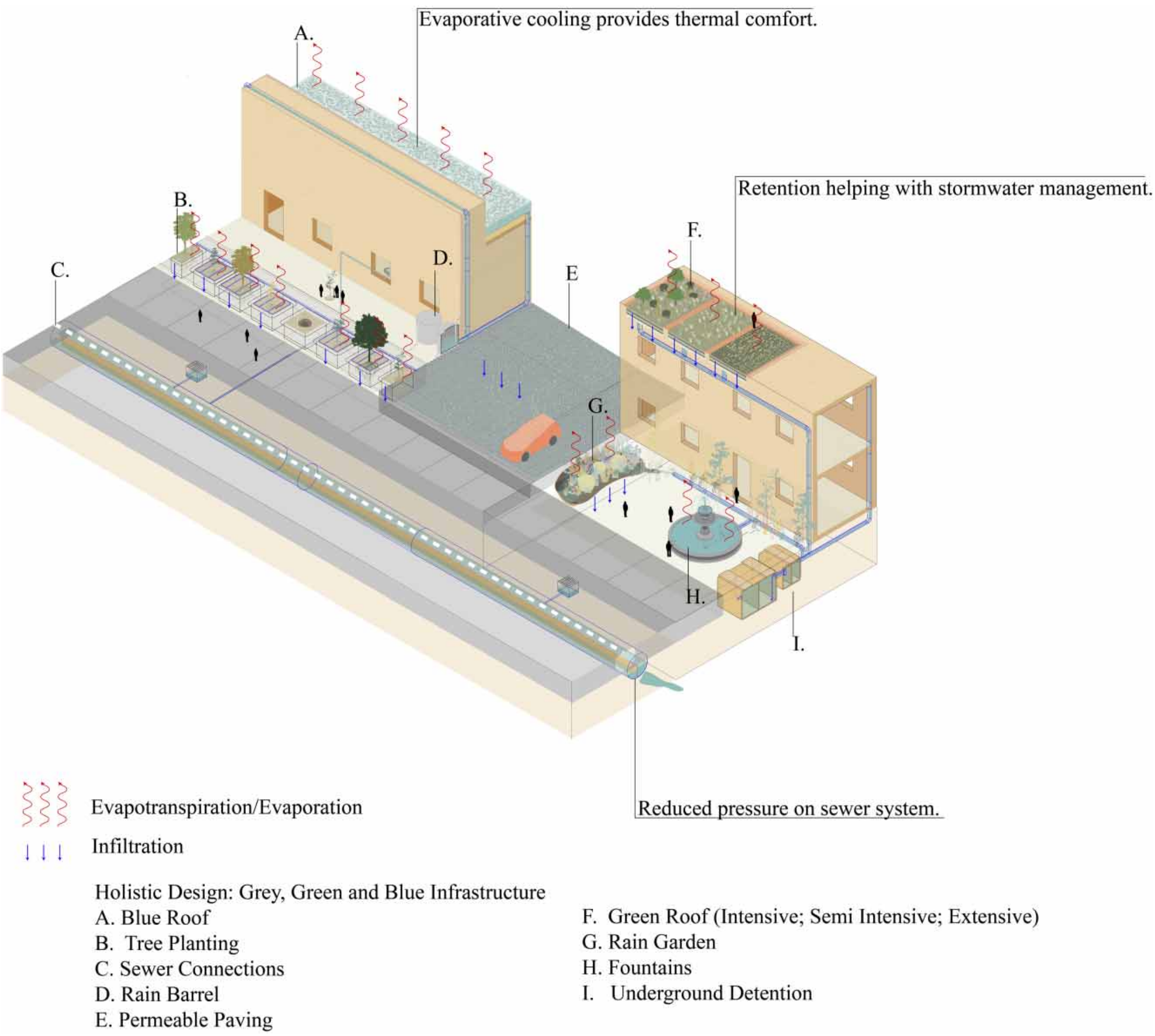



**Figure 2** | Example of an integrated blue-green infrastructure.

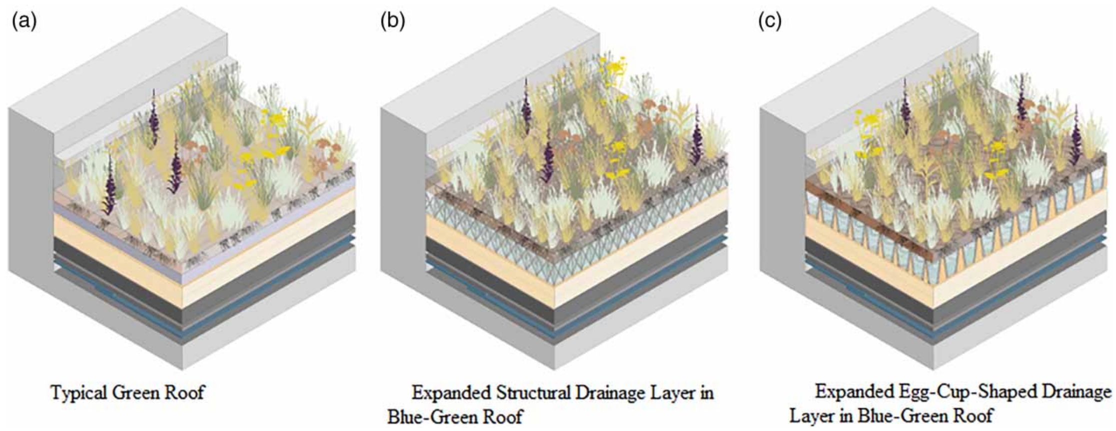



**Figure 3** | Green and blue-green roofs with different drainage layers.

Academic research has sought to examine the effectiveness of green infrastructure. For example, there have been several review studies on green roofs (Li & Babcock 2013; Vijayaraghavan 2016; Shafique *et al.* 2018; Shafique *et al.* 2020), bioretention cells (Liu *et al.* 2014; Spraakman *et al.* 2020), rain gardens (Osheen & Singh 2019) and swales (Ekka *et al.* 2021). In each of these papers, the authors have summarized the previous research on a specific green infrastructure application. Review studies that generally look at green infrastructure more broadly also exist (Zhou 2014; Pour *et al.* 2020; Ying *et al.* 2021). However, none of these reviews have primarily focused on BGI, leaving unanswered questions on the difference in the performance of the well-known green infrastructure and the novel blue and blue-green infrastructure. Although blue infrastructure has received more attention in the last few years, to our knowledge, there exist no structured reviews that have systematically identified and synthesized the potential of BGI, particularly for climate change adaptation. Such a review provides a critically appraised and clear overview of available evidence on BGI, which helps identify unanswered questions and research gaps and consequently identify needs for further research.

This paper gives an overview of state-of-the-art knowledge and presents emerging studies of BGI. In particular, the paper addresses the following questions: (1) What is the potential of BGI to mitigate elevated urban heat? (2) What is the potential of BGI to manage stormwater? (3) What are the barriers to BGI integration? This review paper considers two environmental services of BGI: urban heat mitigation and stormwater management. These two services are vital to BGI as a climate change adaptation strategy. The literature review and discussions presented herein focus on the design and operational aspects of the blue-green applications and their impacts on the hydro-ecological functionality. They are not intended to evaluate the socio-cultural and economic benefits of blue-green practices.

## 2. METHODOLOGY

This study followed a systematic literature review procedure identified in the PRISMA Flow Diagram (Moher *et al.* 2009). Reviewed literature was identified through a keyword search in two academic database platforms: Engineering Village and Scopus, performed on March 20, 2020, July 2, 2021, and October 28, 2021. Search keywords included: '*Blue-green Infrastructure*,' '*Green/Blue-Infrastructure*,' '*Green Blue Infrastructure,*' '*Green and Blue Infrastructure*,' '*Blue-Green Infrastructure*,' '*Blue/Green-Infrastructure*,' '*Blue and Green Infrastructure*,' '*Blue Infrastructure*,' '*Blue-green roof*,' '*Green/Blue-roof*,' '*Green Blue roof*,' '*Blue-Green roof*,' '*Blue/Green-roof*,' '*Blue and Green roof*,' '*Blue roof,*' '*Rooftop Detention*,' and '*Rooftop Storage*.'

The search's returned records were screened based on the inclusion/exclusion criteria depicted in Figure 4. After removing duplicates, 323 records were identified for abstract and title screening. Of these, 156 records were excluded for one or more of the following reasons: (1) records did not consider a blue-green application, (2) records were not peer-reviewed journal articles and/or peer-reviewed conference proceedings, (3) records were abstracts without full-texts, and (4) records were not provided in English.

