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Review

A comparative analysis of methods and tools for low impact development (LID) site selection

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ABSTRACT

The site selection for Low Impact Development (LID) practices is a significant process. It affects the effectiveness of LID in controlling stormwater surface runoff, volume, flow rate, and infiltration. This research paper presents a comprehensive review of various methods used for LID site selection. It starts by introducing different methods and tools. Three main methods: index-based methods, GIS-based multi-criteria decision analysis (MCDA), and multi-criteria models and tools, are discussed in detail. A comparative analysis of these methods is then conducted based on ten different criteria. These criteria include the number of variables, data properties, the scale of analysis, benefits maximization approach, multi-attribute decision analysis, user-friendliness, community and stakeholder participation, and the validation methods. This comparison reveals limitations in each method. These include inadequate data availability and quality, lack of evaluation methods, comprehensive assessment criteria and spatial explicitness. These challenges underscore the need for future research to prioritize spatial clarity, broaden criteria, improve data quality through standardization, incorporate field visits and remote sensing for robust results, integrate big data, and develop web-based, open-source tools for enhanced accessibility. These key strategies provide valuable insights for advancing LID site selection methods.

1. Introduction

Urban expansion has led to a fast increase in impervious areas, hence leading to an increase in compact and impermeable soils (Mustafa and Szydłowski, 2020; Newcomer et al., 2014; Wang et al., 2018; Zölch et al., 2017). Simultaneously, climate change is a major driver behind the rise in the frequency and intensity of rainfall events (Shastri et al., 2019; Szpakowski and Szydłowski, 2018). Moreover, projections indicate a 25% increase in population density in risk-prone coastal areas by 2050, hence exposing more people to the rising impacts of climate change (Szydłowski et al., 2023). The combined effect of urbanization and uncertain rainfall intensity and frequency has caused cities to face several adverse environmental challenges associated with urban sustainability and urban water issues, including floods, stormwater runoff pollution, a high frequency of extreme weather events, shortage of groundwater resources, and sewer overflow (Herslund and Mguni, 2019; Mustafa et al., 2019; Szydłowski et al., 2015, 2023; Wang et al., 2018; Zölch et al., 2017). Among these impacts, stormwater flooding is a frequent and hazardous disaster that is of global concern, as it decreases cities' resilience and can cause severe damage to the economy, environment, infrastructure, and human lives (Herslund and Mguni, 2019; Mustafa et al., 2023; van den Berg et al., 2015). Over the last two decades, floods have impacted 2.3 billion people, as reported by the United Nations (Centre for Research on the Epidemiology of Disasters, UN Office for Disaster Risk Reduction, 2016).

Many strategies have been developed for stormwater management in various countries to enhance the sustainability and resilience of cities and communities such as low impact development (LID) and green infrastructure in the USA (Ahiablame et al., 2012) and Canada (Trenouth and Linden, 2018), sustainable urban drainage system (SUDS) in the United Kingdom (UK) (Fletcher et al., 2015), sponge city (SPC) in China (Yin et al., 2021), water sensitive urban design (WSUD) in Australia (Radcliffe, 2019; Sharma et al., 2016), low impact urban design and development (LIUDD) in New Zealand (Wang et al., 2021) and active beautiful clean waters (ABC Waters) program in Singapore (Liao, 2019). All these stormwater management strategies vary in their

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scope and context but the main idea behind them is the same, which is to restore the disturbed natural hydrological cycle through natural processes (Fryd et al., 2012).

Within the focus of stormwater management strategies, this review paper narrows its focus to low impact development (LID). Coined in the 1990s in Prince George's County, Maryland, the USA, LID is a sustainable urban flood management approach. It compensates for the impacts of land development on on-site hydrology and water quality by utilizing the natural processes for stormwater storage, retention, infiltration, purification, utilization, and drainage. Apart from flood control, and water quality improvement, LID can also function to water conservation, and natural eco-system protection (Coffman, 1999).

Unlike conventional stormwater management system which carries runoff to downstream sewers and outlets, LID focuses on localized treatment, control, and infiltration of stormwater at its source (Coffman, 1999; Dong et al., 2017). Many LID practices such as bioretention cells, rain gardens, porous pavement, green roofs, rainwater harvesting, etc., are applied to recover predevelopment site hydrology by reducing, storing, evaporating, and infiltrating runoff (Coffman, 1999; Kasprzyk et al., 2022). However, each LID practice has specific technical, and non-technical (e.g., removal efficiency, infiltration capacity, cost) characteristics, leading to uncertainties in scope (Jia et al., 2015),values, and implementation feasibility (Mell, 2010; Pankhurst, 2012). Site conditions like topography, soil type, groundwater level, climate, and stormwater characteristics further limit LID implementation (Jia et al., 2015). Therefore, understanding complexity of LID site selection process and associated constraints is crucial.

1.1. LID site selection

The location of the LID is a critical factor to affects its effectiveness and performance (Passeport et al., 2013). Site-specific features impact various aspects such as runoff reduction, peak flow reduction, pollution reduction, soil infiltration potential, to detain and carry water to next LID practices (Agnew et al., 2006; Coleman et al., 2018; Hou et al., 2020; Kong et al., 2017). Natural conditions including soil type, topography, groundwater level, rainfall patterns, runoff, geology, and other hydrological factors change the priority sites of LID implementation along with socio-economic constraints (Charoenkit and Piyathamrongchai, 2019; Guerrero et al., 2020). Site ecology, existing green areas, waterways, air and water pollution level, and land surface temperature also vary by location, influencing LID implementation (Newton, 2012). In Gdańsk, Poland, ongoing efforts involve actively engaging citizens in city's adaptation to climate change through nature-based solutions showing the socio-economic dimension of LID site implementation (Szydłowski et al., 2023). Socioeconomic factors which must be examined include land ownership, urban land use, above and below-ground infrastructure, population, public interest and support, marginalized communities, social and cultural recreational sites, urban planning policies and stakeholders' willingness, etc. (Sinnett et al., 2015; Brown et al., 2016; Brown, 2005). These factors are non-consistent even between neighboring cities therefore local guidelines and local implementation plans are required to address the local issues (Buchholz, 2013).

The relative location (upstream/at-source, downstream/end-of-pipe) of LID practices within the catchment is also essential in the planning framework. The ideal location varies from place to place depending on the type of LID practices, catchment characteristics and project objectives (Zhang and Chui, 2018; Zhen et al., 2004). Few studies have proven the efficiency of downstream LID practices in reducing peak flow, while upstream practices can control runoff at its source, reduce or eliminate pollution and alleviate the load of the downstream stormwater system, hence reducing flooding duration (Giacomoni and John, 2017). The restoration of hydrologic functions at the disturbed source is recommended by the Department of Environmental Resources of Maryland County (1999).

Few LID practices like bioretention cells, porous pavement, rainwater harvesting, are placed for on-site storage and treatment of the stormwater runoff, (Jiang et al., 2015) whereas retention ponds, detention ponds, and infiltration basins store water at downstream areas to control the peak discharge, however, the issue of increase runoff remains the problem (Holman-Dodds et al., 2003). Consequently, LID practices should be placed with a full understanding of the effect of relative location on LID performance, preferences of stakeholders' and demand of the project.

When planning LID practices, it's crucial to consider the effect of LID practices on the surrounding environment along with considering the influence of environment on LID practices. For example, in areas with high groundwater level, LID practices promoting infiltration and recharge leading to groundwater flooding, groundwater pollution (Bhaskar et al., 2018; Zhang and Chui, 2018; Zheng et al., 2018; Voisin et al., 2018), in coastal areas led to seawater intrusion (Li et al., 2017). Placing LID practices in mountainous areas, specifically on steep slopes, may trigger mudslides or landslides when slopes are saturated with water (US EPA, 2014). Green roofs and such practices that increase evaporation, and need irrigation are not a good option in arid-semi arid areas that eventually cause water scarcity (Jiang et al., 2015; Li et al., 2017). Consequently, it demands a holistic approach to ensure sustainable implementation of LID practices.

