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Review Article

Where should the green go? A systematic literature review of methods for siting green infrastructure to mitigate rising heat and stormwater risks in cities worldwide

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ABSTRACT

Heat and flooding are frequently cited as among the deadliest and costliest climate hazards, respectively, and both are intensifying due to urban developments and climate change. In response, many cities worldwide are increasingly turning to green infrastructure (GI) to mitigate climate risks such as extreme heat and flooding while enhancing overall resilience. However, existing research suggests that knowledge systems for GI globally have significant gaps that undermine the effectiveness of these investments. These include a narrow focus on limited functions while neglecting others and a lack of research on the decision-making processes that determine which GI functions are prioritized and where. The metrics and models used for siting GI likely shape its effectiveness in managing stormwater and mitigating heat risks in urban settings as well as who benefits from GI investments. This study systematically reviews the academic literature on GI spatial planning worldwide to analyze the GI types, indicators, and methods proposed for siting GI to address heat and stormwater challenges in cities. Our findings reveal that the spatial planning of GI for heat and stormwater remains largely separate in the academic literature, despite widespread calls for multifunctional GI. GI siting for stormwater management has a more robust and consistent body of literature with similar methodologies compared to that for heat risk mitigation, and the types of GI used differ between the two focus areas. This study provides valuable insights that can inform more integrated and effective approaches to GI planning, enhancing urban resilience to climate hazards.

1. Introduction

Heat and flooding are often reported as the deadliest and costliest climate hazards, respectively (Cigler, 2017). They are both worsening due to urban developments and climate change (Keith et al., 2022). As more cities look for ways to enhance heat and flood resilience, urban greening – often referred to as green infrastructure (GI), as well as nature-based solutions, low-impact development, and more – is one of the most commonly proposed strategies (Brenner et al., 2023; Beaumont et al., 2022; Cao et al., 2023, Chang et al., 2021; Sobhaninia et al., 2023). Many cities are increasingly investing in GI to address climate risks such as extreme heat and flooding and to provide other resilience and sustainability co-benefits (Grabowski et al., 2022; Sobhaninia et al., 2024). For example, a recent survey by Meerow and Keith (2022) of urban planners across the United States (US) showed that urban vegetation and forestry was the most common heat strategy – implemented in over 70 % of cities. The US Environmental Protection Agency heavily promotes GI for stormwater management, as does the Chinese government's sponge city policy, while the European Union advocates for nature-based solutions to provide various benefits (Matsler et al., 2021). This has led cities to develop ambitious GI programs, such as New York City's plan to invest $1 billion in GI (NYC DEP, 2017).

Knowledge systems are social institutions, information, and processes that collectively shape infrastructure, and there is growing recognition that knowledge systems must be transformed to ensure that cities are resilient into the future (Chester et al., 2021; Feagan et al., 2019; Sobhaninia, 2024; Sobhaninia et al., 2025). This is particularly true for GI, which challenges current infrastructure planning approaches

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in many ways. For example, GI is typically promoted for its multiple co-benefits or multifunctionality (e.g., a park for recreation, stormwater mitigation, and wildlife habitat), while traditional 'grey' infrastructure is designed for a single purpose (e.g., sewer pipes for stormwater mitigation) (Matsler et al., 2021). Designing GI to provide multiple functions, however, requires new institutions to coordinate siloed actors and budgets as well as novel evaluation metrics, and it is unclear what institutional models are effective (Larsen, 2015).

Current GI knowledge systems have a number of shortcomings that threaten the effectiveness of GI investments. First, definitions and terminology related to GI differ by field and geography, resulting in confusion about what types of features are considered as GI (e.g., permeable pavement or only vegetation) and what benefit(s) GI is supposed to provide (Matsler et al., 2021). Previous research suggests that GI planning often focuses on one or just a few (usually stormwater-related) functions (Finewood et al., 2019; Kremer et al., 2016; Meerow, 2020), with other important functions (e.g., heat mitigation) being often ignored (Heckert and Rosan, 2018; Hoover et al., 2021). The decision-making processes for the spatial planning of GI, determining which GI functions are prioritized and where GI gets spatially sited – what Meerow terms the "politics of GI planning" – are not well understood (Meerow, 2020). This is an important knowledge gap because research shows that there are tradeoffs between different GI functions, designs, and locations, but these remain under-examined (Choi et al., 2021; Depietri, 2022; Meerow and Newell, 2019). GI impacts are also localized, so the spatial planning of GI has environmental justice implications (Heckert and Rosan, 2018). For example, research suggests that the cooling benefits provided by parks decrease with distance (Algretawee, 2022), so where GI gets implemented likely determines which areas and which residents receive any heat mitigation benefit. To address this knowledge gap, Hoover et al. (2021, 2023) recently examined the rationale US cities provide for GI and the criteria for siting GI in 120 plans from 19 cities. Stormwater-related rationale and siting criteria were both common. Heat mitigation was also frequently cited among cities' rationale for GI, but few plans outlined how heat risks or their mitigation would be factored into siting decisions. It is unclear whether cities lack methods to site GI to maximize heat mitigation, or just do not prioritize it.

In this study, we review the academic literature worldwide to see what guidance it offers for the knowledge systems that should guide the spatial planning of GI to tackle growing heat and stormwater risks in cities. This includes the decision-making process and information used to determine what GI features are implemented where in the city and for what purpose. The primary research question posed was: *What GI types, indicators, basis, and models are proposed in the academic literature for the spatial planning of GI to mitigate heat and stormwater risks?*

The indicators and models used for siting GI shape its effectiveness in mitigating heat and stormwater risks as well as how it is distributed across the city. Thus, the careful selection and application of these tools are fundamental to meeting resilience goals. By employing precise and appropriate metrics, city decisionmakers can identify optimal locations for GI installations where they have the greatest potential to mitigate multiple risks.

2. Background

2.1. Heat resilience and green infrastructure

GI is a well-documented strategy for mitigating heat risks, particularly in urban environments where the urban heat island (UHI) effect can significantly elevate temperatures (Shao and Kim, 2022). GI elements – e.g., green roofs, urban parks, and street trees – combat the UHI by providing shade and facilitating evapotranspiration, a process whereby plants and surface soils release water vapor into the air, effectively cooling their surroundings (Beaumont et al., 2022; Bosch et al., 2021). These natural features can lower surface and air temperatures in urban areas, making them critical in mitigating heat risks (Keith and Meerow, 2022; Pearsall, 2017). Strategically placed trees and vegetation not only block solar radiation but also cool the air as water is released from their leaves through evaporation and transpiration, reducing the ambient temperature and improving comfort levels for city residents (Shao and Kim, 2022; Petri et al., 2019).

Moreover, GI enhances the resilience of cities during extreme heat events, a growing concern as climate change leads to more frequent and severe heatwaves (Jia and Wang, 2022; Meerow and Keith, 2021). By integrating natural landscapes into urban planning, cities can create cooler urban microclimates that reduce the demand for air conditioning, thereby lowering energy consumption and associated greenhouse gas emissions (Norton et al., 2015; Tehrani et al., 2025). Additionally, green spaces provide community gathering spots that offer relief from heat, especially in densely populated areas lacking adequate indoor cooling facilities (Brenner et al., 2023). This accessibility to shaded, cooler outdoor environments is crucial for populations that are more sensitive to heat due to socio-spatial characteristics, such as the elderly, children, and those with health issues (Brenner et al., 2023).

2.2. Stormwater management and green infrastructure

GI can also aid in stormwater management by mitigating surface runoff volumes and flow rates, improving water quality, and enhancing infiltration (Chang et al., 2021). Forms of GI commonly designed to mitigate stormwater include green roofs, rain gardens, and bioretention swales (bioswales), all of which can be implemented at different scales. These scales include the national/regional level, such as river corridors and forests; county/city level, like watercourse edges and parks; and local/site level, such as urban street greenery and community gardens (Skujāne and Spage, 2022).

GI naturally absorbs and filters stormwater, thereby reducing the burden on traditional sewer systems and preventing overflow events in combined sewer systems that can lead to water pollution (Almenar et al., 2021). Unlike conventional grey infrastructure, which typically involves directing stormwater through pipes and concrete channels, GI uses plants, soil, and other natural elements to manage water where it falls. This minimizes surface runoff, can enhance the recharge of local aquifers, and may significantly reduce the contamination of water bodies by pollutants like pesticides, heavy metals, and sediments (Raei et al., 2019; Taghizadeh et al., 2021; Li et al., 2017).

Additionally, effective GI siting in urban areas is critical for enhancing groundwater recharge while managing stormwater. Permeable surfaces such as bioswales, rain gardens, and infiltration basins can reduce surface runoff and facilitate water infiltration into underlying aquifers. Strategic placement of these GI elements in areas with suitable soil permeability and low contamination risk can maximize recharge benefits (Granados-Olivas et al., 2016; McFarland et al., 2019; Addo-Bankas et al., 2024).