After a full-text assessment, another 135 records were excluded because they: (1) only considered a green infrastructure practice without a blue infrastructure application, (2) investigated non-technical aspects of BGI (e.g. social, cultural, and psychological), (3) did not consider urban heat mitigation or stormwater management as the benefit of BGI and/or (4) did not discuss the barriers and challenges to the implementation of BGI. Following the filtering process, a total of 32 records remained and were selected for detailed review.

Through literature research of the publication databases, all the selected records were relatively recent, with the oldest record published in 2013 and the latest record published in 2021. However, the topic is rapidly evolving due to the increasing awareness among researchers and urban planners on the need for sustainable systems to adapt to climate change.

## 3. RESULTS AND DISCUSSION

### 3.1. Urban heat island mitigation

Out of the selected thirty-two records in this literature, nine records assessed the UHI mitigation and the cooling effect of BGI. These studies incorporated different thermal performance indicators and parameters to assess heat mitigation of blue-green applications within various modelling processes. The performance indicator included land surface temperature, air temperature and maximum cooling distance, whereas the parameters included Normal Difference Vegetated Index (NDVI), Normal Difference Water Index (NDWI), Universal Thermal Climate Index (UTCI) and Thermal Sensation Vote (TSV). Despite the differences in employed methodologies and parameters, these studies' overall objective was to optimize the design of BGI by understanding how they mitigate urban heat. Table 1 illustrates a list of the studies that examined the cooling feature of BGI with their objectives, methodologies, scales, and locations. Moreover, the climate for each study location was determined using Köppen climate classification (Köppen 1884) and indicated in Table 1.

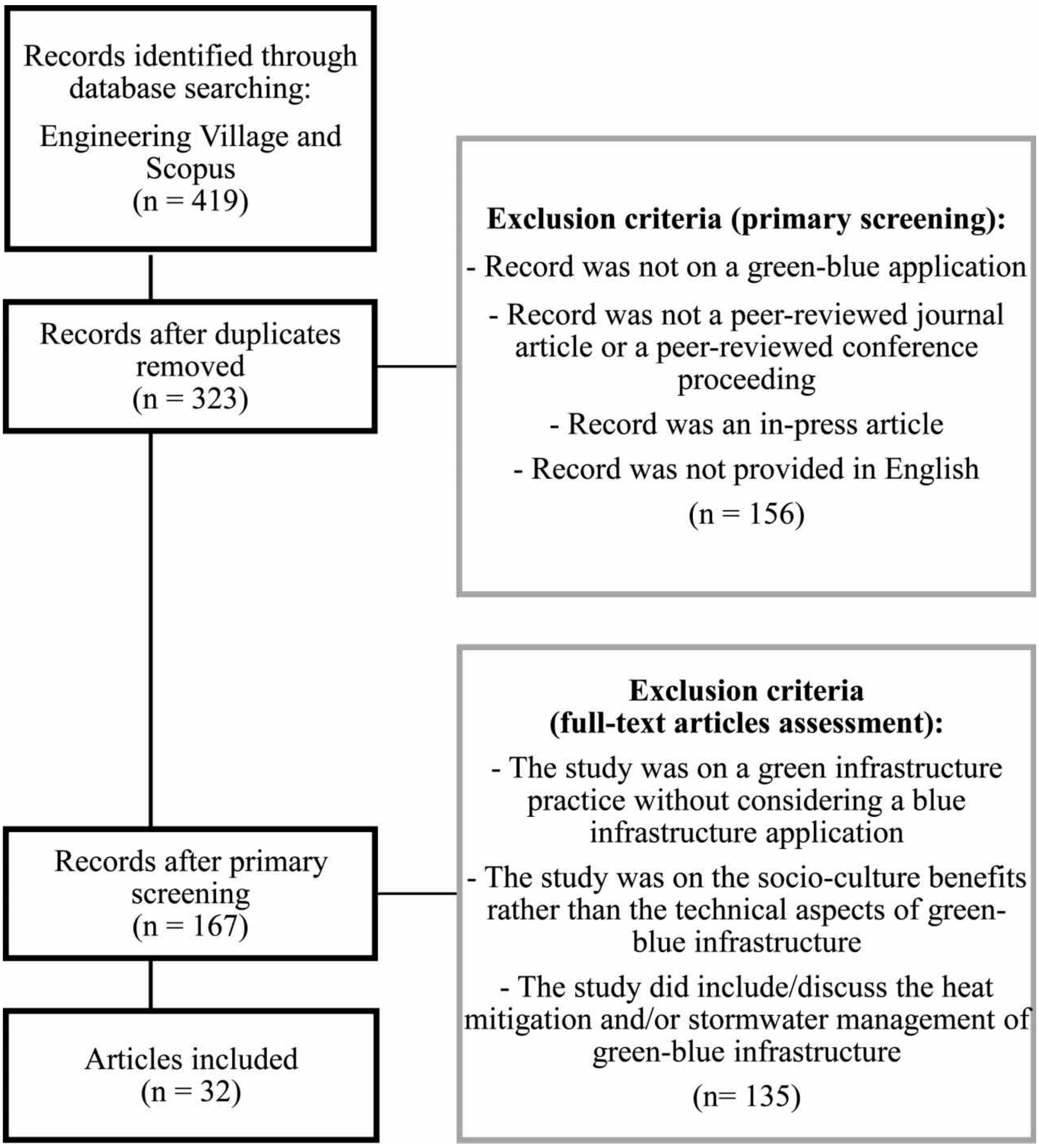



**Figure 4** | Flow diagram for the systematic literature review process.

One of the most distinctive features of blue and blue-green applications is mitigating the effect of urban heat islands by emitting longwave radiation to cool surfaces of high emissivity. However, it is essential to understand how these systems work as inadequately designed BGI exacerbates heat stress (Gunawardena *et al.* 2017). To better understand this cooling functionality, computationally efficient and scientifically defensible urban climate models are required. Early studies adopted a wide range of urban models to simulate the cooling effect of BGI. These models included the CFD-based ENVI-met, SOL-WEIG and RayMan, Temperature of Urban Facets in 3-D (TUF-3D), Vegetated Derivative (VTUD-3D), Canyon Air Temperature (CAT) and The Town Energy Balance (TEB) model. However, it is not generally agreed that these models can provide a comprehensive evaluation of the cooling effect due to several limitations such as model inaccuracy, prediction inadequacy, and the requirement for high-level modelling skills (Broadbent, 2018).

In the absence of efficient tools to model BGI, Broadbent (2018) developed a simple but effective model called The Air Temperature Response to Green/Blue-Infrastructure (TARGET). The developed model provides quick assessments of surface temperature and street-level air temperature in urban areas where the systems of BGI are implemented for heat mitigation purposes. The model depends on the user input data (i.e. land cover,

**Table 1** | List of studies that evaluated the cooling effect of BGI

| Objective | Methodology | BGI Included | Scale | Location | Climate | Reference |
|---|---|---|---|---|---|---|
| BGI effect on the thermal sensation in public spaces | Thermal Sensation Vote (TSV) | Lawn, trees and water fountains | Neighbourhood | Brno, Olomouc, Ostrava, and Plzen, Czech | Humid continental | Lehnert *et al.* (2021) |
| BGI effect on air Temperature | Universal Thermal Climate Index (UTCI) | Ponds | Neighbourhood | Hong Kong, China | Humid sub-tropical | Fung and Jim (2020) |
| BGI effect on surface temperature | Enhanced Thematic Mapper (ETM) | Lakes | Neighbourhood | Wuhan, China | Humid sub-tropical | Wu *et al.* (2019) |
| BGI effect on surface temperature and street-level air temperature | TARGET Climate-service-oriented tool | Tree cover and irrigated grass | Streel-level | Melbourne, Australia | Temperate oceanic | Broadbent (2018) |
| BGI effect on air temperature | Landsat 8 TM, ENVI 5.1 and ArcGIS 10.2 | Reservoirs | Neighbourhood | Pearl River Delta, China | Humid sub-tropical | Wu *et al.* (2018) |
| Maximize the evapotranspiration of BGI | In-situ monitoring using lysimeter | Blue-green roof | Building-scale | Amsterdam, Netherlands | Temperate oceanic | Cirkel *et al.* (2018) |
| Assess the cooling effect of BGI | In-situ monitoring using temperature sensors | Blue-green roof | Modular setups, building-scale | Seoul, South Korea | Humid continental | Shafique & Kim (2017) |
| BGI effect on air temperature | Digital Elevation Model (DEM) and satellite-based ARCSYS | Ponds, lakes and rivers | Regional, city-scale | Vienna, Austria | Temperate oceanic | Žuvela-Aloise *et al.* (2016) |
| Evaluate the cooling efficiency on the urban canopy and boundary layers | Meta-analysis of published studies | Various* | Various* | Various* | Various* | Gunwardena *et al.* (2017) |

*The study is a meta-analysis of other published studies with different BGI combinations, scales, and locations.

meteorological parameters) and the following geometrical inputs: roof width ($W_{roof}$), building height (H), tree width ($W_{tree}$), and street width (W). Following several simulations for 14 days in Melbourne for three types of surfaces (concrete, asphalt, and roof), the temperatures were well predicted with an average bias of 0.88 °C, −0.22 °C and −1.16 °C, respectively.

