Front. Eng. Manag. 2023, 10(4): 566–581
https://doi.org/10.1007/s42524-023-0267-z

REVIEW ARTICLE

Lingwen LU, Faith Ka Shun CHAN, Matthew JOHNSON, Fangfang ZHU, Yaoyang XU

The development of roadside green swales in the Chinese Sponge City Program: Challenges and opportunities

Abstract Roadside green swales have emerged as popular stormwater management infrastructure in urban areas, serving to mitigate stormwater pollution and reduce urban surface water discharge. However, there is a limited understanding of the various types, structures, and functions of swales, as well as the potential challenges they may face in the future. In recent years, China has witnessed a surge in the adoption of roadside green swales, especially as part of the prestigious Sponge City Program (SCP). These green swales play a crucial role in controlling stormwater pollution and conserving urban water resources by effectively removing runoff pollutants, including suspended solids, nitrogen, and phosphorus. This review critically examines recent research findings, identifies key knowledge gaps, and presents future recommendations for designing green swales for effective stormwater management, with a particular emphasis on ongoing major Chinese infrastructure projects. Despite the growing global interest in bioswales and their significance in urban development, China's current classification of such features lacks a clear definition or specific consideration of bioswales. Furthermore, policymakers have often underestimated the adverse environmental effects of road networks, as reflected in existing laws and planning documents. This review argues that the construction and maintenance of roadside green swales should be primarily based on three critical factors: Well-thought-out road planning, suitable construction conditions, and sustainable long-term funding. The integration of quantitative environmental standards into road planning is essential to effectively address the challenge of pollution from rainfall runoff. To combat pollution associated with roads, a comprehensive assessment of potential pollution loadings should be carried out, guiding the appropriate design and construction of green swales, with a particular focus on addressing the phenomenon of first flush. One of the major challenges faced in sustaining funds for ongoing maintenance after swale construction. To address this issue, the implementation of a green finance platform is proposed. Such a platform would help ensure the availability of funds for continuous maintenance, thus maximizing the long-term effectiveness of green swales in stormwater management. Ultimately, the findings of this review aim to assist municipal governments in enhancing and implementing future urban road designs and SCP developments,

Received Feb. 21, 2023; revised Jul. 12, 2023; accepted Jul. 13, 2023

Lingwen LU
Key Laboratory of Urban Environment and Health, Ningbo Observation and Research Station, Institute of Urban Environment, Chinese Academy of Sciences (CAS), Xiamen 361021, China; School of Geographical Sciences, Faculty of Science and Engineering, University of Nottingham Ningbo China, Ningbo 315100, China; Zhejiang Key Laboratory of Urban Environmental Processes and Pollution Control, CAS Haixi Industrial Technology Innovation Center in Beilun, Ningbo 315830, China

Faith Ka Shun CHAN (✉)
School of Geographical Sciences, Faculty of Science and Engineering, University of Nottingham Ningbo China, Ningbo 315100, China; Water@Leeds Research Institute, University of Leeds, Leeds LS2 9JT, UK
E-mail: Faith.chan@nottingham.edu.cn

Matthew JOHNSON
School of Geography, University of Nottingham, Nottinghamshire, NG7 2RD, UK

Fangfang ZHU
Department of Civil Engineering, Faculty of Science and Engineering, University of Nottingham Ningbo China, Ningbo 315100, China

Yaoyang XU (✉)
Key Laboratory of Urban Environment and Health, Ningbo Observation and Research Station, Institute of Urban Environment, Chinese Academy of Sciences (CAS), Xiamen 361021, China; Zhejiang Key Laboratory of Urban Environmental Processes and Pollution Control, CAS Haixi Industrial Technology Innovation Center in Beilun, Ningbo 315830, China
E-mail: yyxu@iue.ac.cn

This research is supported by the National Key R&D Program of China (Grant Nos. 2021YFE0193100 and 2019YFC1510400), the Construction Project of China Knowledge Centre for Engineering Sciences and Technology (Grant No. CKCEST-2022-1-41), the National Natural Science Foundation Program of China (Grant No. NSFC41850410497), and the Institute of Asia Pacific Studies (IAPS) research funds and the Doctoral Training Partnership and the postgraduate research fund at University Nottingham Ningbo China and the Institute of Urban Environment, Chinese Academy of Sciences.

incorporating effective green swale strategies.

Keywords grass swale, infiltration swale, bioswale, wet swale, sponge city

1 Introduction

As the world's human population continues to grow, with an ever-increasing majority living in urban environments, the natural water cycle faces mounting impacts, including the pressing issue of urban water pollution. Climate change, by amplifying extreme weather events such as heatwaves and heavy rainfall, exacerbates these impacts, especially when coupled with human-modified urban landscapes (Bellprat et al., 2019). Urbanization intensifies these problems through the expansion of impervious surfaces, which can lead to increased overland flow and flooding and contribute to urban heat island effects (Brunetti et al., 2016; Logan et al., 2020).

Urban areas concentrate on human activity, leading to the accumulation of surface pollutants, including particulates such as metals and plastics, as well as nutrients from urban surfaces and wastewater. These pollutants are swept into urban stormwater runoff, becoming a key factor in the degradation of global aquatic ecosystems (Moore et al., 2018). However, while urban stormwater runoff is a significant source of pollution, it can also be a valuable resource, particularly in the face of droughts caused by climate change (Zhang et al., 2017).