3. Methodology

This research aimed to identify the types of GI, indicators, methods, and models researchers have proposed for the spatial planning of GI to address heat and stormwater management risks in urban settings. To understand that, a systematic review was conducted using the framework outlined by Moher et al. (2009). The analysis focused on identifying the predominant indicators and models used in the literature for heat resilience and stormwater management. The methodology was guided by and adapted from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) Checklist, as suggested by Tricco et al. (2018).

The initial phase of data collection involved an extensive search on the Web of Science (WoS) database on October 26, 2023. The search aimed to comprehensively cover the literature regarding the siting of GI for tackling both heat and stormwater risks. The search query was structured around two key themes: heat mitigation and stormwater management, and was limited to studies published in English with no time limits. To avoid limiting results geographically because of different terminology, many synonymous terms for GI were included (Matsler et al., 2021). The following search query was used:

TITLE-ABS-KEY(("green infrastructure" OR "low impact development" OR "water sensitive design" OR “water sensitive urban design” OR "sustainable urban drainage" OR "nature-based solution" OR "best management practice" OR “stormwater control measure” OR “sponge city” OR “stormwater quality improvement device” OR “integrated urban water management” OR “nature-based solution” OR “urban forest*”) AND (“urban” OR “city” OR “cities”) AND (“spatial planning” OR “siting” OR “optimization”) AND ((“heat” OR “cool”) OR (“stormwater” OR “hydrolog*” OR “flood*”)))

The search yielded 505 articles, from which abstracts were thoroughly reviewed to pinpoint studies addressing GI siting for heat risk mitigation and/or stormwater management. This initial screening resulted in the exclusion of 363 studies that did not align with the research objectives. Most of these studies were assessing the existing GI’s impacts on heat and stormwater mitigation rather than proposing new GI locations to address heat and stormwater management. The subsequent detailed review of the remaining 142 studies led to the exclusion of an additional 64 studies deemed irrelevant. Most of these studies were focused on assessing design alternatives rather than using heat or stormwater indicators to site GI.

The focused examination of the remaining 78 studies utilized the PRISMA-ScR Checklist (Tricco et al., 2018) to categorize data concerning GI siting. Each study was meticulously analyzed using the qualitative inductive content analysis method. This approach facilitated an organic emergence of categories as the literature was reviewed, allowing for the addition of new information to existing categories or the creation of new ones as necessary. The analysis was comprehensive, ensuring all relevant data was captured and categorized, fostering a comprehensive comparison of different perspectives and minimizing redundancy.

Through this rigorous systematic literature review and inductive content analysis, the most commonly used GI siting metrics and models were distinctly identified for both heat mitigation and stormwater management. Additionally, studies published after the initial October 2023 search were also identified through Google Scholar and were acknowledged and used for their insights, although they were not included in the systematic review. The research methodology

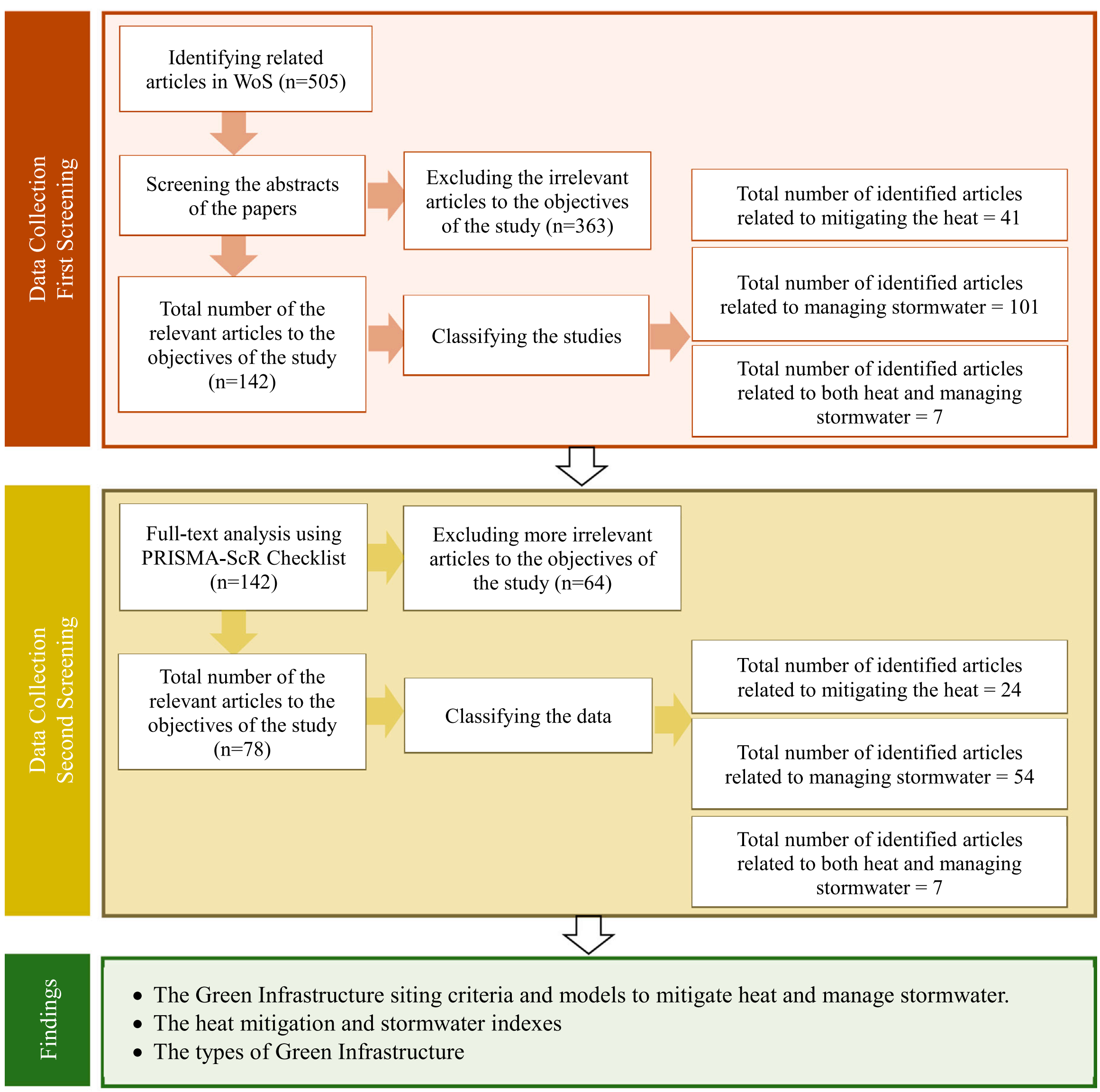

Fig. 1. Systematic Literature Review, adapted from Moher et al. (2009).

incorporated many relevant findings from these additional studies in the background, analysis, and results sections, which enhanced the scope of the research. The number of studies reviewed was deemed sufficient to achieve the research objectives, with further additions unlikely to impact the results significantly. Fig. 1 illustrates the systematic literature review process.

4. Results

First, we examine general trends in studies on the spatial planning of GI for heat mitigation and stormwater management. Fig. 2 shows the temporal trend of these studies. Clearly, the number of relevant studies has increased over time, with almost 80 % of the stormwater mitigation studies and about 70 % of the heat mitigation studies being published in the past five years. Additionally, more studies focus on siting GI to manage stormwater (72 % of studies) rather than on heat mitigation (28 % of studies).

4.1. Geographic distribution of GI spatial planning studies

We examined the geography of the empirical research on GI spatial planning for heat mitigation and stormwater management. Fig. 3 summarizes the geographic distribution of studies using GI to mitigate heat (red dots) and stormwater (blue dots) with the size of the points being proportionate to the number of studies. As can be seen in Fig. 3, Tehran, Iran and Xian, China, are the cities with the most studies on GI spatial planning for stormwater management. Other areas that have been repeatedly studied are Naples in Italy, Wuhan in China, New York, Los Angeles, and Austin in the US. Case studies that were mostly studied to site GI to address heat are the Yanshuei River Basin in Taiwan, Surabaya in Indonesia, and Detroit and Phoenix in the US. Table 1 shows the spatial distribution of studies on siting GI to mitigate heat and stormwater risks.

Next, we examine the GI spatial planning literature focused on heat mitigation and stormwater management in turn, comparing the GI types, siting basis and hazard-related indicators in the studies.

4.2. GI Spatial planning literature on heat mitigation

The literature on spatial planning of GI for heat mitigation focuses on different GI types compared to studies centered on stormwater management. Table 2 and Fig. 4 provide a breakdown of GI types in the heat-focused studies. Street trees, green roofs, urban parks, and green open spaces are the most commonly discussed GI types in this literature. Some studies also used the generic term 'green infrastructure' without specifying which type.