1.2. Constraints in LID implementation

Identifying the location for the construction of LID practices is a planning stage problem and is important for the success of a project. Different criteria exist in guidelines released by relevant organizations for site evaluation of LID practices however they are quite broad and are not explicit according to local situations (Elliott and Trowsdale, 2007). Notably, many LID projects have been sited manually, and have been experimental and opportunistic (Van Roon, 2005; Walsh and Kunapo, 2009) without considering the benefits of site optimization and multi-functionality. Hence, one of the challenges in LID planning and mapping is the lack of consideration of LID multifunctionality because most of the LID practices are implemented with a focus on local stormwater runoff issues which does not cover a broad range of services (environmental, social equity, economic) provided by the LID practices (Matthews et al., 2015; Niemelä, 2014; Sinnett et al., 2015). Environmental benefits include improved air quality, water quality, enhanced biodiversity, while socioeconomic benefits include educational improvements, provision of services, enhanced immune systems, social well-being, and enhanced aesthetics (Kaykhosravi et al., 2019). One major objective of LID site selection is to overcome the above-mentioned restrictions and consider multi-functionality. To maximize the benefits of LID practices, spatial allocation of LID practices is important because the effects of LID practices may vary from site to site.

LIDs are expensive practices that require a lot of time to install and manage, for example in China the sponge city project execution in more than 30 cities involved an investment of more than 10 billion US$ (Jack, 2012; Jia et al., 2013; Li et al., 2016). Hence, if LIDs are to be implemented, it should be based on on-site assessment and site-specific conditions which can maximize their value and expense (Jack, 2012). A need exists to prioritize where to spend resources, thus LID spatial allocation requires a siting framework that can evaluate the local conditions by highlighting the locations not only where it is most needed but where it will bring the most benefits.

To effectively tackle this multi-objective problem, spatial allocation tools and methods are needed which identify the optimal allocation of LID practices based on multi-criteria. Thus far, a considerably larger number of GIS-based site selection frameworks, models and tools have been developed, considering the hydrological, hydraulic, ecological, socioeconomic aspects (Fig. 1). Zhang and Chui (2018) reviewed spatial allocation optimization tools for LID practices, Lerer et al. (2015) and Kuller et al. (2017) focused on water sensitive urban design (WSUD)

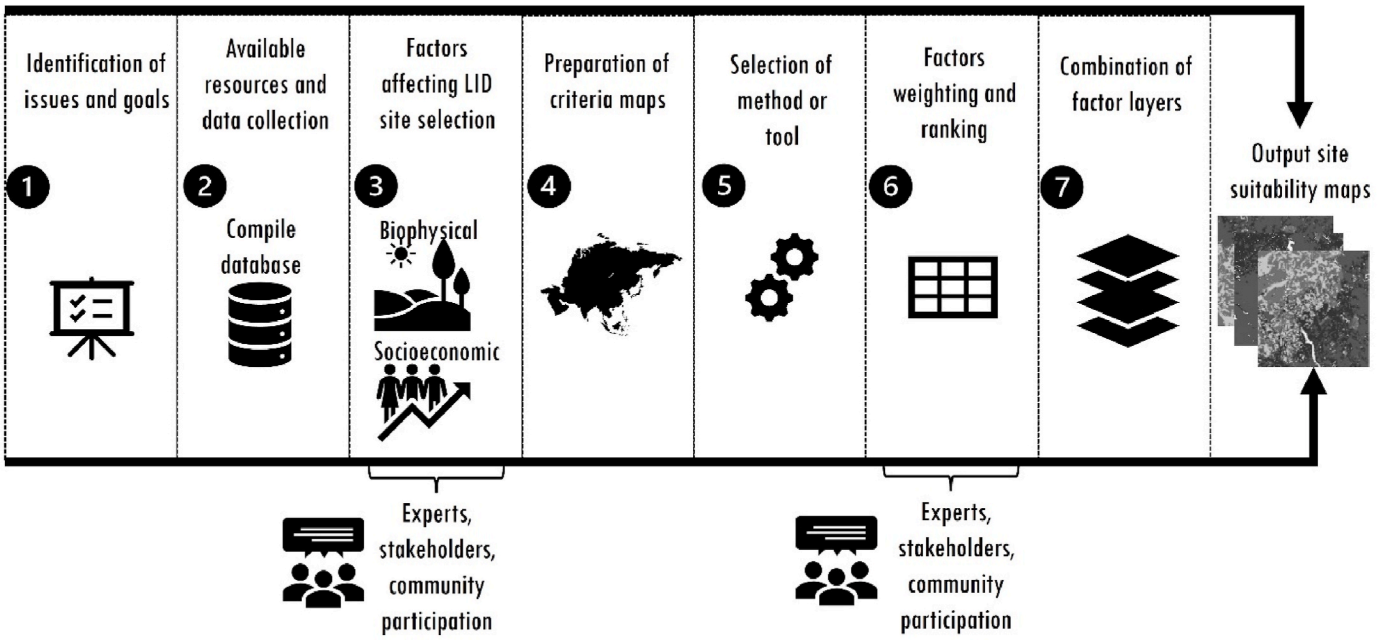

Fig. 1. A general LID site selection workflow.

based on three types of questions they can address i.e. "How Much"--tools, "Where"-tools and, "Which"-tools but, did not delve into the specific nuances of LID site selection. These reviewed studies limited themselves to answering 'what WSUD needs', i.e., favorable conditions that are compatible with chosen WSUD technology. Their focus was not only on LID site selection methods but also included models for runoff estimation, cost analysis, etc.

Consequently, the primary objectives of this paper are as follows:

- Select and review various methods and models available to decision makers in the context of LID site selection through comprehensive literature review.
- Establish robust evaluation criterion derived from existing literature, facilitating framework for comparison.
- Comparison of identified methods based on selected criteria, unraveling their capabilities and limitations.

The outcomes of this review are expected to make substantial contributions:

- Offering researchers, a comprehensive overview for improving and implementing the LID site selection methods, filling existing gaps, and inspiring the development of new methods.
- Presenting recommendations for future research opportunities.

This paper is organized as follows: In section 2, methodology, literature search strategy is described, laying groundwork for next sections. In section 3, LID site selection methods and tools are discussed. In section 4, comparison of the selected methods is done based on the established criteria. In last section 5, summary of key findings and perspectives for future research are outlined.

2. Methodology

A three-fold approach was adopted for reviewing potential site selection methods for green infrastructure. In the following, an elaborate explanation of these three stages is provided: i) selection of site suitability methods, ii) identification of evaluation criteria and iii) eventually the assessment of site suitability methods based on these evaluation criteria.

2.1. *Selection of site suitability methods*

For this part of the study, a systematic literature research was conducted. To make this literature review as integrative and exhaustive as possible, a wide range of relevant sources were examined to find meta-analyses of published scientific papers. Up to January 2023, we searched the following data bases for full journal and peer-reviewed articles as well as proceedings paper, review, and technical reports using a large range of search terms and Boolean operators (e.g. site suitability AND low impact development, green infrastructure AND spatial allocation etc.), the word low impact development was replaced with other terms like green infrastructure and setting the search timespan as all years.

The limited availability of LID site selection methods and tools, especially in comparison to the abundance of hydrological modelling tools, underscored a critical research gap. While, numerous tools facilitate modelling environments, the lack of LID siting tools highlights an existing research gap that needs to be addressed.

The title of each paper was first carefully checked for relevance to 1) the LID concept and 2) the LID site selection, based on their abstracts. This led to the identification of methods that have been used in literature for site suitability analysis of LID practices or green infrastructure. Of these methods, four methods were selected, which included sub-models and tools, based on their prevalence in literature, explicit or implicit usage in LID site suitability, freely accessibility to users. This selection process is significant in addressing the lack of consensus on a single site selection method for LID within the existing literature. Consequently, this review not only critically assesses various LID site selection methods, but also aims to bridge a knowledge gap by addressing the lack of a comprehensive and sophisticated approach to LID site selection.

2.2. *Identification of evaluation criteria*

Following the selection of methods, a list of evaluation criteria is prepared. The selection of evaluation criteria relies on existing literature which identifies the current limitations and gaps in both decision-making processes and readiness of models. The evaluation criteria are: i) the number of factors included, ii) data requirement, iii) data format, iv) data pre-processing time, v) the scale of analysis, vi) benefits maximization approach, vii) multi-attribute decision analysis methods, viii) user-friendliness, ix) community, and stakeholder participation in each method, x) and the existence of validation methods. The chosen criteria are instrumental in assessing the efficacy and applicability of the identified LID site suitability methods.

2.3. *Assessment of methods against the criteria*

After composing the list of methods to review and the criteria that could define their applicability, an assessment was made for every tool separately. The assessment on the proposed evaluation criteria was considered through analyzing the user guides, peer-reviewed literature, and case studies. The thorough evaluation against each criterion not only provides understanding of the capabilities and limitations of each method but also identifies potential research and development opportunities in the spatial allocation of LID practices. By addressing the existing challenges, the findings aspire to deepen the understanding of the LID site selection process. This, in turn, enhance the effectiveness of existing methods, guiding improvements in design and implementation.