However, the modelled air temperatures were biased towards warmer air temperatures in urban areas and cooler air temperatures in rural areas. Based on the TARGET model, heat mitigation scenarios were simulated, as illustrated in Figure 5. These scenarios provide insight into the potential of tree cover and irrigated grass to mitigate the UHI effect. However, with increased drought in some countries due to climate change, future developers must carefully consider the trade-off relationship between using water for irrigation to reduce urban heat and saving water. One solution could be utilizing harvested rainwater and locally treated greywater, as Rozos *et al.* (2013) suggest. Nevertheless, although water reuse at the building level can be a helpful technique, it could cause accelerated deterioration of sewerage infrastructure due to increased solids concentrations and altered characteristics (Kiparsky *et al.* 2013).

The second study assessed the maximum cooling distance as a performance indicator on urban lands adjacent to lakes in Wuhan by employing the NDWI instead of NDVI (Wu *et al.* 2019). The results revealed that the maximum cooling distance, and therefore the cooling effect, has a considerable correlation with the lake size in spring and summer for urban and rural areas. For urban lakes, the largest and smallest maximum cooling distance was 1,232 m and 28 m in summer, and 575 m and 84 m in spring, respectively. The most substantial maximum cooling distance was 532 m in summer and 440 m in spring for rural lakes. Another study in Austria found that building type, time of the day (i.e. daytime, nighttime), and the temperature of water areas (e.g. ponds, lakes, and rivers) affect the capability of the BGI to lower urban heat load (Žuvela-Aloise *et al.* 2016). The research, which employed several case simulations of Vienna's city using the Digital Elevation Model (DEM), concluded that the cooling effect is also affected by the size and location of the surfaces and the land-use characteristics. Current theories hypothesize that establishing minor but combined measures are the best way to optimize BGI's cooling benefits on the city scale (Žuvela-Aloise *et al.* 2016). These measures include a reduction in building density by 10%, a reduction in pavement by 20% and an expansion in green or water spaces by 20%.

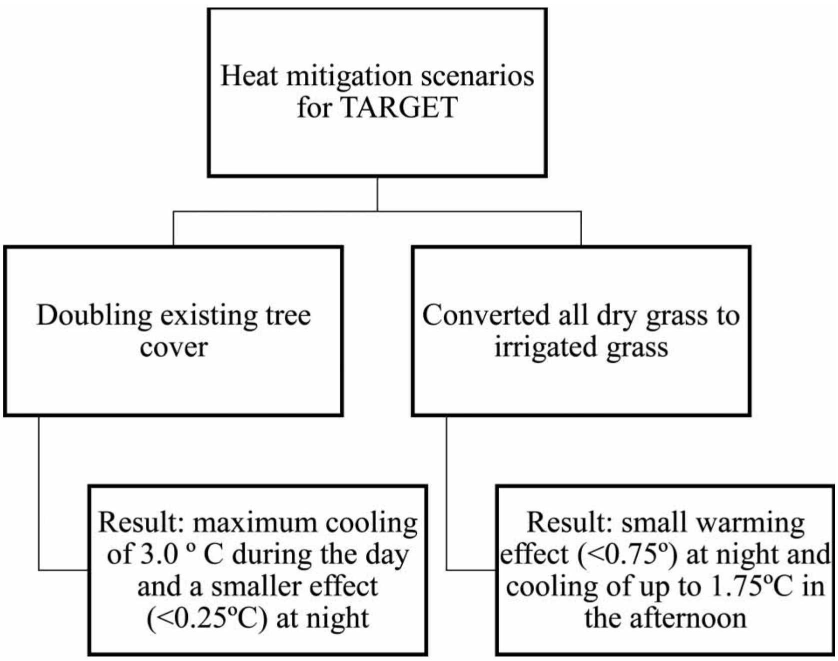



**Figure 5** | Heat mitigation scenarios (Broadbent, 2018) Two of the selected records considered Landsat Thematic Mapper (TM) remote sensing imagery to assess BGI's effect on surface temperature in China. The first study investigated urban land surface temperature adjacent to 12 reservoirs in Pearl River Delta, using Landsat 8 TM (Wu *et al.* 2018). The remote sensing images were processed later by ENVI 5.1 and ArcGIS 10.2 software. NDVI was utilized to demonstrate the differences between different surface types. The results revealed that the reservoirs' cooling effect was significant up to a range of 300 m. The potential of these reservoirs to mitigate heat was also affected by the land type and reservoir capacity. The fastest average temperature rise occurred in built-up land, followed by bare land, sparse forest land and forest land. Forest land absorbed more heat and therefore lowered the heating rate. The larger the reservoir's capacity indicated a more substantial cooling effect.

These studies' emerging findings confirm BGI's potential in lowering surface and air temperatures by providing a cooling effect. It is also vital to consider the differences that arise from different urban fabrics. For example, Fung and Jim (2020) investigated BI's potential through a 1.5 m deep pond on an adjacent lawn microclimate in subtropical Hong Kong. Although the results showed that the pondside lawn has lower air temperatures than a concrete rooftop (control), UTCI calculations indicated hotter mean daytime conditions due to the absence of tree shading. These results would have been different if the same study had been conducted in densely vegetated European cities.

Gunawardena *et al.* (2017) sought to distinguish the BGI effect on UHI mitigation between the canopy and urban boundary layers from the perspective of city planning and urban climatology. The study found that the evapotranspiration-based cooling of BGI is practically relevant for the canopy layer. The magnitude and distance of cooling are influenced by the size, spread and geometry of green infrastructure. In contrast, the cooling effectiveness at the boundary layer was primarily affected by green spaces' surface roughness.

Lehnert *et al.* (2021) turned their attention to thermal sensations experienced in public spaces with BGI (lawns, trees and water fountains) during the summer days in four Czech cities: Brno, Olomouc, Ostrava and Plzen. The study was initially based on bio-meteorological measurements, and indices were then contrasted with questionnaire surveys using TSV. While this study followed a unique approach that allows for assessing the effect of BGI beyond their microclimates functions, the results showed that the thermal comfort is primarily affected by place and time, indicating consistency with the findings of Žuvela-Aloise *et al.* (2016).

Two of the selected records looked into blue-green roofs' potential to mitigate the urban heat island effect. On the roof of a school building in Seoul, South Korea, a blue-green roof made of plastic assemblies was constructed and monitored for different periods in August–September 2014 and April–May 2015 (Shafique & Kim 2017). The monitoring included surface temperature measurements for the blue-green roof and control roof using temperature sensors. The comparison found that the blue-green roof was 4 °C cooler than the control roof and confirmed that such sustainable roofs effectively mitigate urban heat.

Another study found reduced temperatures of blue-green roof systems by investigating cooling due to maximized evaporation (Cirkel *et al.* 2018). The authors considered the storage of precipitation (i.e. the main feature of the blue roof) as a useful practice to increase evaporation. Furthermore, the extra cooling capacity provided additional biodiversity merits through achieving a higher potential for more natural vegetation.

The studies presented on the thermal performance of blue and blue-green roofs support the notion that these systems reduce the air and surface temperatures. However, there remain unanswered questions about their performance compared to typical green roofs (i.e., intensive and extensive) and whether blue-green roofs would create synergies with stormwater management or structural problems due to the enlargement of the storage layer. Furthermore, no study has explicitly looked at the effect of blue and blue-green roofs on the energy performance of buildings. Since these rooftop systems reduce heat fluctuations through the roof, it is expected that they would decrease energy demand and therefore decrease carbon emissions and contribute to climate change mitigation.

The potential of BGI to mitigate the urban heat differs from one place to another due to differences in geographic and climatic features throughout the urban layers. Different climates have different meteorological patterns that influence evapotranspiration, an essential process driving the BGI cooling. The sensibility of evapotranspiration differs between climates (i.e., humid, temperate and dry) (Tabari & Hosseinzadeh Talaee 2014), meaning that special consideration to evapotranspiration promotion needs to be considered and taken into account when incorporating climate change in the design of BGI. Although the factors that impact these systems' cooling effect can be generalized to the global context, special attention needs to be paid to the urban scale. A larger portion of the studies reported in this section considered neighbourhood- and regional-scale but not site- and building-scale. There is still little known about the effectiveness of small-scale BGI to mitigate the UHI effect on a microclimate scale instead of a broader neighbourhood- or regional-scale. Based on the findings of the selected records, Table 2 summarizes the factors that impact the urban heat mitigation of blue-green applications.