4.2.1. The basis for GI spatial planning in the literature focused on heat mitigation

The literature on GI for heat mitigation proposed a wide range of data sources and methods for spatial prioritization (Table 3 and Fig. 5). Almost half the studies used remotely sensed land surface temperatures (LST) in some way for GI siting, for example, to identify areas of high heat vulnerability (Sanchez and Reames, 2019). Some of these studies combined LST with other data types, such as cadastral, or ownership data, to identify promising locations such as vacant land in hotter areas (Pearsall, 2017). Similarly, Cady (2019) proposed siting on vacant land with a high percentage of impervious surface. Studies also used population density and demographic variables to identify locations where people would benefit from GI siting (Beaumont et al., 2022). Researchers also prioritized locations based on various types of accessibility, such as access to cooling centers and green space (Sanchez and Reames, 2019).

The literature proposes various numerical modeling approaches for GI spatial planning for heat mitigation. The most common was the use of microclimate simulation to identify locations where GI could be most effective, with multiple studies using ENVI-Met software to conduct simulations (Lin and Lin, 2016; Zölch et al., 2019). ENVI-Met is a three-dimensional numerical model used to study urban microclimates, offering spatial resolutions from 0.5 to 10 m and temporal resolutions from 1 to 5 seconds. The model dynamically simulates interactions between surfaces, plants, and air at the urban microclimate scale, incorporating shortwave radiation from the sun and longwave radiation from the Earth's surface while accounting for shading, reflection, and re-radiation by buildings and vegetation. It also considers transpiration,

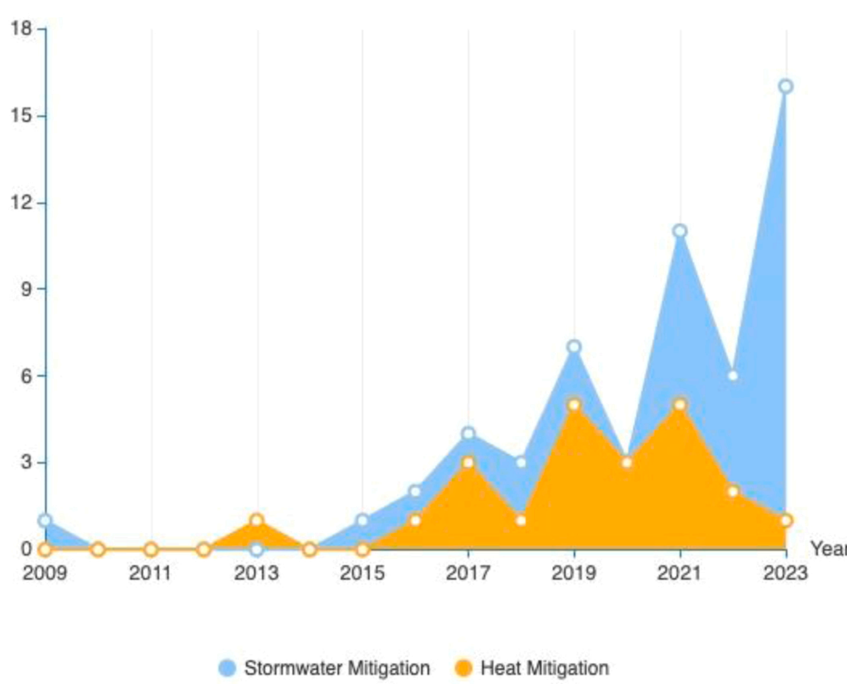

Fig. 2. Temporal trend of studies on siting GI to mitigate heat and stormwater risks.

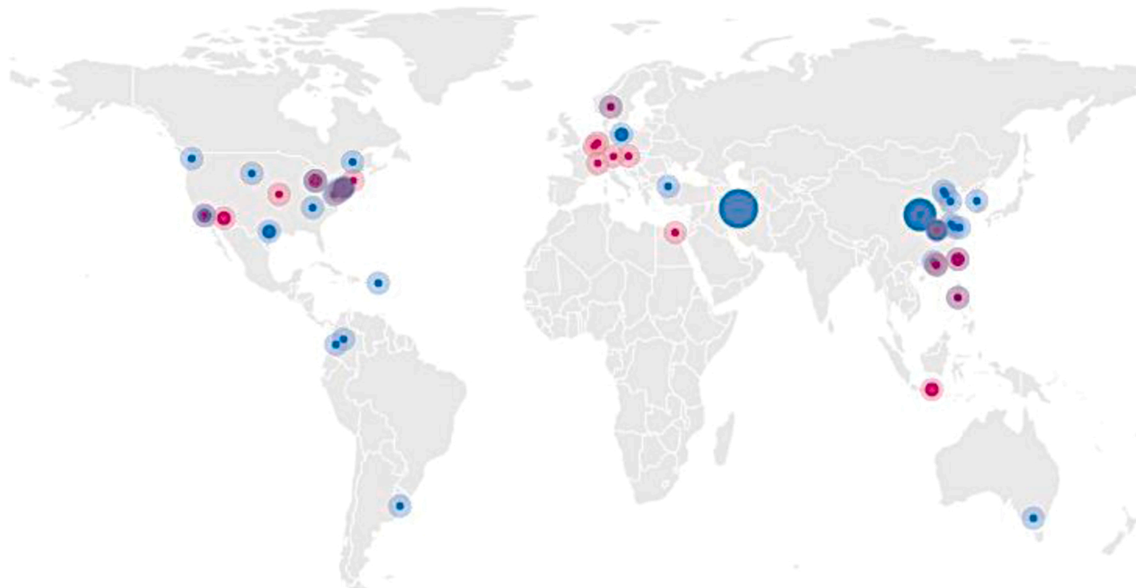

Fig. 3. Geographic distribution of studies on siting GI to mitigate heat and stormwater risks. Blue dots represent stormwater studies, red dots represent heat studies, and the size of the point is proportionate to the number of studies.

Table 1
Geographic distribution of studies on siting GI for heat mitigation and stormwater management.

Country	Number of Heat Case Studies	Number of Stormwater Case Studies
USA	8	14
China	3	16
Germany	2	0
Indonesia	2	0
Taiwan	2	1
Austria	1	0
Belgium	1	0
Egypt	1	0
Norway	1	1
Switzerland	1	0
Philippines	1	0
Australia	0	1
Iran	0	7
Italy	0	2
Turkey	0	1
South Korea	0	1
Colombia	0	2
Canada	0	2

Table 2
GI types in studies focused on heat mitigation.

GI Type	Number of Studies	Sample Studies
Street Tree	7	Pearsall (2017), Beaumont et al. (2022), Elbardisy et al. (2021)
Green Roof	6	Sanchez and Reames (2019), Declet-Barreto et al. (2013), Brenner et al. (2023)
Green Infrastructure (generic)	5	Chang et al. (2021), Reinwald et al. (2019), Pratiwi et al. (2018)
Urban Park	4	Declet-Barreto et al. (2013), Chen et al. (2022), Syafitri et al. (2020)
Green Space	3	Pearsall (2017), Cady (2019), Smith et al. (2017)
Community Garden	1	Smith et al. (2017)
Cooling Corridor	1	Wu et al. (2020)
Green Wall	1	Syafitri et al. (2020)
Public Square	1	Zölch et al. (2019)

evaporation, and the sensible heat flux from vegetation, incorporating plant physical characteristics, dynamic calculations of surface and wall temperatures, as well as water and heat exchanges from the soil, including water uptake by plants (Petri et al., 2019; Lin and Lin, 2016; Reinwald et al., 2019).

Beaumont et al. (2022) used UHI sensitivity to site GI by modeling UHI and population density and evaluating the areas that were most sensitive to UHI effects by analyzing population density, housing density, and the density of sensitive population (population aged 60 and above). In their study, the final prioritization of districts to site GI was achieved by merging the three indicators into a single indicator, known as the UHI Sensitivity Composite Indicator (USCI). Districts with higher USCI were given priority in the greening plan.

Spatial multi-criteria decision analysis (MCDA) is another common modeling approach for GI spatial planning, which typically translates various decision criteria into spatial indicators (e.g., LST or demographic variables), maps those indicators across study areas, and combines indicator layers to identify priority locations (Chang et al., 2021; Meerow, 2019; Meerow and Newell, 2017).

Two studies used downscaled climate models in combination with other data to identify priority areas for GI. For example, Brenner et al. (2023) evaluated the vulnerability of urban areas to heat by analyzing key indicators of heat exposure from a downscaled climate model and population sensitivity from demographic data. The degree of heat exposure was measured by combining different temperature measures under present-day climate conditions and where temperatures would likely increase under climate change projections. A three-step modular approach was used in their study to pinpoint priority locations for green roofs to mitigate heat: assessing the heat vulnerability, compiling green roof inventory and potential sites for greening, and intersecting the results.