Ultimately, this review stands as a valuable resource for researchers, practitioners, and policy makers interested in optimizing the spatial allocation of LID in urban areas.

3. Comparative review of methods of LID site selection

LID spatial planning is a relatively new phenomenon and consequently less well-known and applied in practice. Therefore, each publication was analyzed by scanning the key concerns and the final methods are as follows: LID site selection methods based on indices, GIS-based MCDA, and multi-criteria models, and tools. These include methods and models developed in academia as well as outside of academia.

3.1. *Index-based approaches*

3.1.1. *Topographic index*

The topographic index-based LID siting method find suitable locations for LID construction in urban watersheds by considering variable source area (VSA) and hydrologically sensitive area (HAS). It is based on the idea that suitable locations for LID are hydrologically and ecologically sensitive, that is prone to generating runoff (Sheshukov et al., 2018; Walter et al., 2000). The topographic index focuses on the effect of topography on the generation, spatial distribution, and change of surface runoff area (Hou et al., 2020).

The topographic index establishes a threshold for hydrological sensitive areas that get saturated during rainfall, generate runoff, and carry pollutants. The most common topographic index (Beven and Kirkby, 1979) is expressed as:

$$\lambda = \ln\left(\frac{\alpha}{\tan\beta}\right) \tag{1}$$

Where α is the upslope contributing area, $\tan\beta$ is the topographic slope. Walter et al. (2002) added soil water storage capacity to the topographic index as K_sD:

$$\lambda = \ln\left(\frac{\alpha}{\tan\beta\ K_sD}\right) \tag{2}$$

where K_s is the mean saturated hydraulic conductivity of the soil (md^{-1}), while D is the soil depth to the restrictive layer (m). The deeper the soil depth D the higher the soil hydraulic conductivity K_s, and the lower the value of topographic index λ , hence lower is the surface runoff. As there are different soil layers with different K_s values, so K_s can be defined as:

$$K_s = \frac{d}{\sum_{1}^{n}\left(d_i/k_i\right)} \tag{3}$$

where d is the total thickness of soil above the restrictive layer, d_i is the thickness of layer i, k_i is the saturated hydraulic conductivity of layer i (Qiu, 2009).

Martin-Mikle et al. (2015) further extended the index by changing the depth to restrictive layer D to include the impervious surface areas ISA. The altered D is represented as D_{ISA}:

$$D_{\text{ISA}} = D - (D \times ISA) \tag{4}$$

where D is the original soil depth layer, ISA is the impervious areas. The proportion of soil depth with no water storage capacity was then subtracted from the original soil depth layer to account for decrease soil water storage capacity due to an increase in impervious areas. The modified index was expressed as λ^*:

$$\lambda^* = \ln\left(\frac{\alpha}{\tan\beta\ K_sD_{\text{ISA}}}\right) \tag{5}$$

A higher index value indicates greater number of pixels generating surface runoff. Index value also increases if the areas have zero slope β, whereas the value of index decrease with the increase in contributing areas (Hou et al., 2020). A wide range of topographic index values must be considered for selecting the suitable locations of LID practices siting.

Agnew et al. (2006) attempted to include precipitation in the topographic index as:

$$\lambda^* = \ln\left(\frac{\alpha R}{\tan\beta\ K_sD}\right) \tag{6}$$

where R is the measure of rainfall (md^{-1}), that can be annual, monthly precipitation, etc.

3.1.2. *LID demand index*

Kaykhosravi et al. (2019) introduced LID demand index, incorporating environmental, social factors alongside hydrological-hydraulic factors.

The index classifies sites into two categories: feasibility sites, one where the LID practices can be implemented, and demand sites, where LID practices are needed for their benefits.

Three indices are introduced which are later combined to form one index. The first one is the Hydrological-hydraulic index (HHI), based on hydrological and hydraulic processes, assess runoff quantity on account of parameters like rainfall intensity (R), soil water storage capacity (D), catchment slope (S), and hydraulic conductivity (Ks). It ranks sites depending on their runoff potential.

The environmental index (ENI) identifies sites according to their demand for environmental benefits, considering environmental factors such as air, water, and soil quality, and bio-habitat. The socioeconomic index (SEI) incorporates population density, distance to educational centers, hospitals, and green spaces.

Finally, the socio-economic environmental index (SEENI) is obtained by combining ENI and SEI:

$$\text{SEENI}_j = \text{w}_{\text{en}}\text{ENI}_J + \text{w}_{\text{se}}\text{SEI}_J \tag{7}$$

where SEENI_j is the socio-economic environmental index at cell j, w_{en} and w_{se} are the weights given to the selected environmental and socio-economic factors. LID demand index (LIDDI) is expressed as:

$$\text{LIDDI}_j = \text{HHI}_j + \left(1 + \text{SEENI}_j\right) \tag{8}$$

Due to the multiple benefits provided by SEENI_j it is added as an additive value to the LIDDI_j index. As the main priority is the stormwater runoff control so if the HHI index value is zero i.e. no demand for LID to control runoff then the indirect benefits ENI and SEI are also zero, leading to the overall demand of LID zero to make sure there is no unnecessary implementation of LID in the area.

Both of index's methods discussed above are individual and have not (yet) been translated into a software that is readily accessible by urban planners.

3.2. GIS-based multi-criteria decision analysis

GIS-based multi-criteria decision analysis represents spatial qualitative and quantitative information graphically through GIS with multi-criteria techniques, incorporating decision-makers' preferences, manipulation of data, and rule-based preferences (Al-Shalabi et al., 2006). The MCDA involves four steps: i) converting criterion data to suitability values, ii) assigning weights to each criterion and attributes, iii) combing the suitability values and weights, and iv) creating spatial maps (Malczewski and Rinner, 2015).

MCDA is the most used method for LID site selection in the literature, addressing several site-dependent factors affecting the implementation and performance of LID practices in stormwater management. The selection of criteria for LID MCDA depends on site suitability objectives, regions context, professional advice, and thorough literature review (Mitchell, 2005). These factors encompass biophysical, and socio-economic factors detailed in Table S1 of the supplementary material.

Once the appropriate factors are selected, the next step is assigning weightage or ranking and conducting overlay analysis in GIS. The analytic hierarchy process (AHP) is a widely used method to assign weights, involving a pairwise comparison between factors, and subjective weights from experts and literature. Each factor and its sub-factor are given weights representing their importance in LID siting (Saaty, 1994). Following the AHP weighting process, overlay analysis generates the final map for LID site selection.

3.3. Multi-criteria tools

Based on multi-criteria decision analysis, few models have developed built-in tools for the suitability analysis of LID site selection. The detail about such models is given in Table 1.

3.3.1. SUSTAIN

System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN), a watershed-scale decision support system, solve the problem of cost-effective and practical selection of management practices for any study area. Developed as best management practices (BMP) modeling framework, SUSTAIN combines tools for site suitability analysis, stormwater quality and quantity analysis, cost-effective LID selection optimization, and evaluation of various LID options (Lee et al., 2012).

This review focuses on the LID sitting component within the SUSTAIN model. This tool enables users to evaluate, select and site LID in suitable locations, utilizing ESRI's ArcView and ArcMap spatial analyst extension for site suitability analysis (Lee et al., 2012). The tool generates map-based output representing areas meeting specified criteria, facilitating further analysis or placement of LID's (Shoemaker et al., 2009).

Table 1
Overview of LID site selection models and tools.

Tool/Model name	Developer	Date	Open Access
SUSTAIN	US EPA & Tetra Tech Shoemaker et al., 2009	started in 2003 and version 1.0 was released in 2009 (Shoemaker et al., 2009)	Yes
GreenPlan-IT	San Francisco Estuary Institute (SFEI) and regional partners	2015 (SFEI, 2015a)	Yes
Flexible expert system tool (Flext)	European project, DayWater	2006 (Jin et al., 2006)	Yes
SUDSLOC	Middlesex University, EU SWITCH project, and the EU DayWater project	2006–2011 (Ellis and Viavattene, 2014)	Yes
GISP	Meerow and Newell	2017 (Meerow and Newell, 2017a)	Yes

Notable application of SUSTAIN include its use in Allegheny County, Pennsylvania (Shamsi et al., 2014), in designing green infrastructure for stormwater management in Kansas City (Lee et al., 2012), and in suitability analysis for LID practices at Universitas Indonesia (UI) Campus (Warganda and Sutjiningsih, 2017).