Surface pollution in urban environments originates from various sources, such as vehicle emissions (McIntyre et al., 2021) and airborne pollutants (Shaneyfelt et al., 2017). These pollutants are often mixed with wastewater pollutants in urban drainage systems before being discharged into river channels. This polluted runoff typically contains excess nutrients, trash (including plastics), chemicals (including metals and oils), and sediment, which can harm urban water bodies such as rivers, streams, and lakes.

There are several techniques for managing surface runoff, which can be classified into two groups: Storage devices and infiltration devices. Storage devices encompass detention ponds (Yazdi and Khazaei, 2019), retention ponds (Liu et al., 2019), rainwater harvesting systems (van Dijk et al., 2020), green roofs (Bevilacqua, 2021), rain gardens (Church, 2015), and constructed wetlands (Sossalla et al., 2021). Infiltration devices include infiltration trenches (Locatelli et al., 2015), grass swales (Gavrić et al., 2019), green parking (Bouzouidja et al., 2021), permeable pavements (Hernández-Crespo et al., 2019), and infiltration basins (O'Reilly et al., 2012).

Both categories of devices are integral to Green Infrastructure (GI) programs (Green et al., 2021) and are associated with the concepts of Low Impact Development (LID) (Zhang et al., 2022) and the Sponge City Program (SCP) initiatives (Chan et al., 2022a). GI comprises strategically designed and managed networks of natural and seminatural areas that provide a wide range of ecosystem services and enhance human well-being (Chatzimentor et al., 2020). LID is an alternative stormwater management strategy that utilizes a mix of stormwater runoff detention, infiltration, evapotranspiration, and utilization from impermeable surfaces to help restore the natural hydrology of urban environments (Wang et al., 2020).

In 2013, the Chinese government introduced the concept of "Sponge Cities" and began implementing the SCP in 30 pilot cities in 2015 (Yang et al., 2020). SCP aims to improve a city's resilience to natural disasters and environmental changes by harnessing natural processes such as the purification, infiltration, and storage of stormwater. In China, green swales — dry or wet channels, typically grass-covered, that transport rainfall into retention areas or larger channel systems (Winston et al., 2012) — are prevalent in SCPs.

These green swales, along with bioretention, permeable pavement, detention cells, and constructed wetlands, are among the most frequently constructed SCP facilities in China (Xu et al., 2022). However, financing their construction and maintenance is a key challenge (Zuniga-Teran et al., 2020). Notably, green swales are cost-effective, require less land and are well suited to urban stormwater management and treatment compared to larger-scale solutions such as wetlands or media filters (Yu et al., 2013; Li et al., 2020). Typically, used in conjunction with other GI facilities, green swales can replace traditional road green belts, improving road runoff water quality and managing stormwater before it reaches the drainage system (Che et al., 2014).

Green swales contribute to stormwater runoff volume reduction (Bressy et al., 2014), stormwater quality improvement (Gavrić et al., 2019), aesthetic enhancement, and biodiversity conservation (Kazemi et al., 2011) — all valuable benefits for urban communities. Thus, green swales are a vital element of GI/LID/SCP strategies aiming to purify and regulate urban stormwater.

Although green swales are widely used in Chinese cities, existing design guidance from regulatory agencies primarily focuses on stormwater conveyance functions, with limited attention to water quality reduction and other aspects. Recent reviews on LID practices in China have highlighted major challenges associated with green swales, particularly in terms of water quality, such as their role during and after large storms (i.e., resuspension of deposited particles), risks of clogging over time, and poor performance in particulate removal under cold climates (Qin, 2020; Liu et al., 2021).

Given these circumstances, a comprehensive study is needed to review the use and effectiveness of green swales in China, with a particular emphasis on their impact on water quality. The results of such a study can inform the development of green swale design guidelines that currently lack adequate consideration of water quality issues, despite ongoing major urban infrastructure projects in China. Therefore, this review aims to identify critical knowledge gaps that need to be addressed to enhance understanding and considerations for green swale design in China's urban areas. The specific research objectives are as follows:

(1) To review the type, vegetation, structure, and performance of green swales in China's urban areas and identify current knowledge gaps.

(2) To assess key existing challenges in developing new urban roadside green swale designs in China.

(3) To provide recommendations for green swale design guidance in China's urban areas.

2 Research progress of green swales worldwide

Following the first use of the term "swale" in the academic literature by Gwynne (1942), a total of 1124 articles, reviews, online published papers, and revised edition papers have been published up to 27 August 2022, as determined on the top of "('grassy median') OR ('*swale') OR ('swale*')" through Clarivate's Web of Science Core Collection. The pioneering research on swales as an urban water management technique initially focused on the accumulation patterns of trace metals (cadmium, copper, lead, and zinc) in soils of roadside grass swale drains (Wigington et al., 1986).

To gain a deeper understanding of the global distribution of swale research and international cooperation within these publications, we conducted a corresponding author's country analysis using the R tool "biblioshiny for bibliometrix" (Fig. 1). The analysis revealed that the top three countries with the highest number of articles on swales are the USA, UK, and Australia, with China following closely. Notably, China has shown significant efforts in studying and understanding swales, particularly over the last decade, likely driven by rapid urbanization.