The studies reviewed in this section include factors that affect the thermal performance and cooling effect of BGI. It is concluded that the cooling effect of BGI is a complex process and is influenced by the size of the dynamic BGI systems and the land/building types on which they are implemented. Similar to GI, the shading conditions are also a key parameter in the cooling efficiency of BGI. However, the water temperature in BGI, which is not presented in the typical green infrastructure, is uniquely an additional influencing factor.

**Table 2** | Factors affecting the potential of BGI in mitigating urban heat

| Factor/Finding | Relationship/Effect | Reference |
|---|---|---|
| Shading conditions | Blue-green applications accompanied with shaded conditions (e.g. trees) reduces solar radiation up to 96.5% resulting in a better cooling effect | Fung & Jim (2020) |
| Size and shape of blue-green application | Larger blue-green applications have better capability to mitigate heat | Wu *et al.* (2019), Wu *et al.* (2018), Gunwardena *et al.*, (2017) |
| Land type (i.e. built-up, bare, sparse, forest) | More giant vegetated lands contribute to more significant heat absorption and thus better cooling effect | Wu *et al.* (2018), Žuvela-Aloise *et al.* (2016), Gunwardena *et al.* (2017) |
| Building type, time of the day, water temperature | Reducing building density and pavement surfaces in addition to increasing water spaces improves the cooling function | Žuvela-Aloise *et al.* (2016), Lehnert *et al.* (2021) |
| Thickness of drainage layer in the blue-green roof | Increasing the thickness of the drainage layer enhances evapotranspiration and the cooling effect of blue-green roof | Shafique & Kim (2017); Cirkel *et al.* (2018) |

Significant correlations were obtained between the performance of BGI and meteorological conditions such as air temperature, wind speed, and solar radiation. Additionally, the cooling effect differs during the time of the day. When assessing the thermal benefits of BGI, it is essential to distinguish between human-made, engineered systems and natural water bodies and watercourses. While landscape designers cannot do much on the latter systems, design variables of engineered systems could be altered to provide better performance. Development and rigorous evaluation of these variables (e.g. albedo of surfaces, water release time, plant choice and physical properties of soil) are missing in the literature.

### 3.2. Stormwater management and flood reduction

Climate change, resulting in more frequent and intense storms, can increase surface runoff and elevate flooding risks (Westra *et al.* 2014). Scholars have employed diverse approaches to examine the potential of BGI in reducing runoff and flood magnitude. The most common approaches were rainfall-runoff modelling and computer simulation to estimate runoff volumes, runoff peak rates and flood magnitude. The literature noticeably lacks in-field tested studies. This section reviews ten studies of the selected records that investigated the effects of BGI in managing stormwater.

In reducing runoff discharge, Versini *et al.* (2018) employed rainfall-runoff models to simulate different urban infrastructures, including conventional systems such as impervious pavement, GI systems including permeable pavement, green spaces, green roofs, and green swales and BI systems including retention basins at a neighbourhood located in the eastern suburbs of Greater Paris. The simulation was carried out using Multi-Hydro. Rainfall scenarios were computed for 30 minutes duration and several return periods: 1 month, 2 months, 6 months, 1 year, 2 years, 5 years, 10 years and 20 years. Runoff volumes and peak flows were then averaged for all return periods. The research has established different scenarios depending on the used blue and green applications, including a combined BGI scenario. However, the study does not outline the percentage reductions individually for the peak flow and runoff volume making it difficult to assess which hydrologic performance indicator best. The scenarios with their corresponding average percentage reductions of runoff volume and peak flow are shown in Figure 6. These findings provide convincing evidence that combining blue and green infrastructure (e.g. green swales and retention basins) is the most effective practice to reduce excess runoff discharged into the sewage system, providing a solution to cope with the increasing rainfall due to climate change.

In a further attempt to optimize blue-green solutions to manage stormwater through selection frameworks, Ghofrani *et al.* (2019) used the Stormwater Management Model (SWMM) to assess the flood reduction performance for bio-retention cell, infiltration trench, and vegetative swale as GI components and a rain barrel as a BI component. The components were assessed individually and combined at the regional scale. As its case study, the research, which took the South Gippsland Basin in Victoria, Australia, compared the 'hours flooded' in 10 different junctions of the study area. The authors compared the current situation (where no BI, GI or BGI practices are implemented) with 1 BI scenario, 7 GI scenarios, and 6 BGI scenarios. They found that seven junctions had a

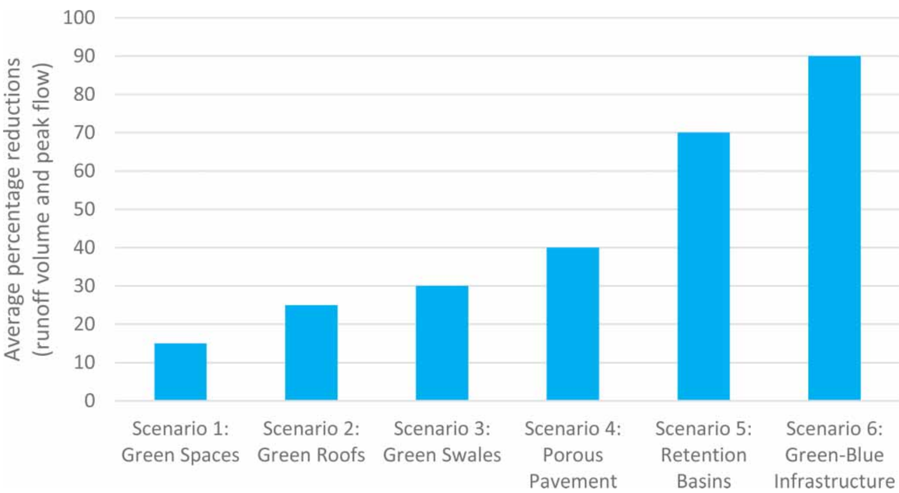



**Figure 6** | Average percentage reductions of runoff volume and peak flow for different green and blue-green applications (Versini *et al.* 2018).

zero hour-flood in the post-development condition. The average reduction in the number of hours in the other three junctions is illustrated in Table 3. BGI reduced 91% of the average flooding hours compared to the conventional scenario, whereas GI reduced average flooding hours by 86%.

Research that did not rely on rainfall-runoff modelling to provide evidence on the potential of BGI in managing stormwater and minimizing floods has also been reported. Sörensen & Emilsson (2019) used long-term trends of Swedish insurance claims to assess BGI efficiency at the neighbourhood scale. The study compared a 3-ha area in Augustenborg that had been retrofitted according to typical design principles of BGI (including detention ponds, temporary storage areas, green roofs, swales and ditches) with adjacent conventional neighbourhoods where no or very few stormwater control measures had been installed. Figure 7 shows the number of flooded properties (obtained from insurance claims) per hectares of area for Augustenborg and the five nearby regions. Given that the study depended on insurance claims, the findings reveal the effectiveness of BGI in reducing flood risks; however, they also provide evidence for the economic benefits to the population in serviced areas.

Bakhshipour *et al.* (2019) developed a simulation-optimization framework to optimize drainage systems considering hybrid infrastructure in Ahvaz, Iran. Design objectives (e.g. direct/peak runoff reduction and water

**Table 3** | Average hours flooded for different blue-green scenarios (Ghofrani *et al.* 2019)

| **Scenario: No GI/BI/BGI** | | **Scenario: B.I.** | |
|---|---|---|---|
| System | Average Hours Flooded | System | Average Hours Flooded |
| | 40.97 | Rain barrel | 3.47 |
| Scenario: GI | | Scenario: BGI | |
| System (s) | Average Hours Flooded | System(s) | Average Hours Flooded |
| Bio-retention cell + Vegetative swale | 5.77 | Rain barrel + Bio-retention cell | 4.59 |
| Bio-retention cell | 5.72 | Rain barrel + Vegetative swale | 4.22 |
| Vegetative swale | 5.68 | Rain barrel + Infiltration trench | 3.34 |
| Infiltration trench | 5.52 | Rain barrel + Bio-retention cell + Infiltration trench | 3.3 |
| Bio-retention cell + Infiltration trench | 5.12 | Rain barrel + Vegetative swale + Infiltration trench | 3.29 |
| Vegetative swale + Infiltration trench | 5.1 | Rain barrel + Bio-retention cell + Vegetative swale + Infiltration trench | 2.25 |
| Bio-retention cell + Vegetative swale + Infiltration trench | 5.1 | | |

quality control), site-specific features, climatic characteristics and costs were taken into account for the optimization process. Figure 8 illustrates a flow chart of the optimization-simulation process. The results suggested that hybrid BGI can economically compete with traditional grey-only pipe networks. However, the infrastructure's vulnerability would increase when rainstorms exceed design storms due to reduced pipe sizes.