3.3.2. GreenPlan-IT tool

The GreenPlan-IT tool was developed to select the cost-effective and the best locations for the placement of green infrastructure using GIS, watershed modeling, and optimization techniques. Just like the SUSTAIN model by EPA, the GreenPlan-IT tool also consists of four tools; a GIS-based site locator tool (SLT) tool for LID, ii) a modeling tool built on the EPA SWMM model, iii) an optimization tool for the selection of best practices and their combinations, and iv) a tracker tool to track the implementation of practices and their performance (Wu et al., 2018a). In SLT of GreenPlan-IT, after the selection of variables, the variables, and their sub-variables are given ranks in weighted overlay analysis through an iterative process (SFEI, 2015b). The output maps can be used by municipal authorities for determining the effective locations for LID.

SLT of GreenPlan-IT was used to locate the suitable sites in the City of Sunnyvale, USA (Wu et al., 2018a), the City of Oakland, USA (Wu et al., 2018b), the City of San Mateo, USA (SFEI, 2015c), and the North Richmond Pump, USA (Wu et al., 2018c).

3.3.3. Flext

A flexible expert system tool (Flext) is a computer-based expert system that gives suggestions and advice to users just like real-world experts (Thévenot and Förster, 2005). The tool requires spatial data for suitability analysis, which is prepared, classified, intersected in the GIS. Flext consists of three main components i.e., knowledge base, inference engine, and user interface apart from the expert system. Based on the available spatial data and professional knowledge, rules representing boundary conditions of all influential factors on different storm water infiltration measures are first formulated in mathematic language. All formulated rules are then organized into a flow chart towards different decisions under different situations. For the planning project, the developed expert system tool Flext is integrated into the GIS platform through a user command. The system reads the input data for each object from the corresponding record of the attribute record set of the layer and saves its outputs back to the corresponding record. Flext was applied to the city of Chemnitz, Germany (Jin et al., 2006).

3.3.4. SUDSLOC

SUDSLOC (Sustainable Urban Drainage System Location) is a GIS decision support tool for the identification of sites appropriate for LID practices installation at an urban scale (Viavattene and Ellis, 2011). It can use both qualitative and quantitative data from a variety of sources to investigate the maximum benefits of LID. After the selection of factors, they are ranked based on their performance for technical, environmental, social, and economic benefits (Ellis et al., 2008). SUDSLOC is coupled with a 1D stormwater model (STORM) and 2D GIS Flood model (FLOODAREA) to compare flood level and water quality before and after LID implementation. SUDSLOC together with these two models was applied to the city of Birmingham, UK(Viavattene and Ellis, 2011).

SUDSLOC provides three options to access LID sites; potential areas tool to identify all potential sites for LID, site by site assessment for each LID, add stormwater BMP (Viavattene and Ellis, 2011).

3.3.5. GISP model

GISP (Green Infrastructure Spatial Planning Model) was introduced by Meerow and Newell (2017a) to identify the priority sites for green infrastructure based on the GIS multi-criteria evaluation method.

The web-based version of the model is also available, which allows a user to select the criteria, give weights, and visualize the results. This web version is available for only four cities i.e. Detroit, New York City, Los Angeles, and Manila (Meerow and Newell, 2017b).

4. Comparison of methods

In this section LID siting methods comparison is done based on different criteria.

4.1. Number of factors

The number of factors considered in LID site selection determines the depth, complexity, and quality of analysis. The more the factors considered the more comprehensive the analysis will be, however, more data will be collected and analyzed. On the other hand, fewer factors can result in a less nuanced analysis that may not consider all factors for decision making process. Therefore, it is important to keep a balance between the number of factors considered and the clarity and usability of analysis. The factors used in LID site selection methods range from a small number to a large number in different methods as given in a comparison Table 2. The topographic index considers a smaller number of required parameters compared to other methods which are only the topographic variables like soil, slope, upstream contributing area, soil hydraulic conductivity, and soil depth to the restrictive layer. On the other hand, a medium number of factors are included in the demand index which are rainfall intensity, the water storage capacity of the soil, hydraulic conductivity, slope, air, water and soil quality, biodiversity, population density, distance to green spaces, distance to hospitals, and distance to educational centers.

GIS-based MCDA is based on a broad set of factors notably environmental, social, economic factors depending upon the conducted research i.e., the choice of factors in MCDA is open to analysis. In the SUSTAIN LID site selection tool, up to nine number of GIS data layers i.e. the factors affecting the site selection process can be used in the tool. These factors are soil type, slope, elevation, water table, stream location, roads, land use, property type, and drainage area. Whereas the data required by the site locator tool (SLT) of GreenPlan-IT to locate and rank the sites can vary depending on the availability and need of the area. It mostly includes depth to the water table, slope, soil type, land use, imperviousness, liquefaction risk, parks, etc.

Flext also does not have a specific number of factors to be added instead it considers the factors to be added by users such as surface slope, soil permeability, soil thickness, distance to vulnerable structures like building foundations, groundwater protection areas, groundwater depth, etc. in spatial database format.

In SUDSLOC, site-specific factors are land use, depth to groundwater, soil type, roof types, slope, area of surface, and drainage area. For the GISP model, six criteria are considered that include stormwater management, air quality, urban heat island effect, access to green space, landscape connectivity, and social vulnerability.

4.2. Data properties and spatial scale of analysis

Table 3 provides a summary of data properties and scale of analysis considered in the different LID site selection methods. These properties include the data format, availability, simplicity or complexity, and data preprocessing time. This is the initial step in screening the method for analysis and let the users select the appropriate method according to their need. Furthermore, it ensures that the decision making is based on high quality and relevant information.

The LID-demand index poses challenges due to lack of data availability for non-easily measurable hydrological-hydraulic index such as hydraulic conductivity, soil storage capacity, concentration-time variables. The LID demand index can be applied at micro, meso, and macro scale.

MCDA can be applied for the selection of sites at the broader scale i.e., in the city master plan but it should be followed up with fine-scale analysis. The availability and simplicity of data depend on the selection of factors as it provides users with several factors to choose according to the objectives of the research. SUSTAIN LID site selection tool collects data through vector and raster format, accommodating multiple scales from watershed scale to site-scale analysis, requiring high-resolution data for the site scale.

GreenPlan-IT's SLT output accuracy depends on the input data accuracy, resolution, coverage. The users may use regional base analysis only, regional/local data only, regional base analysis, and local/regional data according to the available data to improve the output and is also applicable from large to small spatial scale. Flext, applied at the city scale with data acceptable in any GIS format, generates output maps through Geomedia but lacks full GIS integration.

SUDSLOC identify locations at different scales like cadastral, road, park, building, or pavement scale, incorporating user-friendly tools with simple preprocessing. GISP, designed for citywide scale, lacks land use, cost, and other factors for green infrastructure development (Meerow and Newell, 2017a), making it suitable for city-level analysis with finer scale needed afterward.

4.3. Benefits maximization

LID practices are implemented to control stormwater runoff, but they provide other benefits simultaneously i.e., multifunctionality. Table 4 provides a summary of the benefits maximization considered in LID site selection methods. However, multifunctionality can be possible if the spatial placement of LID practices is optimized to areas providing multiple benefits and avoid tradeoffs (Tran et al., 2020).

The topographic index for LID site selection utilizes HSA and VSA, which are used to identify the areas generating runoff which are hydrologically sensitive to water pollution transport risk. Therefore, they do not focus on the physical processes and ground water influence that must be considered for LID site selection but include only the topographic variables (Martin-Mikle et al., 2015). Modifications, including precipitation intensity, amount, and its geospatial or temporal distribution, socio-economic and environmental factors need to be added in the index along with other topographic factors like impervious area, landcover distribution. Studies validating the topographic index yielded mixed results, with some reported alignment with ground truth while

Table 2
Number of factors considered in LID site selection methods.

Comparison factors		Index-based methods		MCDA					
Level 1	Level 2	Topographic index	LID demand index	GIS-based MCDA	MCDA-tools				
					SUSTAIN	SLT of GreenPlan-IT	Flext	SUDSLOC	GISP
Number of factors considered	low	✓							
	medium		✓		✓			✓	✓
	high			✓		✓	✓		

Table 3
Data properties and scale of analysis considered in LID site selection methods.

Comparison factors		Index-based methods		MCDA					
Level 1	Level 2	Topographic index	LID demand index	GIS-based MCDA	MCDA-tools				
					SUSTAIN	SLT of GreenPlan-IT	Flext	SUDSLOC	GISP
Data format	Vector	✓	✓	✓	✓	✓	✓	✓	✓
	Raster	✓	✓	✓	✓	✓	✓	✓	✓
Data requirement	Freely available	✓	×	×	✓	×	✓	✓	✓
	simple data	✓	×	×	✓	×	✓	✓	✓
Data pre-processing time	Takes time	×	×	×	×	×	×	×	×
Spatial scale of analysis	Watershed scale	✓	✓	✓	✓	✓		×	×
	City scale	✓	✓	×	✓	✓	✓	×	✓
	Local-scale	✓	✓	×	✓	✓		✓	×

The topographic index simple data requirement and GIS format make it cost effective for LID site identification in low budget areas, utilizing publicly available DEM and soil data for estimation. It can be applied at various scales i.e., local, intermediate, catchment, and reach scale by changing drainage area size.