4.2.2. *Heat indicators in the literature on GI spatial planning*

Our reviews show that heat risks are measured in different ways, including with Land Surface Temperature (LST), Air Temperature (AT), Mean Radian Temperature (MRT), Physiological Equivalent Temperature (PET), heat vulnerability indices, Green and Open Space factor, and modeled heat index (Table 4 and Fig. 6). LST and AT, however, were by far the most common heat indicators.

LST is a measure of the thermal emission from the Earth's surface. It

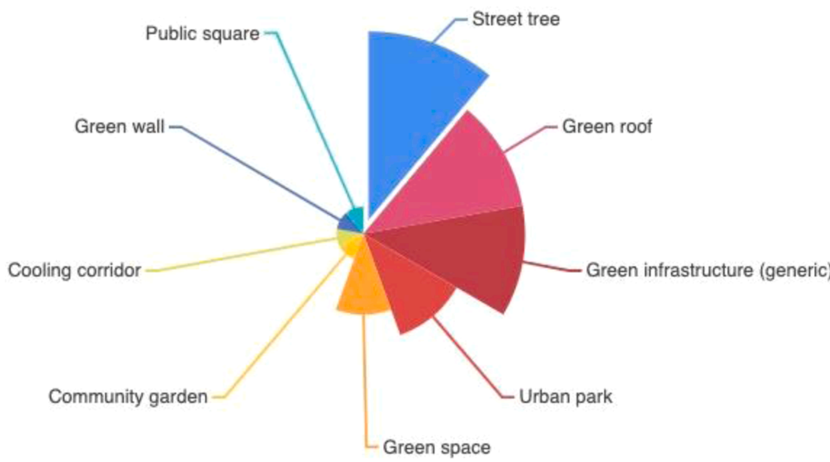

Fig. 4. Proportion of the literature focused on heat mitigation, by GI type.

Table 3
GI siting basis in the literature focused on heat mitigation.

GI Siting Basis	Number of Studies	Sample Studies
Land Surface Temperature (LST)	12	Pearsall (2017), Sanchez and Reames (2019), Smith et al. (2017)
Microclimate Simulation	8	Declet-Barreto et al. (2013), Beaumont et al. (2022), Elbardisy et al. (2021)
Multi Criteria Decision Analysis (MCDA)	5	Chang et al. (2021), Wu et al. (2020)
Land Use/ Land Cover (LULC)	4	Bosch et al. (2021), Werbin et al. (2020), Syafitri et al. (2020)
Cadastral	3	Pearsall (2017), Cady (2019), Smith et al. (2017)
Demographic	3	Brenner et al. (2023), Beaumont et al. (2022), Werbin et al. (2020)
Accessibility	2	Sanchez and Reames (2019), Chen et al. (2022)
Downscaled Climate Model	2	Brenner et al. (2023), Reinwald et al. (2019)
Population	2	Zhuang and Zhongming (2021), Beaumont et al. (2022)
Imperviousness	1	Cady (2019)
Optimization Model	1	Zhuang and Zhongming (2021)
Tree Canopy	1	Bosch et al. (2021)
Landscape Connectivity	1	Wu et al. (2020)
Interpolated Air Temperature	1	Jessup et al. (2021)

reflects how hot the Earth's surface would feel to the touch and is distinct from air temperature. LST is influenced by various factors such as land cover type, soil moisture, vegetation, and the time of day. This metric is typically obtained through remote sensing technologies using satellite data and thermal infrared sensors. LST is important for understanding climate and weather patterns, urban heat islands, and hydrological cycles and for applications in agriculture and forestry (Pearsall, 2017; Sanchez and Reames, 2019; Declet-Barreto et al., 2013; Syafitri et al., 2020). LST was determined using different methods in the reviewed literature, with the most common approach being remotely sensed LST using satellite-based thermal infrared sensors such as Landsat 8 and MODIS (Pearsall, 2017; Sanchez and Reames, 2019; Smith and Turner, 2017; Chen et al., 2022; Werbin et al., 2020; Wu et al., 2020; Siyafitri et al., 2020, Pratiwi et al., 2018; Meerow, 2019, Venter et al., 2021; Meerow and Newell, 2017). Other approaches included modeling LST using mathematical models and simulations based on satellite observation and land surface properties (Declet-Barreto et al., 2013), and interpolated LST using mathematical techniques to infer values based on known temperature data points (e.g., LST) from surrounding areas like weather stations (Chang et al., 2021).

AT is a measure of the warmth of the atmosphere as perceived at a specific location and time, typically recorded at a height of about 1.5 m above the ground (Cady, 2019; Declet-Barreto et al., 2013; Zhuang and Zhongming, 2021). The reviewed literature generally used modeled surface air temperature, estimating atmospheric temperature across the study area using mathematical and computational models that incorporate various data inputs, including weather observations, atmospheric conditions, and physical laws (Beaumont et al., 2022; Elbardisy et al., 2021; Bosch et al., 2021; Lin and Lin, 2016).

Several studies calculated a heat vulnerability index by combining various indicators either theoretically or empirically associated with heat risk, such as UHI intensity, UHI sensitivity, heat exposure, and heat sensitivity. UHI intensity refers to the difference in the temperature between urban areas and their surrounding rural areas (Beaumont et al., 2022). UHI sensitivity refers to the degree to which an urban area's temperature increases in response to specific factors such as population density, land use, and vegetation cover (Brenner et al., 2023; Syafitri et al., 2020).

MRT is another indicator that can more closely approximate the heat people experience (their thermal comfort) by incorporating radiant heat from surrounding surfaces, and it is often calculated by averaging the temperature of all surrounding surfaces and their emissivity (Elbardisy et al., 2021). PET includes even more complexity to approximate thermal comfort, translating complex environmental conditions into an equivalent temperature at which the human body's heat balance is maintained in a standard indoor setting, accounting for factors such as air temperature, humidity, wind speed, and mean radiant temperature (Elbardisy et al., 2021; Reinwald et al., 2019; Zölch et al., 2019).

4.3. GI spatial planning literature focused on stormwater management

We identified GI types, GI siting basis and models, and the stormwater indicators that previous studies used to site GI for stormwater management. We found a lot more similarity across the stormwater studies than in the literature focused on heat mitigation, even though there were more than twice as many studies focused on stormwater.

In terms of GI types, most of the studies included multiple types in their analyses, although they focused on different scales, including county, city, and local/site levels (e.g., Skujāne and Spage, 2022). Permeable pavement, green roof, bioretention cell, and vegetative swales were the most frequently discussed GI, with some focusing broadly on GI, what we classify as generic green infrastructure (Table 5 and Fig. 7).

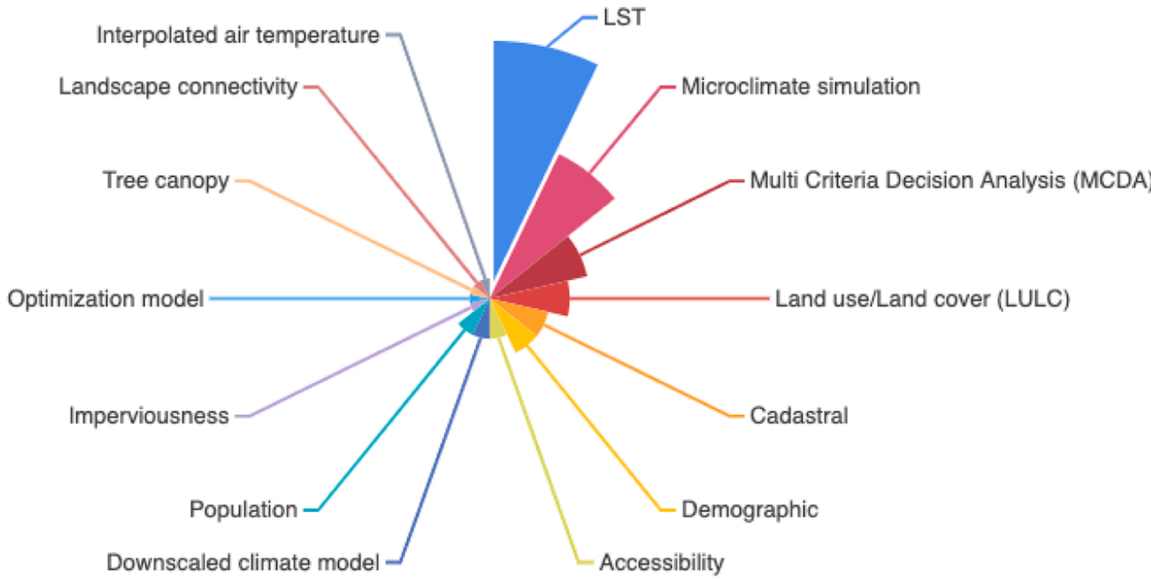

Fig. 5. Proportion of the literature focused on heat mitigation, by the basis for GI spatial siting.