Results obtained by Buonomo *et al.* (2007) demonstrate that extreme rainfall values increase as both the return period of the rainfall becomes longer, and the duration becomes shorter, indicating an adverse impact of climate change (Rodríguez *et al.* 2013). However, increased rainfall trends due to climate change are not consistent throughout the world. For example, while mid- to upper latitude regions have experienced more significant rainfall, reports showed a decreasing rainfall trend in the Mediterranean area (IPCC 2007). The findings of this study warrant further investigation in the used design storms and intensity-duration-frequency (IDF) curves during the planning of blue-green-grey infrastructure.

Another study on hybrid infrastructure compared the hydraulic performance of two scenarios of BGI combinations at the watershed scale in Bueno Aires, Argentina (Kozak *et al.* 2020). The first scenario considered major grey infrastructures with minor BGI retrofits, whereas the second scenario considered major BGI with minor grey applications. Overall, the study found that the first scenario accommodates the excess surface runoff responsible for flooding and damage by expanding conveyance systems. In contrast, the second scenario causes a significant reduction in the initial runoff due to the inclusion of storage systems, meaning that a substantial amount of pollutants in the runoff would be absorbed by the proposed BGI (Kozak *et al.* 2020).

Other scholars such as Rozos *et al.* (2013) have uniquely identified the potential of integrating blue-green measures at the building scale. The integrated BGI system combined harvested rainwater and locally treated greywater to irrigate green roofs using UWOT (the Urban Water Optioneering Tool). Although the results indicated that the combined system provides multiple benefits (e.g. reducing peak runoff and water demand), there was an increase in the required energy due to the pump's use to transfer the water from the tank to the green roof (Rozos *et al.* 2013). The study also points out that this energy increase can be substituted by the energy saved from evaporative cooling without demonstrating this trade-off relationship's numerical quantification.

In Philadelphia, US, a blue-green roof was implemented and accompanied by low-cost water level loggers to monitor the outflow process (Toran 2016). The purpose was to understand the attenuation functionality of such systems. The following results were reported:

1. There was no storage for short storm events (less than an hour), and the roofs immediately drained after the storm ended during a small storm event (less than an hour).
2. For more extended storm events (6 to 12 hours): roofs stored water while the storm intensity dropped, then drained about an hour after the end of the precipitation event.

After analyzing the hydrologic response, the study found that the travel time was too short due to the rapid flow of water from the roofs, consequently reducing the opportunity for evaporation. A suggested solution to mitigate this problem is to decrease the roof outlets' size but ensure that the water level does not exceed the roof capacity.

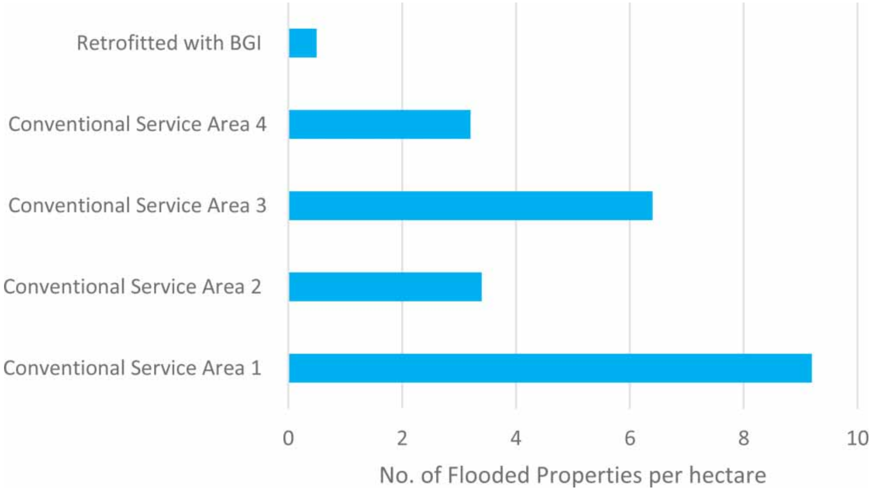



**Figure 7** | Number of Flooded Properties (NFP) per hectare in the study of Sörensen & Emilsson (2019).

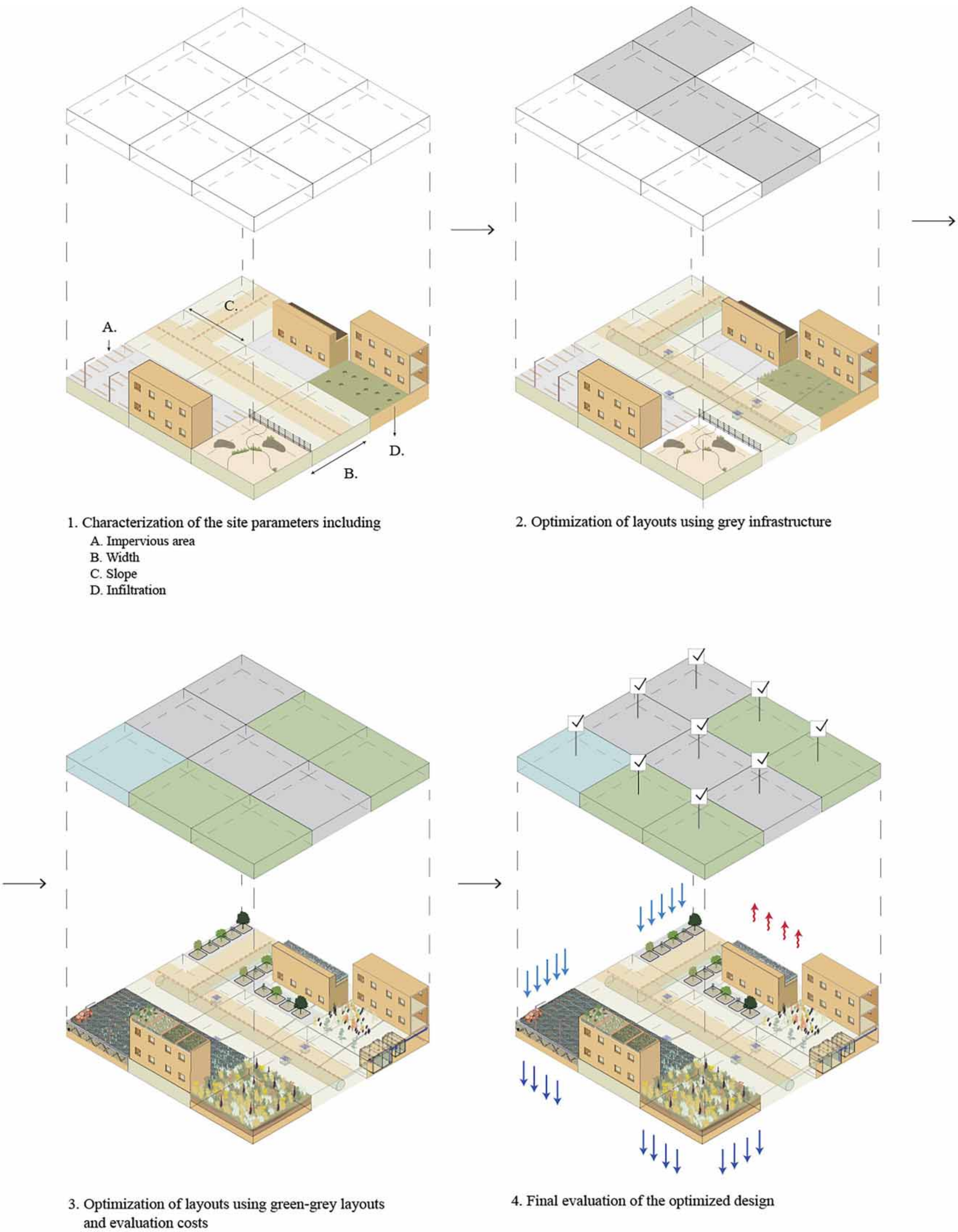



**Figure 8** | Simulation-optimization of blue-green-grey infrastructure (Developed based on the study of Bakhshipour *et al.* 2019).