Table 4
Benefits maximization considered in LID site selection methods.

Comparison factors		Index-based methods		MCDA					
Level 1	Level 2	Topographic index	LID demand index	GIS-based MCDA	MCDA-tools				
					SUSTAIN	SLT of GreenPlan-IT	Flext	SUDSLOC	GISP
Benefits maximization	Hydrological benefits	✓	✓	✓	✓	✓	✓	✓	✓
	Environmental benefits	×	✓	✓	×	✓	×	✓	✓
	Socio-economic benefits	×	✓	✓	×	✓	×	✓	✓

other exhibiting discrepancies, possibly due to diverse soil, climate, land use, and geology. Researchers modified topographic index to improve their predictive ability by including local conditions. Contrarily, the LID demand index considers hydrological-hydraulic factors alongside limited environmental and socio-economic factors.

GIS-based MCDA research often neglects the inclusion of hydrological-hydraulic and socio-economic factors while considers only bio-physical factors. Evidence exists to include a variety of factors in suitability analysis but still, they were neglected in most of the tools and methods (Kuller et al., 2017). Tools like SUSTAIN and Flext also lack the provision of ecological and socioeconomic benefits from LID practices. In contrast, GreenPlan-IT site locator tool let the users add the information about existing green infrastructure, public-private areas, favorable areas, and less favorable areas for green infrastructure based on environmental, socio-economic factors, and areas not suitable for green infrastructure (SFEI, 2015b). Similarly, SUDSLOC considers the technical, environmental, pollutant removal, operation & maintenance, social and urban community, legal and urban planning, and economic benefits. The GISP model also include environmental and social factors beyond hydrological factors.

4.4. Multi-attribute decision analysis with participatory decision support

Many multi-attribute decision analysis methods exist like the weighted linear combination, the analytic hierarchy process, outranking methods, etc. and the spatially explicit methods. Each LID site selection method or tool uses one of these or their combination to give weights to the criteria as shown in Table 5. Public participatory GIS, representing local knowledge, carry out local decision making or empower marginalized communities, engages stakeholders having expertise in LID and urban development issues.

For the topographic index, no decision analysis process is conducted and hence there is no involvement of stakeholders or public participation in decision making. For the LID demand index, a decision analysis process is employed, utilizing a weighted linear method with stakeholders' involvement.

In MCDA, the selection of multi-attribute decision analysis methods and the involvement of stakeholders is associated with uncertainties. Model uncertainty exists because there is no universally accepted model (like AHP or WLC). Therefore, it is recommended to select a model based on data requirement, the decision problem, and complexity. For LID site selection research, AHP and weighted linear combination are the most widely used models for MCDA. Criteria uncertainty involves challenges in defining criteria, their values, and standardization. Additionally,

Table 5
Multi-attribute decision analysis methods and participatory decision support considered in LID site selection methods.

Comparison factors		Index-based methods		MCDA					
Level 1	Level 2	Topographic index	LID demand index	GIS-based MCDA	MCDA-tools				
					SUSTAIN	SLT of GreenPlan-IT	Flext	SUDSLOC	GISP
Multi-attribute decision analysis methods	Weighted linear combination	×	✓	✓	✓	✓	N/A	✓	✓
	AHP	×		✓			N/A		
	other	×					N/A		
Participatory decision support	Stakeholder participation	×	✓	✓	✓	×	✓	✓	✓
	Public participation	×		✓		×	×		

there is uncertainty in assigning weights to criteria, as experts may face challenges due to limited information (Malczewski and Rinner, 2015). MCDA is subjective, lacks consideration of spatial and temporal changes due to focus on multiple benefits, that may introduce bias. Therefore, it is not preferred for wider generalization and when making long term future decisions (Labib, 2019). Disagreement among researchers on factors importance can complicate the process and increase the time. Hence, defining research objective is crucial so that weights are given depending upon the certain goal of the research like stormwater runoff management should be preferred over the socio-economic benefits of LID.

For the SUSTAIN LID site selection tool, the default suitability criteria, used to assign values for the selected factors, are adopted from EPA reports (Shoemaker et al., 2009), however, users can adjust preferences according to local conditions, local knowledge, stakeholder's input through the weighted linear combination.

The SLT of GreenPlan-IT uses a weighted linear combination for input factors however lacks consideration of public and stakeholder involvement. Flext, an expert-based tool, creates certain rules for input factor boundary conditions using input data and professional knowledge. It uses a decision matrix and inference engine to provides advice and recommendations considering expertise knowledge and observing changes input data and relevant rules. In addition to suggesting LID locations, it suggests sites requiring field verification, or specific variables needing accurate data (Jin et al., 2006).

SUDSLOC involves stakeholders through DayWater Multi-criteria Comparator, using a weighted linear analysis method. Both stakeholders and users can also change their preferences in a multi-criteria comparator (Viavattene and Ellis, 2011). In the GISP model, selected criteria are evaluated and weighted through rating, ranking, and pairwise comparison methods by expert stakeholders (Meerow and Newell, 2017a).

4.5. *User-friendliness*

Prioritizing user-friendliness is crucial for accessibility, ease of use, transparency, and communication. The topographic index, LID demand index, GIS-based MCDA, SUDSLOC, and GISP are user-friendly while SUSTAIN model tool, SLT of GreenPlan-IT, and Flext have a complex user interface for handling and processing the data as presented in Table 6. However, SUSTAIN and GreenPlan-IT provides user manual to make it easier for users to use these tools. Kuller et al. (2017) placed Flext in medium level group in terms of complexity of methodology while SUSTAIN in low level complexity group.

4.6. *Validation methods*

The validation of LID site selection methods is critical for ensuring the reliability of the chosen methods. The evaluation processes involve verification, validation, and sensitivity analysis. Verification ensures that model is built correctly according to specifications while validation confirms the accuracy of the model's output when compared to real data. Sensitivity analysis further checks the variation in model output when its parameters are altered (Qureshi et al., 1999).

In the context of LID, validation process is challenging due to the diverse nature of models. Hydrological models provide measurable results, while socio-technical models, often based on expert's judgment, pose difficulties in validation (van Asselt and Rotmans, 2002). For instance, GIS-MCDA, a widely used method, are difficult to validate against field measured data. That is why, to date, most studies have ignored the validation of resulting LID site suitability maps obtained from GIS-MCDA (Kuller et al., 2019).

Studies highlight various approaches to address this challenge. Some (Martin-Mikle et al., 2015; SFEI, 2015c) validated through field visits to verify the feasibility of LID practices indicated by the map, considering factors like site size, topographic features, and land use land cover changes. Error rates for unsuitable sites are calculated after a field visit, providing a quantitative measure of accuracy (Martin-Mikle et al., 2015). Virtual site visits using Google Street View or integration with Google Earth are alternative validation methods (Christman et al., 2018).

Despite the widespread use of topographic index in stormwater runoff studies, varying results highlight a lack of a definite evaluation method. Furthermore, the validation of the LID-demand index is exemplified by the HHI results. The HHI was validated through the physical model (HEC-HMS), and historical flood data. However, economic, and environmental indices faced difficulties in validation due to the complex decision-making model validation process (Kaykhosravi et al., 2019). Among the review models in this study, for GISP model results, evaluation was done for predicted locations but by using the statistical method of Pearson correlation. Notably, GISP is an individual study and has not been converted into a software that can be used for LID site suitability analysis and its web version is available but only for four cities. Table 7 provides an overview of the validation methods considered in LID site selection, emphasizing the need for robust validation methods to ensure the credibility of the chosen indices and models.

While literature recognizes the importance of validation methods, a dichotomy exists between the belief that models cannot be reliable without validation, and the view that, the usefulness of socio-technical models' is important regardless of their validation. The later emphasizes factors such as reducing time, and cost in decision-making, improving analysis results, user-friendliness, and method flexibility (Kuller et al., 2019). Despite this, multi-criteria tools and models lack specific results evaluation methods, underlining the need for a more comprehensive approach of validation in the context of LID site selection.