Furthermore, to explore the research trend of swales, we performed a "trend topics" analysis using the R tool "biblioshiny for bibliometrix" based on the author's keywords with a minimum co-occurrence of 10 (Fig. 2). The analysis process involved extracting keywords from the .txt file exported from Clarivate's Web of Science Core Collection database and constructing a co-occurrence matrix, which facilitated the creation of a keyword network. This network enabled community detection, grouping keywords into clusters with highly related themes. Frequency analysis within each cluster helped determine the dominant research themes in the field of swales, revealing emerging and evolving topics.

The "trend topics" analysis indicated three distinct stages of swale research between 1996 and 2021. The first stage (1996–2005) focused on elevated nutrient levels and how swales may transport pollutants through landscapes, along with studying swale erosion. The second stage (2006–2015) saw a strong association between swale research and sustainable urban drainage systems and best management practices. During this period, studies emphasized water quality management of stormwater runoff using swales as a stormwater control

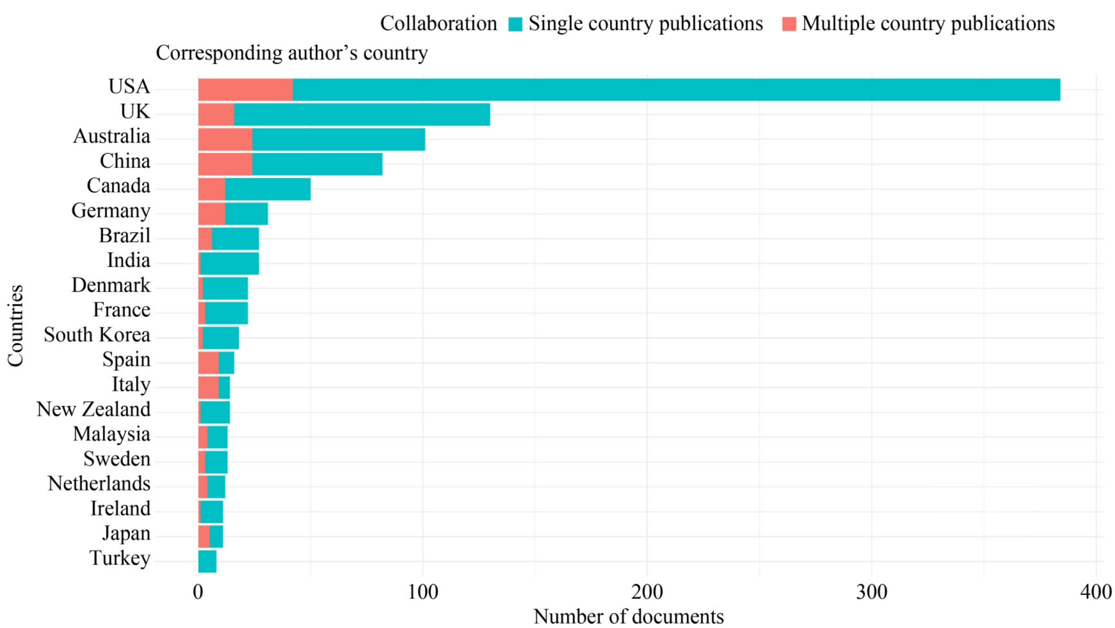

Fig. 1 The most relevant corresponding author's countries with swale research based on Clarivate's Web of Science Core Collection.

