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A critical review on optimization and implementation of green-grey infrastructures for sustainable urban stormwater management

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ABSTRACT

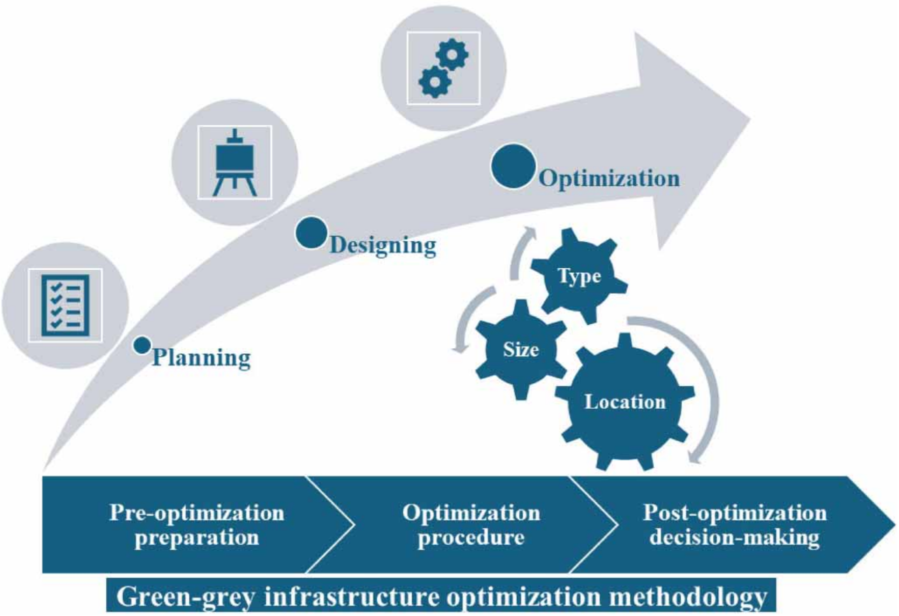
Green-grey infrastructures' implementation has progressed significantly in cities around the globe for sustainable stormwater management. This review study conducted on green-grey infrastructures' optimization represented recent research trends, existing research status, possible study gaps, and future research directions and recommendations needed for further improvements. The findings show that the research on green-grey infrastructures has got significant attention recently (after 2012) because of accessibility to computational resources and the development of hydrological-hydraulic models and optimization algorithms. Furthermore, research on green-grey infrastructures is mostly conducted in ten countries including China, USA and Iran ranked in the first three places, respectively, delivering their advantages to other countries with the essential awareness and knowledge. Most previous studies considered particular quantitative and qualitative optimization objectives and these studies were conducted at smaller retrofitting scales, therefore, future studies need to expand their scope towards socio-ecological objectives with consideration of larger study areas or multi-stage planning, designing, and implementation. Moreover, future research is recommended to consider stakeholders' participation in preliminary planning and designing stages for the successful implementation of sustainable stormwater management approaches. Lastly, the surrogate-based optimization approaches instead of traditional optimization methods can overcome the burden of computational time and resources in future.

Key words: green-grey infrastructures, LID, optimization, planning and designing, review, sustainable stormwater management

HIGHLIGHTS

- A critical review on the urban green-grey infrastructure development.
- State-of-the-art analysis of urban stormwater systems.
- Discussion and recommendation for optimal development of green-grey infrastructures.

GRAPHICAL ABSTRACT



LIST OF ABBREVIATIONS

Abbreviations	Description
ACO	Ant colony optimization
AHP	Analytical hierarchy process
ANN	Artificial neural networks
BMPs	Best management practices
BR	Bioretention cell
DEMATE	Decision making trial and evaluation laboratory
DT	Detention tank
DYCORS	Dynamic coordinate search using response surface models
EESMB	Economic-environmental-social monetization benefit
GA	Genetic algorithm
GDE3	Generalized differential evolution 3
GPS	Generalized pattern search
GR	Green roof
IT	Infiltration trench
LSPC	Loading simulation program in C++
MCDM	Multi-criteria decision-making
MOALOA	Multi-objective antlion optimization algorithm
MOSFLA	Multi-objective shuffled frog leaping algorithm
NBS	Nature based solutions
NSGA-II	Non-dominated sorting genetic algorithm II
PCSWMM	Personal Computer Stormwater Management Model
PICEA-g	Preference-inspired coevolutionary algorithm using goal vectors
PP	Permeable pavement
PROMETHE	Preference ranking organization method for enrichment evaluations
PSO	Particle swarm optimization
RB	Rain barrel
RD	Rooftop disconnection
RG	Roof garden
SA	Simulated annealing algorithm
SCM	Stormwater control measures
SUDS	Sustainable urban drainage system
SUSTAIN	System for urban stormwater treatment and analysis integration

SWMM	Stormwater management model
TOPSIS	Technique of order preference similarity to the ideal solution
TuRBO	Trust region Bayesian optimization
UDS	Urban drainage system
VS	Vegetative swale
WSUD	Water sensitive urban design

1. INTRODUCTION

Global climate change and urbanization are now considered as the main key contributory factors of stormwater management problems (i.e., quantitative and qualitative) in different cities around the world. Climate change mainly triggers the frequency and magnitude of rainfall events while urbanization contributes to increasing more impervious areas by continuous infrastructure development, and both drivers as a result significantly escalate the stormwater load on the urban drainage systems (UDS) (Wang *et al.* 2023b; Zhang & Jia 2023). If the existing UDS is traditionally designed and aged (indirect driver), and its storage and drainage capacities have been significantly reduced over time, in that case, the stormwater management problems become more worse and complex under the compound effects of all the above-mentioned drivers (Tansar *et al.* 2023), and these problems can be solved by sustainable stormwater management approaches considering environmental, economic and socio-ecological factors, as shown in Figure 1. Globally, urban stormwater management challenges, issues, and problems have been recently highlighted by urban planners, stormwater engineers, researchers, policymakers and other stakeholders in order to find mitigation and adaptation opportunities for sustainable stormwater management; however, a critical analysis of previous research studies is necessary to discuss previous research findings and contributions, highlight pros and cons, synthesize different strategies, tools and methods for improving efficiency and effectiveness of UDS' performance, and finally provide recommendations for future research directions to fulfill existing research gaps (Jayasooriya *et al.* 2020).