In Catania, Italy, modular tray-based blue roof systems (Figure 9) were constructed using different geotextile materials (polypropylene and polyester fabrics) and different orifice sizes (5.7 mm and 7.1 mm) (Campisano *et al.* 2018). The selection of geotextile was made carefully to achieve the best permeability and porosity. Orifice size had to be sufficiently small to allow detention and large enough to prevent detention time from exceeding 24 hours. Laboratory tests were carried out by simulating a 2-yr and 10-yr return period rainfall intensities for duration ranges between 30 and 60 minutes. The authors hypothesized that the outflow from the roof is determined by the combined action of geotextile material and orifice size. The laboratory experiments revealed that both the orifice size and the geotextile material are influential design factors.

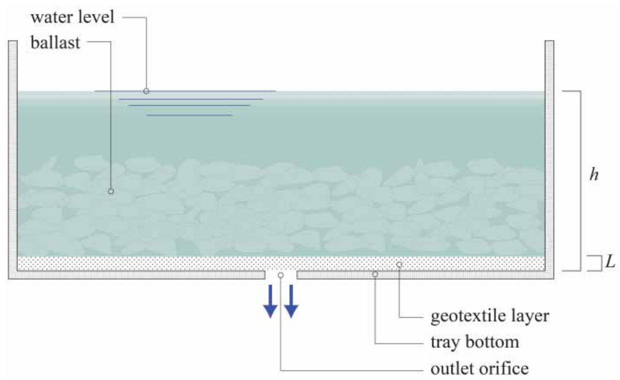



**Figure 9** | Schematic drawing of the modular tray-based blue roof – Adapted from Campisano *et al.* (2018).

Drawing on the previous study, a full-scale pilot installation of a modular tray-based blue roof was established in the same city and monitored for 16 months (Campisano *et al.* 2021). The authors found that although this type of blue roof is designed for detention, it can provide retention benefits reducing an average of 34% of the runoff. Furthermore, Campisano *et al.* (2021) suggest carefully selecting antecedent dry wet period (ADWP) when identifying and separating rainfall events during the analysis. Such a recommendation is essential when further research is established in this area and different contexts need to be made. The findings of these two studies are summarized in Table 4.

Another study in Seoul, South Korea, compared a blue-green roof to a control roof, both made of plastic assemblies (Shafique *et al.* 2016). The blue-green roof assembly was constructed according to the green roof's standard design but included additional storage later, and the control roof was simply an empty assembly. Hydrologic monitoring was carried out during different events in July 2017 at an average rainfall intensity of 90 mm/hr. The findings revealed that surface runoff and peak flow from the blue-green roof were much less than the control roof due to the increase in time of concentration and attenuated rainfall amount. The study, however, offered a limited discussion on the detention time and the used orifice sizes. The detailed stormwater performance reported is summarized in Table 4.

The reviewed literature provides insights into the potential of BGI to manage stormwater and reduce flood risks. These results are site- and scale-specific and may apply only to particular climates, as Fenner (2017) argues. Therefore, it is vital to consider region-specific conditions and regulations when these studies are reflected in other contexts. For instance, Liu *et al.* (2019) examined six municipality-led BGI projects from Beijing in China and Copenhagen in Denmark to suggest necessary considerations for stormwater management at the city scale. The lessons emerged through document review, site observations, and interviews with project managers. While Beijing's case projects were inspiring examples of non-pipe-based practices to stormwater management, Copenhagen's case projects adopted an integrated approach to combine stormwater management targets with amenity improvements. The comparative study gives recommendations for city administrators to implement blue-green solutions and multi-benefit stormwater management practices.

Grey infrastructure, despite its limitations, is still essential in urban areas. The reported studies support the hybrid infrastructure's validity that combines blue-green and grey components in one system. Integrating blue-green-grey infrastructure may provide an excellent opportunity to adapt to climate change by improving their response to the increased hydrologic and hydraulic loading. However, complications of this combination may arise, which is a research aspect that is still not well understood in the literature. The key takeaways that can be concluded from this section are that the addition of blue infrastructure components such as retention basins, temporary rainwater storage, and rain barrels enhances and maximizes the capacity of green infrastructure components such as bioretention cells and vegetative swales. Retrofitting neighbourhoods with BGI noticeably improve stormwater management and consequently reduce flood risks.

Nevertheless, climate change adaptation is marginally incorporated in the design of BGI. Although there are a few, current studies show the promising hydrologic performance of blue and blue-green roofs. However, similar to the point made in the previous section on UHI mitigation, the effect of blue and blue-green roofs' different design parameters on their performance is not examined – unlike studies on the typical green roofs.

**Table 4** | Summary of blue and blue-Green roof studies extracted from

| Context | Roof type | | Precipitation and storm duration | Peak runoff rate reduction | Detention time | Reference |
|---|---|---|---|---|---|---|
| Catania, Italy | Modular tray-based Blue Roof (laboratory study) | Geotextile: Polypropylene – Orifice size: 5.7 mm | 10-yr return period of $P = 89.9$ mm/hr – Duration: 30 minutes | 80% reduction | 6 hours | Campisano *et al.* (2018) |
| | | Geotextile: Polypropylene – Orifice size: 7.1 mm | 10-yr return period of $P = 89.9$ mm/hr – Duration: 30 minutes | 64% reduction | 2 hours | |
| | | Geotextile: Polyester fabrics – Orifice size: 7.1 mm | 2-yr return period of $P = 7.1$ mm/hr – Duration: 60 minutes | 30% reduction | 2 hours | |
| Catania, Italy | Modular tray-based Blue Roof (full scale pilot installation) | Geotextile: Polypropylene Orifice size: 7 mm | 26 events over 16-month long monitoring with average $P =$ 9.9 mm | 60% | 3.3 hours | Campisano *et al.* (2021) |
| Seoul, South Korea | Blue Roof | Plastic assembly consists of a storage layer and orifices | One maximum storm event in July 2014 with a $P = 90$ mm/hr | 70% reduction | Detention time is shorter | Shafique *et al.* (2016) |
| | Blue-green Roof | Plastic assembly consists of vegetation and storage layer | One storm event in September 3, 2014 with a $P = 60$ mm/hr | 66% reduction | Detention time is longer | |

### 3.3. Barriers to BGI integration

Technical, social, and institutional barriers hinder the development of integrated applications of BGI. Recent studies have yielded important insights into these barriers, which significantly varied among countries with different legislation, income levels, and industrial development. Despite regional differences, there are several common themes related to BGI implementation are repeated within the literature. For instance, there is a lack of collaboration between public and private sectors and intersectional actors in Belgium, the Netherlands, Sweden, Brazil, and Pakistan (Amaral *et al.* 2021; Casiano Flores *et al.* 2021; Mumtaz 2021; Toxopeus & Polzin 2021; Suleiman 2021). Casiano Flores *et al.* (2021) stressed the importance of multilevel coordination, which often includes different government levels to allocate specific actions and responsibilities concerning BGI in Belgium. Toxopeus & Polzin (2021) hinted at a link between the absence of coordination across public and private sectors and obtaining finance for BGI in the Netherlands. Another study in Sweden suggested reordering relations and renegotiating the roles of planners and water professionals to overcome the barriers to BGI (Suleiman 2021). Similarly, in Brazil, Amaral *et al.* (2021) found a need for intersectoral action. In Pakistan, a study found a lack of intersectoral cooperation concerning BGI and weak linkage among local and international organizations (Mumtaz 2021).

Budget constraints were found to be present in low-income countries such as Pakistan (Mumtaz 2021) but also in higher-income countries such as Belgium (Casiano Flores *et al.* 2021), the US, the UK, and the Netherlands (O'Donnell *et al.* 2021). Limited financial resources in low-income countries rationalize the financial barriers imposed on BGI implementation. However, in higher-income countries, the main reasons are the lack of funding mechanisms and the inability to secure funding for initial investments and long-term maintenance. Financing BGI projects may create social injustice. For instance, Toxopeus & Polzin (2021) argued that not everyone is exposed to the same flood risk, affecting willingness to pay through public (taxation) and private funding. Acknowledging these social injustices is crucial to expanding the implementation of BGI (Amaral *et al.* 2021). Furthermore, there seems to be a general agreement that existing maintenance practices and the lack of systemic monitoring are not only an operational challenge but also a financial barrier to BGI (Suleiman 2021).

Andenæs *et al.* (2021) sought to problematize the lack of risk reduction framework on BGI. In their study, which investigated the building risks associated with blue and blue-green roofs in Norway, the authors indicated that the BGI challenges around the building risks lie not only on the technical level but also on the processual group, which can be mitigated by raising awareness. This recommendation is congruent with O'Donnell *et al.* (2021), who surveyed the international perceptions of BGI in four cities in the US, the UK, the Netherlands and China. Nevertheless, the availability of risk reduction frameworks in Norway, such as the Norwegian standard for safe moisture design (Standard Norway 2020) and guidelines for procurement of climate-adapted buildings (Sivertsen *et al.* 2019), still pave the way to overcome the hurdles. In under-developed countries, where such guidelines are absent, the journey for BGI implementation is expected to be longer.