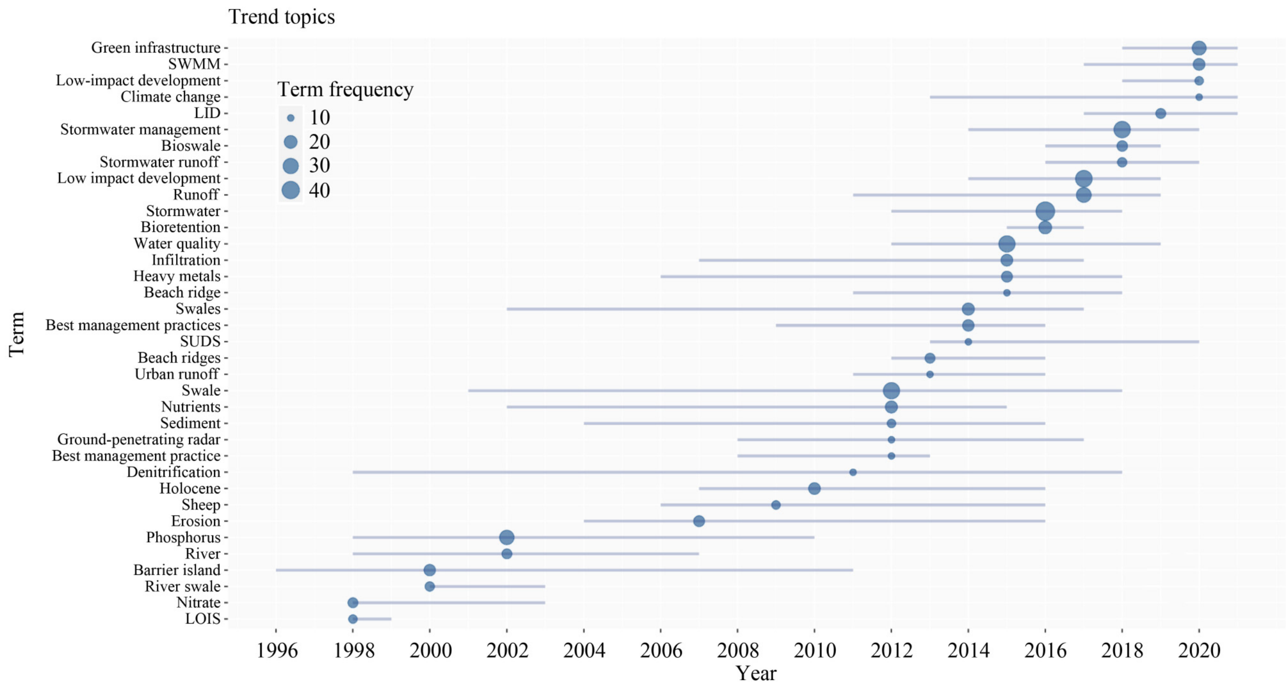

Fig. 2 The trend topics with swale research based on Clarivate's Web of Science Core Collection (among these terms, "SUDS" represents "sustainable urban drainage systems" and "LOIS" stands for "land ocean interaction study").

measure (Gülbaz and Kazezyilmaz-Alhan, 2014; Roy et al., 2014). In the third stage (2016–2021), bioswales gained prominence as a key focus within the swale research field, particularly due to their significance as a control strategy for road and urban runoff management in the context of global climate change.

From the trend topic terms (Fig. 2), it becomes apparent that the concept of SCP in China has played a pivotal role in driving swale research. The assessment of swale performance is often limited by financial, logistical, and material resources; hence, modelling frameworks are commonly employed to evaluate potential swale effectiveness before construction. The stormwater management model (SWMM) has emerged as a widely used tool to explore how swale design interacts with stormwater pollutant removal, urban drainage, and flood mitigation (Rezaei et al., 2021; Saniei et al., 2021). Moreover, the hydrological performance and life-cycle cost of LID practices, including bioretention, grass swale, and permeable pavement, have been assessed using SWMM under sponge city construction in China (Li et al., 2020). The results suggest that green swales offer a higher cost-effective ranking than bioretention and permeable pavement.

While there exists science-based swale design guidance for global use (Ekka et al., 2021), the selection of a specific swale type and its components depends on site constraints, local climate, and various social, economic, and environmental factors, especially in China's cities, which are increasingly focused on SCP construction methodologies.

3 Basic characteristics of urban green swales

3.1 Type of green swale

The terminology associated with swales is intricate, encompassing various terms that are often used interchangeably to describe similar or identical features. These terms include grassy median (Barrett et al., 1998), biofiltration swale (Mazer et al., 2001), grass swale (Kirby et al., 2005), infiltration swale (Fach et al., 2011), bioretention swale (Kazemi et al., 2011), planted swale (Leroy et al., 2015), bioswale (Anderson et al., 2016), wet swale (Tang et al., 2016), and vegetated swale (García-Serrana et al., 2017). To evaluate the performance of swales, a database comprising 59 studies classified swales into four categories: Standard, dry, wet, and bioswales (Fardel et al., 2019). Despite this classification attempt, a lack of standardized swale terminology remains, resulting in communication barriers within research, regulatory, design, and maintenance communities.

At the national level, the *Sponge City Construction Technology Guide* (SCCTG) issued by the Ministry of Housing and Urban-Rural Development of the People's Republic of China (MHURD) in 2014 categorizes green swales into grass swales (focused on transporting runoff), dry swales (focused on infiltrating runoff), and wet swales but lacks standardized definitions or functional descriptions for these features. While more specific definitions exist in planning documents at the local urban scale, they remain incomplete. For instance, the *Ningbo Sponge City Planning and Design Guidelines* (NSCPDG) released by the Ningbo Housing and Urban-Rural Development Commission in 2019 further divides green swales into grass swales, dry swales, wet swales, and infiltration swales, yet it fails to introduce bioswales. The document outlines the following specific definitions: Grass swales are solely used as transmission facilities; dry swales possess a planting soil layer with relatively good permeability and buried infiltration and drainage pipes; wet swales function similarly to linear shallow ground and boast better pollution removal effects; and infiltration swales can transmit and accommodate large amounts of runoff and occupy a larger area. Notably, bioswales, despite being a significant area of research, are not adequately addressed in China's technical guidelines.

To address the current lack of standardized definitions and functional attributes of green swales in China, we propose a modified version of the terminology presented by Ekka and Hunt (2020) specifically tailored for use in China (Table 1). This new classification includes information about bioswales and incorporates distinct differentiating characteristics, thereby enhancing our comprehension of green swales in China. Table 1 presents typical types of green swales within the four categories, while relevant key components and treatment processes are shown in Figs. 3 and 4, respectively.

3.2 Vegetation in green swales

The choice of vegetation in green swales significantly influences their performance, particularly in areas such as stormwater runoff reduction (Zaqout and Andradottir, 2021) and stormwater quality improvement (Gavrić et al., 2019). Commonly, simplified structural vegetation classifications for green swales include a high-stratum layer, consisting of trees as the predominant growth form; a middle-stratum with sedges, rushes, shrubs, and medium-height grass species; and a low-stratum layer comprising ground cover species (Specht and Specht, 1999; National Committee on Soil and Terrain (Australia), 2009).