Table 4
Heat indicators in the literature focused on mitigating heat.

Heat Indicator	Number of Studies	Sample Studies
Remotely Sensed LST	11	Pearsall (2017), Sanchez and Reames (2019), Smith et al. (2017)
Modeled Air Temperature	8	Cady (2019), Declet-Barreto et al. (2013), Beaumont et al. (2022)
Heat Vulnerability Index	3	Brenner et al. (2023), Beaumont et al. (2022), Werbin et al. (2020)
Modeled Physiological Equivalent Temperature (PET)	3	Elbardisy et al. (2021), Reinwald et al. (2019), Zölch et al. (2019)
Modeled LST	1	Declet-Barreto et al. (2013)
Modeled Mean Radiant Temperature	1	Elbardisy et al. (2021)
Interpolated LST	1	Chang et al. (2021)
Green and Open Space Factor	1	Reinwald et al. (2019)
Modeled Heat Index	1	Bodnaruk et al. (2017)

4.3.1. The basis for GI spatial planning in the literature focused on stormwater management

We identified the following categories for the methods and indicators proposed as a basis for siting GI for stormwater mitigation: flood mitigation, hydrologic simulation, optimization model, cost, pollution reduction, multi-criteria decision analysis (MCDA), flood risk, land use/land cover (LULC), equity, climate change scenarios, CSO, and downscaled climate model (Table 6 and Fig. 8). Most studies proposed a combination of different methods for GI siting to provide multiple co-benefits, or to balance multiple competing objectives. For instance, Wang et al. (2023b) identified the flood risk points and the sub-catchments upstream to find an optimal balance between the flood risk reduction rate and life cycle cost. Life cycle cost is the total cost of a project or asset over its entire lifespan, including initial investment, operation, maintenance, and disposal costs (Xu et al., 2019). Cao et al. (2023) used an optimization model and hydrologic simulation (Urban-BEATS) to balance flood mitigation, pollution reduction, and cost. Chang et al. (2021) used a combination of hydrologic simulation, MCDA, and flood risk evaluation to site GI. As part of their MCDA, they integrated six GI co-benefits, including social vulnerability reduction, health and education improvement, stormwater management, UHI mitigation, air quality improvement, and landscape connectivity increase. Jessup et al. (2021) included biodiversity and public health co-benefits in addition to stormwater management and water quality benefits. Additionally, Skujāne and Spage (2022) incorporated social and cultural aspects to identify the most suitable places to site GI.

Because there were many similarities in the modeling approaches used to site GI in the literature, we quantified how many studies used each of the various models (Table 7 and Fig. 9). The most prevalent models used in the literature are the Storm Water Management Model (SWMM) and the Non-dominated Sorting Genetic Algorithm (NSGA-II). Other studies used models such as Soil and Water Assessment Tools (SWAT), System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN), and Green Infrastructure Spatial Planning (GISP).

Over 70 percent of the studies focused on stormwater management used SWMM. Some simply used the original SWMM, while others adapted the model to fit their specific case studies and research goals. SWMM is a rainfall-runoff simulation tool that was developed by the US Environmental Protection Agency (EPA) for urban areas. It is widely used to model the quantity and quality of surface runoff in urban watersheds, helping engineers and planners design and evaluate stormwater systems (Koc et al., 2021; Kim et al., 2022). SWMM simulates the impact of rainfall on land surfaces, tracking the flow of stormwater through drainage networks, including pipes, channels, and storage units. The model analyzes the long-term impacts of stormwater management practices and infrastructure improvements on flood prevention, water quality, and ecosystem health. With its detailed hydrological and hydraulic capabilities, SWMM supports the development of sustainable urban water management strategies (Nazari et al., 2023; Tansar et al., 2023; Gao et al., 2023).

The Nondominated Sorting Genetic Algorithm (NSGA)-II is an optimization model algorithm, and it was used in more than a quarter of the reviewed stormwater focused studies, often in combination with hydrologic models like SWMM. NSGA-II and other optimization models can be useful for stormwater management because they allow users to optimize the design and operation of stormwater systems, which often involve multiple conflicting objectives, such as minimizing flooding risks while maximizing water quality and cost efficiency (Zhu et al., 2023). By leveraging NSGA-II's ability to generate a diverse set of optimal solutions, engineers and urban planners can evaluate trade-offs between competing goals, such as controlling runoff volumes and improving pollutant removal (Raei et al., 2019; Tavakol-Davani et al., 2019).

As previously noted, the GISP model is a GIS-based multi-criteria decision-making tool designed to identify priority areas for GI by

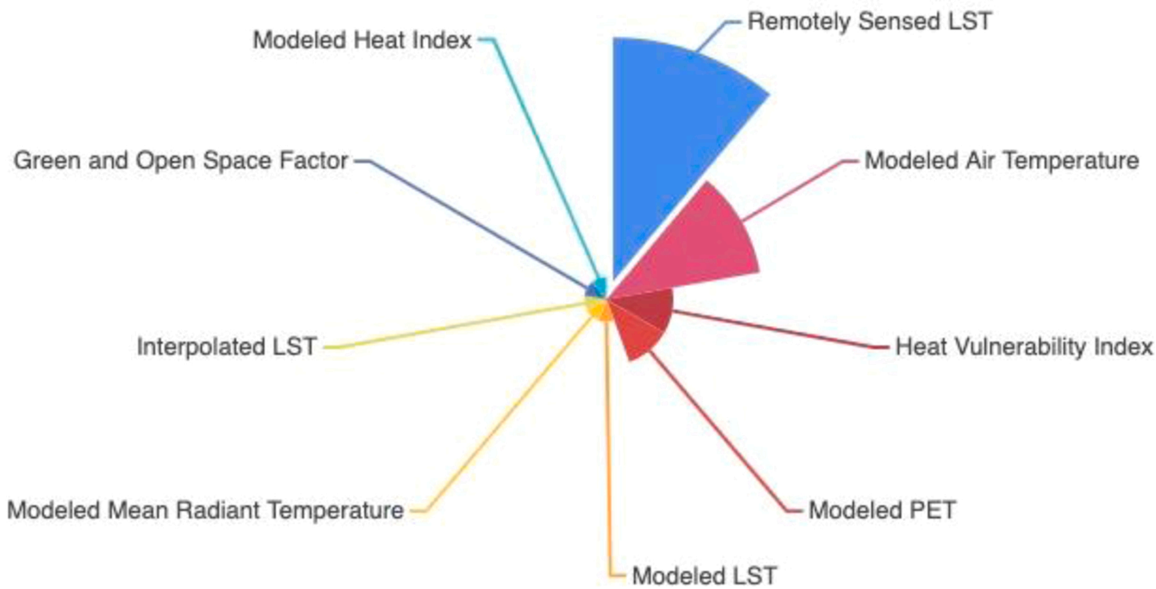

Fig. 6. Proportion of the literature focused on heat mitigation, by heat indicator.

Table 5
GI types in studies focused on stormwater management.

GI Type	Number of Studies	Sample Studies
Permeable pavement	34	Wang et al. (2023b), Saeedi et al. (2023), Cao et al. (2023)
Green roof	28	Pugliese et al. (2022), Cao et al. (2023), Yao et al. (2022)
Bioretention cell	14	Wang et al. (2023b), Tansar et al. (2023), Ghodsi et al. (2023)
Vegetative swale	14	Wang et al. (2023b), Pugliese et al. (2022), Janbehsarayi et al. (2023)
Infiltration trench	11	Janbehsarayi et al. (2023), Saeedi et al. (2023), Pugliese et al. (2022)
Rain garden	10	Castonguay et al. (2018), Tansar et al. (2023), Herbst et al. (2023)
Bioretention	9	Tebyanian et al. (2023), Herbst et al. (2023), Zhu et al. (2023)
Green infrastructure (generic)	8	Chang et al. (2021), Zhou and Wu (2023), Yavari Bajehbaj et al. (2023)
Rain barrel	6	Saeedi et al. (2023), Nazari et al. (2023), Li et al. (2017)
Green space	4	Han et al. (2022), Zhu et al. (2023), Xu et al. (2019)
Bioretention basin	3	Saeedi et al. (2023), Gao et al. (2022), Taghizadeh et al. (2021)
Pond	2	Castonguay et al. (2018), Yang et al. (2023)
Green belt	2	Cao et al. (2023), Li et al. (2017)
Impervious conversion	2	Herbst et al. (2023), Torres et al. (2021)
Wetland	1	Castonguay et al. (2018)
Basin	1	Castonguay et al. (2018)
Open detention basin	1	Yang et al. (2023)
Dry pond	1	Nazari et al. (2023)
Stormwater detention cell	1	Xu et al. (2019)
Cistern	1	Her et al. (2017)
Rainwater harvesting tank	1	Alves et al. (2016)
Constructed stormwater wetland	1	Jessup et al. (2021)
Outfall retrofit	1	Jessup et al. (2021)

integrating multiple environmental and social benefits. It incorporates six key criteria: stormwater management, social vulnerability, green space, air quality, urban heat island mitigation, and landscape connectivity. By considering these interconnected factors, the model helps planners and policymakers identify optimal locations for GI investments that can maximize environmental benefits while addressing social equity (Meerow and Newell, 2017; Meerow, 2019).