Traditionally, grey infrastructure (i.e., pipes/drains and detention tanks) was mainly used for collection, storage and conveyance of stormwater load from point sources to receiving water bodies (Duan *et al.* 2016; Li *et al.* 2019). Over the last two decades, green infrastructures, also known as stormwater control measures (SCM) and best management practices (BMPs) in the United States, low impact developments (LID) in China, water sensitive urban design (WSUD) in Australia and New Zealand, and sustainable urban drainage system (SUDS) and nature based solutions (NBS) in Europe, have been extensively studied, evaluated, and applied separately or in combination with existing UDS to mitigate stormwater management problems (Islam *et al.* 2021). The most commonly applied green infrastructures are bioretention cells (BC), green

Figure 1 | Relationship between key drivers and affected factors for sustainable stormwater management.

roofs (GR), rain gardens (RG), permeable pavements (PP), infiltration trenches (IT), vegetative swales (VS), and rooftop downspout disconnections.

Several recent studies conducted for performance evaluation of green infrastructures proved their significant contributions towards solving quantitative and qualitative stormwater management problems (Samouei & Özger 2020; Pei *et al.* 2021; Yang *et al.* 2021; Wang *et al.* 2021a; Mohammed *et al.* 2022). However, the accurate planning, design and construction of green and grey infrastructures in individual and combined settings within urban catchments is a difficult and complex process, as multiple influencing factors including topographical, land-use, weather patterns, groundwater conditions and economic resources need to be considered during construction. Urban planners need to carefully decide the type, size and location of green infrastructures, and size/volume and location of grey infrastructures (i.e., pipe/detention tank). The careful planning and implementation of both stormwater management systems boost their collective advantages and stormwater load management efficiencies.

Recently, heuristic optimization approaches for green and grey infrastructures optimization have become widely popular for exploring optimal designs of both infrastructures due to their capability to solve highly non-linear, complex and discrete optimization problems (Zhang & Jia 2023). The synthesis of recent review studies represents their main contributions to analyze the uncertainties for optimal design of stormwater systems (Duan *et al.* 2016), discuss different optimization methods for stormwater management (Shishegar *et al.* 2018), explain multi-objective optimization of green infrastructures considering their functional evaluations (Wang *et al.* 2020) and critical analysis of different obstacles, issues and opportunities recognized during their applications in the industrial region (Jayasooriya *et al.* 2020), evaluate spatial allocation processes with evaluation of multiple optimization tools and approaches (Zhang & Chui 2018), develop a comprehensive optimization framework with synthesis of existing research gaps and future research directions (Zhang & Jia 2023), and present a systematic literature review analysis considering the optimization and resilience of green infrastructures (Islam *et al.* 2021). Although a few recently published review studies synthesize green infrastructure optimization considering multiple factors (Jayasooriya *et al.* 2020; Wang *et al.* 2020; Zhang & Jia 2023), a comprehensive critical synthesis of green and grey infrastructures considering planning and designing as preliminary stages, and their impacts on optimization and implementation was left unexplored. Moreover, the current study explained generalized optimization procedures, and synthesized previous research studies considering their objective functions, retrofitting scales, publication time-scales and countries. Further, this review paper mainly contributes to synthesize existing literature on planning, design and optimization of green-grey infrastructures, highlights pros and cons, and discusses required improvements and future recommendations needed for improving green-grey optimization approaches.

2. METHODOLOGY

2.1. Systematic review process

The articles were searched from 2000 to 2023 on Web of Science with a search string based on 'low impact developments' OR 'LID' OR 'sustainable stormwater management' OR 'green infrastructures' OR 'best management practices' OR 'BMPs' OR 'water sensitive urban design' OR 'nature-based solutions' OR 'blue-green systems' OR 'sponge cities' OR 'green infrastructures' OR 'green-grey' AND 'Optimization'/'Optimal'. Based on these keywords and initial screening, 149 articles were selected, and a further search was conducted on Google Scholar to include the most relevant articles related to the optimization of green-grey infrastructures in the review process. Figure 2 represents annual publication and citation records based on the above-mentioned keywords. The analysis of publication records clearly shows that few studies were published between 2000 and 2010, however, a significant rising trend of publications on green-grey infrastructures' optimization was observed over the last decade (2011–2020). There are multiple reasons, including but not limited to the availability of high computational resources (i.e., high computational computer system, parallel processing, etc.), development of planning and green infrastructures optimization tools, development of existing hydrological-hydraulic models in different computer languages, awareness and acceptability of local stakeholders about the significance of investments on stormwater management practices, etc. Figure 3 represents the spatial distribution of the authors whose countries published their work for optimization of green-grey infrastructures. Only the top 10 countries are labeled, in which China ranked in first place with 72 publications, followed by USA with 44 and Iran with 18, followed by other countries. The geographical distribution of publications on the optimization of green-grey infrastructures indicates that globally specific countries/regions have significant contributions in research on stormwater management practices and other countries made little progress in this domain.

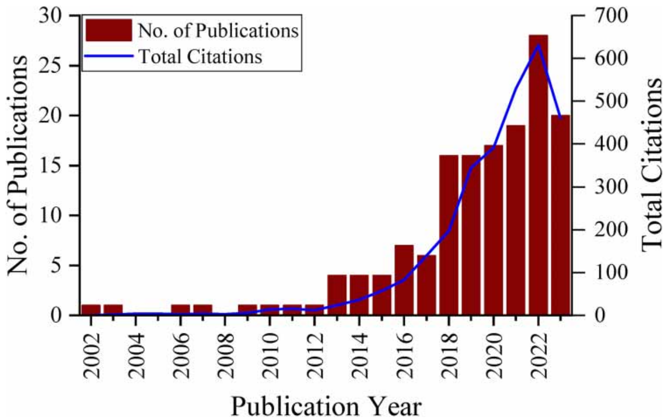


Figure 2 | Annual publications and citations records.