Reviewing global literature on vegetation in green swales in Table 2, it is observed that most plants found in swales are perennial herbs, such as *Juncus effusus* and *P. arundinaceae*, which exhibit resistance to both dry and wet conditions. A total of 14 plant species are listed in green swales, all serving common functions, including excellent soil and water conservation properties. In China, bioswales are also planted with cold and drought-tolerant vegetation, such as *Ligustrum lucidum* and *Ophiopogon japonicus* in Xi'an, China. These plant species have proven to improve water reduction in bioswales more effectively than other species, such as *boxwood and ryegrass*, *shiny privet* and *Chlorophytum comosum* "Variegatum", or having no plant at all (Li et al., 2016). However, it is worth noting that discussions on waterlogging, salt tolerance, and other relevant factors are relatively scarce. In areas prone to waterlogging, we recommend planting vegetation that can withstand such conditions. Similarly, in regions where snowstorms and snow-melting agents (mainly industrial salt) are commonly used, salt-tolerant plant species should be selected for green swales to mitigate potential adverse effects.

In the context of bioretention systems, plants play a crucial role in various environmental and landscape aesthetic aspects. When selecting plants for bioretention systems, six key factors should be considered: Native to the region, thick and extensive root systems, drought tolerance potential, minimal nutrient requirements and maintenance, high aboveground plant biomass, and high phytoremediation potential (Vijayaraghavan et al., 2021). It is important to note that the efficacy of plants in reducing flow and pollutants in swales varies depending on geographical location, local characteristics, and climatic conditions. For instance, a bioswale planted with *Platanus x acerifolia* "Bloodgood" in California, USA, reduced runoff by 88.8% and total pollutant loading by 95.4%. On the other hand, a bioswale in Hefei, China, planted with *Scirpus validus* and *Typha latifolia linn*, reduced the total runoff volume by 50.4%, with pollutant loads substantially reduced from 70% to 85%. However, it is important to recognize that vegetation is just one of the factors that determine the local performance of green swales, and other factors, such as design and local

Table 1 Standard terminology of green swales for work in China (modified from Ekka and Hunt (2020))

Swale type	Distinguishing features	Pollutant removal mechanisms	Examples of Chinese cities
Grass swale	Established, dense turf with grass	Filtration, sedimentation (modest); Infiltration, chemical precipitation, microbial degradation, and vegetation uptake	Xicheng District in Beijing (Yuan et al., 2019)
Infiltration swale	Like a grass swale but with the addition of check dams to temporarily hold water	All processes of grass swale plus enhanced infiltration and sedimentation	Ningbo (Tang et al., 2021)
Bioswale	Permeable soil mix or high flow engineered media; Underdrains may be present; Forebay or plunge pool is typical	Enhanced infiltration by underdrains and permeable soil mix or media; Enhanced chemical and biological transformations by the engineered media and internal water storage zone	Fengxi New City, Xi'an (Jiang et al., 2020)
Wet swale	Emergent wetland vegetation; Microtopographic pools and shallow areas; Seasonal high-water table; Wetland soils	Enhanced gross filtration, sedimentation, and chemical/biological transformations; Evapotranspiration and volatilization	Luzhou Road, Hefei (Tang et al., 2016)

Fig. 3 Four types of green swales were constructed in different areas, including (a) grass swales, (b) infiltration swales, (c) bioswales, and (d) wet swales.

conditions, also play significant roles.

3.3 Structure of green swales

Research on green swale structures has primarily focused on several key aspects, including cross-sectional shape, swale area and length, and the geometry of longitudinal and side slopes. Based on the database compiled by Fardel et al. (2019), green swales are commonly classified into rectangular (1 study), triangular (15 studies), trapezoidal (24 studies), or parabolic (2 studies) shapes. The choice of cross-sectional shape plays a significant role in swale functionality; for example, trapezoidal green swales demonstrated an average of 10% higher total suspended solids (TSSs) removal rates compared to triangular green swales with similar design characteristics (Winston et al., 2017).

Another important factor to consider is the lot size of green swales, which varies widely from 3 to 320000 m^2 in different research fields and is considered an influential parameter (Li et al., 2020; Rezaei et al., 2021). Additionally, the length of green swales is a crucial independent parameter positively correlated with the effectiveness of removing pollutants such as total phosphorus (TP), zinc (Zn), and copper (Cu) (Fardel et al., 2019). Lengthening the green swale allows for increased flow residence time, facilitating the settling of particles, particularly for pollutants present in runoff in particle form.

In sloped grassy regions, sediment reduction follows an asymptotic function of length (Winston et al., 2017) (Table 3). For example, the effectiveness of TSS removal showed negligible increases beyond a swale length of 15 m (Lucke et al., 2014). The side slopes and centerline slopes of green swales also play a crucial role in influencing hydraulic transport time and the removal efficiency of runoff pollutants. For instance, side slopes designed up to 3:1 (H:V) for trapezoidal channels and 6:1 (H:V) or shallower for triangular swales have proven effective in urban runoff volume reduction and water quality treatment (Barrett et al., 1998; Winston et al., 2017). To prevent "short-circuiting", it is recommended that the longitudinal slope in green swales should be kept at less than 3% (Ekka et al., 2021).