5. Conclusion and recommendations

To mitigate the significant effect of urbanization on the urban environment, low-impact development practices are becoming increasingly popular in both academic research and engineering applications. The spatial allocation of LID practices gains attention, leading to the development of number of methods and tools that provide considerable support to LID planning process.

GIS-based MCDA stands out for its spatially explicit assessment, accommodating large numbers of factors, has flexibility of scale, ease of use, visual and intuitively interpretable output. However, GIS-based MCDA has its problems like data ambiguity, model selection, specification of weights, standardization of maps, different results from different models, and lack of evaluation methods. Furthermore, the complexity grows with more criteria, posing challenges in determining influential criteria and weightage, thus introducing potential human bias. Conversely, among multicriteria models, and tools, none proved

Table 6
User friendliness in LID site selection methods.

Comparison factors		Index-based methods		MCDA					
Level 1	Level 2	Topographic index	LID demand index	GIS-based MCDA	MCDA-tools				
					SUSTAIN	SLT of GreenPlan-IT	Flext	SUDSLOC	GISP
User-friendly method		✓	✓	✓	×	×	×	✓	✓

Table 7
Validation methods considered in LID site selection methods.

Comparison factors		Index-based methods		MCDA					
Level 1	Level 2	Topographic index	LID demand index	GIS-based MCDA	MCDA-tools				
					SUSTAIN	SLT of GreenPlan-IT	Flext	SUDSLOC	GISP
Validation methods exist or not	Yes		✓						
	No	✓		✓	✓	✓	✓	✓	✓

adequately extensive or sophisticated. They focus on a small number of mainly biophysical factors, overlooking a broad variety of suitability factors.

LID site selection methods are valuable for informed decision-making. Their successful implementation relies on assessing project-related factors and adapting approaches to real-world conditions. Collaboration with experts, stakeholders and adherence to regulatory compliance is crucial for practical implementation, requiring in-depth and spatially explicit assessment. The review highlights a need for user friendly, flexible, and heuristic but methodologically rigorous tools considering the full spectrum of suitability factors. However, as planning processes and tools grow complex, transparency and user friendliness may decrease, impacting accuracy and interpretability. Nevertheless, it is important not to disregard the complexity of reality in LID spatial planning.

Addressing various aspects and challenges is crucial in the development of future LID site selection methods or research:

- LID site selection methods must be spatially explicit, broader in scope, and comprehensive in assessing criteria, interpreting outcome, and considering the full spectrum of suitability criteria. Considerations should include more diverse ecological, subsurface hydrological processes and landscape metrices in the planning process.
- Efforts are needed to improve data availability and quality, involving standardization and spatial data integration.
- Ensuring transparency in the selection process of alternatives, criteria, and weights.
- Conducting sensitivity analysis helps understand how weights and score influence GIS-based MCDA model results.
- Standardizing maps could be done using predetermined standards for mapping process such as scale of map, spatial resolution and ensuring consistent data sources.
- Evaluation methods such as field verification, and remote sensing are essential.
- Future LID site selection methods could leverage big data to overcome spatial problems involving; i) a large amount of non-linear and multivariate data, ii) unclear expert decisions. This requires further research into data gaps, and ecological/socio-economic impacts.
- Web-based tools are recommended to let the users select the goal, criteria and rank them to find a suitable location for LID practices. Web-based tools provide greater accessibility, distant collaboration, public engagement, and adoptability to various geographic and socio-economic environments. Open-source LID site selection tools are suggested, allowing local authorities to incorporate their specific GIS-data and adapt methods.
- Climate resilience is crucial, commending LID methods to incorporate climate projections and vulnerability assessments.
- A thorough preliminary site analysis is necessary for efficient LID design, identifying impervious areas, suitable LIDs, their combinations and required sizes, retrofitting criteria and maximization of its target benefits.

CRediT authorship contribution statement

Khansa Gulshad: Conceptualization, Investigation, Methodology, Visualization, Writing – original draft. **Michał Szydłowski:** Supervision, Writing – review & editing. **Andaleeb Yaseen:** Writing – review & editing. **Rana Waqar Aslam:** Writing – review & editing.

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.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.120212.

References

Agnew, L.J., Lyon, S., Gérard-Marchant, P., Collins, V.B., Lembo, A.J., Steenhuis, T.S., Walter, M.T., 2006. Identifying hydrologically sensitive areas: bridging the gap between science and application. J. Environ. Manag. 78, 63–76. https://doi.org/10.1016/J.JENVMAN.2005.04.021.

Ahiablame, L.M., Engel, B.A., Chaubey, I., 2012. Effectiveness of low impact development practices: literature review and suggestions for future research. Water Air Soil Pollut. 223, 4253–4273. https://doi.org/10.1007/s11270-012-1189-2.

Al-Shalabi, M.A., Mansor, S. Bin, Ahmed, N. Bin, Shiriff, R., 2006. GIS based multicriteria approaches to housing site suitability assessment. In: XXIII FIG Congress, Shaping the Change. October, Munich, Germany, pp. 8–13.

Beven, K.J., Kirkby, M.J., 1979. A physically based, variable contributing area model of basin hydrology/Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant. Hydrol. Sci. Bull. 24, 43–69. https://doi.org/10.1080/02626667909491834.

Bhaskar, A.S., Hogan, D.M., Nimmo, J.R., Perkins, K.S., 2018. Groundwater recharge amidst focused stormwater infiltration. Hydrol. Process. 32, 2058–2068.

Brown, R.R., 2005. Impediments to Integrated Urban Stormwater Management: The Need for Institutional Reform. Environ. Manage. 36, 455–468. https://doi.org/10.1007/s00267-004-0217-4.

Brown, H.L., Bos, D.G., Walsh, C.J., Fletcher, T.D., RossRakesh, S., 2016. More than money: how multiple factors influence householder participation in at-source stormwater management. J. Environ. Plann. Manag. 59, 79–97. https://doi.org/10.1080/09640568.2014.984017.

Buchholz, N., 2013. Low-Impact Development & Green Infrastructure Implementation: Creating a Replicable GIS Suitability Model for Stormwater Management & the Urban Heat Island Effect (Dallas, Texas).

Centre for Research on the Epidemiology of Disasters (CRED), UN Office for Disaster Risk Reduction (UNISDR), 2016. The Human Cost of Weather Related Disasters 1995-2015 (Geneva, Switzerland).

Charoenkit, S., Piyathamrongchai, K., 2019. A review of urban green spaces multifunctionality assessment: a way forward for a standardized assessment and comparability. Ecol. Indicat. 107, 105592 https://doi.org/10.1016/J.ECOLIND.2019.105592.

Christman, Z., Meenar, M., Mandarano, L., Hearing, K., 2018. Prioritizing suitable locations for green stormwater infrastructure based on social factors in Philadelphia. Land 7, 145.

Coffman, L., 1999. Low-impact development design strategies, an integrated design approach. Prince George's County, Maryand. Department of Environmental Resources (PGDER), Largo, Maryland.

Coleman, S., Hurley, S., Rizzo, D., Koliba, C., Zia, A., 2018. From the household to watershed: a cross-scale analysis of residential intention to adopt green stormwater infrastructure. Landsc. Urban Plann. 180, 195–206. https://doi.org/10.1016/J.LANDURBPLAN.2018.09.005.

Dong, X., Guo, H., Zeng, S., 2017. Enhancing future resilience in urban drainage system: green versus grey infrastructure. Water Res. 124, 280–289. https://doi.org/10.1016/J.WATRES.2017.07.038.

Elliott, A.H., Trowsdale, S.A., 2007. A review of models for low impact urban stormwater drainage. Environ. Model. Software 22, 394–405. https://doi.org/10.1016/J.ENVSOFT.2005.12.005.

Ellis, J.B., Viavattene, C., 2014. Sustainable urban drainage system modeling for managing urban surface water flood risk. Clean 42, 153–159. https://doi.org/10.1002/clen.201300225.

Ellis, J.B., Revitt, D.M., Scholes, L., 2008. The DayWater multi-criteria comparator. Cht 9, 87–96.

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

Fryd, O., Dam, T., Jensen, M.B., 2012. A planning framework for sustainable urban drainage systems. Water Pol. 14, 865–886.

Giacomoni, M.H., John, J., 2017. Multi-objective evolutionary optimization and Monte Carlo simulation for placement of low impact development in the catchment scale. J. Water Resour. Plann. Manag. 143, 04017053 https://doi.org/10.1061/(ASCE)WR.1943-5452.0000812.

Guerrero, J., Alam, T., Mahmoud, A., Jones, K.D., Ernest, A., 2020. Decision-support system for LID footprint planning and urban runoff mitigation in the lower rio grande valley of south Texas. Sustainability 12, 3152.