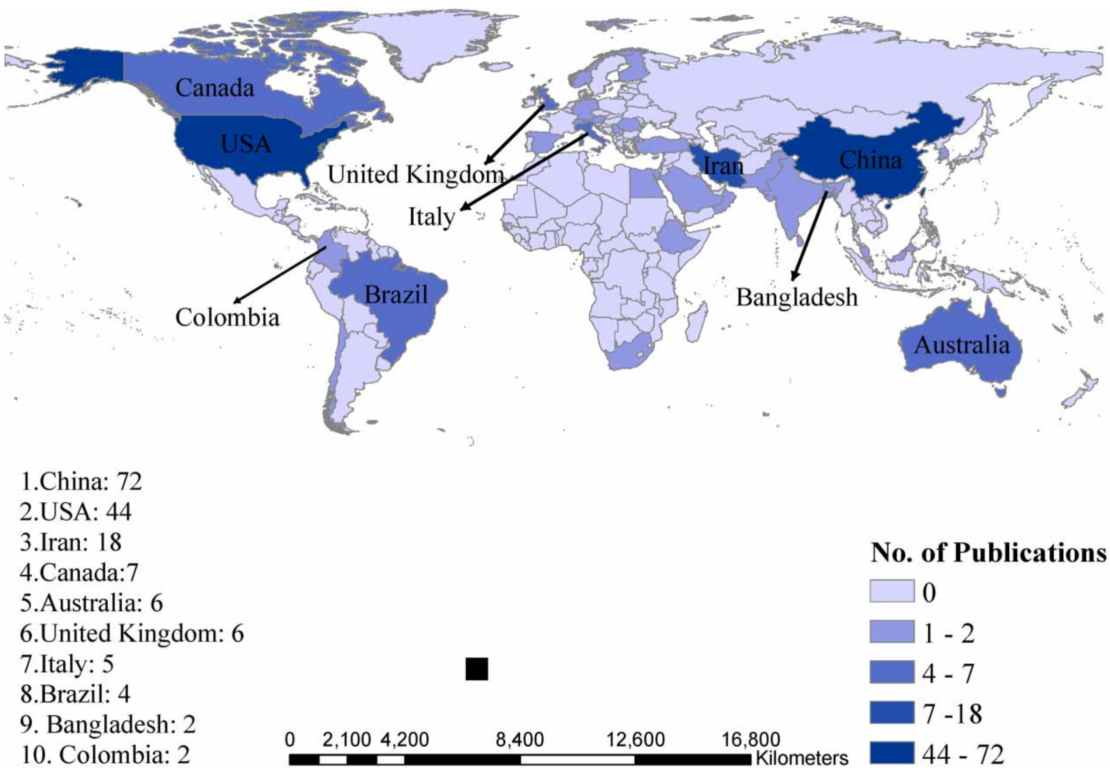


Figure 3 | Geographical distribution of countries that published articles on green infrastructure optimization. The top ten countries are labeled, and their ranks with the published number of articles are mentioned on the bottom-left side.

3. CRITICAL ANALYSIS OF PLANNING AND DESIGN OF GREEN-GREY INFRASTRUCTURES

The preliminary comprehensive planning and design of green-grey infrastructures is a complex and difficult task as it involves consideration of several factors including local climate and urbanization patterns, land-use spatial dynamics, short-term and long-term climate change projections, waterlogging conditions, identification of flood hot-spots, stakeholders' participations, and availability of space and economic resources (Tanyanyiwa *et al.* 2023). Kuller *et al.* (2017) presented a reciprocal WSUD planning concept in terms of '*opportunities*' and '*needs*' by stating that '*WSUD needs a place*' or '*a place needs WSUD*'. The WSUD planning-support tool was developed for spatial placement of green infrastructures considering biophysical, socio-economic, planning and governance as '*opportunities*' and ecosystem services as '*needs*', and their baseline factors and indicators are thoroughly explained (Kuller *et al.* 2019). Zhang & Chui (2018) presented a strategic planning cycle of green infrastructures which mainly emphasizes the determination of location, selection of type, and designing and sizing of green infrastructures based on pre-determined installation objectives and target areas. They presented a schematic representation of three main elements of the strategic cycle, i.e., location, type and size and their mathematical relationships with three main factors including composition, aggregation, and distribution pattern. The critical analysis of the relationship between these main elements and influencing factors explains different combinations, arrangements, and possible patterns of green infrastructure placements and their impacts on surface and groundwater hydrological dynamics before and after applications of green infrastructures.

Generally, the first step of planning and designing green infrastructures is to identify appropriate locations for installation and then appropriate types and retrofitting sizes carefully designed considering stormwater quantitative and qualitative management objectives. The urban planners and engineers need to include local stakeholders' interests and participation in the initial planning phase considering their concerns about locations and attitudes towards the retrofitting process. The socio-economic constraints (including, e.g., stakeholders' concerns and land acquisition/availability) need to be fully resolved at the initial phase for the successful implementation of projects. Moreover, a preliminary technical study of catchment characteristics is necessary to understand local land-use spatial dynamics, soil characteristics, slope, groundwater conditions, drainage and impervious areas, as well as evaluation of existing green infrastructures.

The effectiveness and efficiency of green-grey infrastructures significantly change at different locations, for example, at upstream or downstream, at-source or close to receiving water bodies, retrofitting them at sub-catchments with different imperviousness, soil permeability and groundwater table conditions, as shown in Figure 4. For example, larger drainage and impervious areas produce greater storm runoff, and installation of green infrastructures at optimal locations with the best design configurations (i.e., optimal design parameters of green infrastructure including surface, soil and storage layers) can help to produce an optimum potential for the highest surface runoff collection, treatment and storage as groundwater recharge. Similarly, the grey infrastructures are placed within urban catchment by considering the above-mentioned factors, meanwhile, the optimal sizes and locations are carefully designed considering the requirements of stormwater storage