Thorne *et al.* (2018) and O'Donnell *et al.* (2017) carried out structured and semi-structured interviews with stakeholders, water resource engineers and land/facilities owners from relevant institutional agencies to investigate the barriers to the implantation of BGI in Portland, Oregon, United Stated and Newcastle, United Kingdom. Figure 10 summarizes the one-sided and mutual barriers reported from both cities. The surveys' results demonstrated that uncertainties of hydrologic performance and maintenance concerns are the main technical challenges. There is a general agreement between the two studies that the social and institutional barriers for BGI implementation pose a more significant challenge than their technical counterparts (O'Donnell *et al.* 2017; Thorne *et al.* 2018). Undoubtedly, combination sets of BGI magnify the aforementioned challenges due to the increased complexity of hydro-ecological functionality between individual BGI measures and anticipated higher costs and maintenance.

A follow-up study was performed by O'Donnell *et al.* (2021) to investigate the international perception of urban BGI in four different cities: Newcastle, UK, Oregon, USA, Rotterdam, Netherlands and Ningbo, China. The cross-country investigation found that the key steps to overcome the barriers to BGI implementation, increased awareness, a wider range of funding, implementation in new developments and increased funding were equally perceived among the four surveyed cities.

Another example that explains how functional and institutional aspects negatively affect the integration of BGI is found in the study of Ioja *et al.* (2018). Although the study recognizes that better connectivity was established over the past years between urban waters and green spaces in the city of Bucharest, Romania, some of the


**Figure 10** | The reported barriers for integrating BGI (O'Donnell *et al.* 2017; Thorne *et al.* 2018).

surroundings around the city's lakes have been used for residential purposes, neglecting the fact that they were initially designed to boost green spaces. Hydrologic and ecologic connectivity is a crucial aspect to consider in climate change-oriented BGI. When BGI applications are well connected, they provide backup for each other (Voskamp & Van de Ven 2015). For instance, when one application reaches its capacity, another application takes over and retains the water.

In addition to the general challenges of BGI, challenges of retrofitting old roofs to blue-green roofs were assessed through semi-structured interviews with engineers, consultants, and architects, followed by an execution of two case studies in Trondheim and Oslo, Norway (Skjeldrum & Kvande 2017). The results from the interviews revealed the following challenges:

1. Increasing loads on existing infrastructure;
2. The need for a proper substrate;
3. Preserving the waterproof membrane during construction; and
4. Challenges related to transitions between roof drains.

The study discusses these concerns that need to be considered when constructing a blue-green roof (e.g. cold climate could lead to building up of ice and leakage). Some of the green infrastructure manuals, such as the UK's CIRIA SuDS Manual (Woods Ballard *et al.* 2015) and Canada's Low Impact Development Stormwater Management Planning and Design Guide (TRCA & CVC 2011), refer clearly to these challenges as critical considerations when designing and constructing green roofs. However, no study has precisely quantified 'how' and 'to what extent' these challenges vary and differ between the novel blue and blue-green roofs and well-known green roofs.

## 4. SUMMARY OF RESULTS

Thirty-two studies on blue and blue-green infrastructure were identified and analyzed in this paper. This review's main goal was to investigate the thermal and hydrologic performance of BGI through mitigating UHI and reducing stormwater runoff volumes and rates. The review is systematic, with strict inclusion/exclusion criteria that only include studies on blue- and blue-green infrastructure and excludes green infrastructure studies that do not consider a blue component. This focus is currently needed to acknowledge the recent emergence of blue infrastructure and encourage the distinction between it and green infrastructure. Despite the increased interest in blue-green infrastructure, this review's findings show that only a few studies have assessed their performance and distinguished it from the green infrastructure's performance. The selected papers of this review are summarized in Table 5.

The research attention on BGI has been equally distributed between UHI mitigation and stormwater management, with a slightly more focus on stormwater management, as demonstrated in Figure 11. The vast majority of BGI studies were performed on a large urban scale (e.g., regional- and city-level) in comparison to small scale (building- and street-level), as shown in Figure 11. Undoubtedly, the scale issue is critical in understanding urban infrastructures performance and the influence of the spatial scale's design parameters.

Furthermore, the reviewed records' assessment methods varied, with modelling and simulations and in-situ monitoring sensors being the dominant approaches for the case studies (Figure 12). In records that did not have actual case studies and were more oriented toward understanding the challenges and limitations of BGI than the actual performance of these systems, interviews and document review were the dominant methods.

**Table 5** | Synthesis of the selected studies on blue and blue-Green infrastructure

| | | | | Environmental Services | | Urban Scale | | | Assessment Methods | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No | Author | Year | BGI | UHI | SWM | Laboratory setup | Small building- or street-level | Large regional- or neighbourhood scale | Modelling and Simulation | In-situ monitoring | Remote sensing | Interviews and document/ literature reviews | Insurance claims |
| 1 | Rozos *et al.* (2013) | 2013 | Rainwater harvesting and green roof | | √ | | √ | | √ | | | | |
| 2 | Voskamp & Van de Ven (2015) | 2015 | Various BGI | √ | √ | | √ | √ | | | | √ | |
| 3 | Žuvela-Aloise *et al.* (2016) | 2016 | Ponds, lakes and rivers | √ | | | | √ | √ | | √ | | |
| 4 | Gunawardena *et al.* (2017)[a] | 2016 | Various BGI | √ | | | √ | √ | | | | | |
| 5 | Toran (2016) | 2016 | Blue-green roof | | √ | | √ | | | √ | | | |
| 6 | Shafique *et al.* (2016) | 2016 | Blue-green roof | | √ | | √ | | | √ | | | |
| 7 | Shafique & Kim (2017) | 2017 | Blue-green roof | √ | | | √ | | | √ | | | |
| 8 | O'Donnell *et al.* (2017)[b] | 2017 | Various BGI | | √ | | | | | | | √ | |
| 9 | Skjeldrum & Kvande (2017)[b] | 2017 | Various BGI | √ | √ | | | | | | | √ | |
| 10 | Broadbent (2018) | 2018 | Tree covers and irrigated grass | √ | | | √ | | √ | | | | |
| 11 | Wu *et al.* (2018) | 2018 | Reservoirs | √ | | | | √ | | | √ | | |
| 12 | Cirkel *et al.* (2018) | 2018 | Blue-green roof | √ | | | √ | | | √ | | | |

(*Continued.*)

**Table 5** | Continued

| | | | | Environmental Services | | Urban Scale | | | Assessment Methods | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **No** | **Author** | **Year** | **BGI** | **UHI** | **SWM** | **Laboratory setup** | **Small building- or street-level** | **Large regional- or neighbourhood scale** | **Modelling and Simulation** | **In-situ monitoring** | **Remote sensing** | **Interviews and document/ literature reviews** | **Insurance claims** |
| 13 | Versini *et al.* (2018) | 2018 | Green spaces, green roofs, swales, porous pavement, retention basins and mixed BGI | | √ | | | √ | √ | | | | |
| 14 | Campisano *et al.* (2018) | 2018 | Modular tray-based blue roof | | √ | √ | | | | √ | | | |
| 15 | Thorne *et al.* (2018)[b] | 2018 | Various BGI | √ | √ | | | | | | | √ | |
| 16 | Ioja *et al.* (2018) | 2018 | Various BGI | √ | √ | | | √ | | | | √ | |
| 17 | Wu *et al.* (2019) | 2019 | Lakes | √ | | | | √ | | | √ | | |
| 18 | Ghofrani *et al.* (2019) | 2019 | Rain barrel, bioretention cells, swales, and infiltration trenches | | √ | | | √ | √ | | | | |
| 19 | Sörensen & Emilsson (2019) | 2019 | Detention ponds, temporary storage areas, green roof, swales and ditches | | √ | | | √ | | | | | √ |

(*Continued.*)