In China, the SCCTG recommends that the side slope

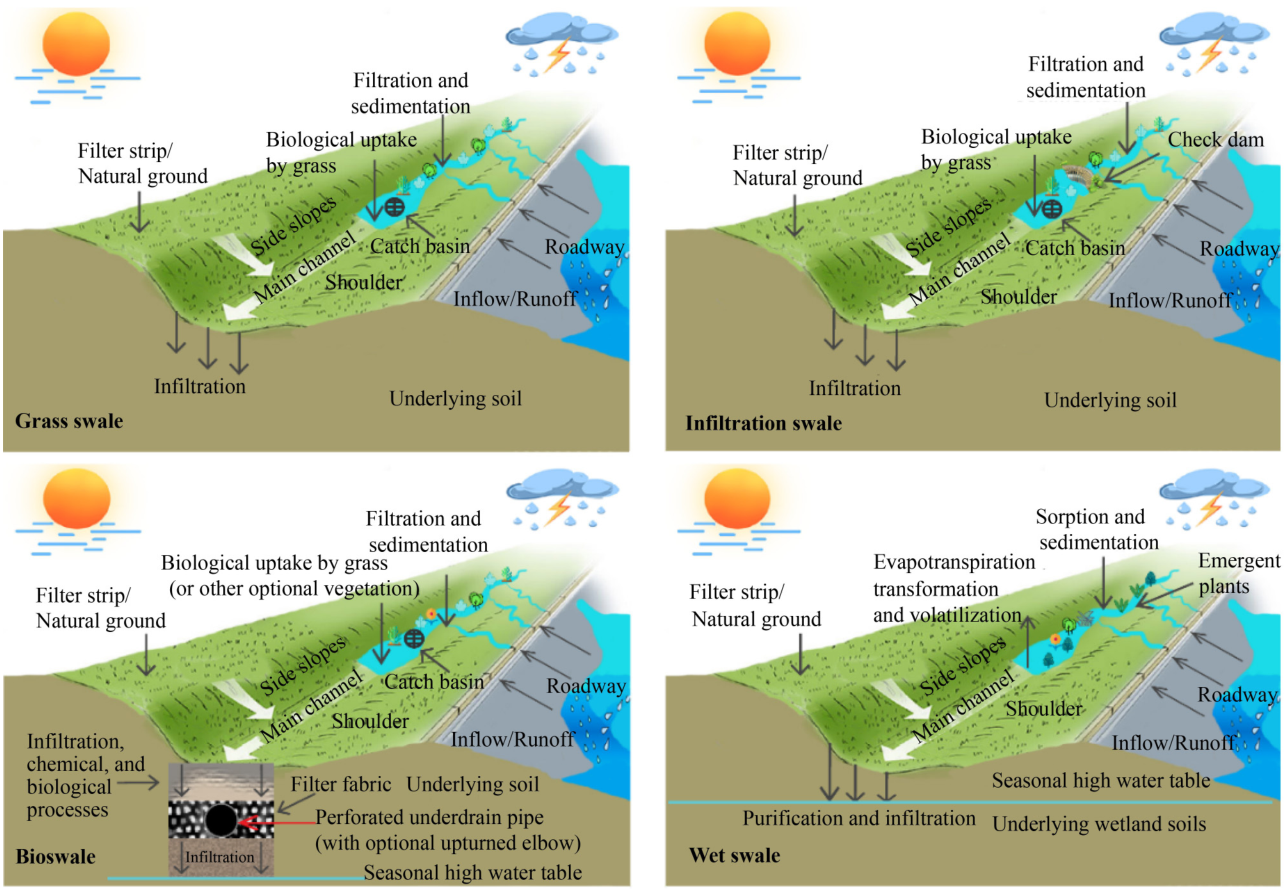

Fig. 4 Key components and treatment processes of green swales include grass swales, infiltration swales, bioswales, and wet swales.

Table 2 Characteristics of different plant types and functions in green swales

Location	Type of plants	Runoff type/function	Citations
Normandy, France (Grass swale)	Soft rush (*Juncus effusus*), reed canary grass (*Phalaris arundinacea*), and yellow flag (*Iris pseudacorus*), a mix of grass seeds (Case 1) Macrophytes (*P. arundinaceae*, *J. effusus* and *I. pseudacorus*) or grassed (Case 2)	Road, only 0.07% to 0.22% of total polycyclic aromatic hydrocarbons (PAHs) were released in water outflow after one year (Case 1) Mephytoextraction in plant roots was more efficient in mesocosms planted with *P. arundinacea* and grass (Case 2)	Leroy et al. (2015; 2017)
Hoppegarten, Germany (Bioswale)	Dandelion, plantain, clover, and orache; swale is covered with a rather uniform grass lawn (Site 1) Vegetation consists of a wide variety of bushes and small trees; a few long grasses and rush in between (Site 2) Dock (Rumex) with large, deep taproots (Site 3)	Road, parking area and roof (Site1) Approach road and sidewalk (Site 2) Road, residential area (Site 3) Returning infiltration rates in the range of 10^{-7} to 10^{-5} m/s, organic matter contents ranging from a few to almost 7%	Ingvertsen et al. (2012)
Dortmund & Berlin, Germany (Bioswale)	The vegetation consisted of grass and mosses as well as smaller weed plants (Dortmund) Densely covered with vigorous grasses, a few mosses, and small weed plants (Berlin)	Roof, parking area and sidewalk (Dortmund) Road and sidewalk (Berlin) Returning infiltration rates in the range of 10^{-7} to 10^{-5} m/s, organic matter contents ranging from a few to almost 7%	Ingvertsen et al. (2012)
California, USA (Bioswale)	London Planetree (*Platanus x acerifolia* “Bloodgood”)	Parking area, the bioswale reduced runoff by 88.8% and total pollutant loading by 95.4%	Xiao and McPherson (2011)
Xi’an, China (Bioswale)	*Ligustrum lucidum* and *Ophiopogon japonicus*	For urban runoff, the water reduction rate grew linearly with increasing plant factor and artificial filler infiltration rate	Li et al. (2016)
Hefei, China (Bioswale)	*Scirpus validus* and *Typha latifolia linn*	Roadway runoff, reduced the total runoff volume by 50.4%; pollutant loads were also substantially reduced from 70% to 85%	Tang et al. (2016)
New York, USA (Bioswale)	Five native plant species: *Aronia melanocarpa*, *Eupatorium dubium*, *Nepeta&faassenii*, *Panicum virgatum*, and *Spiraea nipponica*	High variation in transpiration rates across species, and *Nepeta&faassenii* was the highest conductor, while *Panicum virgatum* was the lowest conductor	Brodsky et al. (2019)