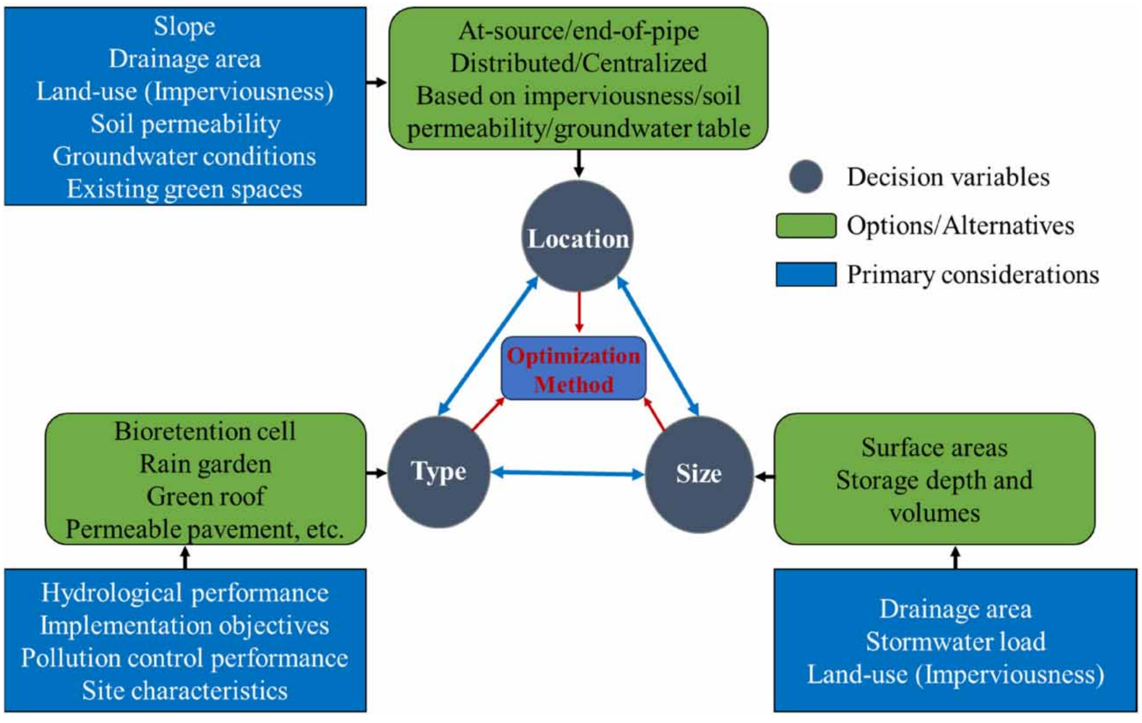


Figure 4 | Schematic representation of interrelationship of optimization method with green-grey infrastructure retrofitting factors (decision variables), along with available choices based on primary consideration factors.

and availability of space in densely urbanized areas. Furthermore, the combined installation of green and grey infrastructures must be planned in a way that both infrastructures' benefits are synchronized by (1) collection and infiltration of stormwater with green infrastructures, and (2) storage of excessive stormwater with grey infrastructures such as detention tanks.

4. GREEN-GREY INFRASTRUCTURES OPTIMIZATION METHODOLOGY

The systematic and strategic planning of complete optimization processes with consideration of significant surrounding topological, hydrological, environmental, climatic and sub-surface influencing factors are crucial for the accurate determination of optimal design of green-grey infrastructures. The comprehensive and generalized complete optimization framework is divided into three parts: (1) pre-optimization preparation, (2) optimization procedure, and (3) post-optimization decision-making, as shown in Figure 5.

4.1. Pre-optimization preparation

The preliminary analysis before optimization involves considerations of multiple factors including target/required scale and appropriate locations where retrofitting of green-grey infrastructures is planned. The technical survey, planning and evaluation of existing land-use and topographical characteristics of the catchment provide reasonable information for informed decision-making to decide the magnitude/degree of retrofitting scale and suitable locations for implementation (Zhou & Wu 2020). The primary land-use assessment quantifies impervious and pervious areas of each sub-catchment in the catchment/watershed and calculates the maximum level of imperviousness of each sub-catchment which can be practically retrofitted with different types of green infrastructures (Yang *et al.* 2023b). The specific land-use analysis can also provide information about the maximum retrofit size of each type of green infrastructure that can be defined as the maximum retrofit limit in the optimization algorithm. Similarly, the preliminary assessment of space availability can be conducted for detention tank placement considering existing and future construction plans of local stakeholders (Haghighatafshar *et al.* 2019; Latifi *et al.* 2023). Furthermore, the selection of the retrofitting scale also depends on the availability of resources like planning and implementation time, development budget, retrofitting stages, computational model, and stakeholders' willingness and participation (Xu *et al.* 2020; Zhang *et al.* 2023). In case of limited time and budget, the retrofitting scale of green-grey infrastructure reduces and can be shifted into different planning and implementation stages. However, it is important to highlight that the understanding of the functional performance and implications of green infrastructures at smaller scales to mitigate target objectives are well-understood by many recently conducted studies, however, the optimization of green