**Table 5** | Continued

| No | Author | Year | BGI | Environmental Services | | Urban Scale | | | Assessment Methods | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | UHI | SWM | Laboratory setup | Small building- or street-level | Large regional- or neighbourhood scale | Modelling and Simulation | In-situ monitoring | Remote sensing | Interviews and document/ literature reviews | Insurance claims |
| 20 | Liu *et al.* (2019) | 2019 | BGI | | √ | | | √ | | | | √ | |
| 21 | Bakhshipour *et al.* (2019) | 2019 | Hybrid Grey-BGI | | √ | | | √ | √ | | | | |
| 22 | Mulligan *et al.* (2019) | 2019 | Various BGI | √ | √ | | | √ | | | | √ | |
| 23 | Fung & Jim (2020) | 2020 | Ponds and Lawns | √ | | | | √ | | √ | | | |
| 24 | Kozak *et al.* (2020) | 2020 | Hybrid Grey-BGI | | √ | | | √ | √ | | | | |
| 25 | Lehnert *et al.* (2021) | 2021 | Lawns, trees and water fountains | √ | | | | √ | | √ | | √ | |
| 26 | Campisano *et al.* (2021) | 2021 | Modular tray-based blue roof | | √ | | √ | | | √ | | | |
| 27 | Casiano Flores *et al.* (2021)[b] | 2021 | Various BGI | | √ | | | | | | | √ | |
| 28 | Toxopeus & Polzin (2021)[b] | 2021 | Various BGI | √ | √ | | | | | | | √ | |
| 29 | Amaral *et al.* (2021)[b] | 2021 | Various BGI | √ | √ | | | | | | | √ | |
| 30 | Mumtaz (2021)[b] | 2021 | Various BGI | √ | √ | | | | | | | √ | |
| 31 | Suleiman (2021)[b] | 2021 | Various BGI | | √ | | | | | | | √ | |
| 32 | O'Donnell *et al.* (2021)[b] | 2021 | Various BGI | | √ | | | | | | | √ | |

[a]This study is a meta-analysis of other studies.
[b]Discussion articles with no real case studies.

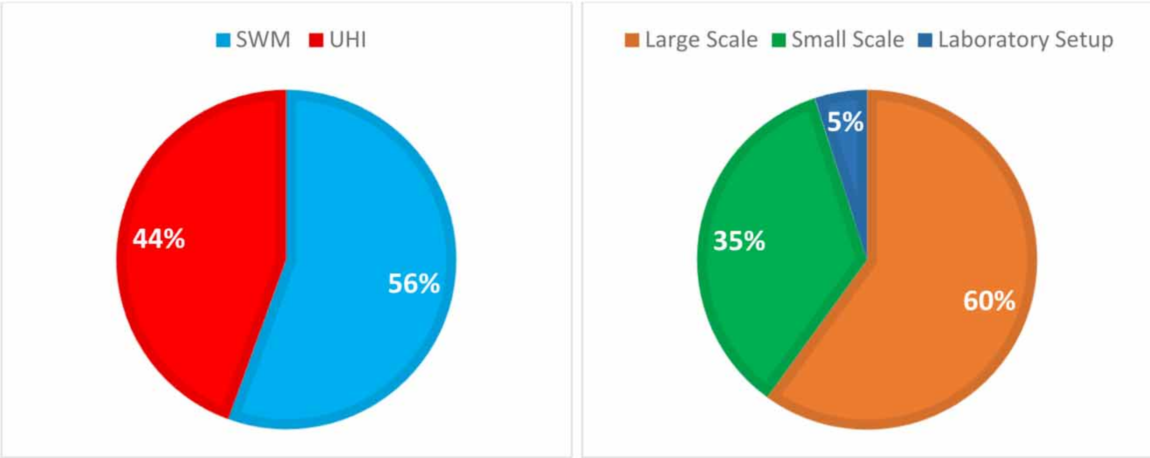



**Figure 11** | The environmental services (left) and urban scales (right) considered in the selected records.

Out of the thirty-two studies, only five studies assessed the blue- and blue-green roofs. These studies focused on one benefit at a time (i.e. thermal or hydrologic performance) and did not consider promoting multiple benefits simultaneously. The absence of studies on multifunctional blue-green roofs creates uncertainties about the trade-offs that would emerge from promoting thermal and hydrologic benefits. For instance, Toran (2016) found that the rapid drainage of rainwater in the blue roof does not allow for storage unless the rainfall event is extended. The use of small orifice sizes on blue roofs leads to reduced drainage. Therefore, greater storage will be achieved, providing hydrologic benefits and thermal benefits due to the promoted evaporation. However, the current literature lacks studies that demonstrate the nature of this trade-off relationship.

Similar to conventional stormwater management technologies, blue and blue-green roofs are usually designed as passive systems with static flow control devices. Emerging literature indicates several advantages in transforming the operation of stormwater systems from static to adaptive through the use of low-cost sensors and controllers (Kerkez *et al.* 2016). The performance of blue- and blue-green roofs can be substantially improved by using adaptive and actively controlled drainage layers. However, as a recent review study concluded, no studies incorporated real-time control (RTC) in green roofs, indicating the immaturity of this research area (Brasil *et al.* 2021).

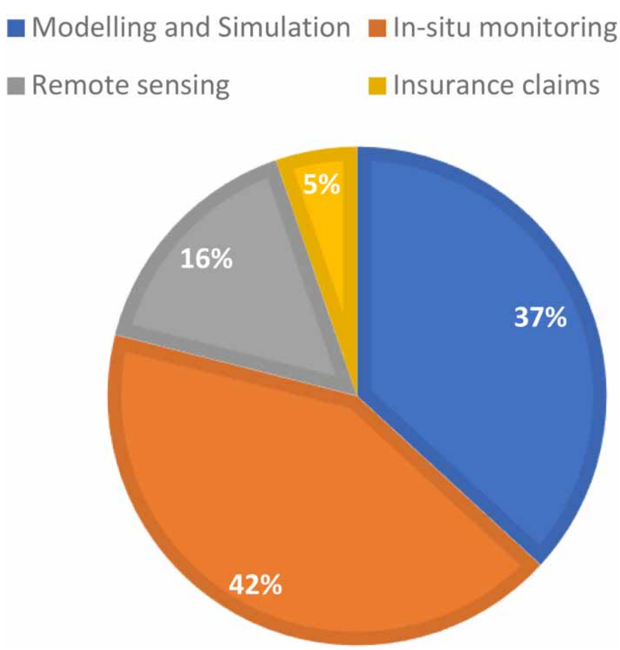



**Figure 12** | Methods of BGI assessment considered in the selected records.

## 5. CONCLUSIONS AND RECOMMENDATIONS

This systematic literature review adopted a comprehensive approach to presenting recent findings on BGI as a means of adapting to and mitigating the climate change effects by identifying two primary environmental services: urban heat mitigation and stormwater management. Because green infrastructure is relatively not a new topic, this paper's methodology excluded the studies that only considered a green infrastructure practice without a blue infrastructure measure. The review identified 32 relevant records that employed a wide range of tools and a diverse set of methodologies in different locations worldwide.

Overall, the selected studies support the notion that BGI can adapt to climate change by mitigating its environmental impacts: UHI mitigation and stormwater management. However, the number of studies that evaluated the BGI effectiveness of UHI mitigation and climate improvement is slightly less than stormwater management. Furthermore, current research shows the potential to implement hybrid blue-green-grey systems by integrating BGI with traditional grey measures. Various assessment methods were considered, including modelling, simulations and monitoring. Models and decision-support tools relatively lack accuracy, prediction adequacy and are only applicable to large-scale retrofits. This fact provides a possible explanation of why most of the literature considered a large urban scale (i.e., regional and neighbourhood) rather than a smaller scale (i.e. building- and street-level).

Additionally, BGI projects' findings cannot be generalized beyond their case studies (e.g., urban scale and local conditions such as climatic and geological factors). Although blue and blue-green roofs can be a valuable opportunity in urban areas, where the lack of space poses a barrier for BGI implementation, scant attention was given to their application compared to the general theme of BGI. Therefore, their role in adapting to the adverse environmental impacts of climate change is still poorly understood, and the impact of the design variables is uncertain. This lack of in-field tested studies on blue- and blue-green roofs is a critical reason why there are not enough design guidelines on their implementation.

Barriers to implementing BGI were explored in this review and similar obstacles are often reported by researchers regardless of their country of origin. Most of the selected records presented a lack of collaboration between public and private sectors and funding constraints. Existing maintenance techniques are commonly considered a financial barrier, not just an operational challenge.

Future research will need to continue investigating the BGI environmental benefits, especially those related to climate change, with a further focus on thermal performance. Understanding how BGI performs at smaller urban scales and microclimate should be considered. More in-situ monitoring is needed to account for computer models' limitations in providing high-quality representation of smaller-scale BGI. Finally, this review paper's contribution warrants further investigation in blue and blue-green roofs, particularly in quantifying their environmental benefits and distinguishing between them and the well-known green roofs in terms of performance, advantages, and limitations. Moreover, decision-makers and governmental actors will have to continue exploring strategies to overcome the barriers imposed on BGI, particularly by identifying funding mechanisms and encouraging collaboration between the different local sectors.

## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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