Herslund, L., Mguni, P., 2019. Examining urban water management practices – challenges and possibilities for transitions to sustainable urban water management in Sub-Saharan cities. Sustain. Cities Soc. 48, 101573 https://doi.org/10.1016/J.SCS.2019.101573.

Holman-Dodds, J.K., Bradley, A.A., Potter, K.W., 2003. Evaluation of hydrologic benefits of infiltration based urban storm water management. JAWRA Journal of the American Water Resources Association 39, 205–215. https://doi.org/10.1111/j.1752-1688.2003.tb01572.x.

Hou, J., Zhu, M., Wang, Y., Sun, S., 2020. Optimal spatial priority scheme of urban LID-BMPs under different investment periods. Landsc. Urban Plann. 202, 103858 https://doi.org/10.1016/J.LANDURBPLAN.2020.103858.

Jack, A., 2012. Low Impact Development (LID) Siting Methodology: A Guide to Siting LID Projects Using a GIS and AHP.

Jia, H., Yao, H., Yu, S.L., 2013. Advances in LID BMPs research and practice for urban runoff control in China. Front. Environ. Sci. Eng. 7, 709–720. https://doi.org/10.1007/s11783-013-0557-5.

Jia, H., Yao, H., Tang, Y., Yu, S.L., Field, R., Tafuri, A.N., 2015. LID-BMPs planning for urban runoff control and the case study in China. J. Environ. Manag. 149, 65–76. https://doi.org/10.1016/J.JENVMAN.2014.10.003.

Jiang, Y., Yuan, Y., Piza, H., 2015. A review of applicability and effectiveness of low impact development/green infrastructure practices in arid/semi-arid United States. Environments 2, 221–249.

Jin, Z., Sieker, F., Bandermann, S., Sieker, H., 2006. Development of a GIS-based expert system for on-site storm-water management. Water Pract. Technol. 1 https://doi.org/10.2166/wpt.2006016.

Kasprzyk, M., Szpakowski, W., Poznańska, E., Boogaard, F.C., Bobkowska, K., Gajewska, M., 2022. Technical solutions and benefits of introducing rain gardens – Gdańsk case study. Sci. Total Environ. 835, 155487 https://doi.org/10.1016/J.SCITOTENV.2022.155487.

Kaykhosravi, S., Abogadil, K., Khan, U.T., Jadidi, M.A., 2019. The low-impact Development Demand Index: a new approach to identifying locations for LID. Water (Switzerland) 11. https://doi.org/10.3390/w11112341.

Kong, F., Ban, Y., Yin, H., James, P., Dronova, I., 2017. Modeling stormwater management at the city district level in response to changes in land use and low impact development. Environ. Model. Software 95, 132–142. https://doi.org/10.1016/J.ENVSOFT.2017.06.021.

Kuller, M., Bach, P.M., Ramirez-Lovering, D., Deletic, A., 2017. Framing Water Sensitive Urban Design as Part of the Urban Form: A Critical Review of Tools for Best Planning Practice. Environmental Modelling and Software. https://doi.org/10.1016/j.envsoft.2017.07.003.

Kuller, M., Bach, P.M., Roberts, S., Browne, D., Deletic, A., 2019. A planning-support tool for spatial suitability assessment of green urban stormwater infrastructure. Sci. Total Environ. 686, 856–868. https://doi.org/10.1016/J.SCITOTENV.2019.06.051.

Labib, S.M., 2019. Investigation of the likelihood of green infrastructure (GI) enhancement along linear waterways or on derelict sites (DS) using machine learning. Environ. Model. Software 118, 146–165. https://doi.org/10.1016/J.ENVSOFT.2019.05.006.

Lee, J.G., Selvakumar, A., Alvi, K., Riverson, J., Zhen, J.X., Shoemaker, L., Lai, F.H., 2012. A watershed-scale design optimization model for stormwater best management practices. Environ. Model. Software 37, 6–18. https://doi.org/10.1016/J.ENVSOFT.2012.04.011.

Lerer, S.M., Arnbjerg-Nielsen, K., Mikkelsen, P.S., 2015. A mapping of tools for informing water sensitive urban design planning decisions—questions, aspects and context sensitivity. Water (Basel) 7, 993–1012. https://doi.org/10.3390/w7030993.

Li, X., Li, J., Fang, X., Gong, Y., Wang, W., 2016. Case studies of the sponge city program in China. In: World Environmental and Water Resources Congress 2016, pp. 295–308.

Li, H., Ding, L., Ren, M., Li, C., Wang, H., 2017. Sponge city construction in China: a survey of the challenges and opportunities. Water (Basel) 9, 594.

Liao, K.-H., 2019. The socio-ecological practice of building blue-green infrastructure in high-density cities: what does the ABC Waters Program in Singapore tell us? Socioeco Prac Res 1, 67–81. https://doi.org/10.1007/s42532-019-00009-3.

Malczewski, J., Rinner, C., 2015. Advances in Geographic Information Science Multicriteria Decision Analysis in Geographic Information Science.

Martin-Mikle, C.J., de Beurs, K.M., Julian, J.P., Mayer, P.M., 2015. Identifying priority sites for low impact development (LID) in a mixed-use watershed. Landsc. Urban Plann. 140, 29–41. https://doi.org/10.1016/J.LANDURBPLAN.2015.04.002.

Matthews, T., Lo, A.Y., Byrne, J.A., 2015. Reconceptualizing green infrastructure for climate change adaptation: barriers to adoption and drivers for uptake by spatial planners. Landsc. Urban Plann. 138, 155–163. https://doi.org/10.1016/J.LANDURBPLAN.2015.02.010.

Meerow, S., Newell, J.P., 2017a. Spatial planning for multifunctional green infrastructure: growing resilience in Detroit. Landsc. Urban Plann. 159, 62–75. https://doi.org/10.1016/j.landurbplan.2016.10.005.

Meerow, S., Newell, J.P., 2017b. GISP [WWW Document]. URL. https://sites.google.com/view/gispmodel/home. accessed 10.20.22.

Mell, I.C., 2010. Green Infrastructure: Concepts, Perceptions and its Use in Spatial Planning. Newcastle University, Newcastle.

Mitchell, G., 2005. Mapping hazard from urban non-point pollution: a screening model to support sustainable urban drainage planning. J. Environ. Manag. 74, 1–9. https://doi.org/10.1016/J.JENVMAN.2004.08.002.

Mustafa, A., Szydłowski, M., 2020. The impact of spatiotemporal changes in land development (1984–2019) on the increase in the runoff coefficient in Erbil, Kurdistan Region of Iraq. Rem. Sens. 12, 1302.

Mustafa, A.M., Muhammed, H., Szydłowski, M., 2019. Extreme rainfalls as a cause of urban flash floods; a case study of the Erbil-Kurdistan region of Iraq. Acta Scientiarum Polonorum Formatio Circumiectus 18, 113–132.

Mustafa, A., Szydłowski, M., Veysipanah, M., Hameed, H.M., 2023. GIS-based hydrodynamic modeling for urban flood mitigation in fast-growing regions: a case study of Erbil, Kurdistan Region of Iraq. Sci. Rep. 13, 8935.

Newcomer, M.E., Gurdak, J.J., Sklar, L.S., Nanus, L., 2014. Urban recharge beneath low impact development and effects of climate variability and change. Water Resour. Res. 50, 1716–1734.

Newton, P.W., 2012. Liveable and sustainable? Socio-technical challenges for twenty-first-century cities. J. Urban Technol. 19, 81–102. https://doi.org/10.1080/10630732.2012.626703.

Niemelä, J., 2014. Ecology of urban green spaces: the way forward in answering major research questions. Landsc. Urban Plann. 125, 298–303. https://doi.org/10.1016/J.LANDURBPLAN.2013.07.014.

Pankhurst, H., 2012. Green Infrastructure: Mainstreaming the Concept Understanding and Applying the Principles of Green Infrastructure in South Worcestershire.

Passeport, E., Vidon, P., Forshay, K.J., Harris, L., Kaushal, S.S., Kellogg, D.Q., Lazar, J., Mayer, P., Stander, E.K., 2013. Ecological engineering practices for the reduction of excess nitrogen in human-influenced landscapes: a guide for watershed managers. Environ. Manag. 51, 392–413. https://doi.org/10.1007/s00267-012-9970-y.

Qiu, Z., 2009. Assessing critical source areas in watersheds for conservation buffer planning and riparian restoration. Environ. Manag. 44, 968–980. https://doi.org/10.1007/s00267-009-9380-y.