Table 3 Comparison of swale performance for a 2% longitudinal slope, 7.6 m length (swale), and an 1000 m^2 catchment (sourced from Winston et al. (2017))

Type of green swales	Side slopes/Flow depth (cm)	TSS removal efficiency (%)
Triangular swale	4:1/13.8	33
	5:1/12.6	35
	6:1/11.8	36
Trapezoidal swale	3:1/5.2	47
	4:1/5.2	47
	5:1/5.1	47
	6:1/5.1	47

of green swales (V:H) should not exceed 1:3, and the centerline slope should be limited to 4% at maximum. Drawing from international design guidelines for swales suggested by Ekka et al. (2021), we propose that green swales in China should adopt a trapezoidal or parabolic cross-section design to increase the contact area between stormwater runoff and swales. This design approach allows for enhanced water infiltration and pollutant removal capacity.

In line with the SCCTG, each sponge city pilot in China has released specific guidelines for future green swale designs. For instance, the *Ningbo Urban Planning & Design Guideline for Sponge City* issued by the Ningbo Housing and Urban-Rural Development Committee in 2017, emphasizes the establishment of a hierarchical control structure to manage slope gradients exceeding 4%. This valuable experience gained in Ningbo can serve as a reference for other regions globally when local construction conditions do not permit achieving a longitudinal gradient of less than 3% for the entire green swale design.

4 Current green swales performance in China

4.1 Runoff volume reduction

Green swales play a crucial role in conveying stormwater runoff, mitigating urban runoff peak flow, and reducing runoff volumes. To evaluate the effectiveness of green swales in urban runoff reduction, a field trial was conducted in China by Jia et al. (2015). The results showed significant variability in the performance of green swales, with peak flow reduction ranging from 17% to 79% and runoff volume reduction ranging from 9% to 74% during the period from May 2012 to September 2013. Further analysis of the monitoring data from Jia et al. (2015) indicated that the average reduction rates of runoff in green swales were 15.3% and 57.0% in 2012 and 2013, respectively. Similarly, the average reduction rates of peak runoff were 22.5% and 66.2% for the same years. Notably, all monitored runoff and runoff peak reduction rates in 2013 were higher than those in 2012, potentially due to the green swales being in their earliest stages of construction when they were completed in the spring of 2012.

In different locations, green swales have shown varying effects on runoff reduction. For example, in eastern North Carolina, USA, a swale demonstrated significant runoff volume reductions averaging 23% during an 11-month sampling period (Knight et al., 2013). Similarly, a grass swale with rock check dams in North Carolina, USA, reduced runoff volume by 17% (Winston et al., 2019). On the other hand, some studies have found that green swales have little effect on reducing runoff volume in certain situations. For instance, a study conducted in the mountainous Fragrance Hills region of Beijing, China (Luan et al., 2017), found that vegetative swales reduced runoff volume by only 2.2% (1-year return period), 0.3% (2-year return period), 0.1% (5-year return period), and 0.1% (10-year return period).

Two main reasons can explain such variations in green swale performance. First, there is a limit to the size and quantity of vegetative swales, impacting their water storage capacity and resulting in less effective peak discharge reduction in certain areas. Second, the coupling reaction of local waterlogging and interval flooding in low-lying regions becomes more prominent as storm intensity increases. These findings demonstrate that multiple factors can influence the performance of green swales, and not all green swales constructed in different locations are equally efficient. Regional factors, such as rainfall patterns and the size of the facility, must be carefully considered during the design of roadside swales.

4.2 Water quality treatment

Urban precipitation leading to surface runoff is a significant cause of water pollution because it can transport particles from impermeable surfaces into nearby water bodies. Green swales offer an effective solution by capturing this material before it reaches freshwater sources, thereby reducing the risk of pollution. The SCCTG highlights that TSS control in China is a crucial concern of the SCP, and sponge cities that implement various LID facilities typically achieve TSS removal rates ranging from 40% to 60%. Green swales play a crucial role in the removal of TSS in Chinese sponge cities due to their relatively high removal rates (e.g., 48%–98%) (see Table S1 in Supporting Information), surpassing the minimum TSS removal requirements (40%) set by SCP building regulations.