SWAT is a comprehensive, basin-scale hydrological model used in stormwater management to assess the impact of land use, climate, and management practices on water resources. The model helps planners and engineers simulate the movement of water, sediment, and nutrients across large, complex watersheds, providing insights into how different stormwater management strategies affect water quality and quantity (Her et al., 2017). It can evaluate the effectiveness of GI, best management practices (BMPs), and other interventions in reducing runoff, controlling erosion, and improving water quality (Chang et al., 2021; Jia et al., 2022).

Developed by the US EPA, SUSTAIN allows engineers, planners, and decision-makers to evaluate the performance and cost-effectiveness of various stormwater control measures, such as GI and BMPs (Gao et al., 2022). By simulating different stormwater scenarios and integrating hydrological, hydraulic, and pollutant load data, SUSTAIN helps identify optimal solutions to minimize runoff, control flooding, and improve water quality (Nazari et al., 2023). Both developed by the EPA, SWMM is primarily focused on modeling stormwater quantity and quality in urban drainage systems, while SUSTAIN, in addition to including the SWMM method, is designed to help evaluate and optimize BMPs for watershed-scale stormwater management to achieve water quality goals (Nazari et al., 2021).

4.3.2. Stormwater indicators in the literature on GI spatial planning

Our review confirms that there are many ways to assess stormwater risk and mitigation. We see that these indicators fall into two overarching categories: those focused more on water quantity versus those assessing water quality. Forty-nine studies focused on water quantity, including indicators such as runoff volume, peak flow, runoff reduction rate, and flood volume. Twenty-one studies assessed water quality, including indicators such as total nitrogen, total suspended solids, and total phosphorus, and 16 studies used both water quantity and water quality (Table 8 and Fig. 10).

5. Discussion

Our literature review shows that researchers have proposed many methods and tools to support GI spatial planning, especially for

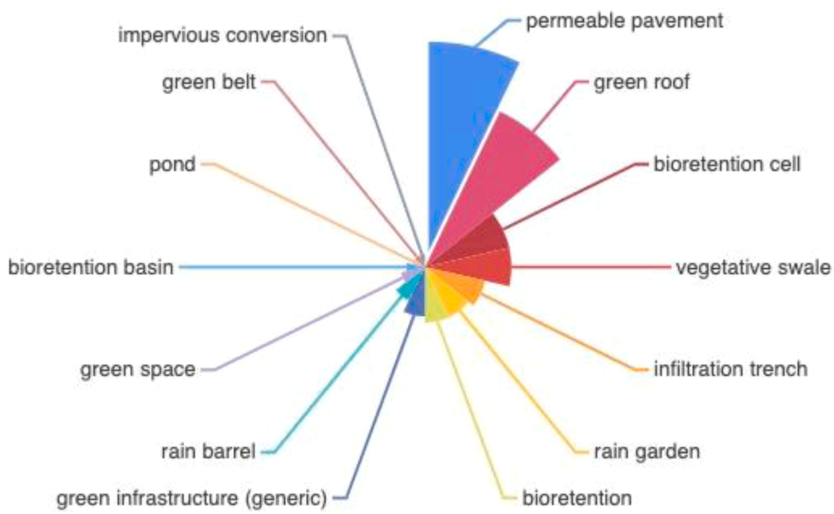

Fig. 7. Proportion of the literature focused on stormwater management, by GI type.

Table 6
GI siting basis in the literature focused on stormwater management.

GI Siting Basis	Number of Studies	Sample Studies
Flood mitigation	46	Wang et al. (2023b), Zhou and Wu (2023), Saeedi et al. (2023)
Hydrologic simulation	44	Chang et al. (2021), Castonguay et al. (2018), Wang et al. (2023a)
Optimization model	37	Wang et al. (2023b), Saeedi et al. (2023), Pugliese et al. (2022)
Cost	26	Pugliese et al. (2022), Cao et al. (2023), Janbehsarayi et al. (2023)
Pollution reduction	16	Castonguay et al. (2018), Cao et al. (2023), Janbehsarayi et al. (2023)
Multi Criteria Decision Analysis (MCDA)	12	Chang et al. (2021), Zhou and Wu (2023), Saeedi et al. (2023)
Flood risk	7	Tebyanian et al. (2023), Zhou and Wu (2023), Meerow (2019)
Land Use/Land Cover (LULC)	6	Zhou and Wu (2023), Meerow (2020), Jessup et al. (2021)
Equity	1	Herbst et al. (2023)
Climate change scenarios	1	Ghodsi et al. (2023)
Combined Sewer Overflow (CSO)	1	Jean et al. (2021)
Downscaled climate model	1	Ghodsi et al. (2020)

stormwater mitigation, and to a lesser degree for heat mitigation or both heat and stormwater. Nevertheless, GI spatial planning approaches to mitigate heat appear largely siloed from those to mitigate stormwater issues in the academic literature. We found few studies that included methods to site GI based on both stormwater and heat, and the two literatures focused on different types of GI and methods. This separation seems to persist despite widespread normative calls in the literature for the promotion of multifunctional GI that can simultaneously address a variety of urban challenges (Hansen and Pauleit, 2014; Matsler et al., 2021). This disconnect has also been identified in practice, where studies indicate that city plans and policy discourse cite multiple co-benefits when making the case for GI, but then these do not translate into the criteria for siting in plans or implementation (Hoover et al., 2023; Meerow and Newell, 2017). For example, Hoover et al.'s (2023) analysis of the content of 120 plans from 19 US cities showed that heat and stormwater benefits were among the most common rationale for GI, but while hydrologic criteria were commonly included as a basis for siting, heat almost never was. More research is needed to determine whether the same mismatch translates from planning to implementation across the US, and if these patterns hold for other countries. If so, this lack of integration might result in missed opportunities to develop comprehensive, multifunctional GI strategies that deliver broad environmental, social, and economic benefits. Bridging the gap between these two aspects of GI planning is essential for creating resilient urban spaces capable of addressing both climate adaptation and water management challenges in a cohesive and efficient manner.

Among the few studies that used models to evaluate the multi-benefits of green GI siting, most rely on MCDA as a foundational approach. For instance, Meerow and Newell (2017) developed the GISP model, which uses MCDA to site GI for multiple resilience benefits in Detroit. Chang et al. (2021) build on Meerow and Newell's work, combining a modified GISP model with SWAT to identify optimal GI locations in the Yanshuei River Basin in Taiwan, mapping synergies and trade-offs for stormwater management and heat mitigation. Similarly, Jessup et al. (2021) employed MCDA to prioritize GI siting in Los Angeles, focusing on co-benefits for stormwater runoff and heat resilience. Venter et al. (2021) also relied on MCDA to guide GI siting, emphasizing locations that maximize co-benefits. These studies highlight the consistent use of MCDA as a framework for integrating multiple objectives in GI planning.

Additionally, the literature focused on GI spatial planning for stormwater management appears more developed than for heat mitigation. The body of literature surrounding stormwater management using GI was larger and more comprehensive, with well-established, consistent methodologies that had been refined over time. This is likely due to the growing recognition of stormwater runoff as a critical issue in urban planning. Researchers have developed a variety of tools and models – such as the SWMM – with many adapted versions that provided detailed insights into the hydrological impacts of GI, enabling more precise siting decisions and performance assessments. The advanced state of research in this area likely reflects the strong demand from practice, linked to established regulations, like the Clean Water Act in the US, related to managing water systems. This is well-documented as a major driver for GI (Finewood et al., 2019; Baker et al., 2019). In contrast, heat hazards have received less attention in research or practice until recently, and remain largely unregulated (Meerow and Keith, 2024). The result is there exist more mature planning frameworks and strategies for integrating GI into urban landscapes for stormwater management than for heat. The literature on siting GI for heat mitigation appears to be still evolving, with more variation in methods and less consensus on best practices.