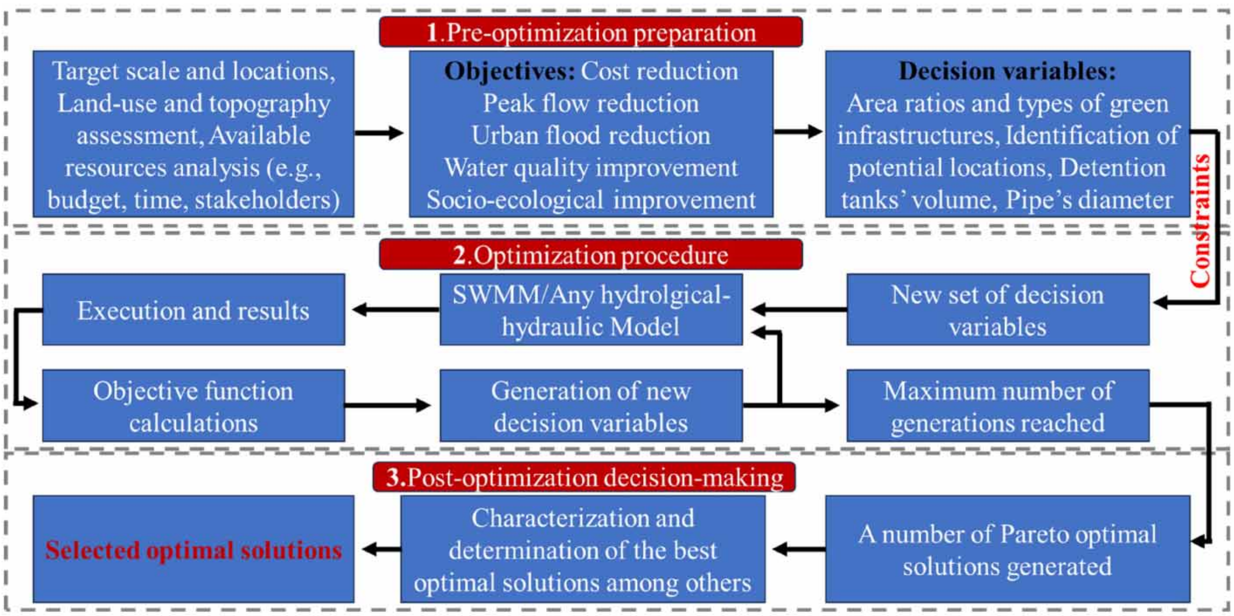


Figure 5 | Green-grey infrastructure planning and optimization framework.

infrastructures at the larger or different scales is relatively unexplored and complex (Zhang & Jia 2023). In addition, selection of an appropriate hydrological-hydraulic simulation model is one of the crucial steps by considering the modelling scale and required hydrological and water quality modelling outputs as objectives. Furthermore, multiple hydrological-hydraulic simulation models are available for stormwater modelling, exemplified as Stormwater Management Model (SWMM) (Rossman 2010), Personal Computer Stormwater Management Model (PCSWMM) (James *et al.* 2010), InfoWorks ICM (Autodesk Inc. 2024) and MIKE URBAN (Dhi 2008). Each of them has its pros and cons, so that selection of an appropriate model considering required modelling objectives and coupling/interface compatibility with optimization algorithms is critical (Ferrans *et al.* 2022).

4.2. Optimization procedure

Multiple optimization algorithms are available for the optimization of water resources systems' problems, like evolutionary algorithms, genetic algorithm (GA) (with its different extensions as non-dominated sorting genetic algorithm II & III) (Kumar *et al.* 2022), ant colony optimization (ACO) (Hou *et al.* 2019), generalized pattern search (GPS) (Audet & Dennis 2002), simulated annealing algorithm (SA) (She *et al.* 2021), particle swarm optimization (PSO) (Jean *et al.* 2021), artificial intelligence-based methods like artificial neural networks (ANN) (Chu *et al.* 2020), and machine learning algorithms. These optimization algorithms have different capabilities including the potential for solving optimization problems, computational efficiencies, and coupling/interface flexibilities with numerical models. The selection of an appropriate optimization algorithm considering the factors as mentioned earlier makes the optimization process more efficient and practically implementable, and the synthesis of recent optimization algorithms (Dong *et al.* 2021; Liang *et al.* 2023; Zamani *et al.* 2023; Zhu *et al.* 2023) employed for green-grey infrastructures proves NSGA-II is the most extensively applied optimization algorithm compared to others because of its configuration structure and comparatively easy integration with different numerical models and availability in various programming languages.

The optimization problem is mainly based on three components: objective functions, decision variables and constraints. Generally, the objective functions are calculated based on simulated outputs of numerical models (i.e., surface runoff, peak runoff, flood volume, pollutant concentration, etc.), or mathematical models (i.e., life cycle retrofitting cost, flood damage calculation, etc.). Meanwhile, objective functions are usually defined with the maximization of benefits versus the minimization of costs. In terms of decision variables (such as types, sizes and locations of green infrastructures, and storage volume and locations of detention tanks), these variables are determined by local land-use and topographical assessments (Saniei *et al.* 2021; Leng *et al.* 2022). In the optimization process, initial sets of decision variables are randomly generated or assigned with original values/ranges; then each set of decision variables is iteratively simulated by a numerical model; and afterwards, model responses are employed to calculate objective functions with defined constraints. This iterative process is repeated until the specified number of iterations/stopping criteria is reached. Multiple optimal solutions are iteratively calculated and improved based on a non-dominating optimization process, and the final optimal solutions are calculated based on the last iteration against optimal designs of decision variables (Leng *et al.* 2021).

4.3. Post-optimization decision-making

Decision-making as a post-optimization step plays a significant role in the selection of appropriate/best optimal solutions among different optimal solutions/alternatives against their optimal designs which are calculated accordingly for practical implementations. Different multi-criteria decision-making (MCDM) tools such as analytical hierarchy process (AHP), technique of order preference similarity to the ideal solution (TOPSIS), decision-making trial and evaluation laboratory (DEMATE), preference ranking organization method for enrichment evaluations (PROMETHE), etc. have been developed over recent years (Tan *et al.* 2021), and AHP and TOPSIS among all MCDM techniques have been extensively applied for planning and decision-making of green-grey infrastructures. As an example, the detailed procedure of TOPSIS is discussed among all MCDM methods. Firstly, the specific evaluation indicators/criteria (e.g., cost, flood volume, urban drainage system resilience, pollutant concentration, etc.) are defined based on which different optimal solutions/alternatives would be evaluated. Secondly, a decision matrix is constructed based on optimal solutions and criteria to evaluate the performance of each optimal solution against each defined criterion. Thirdly, the decision matrix is standardized by considering the equal/determined importance of all criteria. During this normalization process, weights are assigned to all criteria based on their relative significance estimated through stakeholder preferences, expert opinions, and analytical methods. The next step is to determine the ideal and negative ideal solutions and their Euclidean distances from each alternative and between each alternative, their relative closeness to ideal solutions. Finally, the alternatives/optimal solutions are ranked based on relative closeness to ideal solutions (TOPSIS score), with the highest value classified as the best option (She *et al.* 2021; Tansar *et al.* 2023).