Qureshi, M.E., Harrison, S.R., Wegener, M.K., 1999. Validation of multicriteria analysis models. Agric. Syst. 62, 105–116. https://doi.org/10.1016/S0308-521X(99)00059-1.

Radcliffe, J.C., 2019. History of water sensitive urban design/low impact development adoption in Australia and internationally. In: Approaches to Water Sensitive Urban Design. Elsevier, pp. 1–24.

Saaty, T.L., 1994. How to make a decision: the analytic hierarchy process. Interfaces 24, 19–43.

SFEI, 2015a. GreenPlan-it: a Toolkit for Planning Green Infrastructure at the Watershed Scale.

SFEI, 2015b. GreenPlan-IT [WWW Document]. URL. https://greenplanit.sfei.org/. accessed 10.20.22.

SFEI, 2015c. Bay Area Green Infrastructure Master Planning Project.

Shamsi, U.M., Schombert, J.W., Lennon, L.J., 2014. SUSTAIN applications for mapping and modeling green stormwater infrastructure. Journal of Water Management Modeling C 379.

Sharma, A.K., Pezzaniti, D., Myers, B., Cook, S., Tjandraatmadja, G., Chacko, P., Chavoshi, S., Kemp, D., Leonard, R., Koth, B., 2016. Water sensitive urban design: an investigation of current systems, implementation drivers, community perceptions and potential to supplement urban water services. Water (Basel) 8, 272.

Shastri, H., Ghosh, S., Paul, S., Shafizadeh-Moghadam, H., Helbich, M., Karmakar, S., 2019. Future urban rainfall projections considering the impacts of climate change and urbanization with statistical–dynamical integrated approach. Clim. Dynam. 52, 6033–6051. https://doi.org/10.1007/s00382-018-4493-8.

Sheshukov, A.Y., Sekaluvu, L., Hutchinson, S.L., 2018. Accuracy of topographic index models at identifying ephemeral gully trajectories on agricultural fields. Geomorphology 306, 224–234. https://doi.org/10.1016/J.GEOMORPH.2018.01.026.

Shoemaker, L., Riverson, J., Alvi, K., Zhen, J.X., Paul, S., Rafi, T., 2009. SUSTAIN, a Framework for Placement of Best Management Practices in Urban Watersheds to Protect Water Quality (Cincinnati).

Sinnett, D., Smith, N., Burgess, S., 2015. Handbook on Green Infrastructure: Planning, Design and Implementation. Edward Elgar Publishing.

Szpakowski, W., Szydłowski, M., 2018. Probable rainfall in Gdańsk in view of climate change. Acta Scientiarum Polonorum Formatio Circumiectus 3, 175–183.

Szydłowski, M., Mikos-Studnicka, P., Zima, P., Weinerowska-Bords, K., Hakiel, J., Szawurska, D., 2015. Stormwater and snowmelt runoff storage control and flash flood hazard forecasting in the urbanized coastal basin. In: 14th International Symposium Water Management and Hydraulic Engineering.

Szydłowski, M., Gulshad, K., Mustafa, A.M., Szpakowski, W., 2023. The impact of hydrological research, municipal authorities, and residents on rainwater management in Gdańsk (Poland) in the process of adapting the city to climate change. Acta Scientiarum Polonorum. Formatio Circumiectus 22, 59–71. https://doi.org/10.15576/ASP.FC/2023.22.3.11.

Thévenot, D.R., Förster, M., 2005. Developing the DayWater adaptive decision support system for urban stormwater source control: a challenge. In: Proceeding of the Tenth International Conference on Urban Drainage.

Tran, T.J., Helmus, M.R., Behm, J.E., 2020. Green infrastructure space and traits (GIST) model: integrating green infrastructure spatial placement and plant traits to maximize multifunctionality. Urban For. Urban Green. 49, 126635 https://doi.org/10.1016/J.UFUG.2020.126635.

Trenouth, W.R., Linden, W.K. Vander, 2018. Canadian low impact development retrofit approaches: a 21st-century stormwater management paradigm. In: International Low Impact Development Conference 2018. American Society of Civil Engineers Reston, VA, pp. 193–202.

US EPA, 2014. Coastal Stormwater Management through Green Infrastructure A Handbook for Municipalities.

van Asselt, M.B.A., Rotmans, J., 2002. Uncertainty in integrated assessment modelling. Clim. Change 54, 75–105. https://doi.org/10.1023/A:1015783803445.

van den Berg, M., Wendel-Vos, W., van Poppel, M., Kemper, H., van Mechelen, W., Maas, J., 2015. Health benefits of green spaces in the living environment: a systematic review of epidemiological studies. Urban For. Urban Green. 14, 806–816. https://doi.org/10.1016/J.UFUG.2015.07.008.

Van Roon, M., 2005. Emerging approaches to urban ecosystem management: the potential of low impact urban design and development principles. J. Environ. Assess. Pol. Manag. 7, 125–148. https://doi.org/10.1142/S1464333205001943.

Viavattene, C., Ellis, J.B., 2011. Development and application of SUDSLOC in Birmingham, UK. In: Proc. Sustainable Urban Drainage Systems Workshop.

Voisin, J., Cournoyer, B., Vienney, A., Mermillod-Blondin, F., 2018. Aquifer recharge with stormwater runoff in urban areas: influence of vadose zone thickness on nutrient and bacterial transfers from the surface of infiltration basins to groundwater. Sci. Total Environ. 637, 1496–1507. https://doi.org/10.1016/J.SCITOTENV.2018.05.094. –638.

Walsh, C.J., Kunapo, J., 2009. The importance of upland flow paths in determining urban effects on stream ecosystems. J. North Am. Benthol. Soc. 28, 977–990. https://doi.org/10.1899/08-161.1.

Walter, M.T., Walter, M.F., Brooks, E.S., Steenhuis, T.S., Boll, J., Weiler, K., 2000. Hydrologically sensitive areas: variable source area hydrology implications for water quality risk assessment. J. Soil Water Conserv. 55, 277–284.

Walter, M.T., Steenhuis, T.S., Mehta, V.K., Thongs, D., Zion, M., Schneiderman, E., 2002. Refined conceptualization of TOPMODEL for shallow subsurface flows. Hydrol. Process. 16, 2041–2046. https://doi.org/10.1002/hyp.5030.

Wang, C., Middel, A., Myint, S.W., Kaplan, S., Brazel, A.J., Lukasczyk, J., 2018. Assessing local climate zones in arid cities: the case of Phoenix, Arizona and Las Vegas, Nevada. ISPRS J. Photogrammetry Remote Sens. 141, 59–71. https://doi.org/10.1016/J.ISPRSJPRS.2018.04.009.

Wang, Y., van Roon, M., Knight-Lenihan, S., 2021. Opportunities and challenges in water sensitive industrial development: an Auckland case study, New Zealand. Int. J. Sustain. Dev. World Ecol. 28, 143–156. https://doi.org/10.1080/13504509.2020.1783717.

Warganda, T.K., Sutjiningsih, D., 2017. Placement of BMPs in urban catchment area using SUSTAIN model: case study at Universitas Indonesia Campus, Depok, West Java, Indonesia. In: MATEC Web of Conferences. EDP Sciences, 06007.

Wu, J., Kauhanen, P., Hunt, J., Mckee, L., 2018a. Green Infrastructure Planning for the City of Sunnyvale with GreenPlan-IT.

Wu, J., Kauhanen, P., Hunt, J., Mckee, L., 2018b. Green Infrastructure Planning for the City of Oakland with GreenPlan-IT.

Wu, J., Kauhanen, P., Hunt, J., Mckee, L., 2018c. Green Infrastructure Planning for North Richmond Pump Station Watershed with GreenPlan-IT.

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

Zhang, K., Chui, T.F.M., 2018. A comprehensive review of spatial allocation of LID-BMP-GI practices: strategies and optimization tools. Sci. Total Environ. 621, 915–929. https://doi.org/10.1016/J.SCITOTENV.2017.11.281.

Zhen, J.X., Yu, S.L., Zhai, Y., 2004. A planning tool for watershed LID-BMP implementation. In: Critical Transitions in Water and Environmental Resources Management, pp. 1–10.

Zheng, Y., Chen, S., Qin, H., Jiao, J.J., 2018. Modeling the spatial and seasonal variations of groundwater head in an urbanized area under low impact development. Water (Basel) 10, 803.

Zölch, T., Henze, L., Keilholz, P., Pauleit, S., 2017. Regulating urban surface runoff through nature-based solutions – an assessment at the micro-scale. Environ. Res. 157, 135–144. https://doi.org/10.1016/J.ENVRES.2017.05.023.