Importantly, studies considered very different GI types depending on whether the focus was on heat mitigation or stormwater management. The GI types identified in stormwater management studies were more

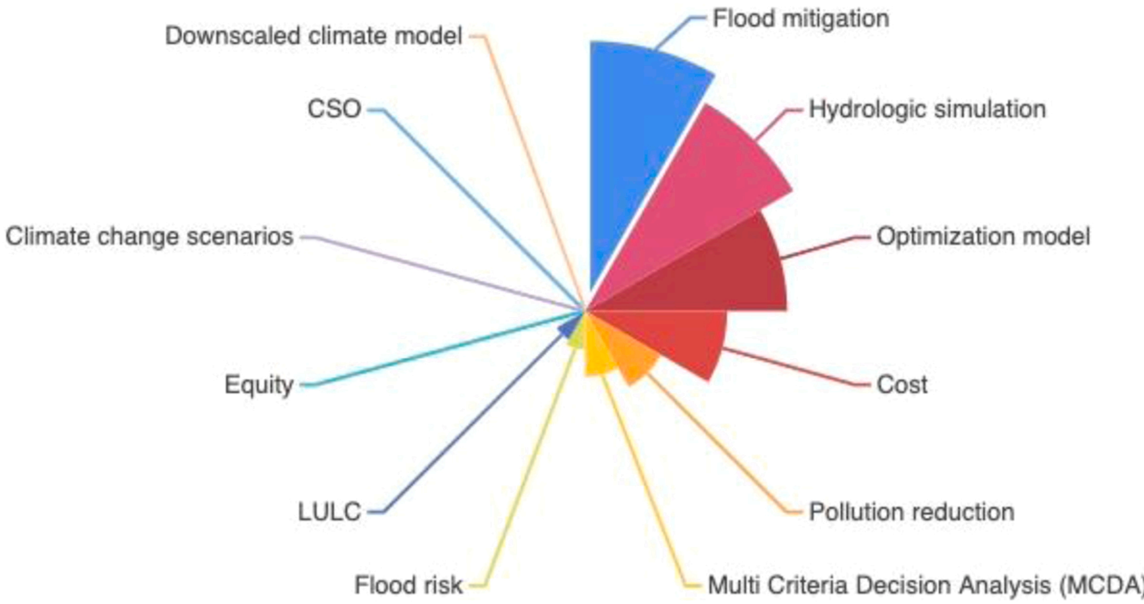

Fig. 8. Proportion of the literature focused on stormwater management, by the basis for GI spatial siting.

detailed, explicit, and granular compared to those in heat mitigation research. This divergence reflects the disciplinary silos that shape these fields, creating an artificial separation between GI strategies that offer both stormwater management and heat mitigation benefits. This division presents a challenge not only for researchers but, more importantly, for practitioners seeking to implement integrated, multifunctional GI solutions. The most common GI type in the stormwater-focused literature was permeable pavement, while the most commonly studied type in the heat literature were street trees. Notably, none of the stormwater management studies specifically emphasized street trees, and conversely, none of the heat studies included permeable pavement. From a practical standpoint, this reinforces the need for spatial planning based on multiple benefits since whether the focus is on stormwater or heat may lead to very different designs, which may or may not provide desired co-benefits (Hoover et al., 2023). Green roofs seem to be one area of overlap, being the second most common GI type in both the heat and stormwater literature. For heat mitigation, in addition to street trees and green roofs, the most commonly used GI types were urban parks and open spaces, which have demonstrated cooling effects. In contrast, studies on stormwater management primarily featured GI solutions such as bioretention cells, vegetative swales, infiltration trenches, and rain gardens, in addition to permeable pavement and green roof, all of which are designed to manage runoff by enhancing infiltration and reducing surface water flow volumes and rates. This distinction in GI use highlights how different GI types are tailored to address specific environmental challenges in urban settings. Future research should explicitly examine potential trade-offs between different GI types and their respective heat mitigation and stormwater management benefits, or perhaps even other potential benefit priorities, such as supporting biodiversity, improving air quality, or offering opportunities for people to recreate. In these assessments, it will be important to acknowledge other potential trade-offs, for example, new vegetation may mitigate both stormwater and heat but require irrigation during a drought or in arid regions (Gober et al. 2012). Even in this case, designing to maximize multifunctionality is likely beneficial, for example, precipitation could be captured and used to offset irrigation requirements for vegetation that mitigates heat.

The modeling approaches used for siting GI for heat mitigation and stormwater management differ significantly in the academic literature, with a notable divergence in consistency and methodology. For stormwater management, models tended to follow more standardized and consistent frameworks, such as models like SWMM and NSGA-II. In contrast, models for heat mitigation were much more varied and fragmented. Heat mitigation studies employed diverse methodologies, ranging from LST and microclimate simulation to demographic data and landscape connectivity. This disparity highlights how stormwater management has achieved greater methodological consensus, whereas heat mitigation remains a more complex and less standardized field, with ongoing debate about the best models and methods to use for assessing risk and siting GI to address urban heat.

This literature review was limited to the scientific literature in order to see how academic literature has used GI types and tools to mitigate heat and stormwater runoff. There are, however, likely other tools/applications in use and documented in grey literature sources – e.g., technical and engineering reports, watershed plans). While we identify important differences between the academic literature on GI spatial planning for heat and stormwater mitigation, including the number of studies, the prioritization of different GI types, and very different degrees of consistency in modeling approaches, future studies should examine whether these differences persist in actual urban planning practice. Are cities indeed using street trees primarily for heat mitigation and permeable pavement for stormwater mitigation, for example, or are different combinations more prevalent? Recent research on heat planning in the United States does suggest that urban forestry and other forms of vegetation are one of the leading strategies for cities, but they do not focus on the siting practices (Meerow and Keith, 2022; Turner et al., 2022). A global assessment of nature-based solutions found that heat mitigation was one of the most common challenges addressed and reported outcomes for the interventions (Li et al., 2025). Are cities using more varied approaches and information to site GI in order to address heat than to manage stormwater? More research is needed.

And finally, if GI is going to be studied and implemented in a truly multifunctional way – to maximize both heat mitigation and stormwater management – what approaches show promise? The academic literature seems to point to two approaches: MCDA and the use of LULC data. MCDA is particularly useful for balancing the diverse objectives of GI projects, ensuring that solutions can simultaneously address stormwater runoff and heat mitigation. By systematically weighing factors such as cost, performance, and community impact, MCDA provides a robust framework for identifying optimal GI locations. Meanwhile, LULC analysis focuses on understanding the existing landscape's characteristics – such as vegetation, impervious surfaces, and land use patterns –

Table 7
Models used in the literature on stormwater management.

GI Siting Basis	Number of Studies	Sample Studies
Storm Water Management Model (SWMM)	38	Giacomoni (2015), Chui et al. (2016), Tavakol-Davani et al. (2019)
Non-dominated Sorting Genetic Algorithm (NSGA-II)	15	Alves et al. (2016), Giacomoni and Joseph (2017), Martínez et al. (2018)
Soil and Water Assessment Tools (SWAT)	3	Her et al. (2017), Jia et al. (2022), Chang et al. (2021)
System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN)	3	Gao et al. (2022), Nazari et al. (2023), Saeedi et al. (2023)
Green Infrastructure Spatial Planning (GISP)	3	Meerow and Newell (2017), Meerow (2019), Meerow (2020)
Borg	2	Eckart et al. (2018), Herbst et al. (2023)
General Circulation Models (GCM)	2	Ghodsi et al. (2020), Ghodsi et al. (2023)
Genetic Algorithm (GA)	2	Lu and Qin (2019), Ghodsi et al. (2020)
Multiobjective Evolutionary Algorithm (MOEA)	2	Giacomoni (2015), Eckart et al. (2018)
UrbanBEATS	1	Castonguay et al. (2018)
DynaMind	1	Castonguay et al. (2018)
EPA (Best Management Practice) BMP Siting tool	1	Saeedi et al. (2023)
InfoWorks ICM	1	Cao et al. (2023)
FRAGSTATS	1	Han et al. (2022)
Social Vulnerability Index (SVI)	1	Herbst et al. (2023)
Topographic wetness index	1	Yavari Bajehbaj et al. (2023)
CityDrain II	1	Torres et al. (2021)
Integrated Planning and Optimization Program (iPOP)	1	Jean et al. (2021)
Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS)	1	Gao et al. (2021)
MIKE FLOOD	1	Yao et al. (2020)
Optimization Software Toolkit for Research Involving Computational Heuristics (OSTRICH)	1	Macro et al. (2019)
Unified Subwatershed and Site Reconnaissance	1	Brown et al. (2009)
Watershed Treatment Model	1	Brown et al. (2009)

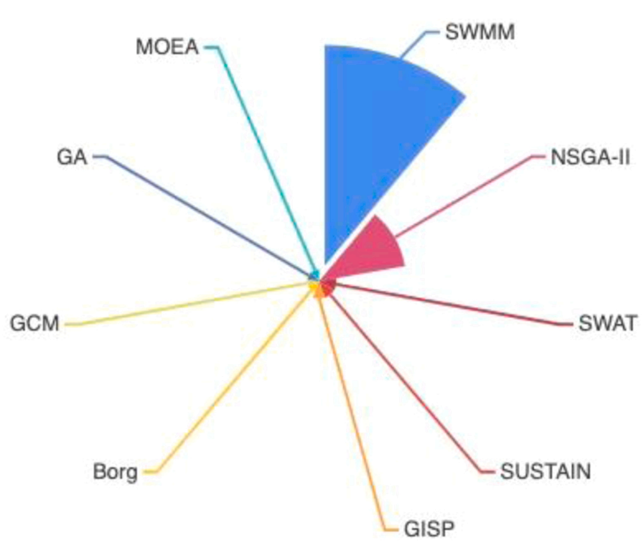

Fig. 9. Proportion of the literature focused on stormwater management, by model.