5. SYNTHESIS OF LITERATURE ON GREEN-GREY INFRASTRUCTURES OPTIMIZATION – FUTURE RESEARCH DIRECTION AND RECOMMENDATIONS

A critical literature review analysis of 97 studies was conducted to understand the distribution of studies in different countries focused on particular optimization objectives, and their impacts on retrofitting scales, as shown in Figure 6. The most commonly used six objective functions in previous studies are surface runoff volume, peak flow, flood volume, retrofitting cost, pollutant loads (e.g., total nitrogen, total phosphorus, etc.) and total suspended solids, as shown in Figure 6(a). The majority of

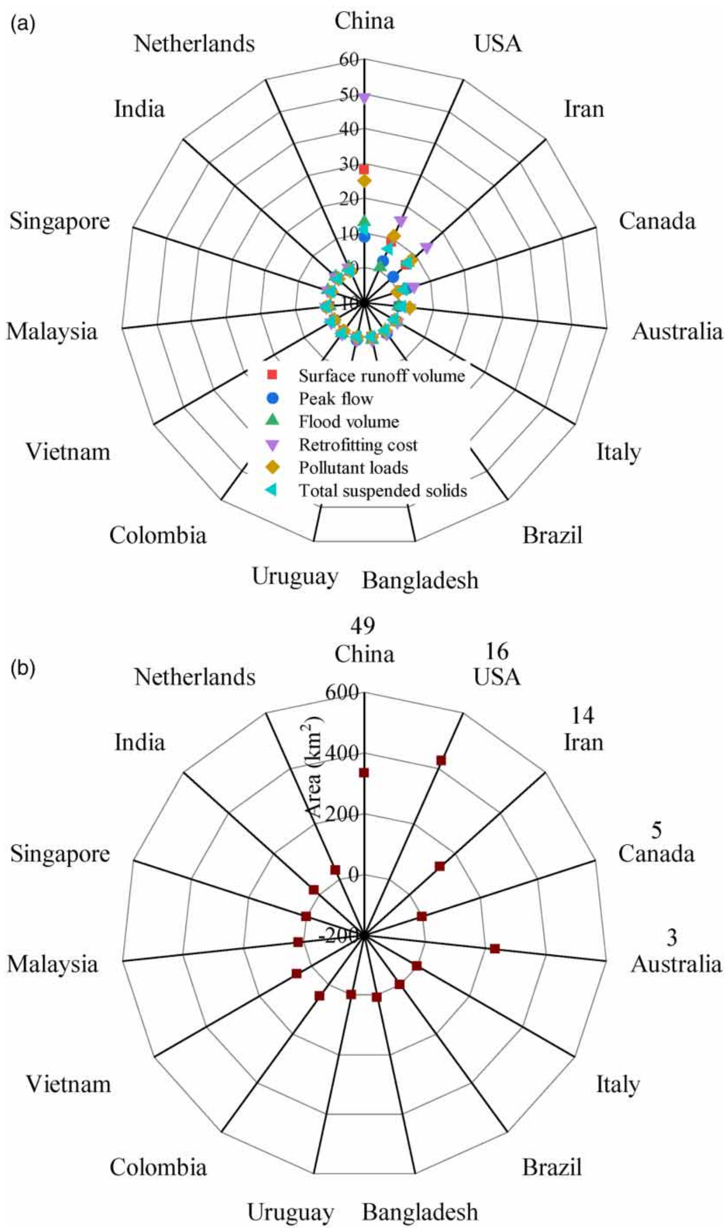


Figure 6 | (a) Countries' representation along with statistics of different objective functions considered in previous studies. (b) Countries' representation along with study area size distribution. The numbers on some countries' names represent the number of studies whose average study areas are represented.

past green-grey infrastructures optimization studies were mainly conducted to understand the potential of control/reduction of surface runoff, and different pollutant loads (followed by flood volume and peak flow reductions) against retrofitting costs in China, USA, Iran and Canada. Other countries represented a limited number of optimization studies with the same probability of all earlier mentioned objective functions.

Retrofitting scale is one of the significant factors considered for planning, designing, optimization, and implementation of green-grey infrastructures (Zhang & Chui 2018). Figure 6(b) clearly illustrates the scales of study areas of four countries (i.e., China, USA, Iran and Australia) where research on green-grey infrastructures optimization was extensively conducted compared to other countries, implemented stormwater management practices on relatively larger study scales (i.e., average study area size is greater than 136 km^2), however, the remaining countries mostly conducted studies at the smaller scales (i.e., less than 55 km^2). More specifically, it is interesting to note that the majority of optimization studies in the above-mentioned countries (including Canada) were conducted at a smaller scale (i.e., less than 50 km^2) and few optimization studies were conducted at a larger scale, as shown in Figure 7. Furthermore, another important aspect is to highlight that the majority of optimization studies were conducted over the recent decade (after 2012) because of the availability of computational resources; however, the researchers have mostly focused on smaller scales over recent years, and a few studies were conducted at larger scales in USA and China.

The above-mentioned findings of previous optimization studies highlighted some facts and research gaps that need to be emphasized in the future. The previous studies mainly focused on specific quantitative and qualitative objectives of green-grey infrastructures (as mentioned in Figure 6(a)), however, green-grey infrastructures optimization objectives need to be broadened to consider social and ecological optimization objectives. A limited number of studies recently investigated these objectives (Jia *et al.* 2022; Liu *et al.* 2023; Zhu *et al.* 2023) (as shown in Table 1); however, more research is needed to clearly understand green infrastructures' holistic benefits and development of more socio-ecological indexes (Pugliese *et al.* 2022; Zhang & Jia 2023).

Besides, the local stakeholders are key players in the practical implementation of these stormwater control measures, the consideration and quantification of their opinions at the planning, design and optimization stages as social acceptability indicators can provide insights into project success, and addressing their concerns can improve the probability of success to achieve target design goals. In addition to the earlier mentioned benefits of green-grey infrastructures implementation, it is important to highlight how these stormwater management approaches contributed to improving the resilience of UDS,

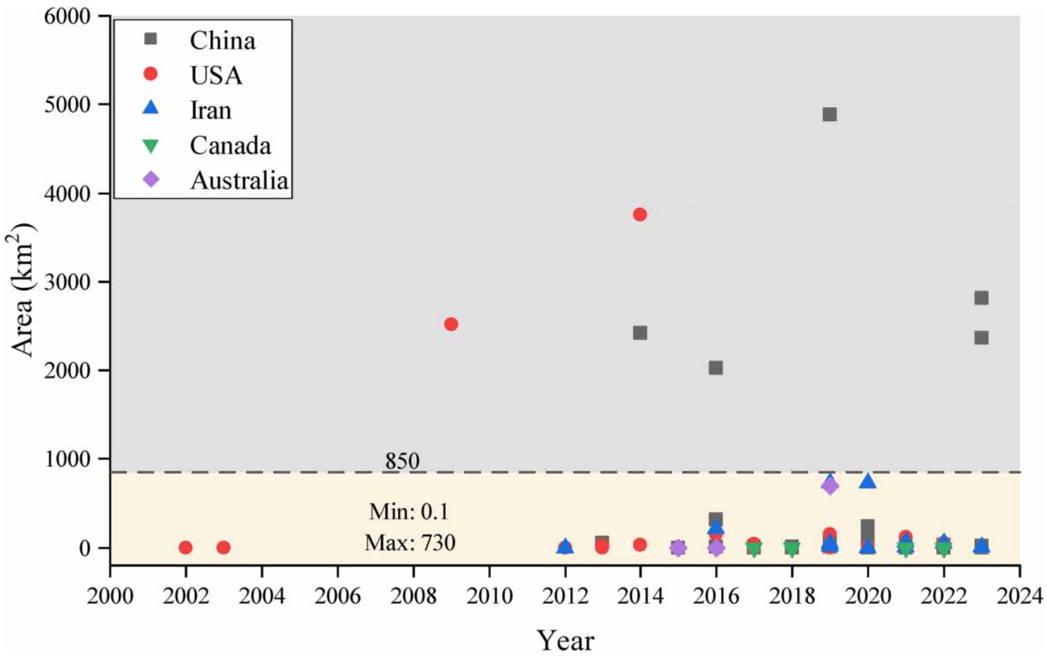


Figure 7 | Scales of study area in top five selected countries between 2001 and 2023.

Table 1 | Summary of green-grey infrastructures optimization characteristics found in the selected 31 recent studies on/after 2019

Source	Optimization objective functions	Decision variables	Retrofitting scale, Study area (km^2)	Green-grey infrastructure types	Stormwater management approach	Simulation model & optimization algorithm
(Zamani et al., 2023)	▲★●	▼O✹	Catchment, 8	VS, BR, PP, DT	⊠	SWMM+NSGA-II
(Yang et al., 2023b)	▲☐⊙	▼✹	Catchment, 0.8453	BC, GR, PP	✕	SWMM+NSGA-II
(Liu et al., 2023)	○▲⛊	▼O✹	Planning region, 2358	BC, GR, VS, PP, DT	⊠	SWMM+NSGA-II
(Li et al., 2023)	▲●	▼✹	Watershed, 2812	BC, RG, VS	✕	LSPC + Bayesian
(Latifi et al., 2023)	○●■	▼O✹	Catchment, 13.3	VS, BC, IT	✕	SWMM+NSGA-III
(Eskandaripour et al., 2023)	●■	▼✹	District, 8.17	VS, BC, PP	✕	SWMM + Slime mould algorithm
(Zhu et al., 2023)	○▲EESMB	▼O✹	Pilot area, 19.36	PP, VS, BC, RG	✕	SWMM+NSGA-II
(Wang et al., 2023a)	▲◆	▼O	Two case studies: 0.934, 0.914	BC, PP	⊠	SWMM+NSGA-II
(Yang et al., 2023a)	○▲⅄	▼O	Pilot study, 0.435	VS, RG, BC	✕	SWMM+NSGA-II
(Tansar et al., 2023)	▲◎◆	▼✹	Catchment, 10.2	BC, GR, PP, RG	⊠	SWMM+NSGA-II
(Zhi et al., 2022)	○▲●	▼O✹	Pilot study, 0.58	GR, PP	✕	SWMM+NSGA-II
(Yu et al., 2022)	☐▲	▼✹	Residential colony, 0.152	BB, RG, PP, GR	✕	SWMM+PICEA-g
(Wang et al., 2022b)	○▲	▼✹	Campus, 0.97	GR, RB, RD, PP, RG, BC, VS, IT	✕	SWMM+GDE3
(Wang et al., 2022a)	★▲ Land occupied	▼O✹	Catchment, 3.95	BC, GR, PP	⊠	SWMM+NSGA-III
(Leng et al., 2022)	○★●▲	▼O	City, 5.5	BC, GR, PP	✕	SWMM+NSGA-III
(Lu et al., 2022)	▲◎	▼O	Catchment, 0.36	BC, GR, PP	✕	SWMM+DYCORS/TuRBO
(Gao et al., 2022)	▲◎	▼✹	District, 0.2336	GR, PP, BC, VS	⊠	SWMM+SUSTAIN
(Abduljaleel and Demissie, 2022)	○☐▲	▼O✹	Catchment, 53.82	IT, RB, RG, BC, PP	✕	SWMM+NSGA-II
(Tang et al., 2021)	○☐▲■	▼✹	Pilot study, 0.40	BC, RG, GR, PP	✕	SWMM+NSGA-II
(Taghizadeh et al., 2021)	●■	▼✹	District, 0.60	IT, BC, PP	✕	SWMM+PSO
(Leng et al., 2021)	○▲●	▼O✹	Study site, 0.120	GR, PP, RG, BC	⊠	SWMM+NSGA-II
(Saniei et al., 2021)	★▲●■	▼✹	Catchment, 8	VS, BC, PP, DT	⊠	SWMM+NSGA-II
(Ghodsi et al., 2020)	○▲	▼O	Watershed, 730	PP, BC, VS, IT	✕	SWMM+NSGA-II
(Dong et al., 2020)	▲●	▼✹	Watershed, 242.8	GR, PP, IT	✕	SUSTAIN+ NSGA-II
(Minh Hai, 2020)	▲■	▼✹	Basin, 55.53	GR, PP, BC	✕	SWMM+NSGA-II
(Men et al., 2020)	○☐▲●	▼✹	Pilot study, 0.94	VS, PP, GR, RB	✕	SWMM+NSGA-II
(Alamdari and Sample, 2019)	○▲●■	▼O✹	Watershed, 150	BC, VS, PP, GR, DT	⊠	SWMM+NSGA-II
(Liu et al., 2019)	▲●	▼O✹	University, 0.58	GR, PP	✕	SWMM+MOSFLA
(Loáiciga et al., 2019)	○★▲	▼	District, 21.5	PP, BC, IT, VS	✕	SWMM+MOALOA
(Raei et al., 2019)	○●▲	▼O	Catchment, 20	BC, VS	✕	SWMM+NSGA-II
(You et al., 2019)	○▲●	▼	Community, 0.20	BS, PP, BC, GR, RB	✕	SUSTAIN+ NSGA-II