Table 8
Stormwater indicators in the literature focused on stormwater management.

Stormwater Indicator Category	Stormwater Indicator	Number of Studies	Sample Studies
Water quantity (49 studies)	Runoff volume	20	Saeedi et al. (2023); Pugliese et al. (2022); Tebyanian et al. (2023)
	Peak flow	15	Janbehsarayi et al. (2023); Yao et al. (2022); Han et al. (2022)
	Runoff reduction rate	12	Wang et al. (2023a); Tebyanian et al. (2023); Cao et al. (2023)
	Flood volume	10	Wang et al. (2023b); Tansar et al. (2023); Yang et al. (2023)
	Combined Sewer overflow (CSO)	5	Rodriguez et al. (2021); Torres et al. (2021); Jean et al. (2021)
	Imperviousness	4	Ghodsi et al. (2020); Meerow (2019); Meerow (2020)
	Peak flow reduction rate	3	Zhu et al. (2023); Chui et al. (2016); Martínez et al. (2018)
	Flood risk	2	Chang et al. (2021); Zhou and Wu (2023)
	Flood volume reduction rate	2	Zhu et al. (2023); Martínez et al. (2018)
	Hydrologic footprint residence	2	Giacomoni and Joseph (2017); Giacomoni (2015)
	Flood mitigation	1	Zhou and Wu (2023)
	Flood damage costs	1	Tansar et al. (2023)
	Topographic wetness index	1	Yavari Bajehbaj et al. (2023)
	Peak flood volume	1	Kim et al. (2022)
	Separate Sewer Overflow (SSO)	1	Torres et al. (2021)
	Infiltration potential	1	Senes et al. (2021)
	Water budget restoration coefficient	1	Tavakol-Davani et al. (2019)
Water quality (21 studies)	Total Suspended Solid (TSS)	9	Cao et al. (2023); Janbehsarayi et al. (2023); Yang et al. (2023)
	TSS reduction rate	7	Gao et al. (2023); Gao et al. (2021); Shojaeizadeh et al. (2021)
	Total Nitrogen (TN)	6	Castonguay et al. (2018); Cao et al. (2023); Zhu et al. (2023)
	Total Phosphorus (TP)	6	Cao et al. (2023); Zhu et al. (2023); Koc et al. (2021)
	Chemical Oxygen Demand (COD)	2	Koc et al. (2021); Li et al. (2017)
	COD reduction rate	2	Raei et al. (2019); Yao et al. (2020)
	Bacteria reduction rate	1	Shojaeizadeh et al. (2021)
	Phosphorus (P) reduction rate	1	Taghizadeh et al. (2021)
	Nitrogen (N) reduction rate	1	Taghizadeh et al. (2021)
	Total Copper	1	Jessup et al. (2021)
	Total Lead	1	Jessup et al. (2021)
	Total Zinc	1	Jessup et al. (2021)

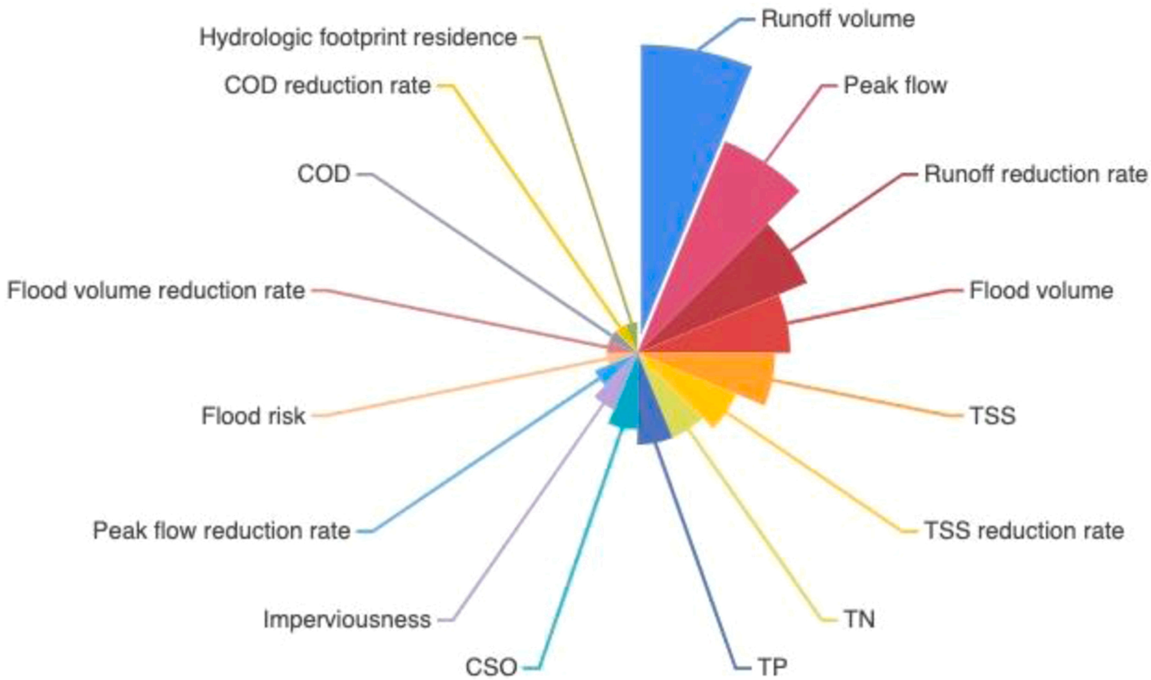

Fig. 10. Proportion of the literature focused on stormwater management, by stormwater indicator.

which are crucial for determining where GI interventions will be most effective. While the few existing studies of GI spatial planning practice indicated that GI was not being strategically sited to maximize multi-functionality (Hoover et al., 2023; Meerow and Newell, 2017), this may change as mitigating heat risks becomes a greater priority.

Future research on the multifunctional benefits of GI for heat mitigation and stormwater management should focus on breaking down disciplinary and geographic silos and fostering integrated approaches (Mell et al., 2025; Mell and Whitten, 2024). Comparative studies analyzing GI performance across different climatic and urban contexts can provide insights into synergies and trade-offs. Additionally, advancing modeling techniques to assess co-benefits at multiple scales, from site-specific interventions to regional networks, would support evidence-based planning. Research should also explore policy and governance mechanisms that enable cross-sectoral collaboration, ensuring that GI strategies are designed and implemented to maximize resilience and sustainability.

6. Conclusion

The combined impacts of urban development and climate change are increasing the imperative for cities worldwide to mitigate growing heat and stormwater risks simultaneously. GI is widely promoted as a strategy for addressing both challenges, but the benefits are shaped by the type of GI and where within the city it is implemented. It is unclear how local decisionmakers should make these GI spatial planning decisions, from a heat, stormwater mitigation, or multifunctional perspective. We systematically reviewed the academic literature on GI spatial planning focused on heat and stormwater mitigation to assess the methods researchers propose to site GI. We find the literature on GI spatial planning for heat and stormwater management to be distinct, with a small minority of the studies proposing approaches that consider both. We see that assessing both heat and stormwater risks are complex, with a variety of potential indicators for both hazards. The literature focused on GI spatial planning for stormwater shows more consistent approaches and models, while the heat-focused literature is smaller and more disparate. We also find that they focus on very different types of GI. Together, our findings suggest some challenges for more multifunctional GI spatial planning that maximizes heat and stormwater mitigation co-benefits, win-wins that are likely needed as cities combat climate change and other challenges.

CRediT authorship contribution statement

Sobhaninia Saeideh: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Meerow Sara:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Dugger Aubrey:** Writing – review & editing, Validation, Supervision. **Hopson Thomas:** Writing – review & editing, Validation, Supervision. **He Cenlin:** Writing – review & editing, Validation, Supervision. **Wilhelmi Olga:** Writing – review & editing, Validation, Supervision.

Declaration of Competing Interest

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

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or the NSF NCAR. This work was done/data was collected prior to January 2025.

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