Note: **Optimization objective functions:** ○Surface runoff volume, ☐Peak flow, ★Flood volume, ▲Retrofitting cost, ◎Damage, ◆Resilience, ●Pollutant load, ■ Total suspended solids, ⊙Catchment outflow, ⛊Ecological benefits, ⅄Surcharge/overflow time
Decision variables: ▼Size, Olocation, ✹type
Stormwater management approach: ✕ = Single: Green infrastructure only; ⊠ = Combined: Green and grey infrastructures

reducing damages to local infrastructures, changing local groundwater table quality and quantity, as very few studies recently considered them (Bakhshipour *et al.* 2021a, 2021b; Wang *et al.* 2021b; Tansar *et al.* 2023; Wang *et al.* 2023a, 2023c), and further work is needed for deeper understanding. Furthermore, stormwater management practices have been significantly studied and implemented in a few countries, however, more awareness about their comprehensive benefits is needed to expand their sustainable stormwater management benefits to other countries.

Most previous optimization studies have focused on smaller scales, however, their impact at the larger scale is rarely explored for multiple reasons including but not limited to computational and economic resource limitations, technical expertise and experiences, hydro-meteorological data unavailability, stakeholder's concerns, etc. However, the findings of optimization studies at the smaller scale may be generalized for larger scales, assuming similarities in their regional topographical and hydro-meteorological conditions, land-uses, flood risks, drainage infrastructures, urban developments, climate change impacts, etc. (Chui 2017; Wang *et al.* 2020; Yang *et al.* 2023a). Meanwhile the benefits of stormwater management practicesin reality may be significantly different for larger scales like at watersheds and city scales because of their regional topographical and drainage infrastructures dynamics. So, multiscale optimization studies are needed in order to compare their benefits at smaller and larger scales by fulfilling existing research gaps, however, its implementation may face challenges because of variations in types, sizes and locations of stormwater management practices. Furthermore, another planning, design and optimization approach can be adopted in which some specific area (i.e., the area having higher flood risk) among larger scale areas (i.e., watersheds and city) is prioritized for retrofitting, followed by retrofitting by other regions based on the availability of resources (Wang *et al.* 2017; Xu *et al.* 2018; Xu *et al.* 2020; Zhang *et al.* 2023). This approach is also known as multi-stage planning and implementation based on priority levels of different regions.

Table 1 provides summarized information of 31 green-grey infrastructures optimization studies along with their optimization objectives, decision variables, retrofitting scales, green-grey infrastructure types, stormwater management approach, and simulation model with optimization algorithm. Only nine out of 31 reported studies in Table 1 have used a combined stormwater management approach (i.e., green and grey infrastructures optimization), while other studies considered only green infrastructures optimization. Future research studies should consider/prefer a combined stormwater management approach in order to fully understand the potential and limitations of both systems against extreme rainfall conditions considering future uncertainties (i.e., urban development and climate change). Furthermore, the majority of reported studies in Table 1 have employed metaheuristic algorithms (i.e., NSGA-II, PSO, etc.) whose computational time is one of the main challenge reported in stormwater management optimization studies. The computational time to converge optimization problem depends on many factors, mainly on the number of objective functions, number of decision variables, study area size, number of iterations, population size, cross-over, mutation rates, etc. Considering this limitation, many previous optimization studies have considered smaller study areas to perform optimization of green-grey infrastructures, and have discussed this as one of the limitations in their research findings. Recently, the surrogate-based/data-driven optimization approaches have grabbed significant attention and have reduced substantial computational time in comparison to traditional optimization approaches, in which this method replicates the optimization problem by developing surrogate models based on input-output datasets and objective functions, the developed surrogate model takes significantly less simulation time in comparison with the original model (i.e., hydrological-hydraulic simulation model). As a result, the convergence of optimization problem to find an optimal solution with a surrogate-based model collectively reduces computation time in comparison with the traditional optimization method.

6. CONCLUSIONS

A critical review study is conducted on green-grey infrastructures planning, design and optimization, analyzed its recent trends of development and implementation at different regions around the globe, its current status, research gaps and possible future research direction and recommendations. The statistical analysis of previous research studies that mainly focused on green-grey infrastructures optimization represents that the trend of such studies started from 2012 onwards, and the major portion of optimization research was conducted from the top ten countries, as China, USA and Iran ranked in the first three places, respectively.

The comprehensive planning and designing as a preliminary step before green-grey infrastructures optimization should consider multiple factors including local climate and urbanization patterns, land-use spatial dynamics, short-term and long-term climate change projections, waterlogging conditions, identification of flood hot spots, stakeholders' participation, and availability of space and economic resources, which play critical roles in the practical implementation of the designed project. Following that, the optimization problem is based on defined objective functions, decision variables (i.e., types, sizes and locations of green infrastructures, and storage volume and locations of detention tanks), and constraints which are solved by coupling any hydrological-hydraulic simulation models with optimization algorithms.

Furthermore, the previous optimization studies mostly considered specific quantitative and qualitative objective functions for optimization, while socio-ecological optimization objectives were rarely explored. Therefore, future research is recommended to quantify comprehensive social and ecological benefits to expand the horizon of current green-grey infrastructures' advantages. Lastly, future optimization studies should consider a larger retrofitting scale (i.e., watershed or city scale) to understand green infrastructures' holistic benefits on a bigger horizon by using surrogate-based optimization methods to reduce computational time. Furthermore, the concept of multi-stage planning and implementation of stormwater management practices needs to be applied in practice in which high flood-risk areas are prioritized for retrofitting compared to others, providing support to cope with economic constraints.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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