However, the effectiveness of nitrogen removal in green swales varies significantly due to environmental factors. Nitrogen removal from stormwater requires anaerobic conditions for nitrification and denitrification reactions to occur (Hunt et al., 2012), which can be facilitated by incorporating internal water storage zones within green swales (Ekka et al., 2021). Studies conducted in China show that the effectiveness of nitrogen removal using green swales ranges from –10% to 57% (Table S1), indicating considerable uncertainty in nitrogen treatment and the potential for increased nitrogen loads (i.e., –10%) (Zhang et al., 2009). The supply of nitrogen from extraneous organic matter, such as grass clippings and plant waste, negatively impacts the removal of NH_3-N (Zhang et al., 2009). Additionally, green swale performance exhibits seasonality, with clearance rates for total nitrogen (TN) of 32% in summer and 57% in winter (Yuan et al., 2019).

Similar to nitrogen, phosphorus concentration in water bodies significantly affects urban receiving water eutrophication. The data in Table S1 reveal that the removal rates of phosphorus in green swales vary from 13% to 77%, showing high variability in swale effectiveness, similar to nitrogen. Seasonal effects also impact phosphorus removal, with experimental devices demonstrating better TP removal in summer (19.7%) than in winter (13.3%) (Yuan et al., 2019). Bioswales stand out as one of the most effective stormwater control strategies for phosphorus removal compared to other green swale types (Ekka et al., 2021). The use of engineered media and amendments can enhance phosphorus removal rates, and ongoing research is investigating new technologies to remediate urban road runoff (Lee et al., 2021). However, there is a lack of studies on the performance of bioswales in China, leaving this as an area for future research.

In China, there is significant uncertainty in the removal rates of green swales compared to those in other countries. While China achieves greater TSS and TN removal rates than other nations (40%–85% for TSS, 45%–65% for TN) (Table S1), its TP removal rates are inferior. Several internal and external factors influence a swale's pollutant removal capacity. Internal factors include swale length, longitudinal slope, the presence of check dams, mean hydraulic detention duration, surface loading rate, and area (Yu et al., 2001; Bäckström, 2003). External factors encompass the soil's saturated hydraulic conductivity, the width of adjacent roads, and volume percentile (García-Serrana et al., 2018). External factors also include local rainfall patterns, volume capture requirements, drainage area antecedents, and dry weather periods (Monrabal-Martinez et al., 2018; Gong et al., 2019). Pollutant inflow concentration, swale length, and active discharge area are three key variables correlated with the performance of green swales in pollutant removal (Fardel et al., 2019). Evaluating the regularity and types of maintenance for green swales is crucial for their long-term performance, although further experimental work is needed in this area (Houser et al., 2008; Smith et al., 2021).

4.3 Roadside design specifications

The specifications for designing urban roadside green swales can be improved by incorporating examples of urban roadside design, such as rainfall pipe channels. The *Outdoor Drainage Design Standard* (ODDS) issued in 2021 by the MHURD presents various rainwater pipe channel designs (traditional grey infrastructure in roadside areas for transporting stormwater runoff) tailored to different rainfall return periods (see Table S2 in Supporting Information). The design considers flow rate and water quality, with each rainwater pipe channel being carefully planned based on factors such as catchment area, city type, terrain characteristics, and climate.

Moreover, cities and towns with high population density, frequent waterlogging, and/or prosperous economic conditions are advised to adopt the upper limit of the design return period. To determine the outdoor drainage water quality in rainwater pipes, the design standard is calculated using survey data or by consulting the water quality of neighbouring towns, comparable industrial districts, and residential areas. Statistical data from 23 urban living areas in China suggest that for domestic sewage, TSS can be estimated at 40–70 g/person/day, TN at 8–12 g/person/day, and TP at 0.9–2.5 g/person/day if specific survey data are unavailable.

In terms of water quality rules, Chinese citizens' drainage should meet the Environmental Quality Standards for Surface Water, specifically Class IV level (TN = 1.5 mg/L; TP = 0.3 mg/L); sourced from the Ministry of Ecology and Environment of the People's Republic of China and ecological document GB3838-2002. This standard serves as a crucial reference for the water quality design criteria of green swales in China, especially considering the lack of a unified design standard in the country.

5 Challenges in developing new urban roadside design in China

5.1 Integration with road planning and environmental practices

Road planning is a comprehensive process that requires considering various factors, yet the environmental impact of road networks is often underestimated by planners. With the adoption of the Open-Door Policy in 1979, China's economy, industry, and society have rapidly developed, leading to an increased scarcity of construction space. This has resulted in the construction of significant grey infrastructure, particularly concrete-lined roadside drainage channels, in densely populated urban areas. These channels quickly transfer surface runoff to nearby water bodies, posing a significant negative influence on the urban water environment.

To effectively address the issue of urban water pollution in China, the state and local governments have issued guidelines for water pollution prevention and control measures (see Table S3 in Supporting Information). These documents highlight that urban and rural nonpoint source pollution is increasingly becoming a major obstacle to improving the water environment in some areas. Addressing the quality of stormwater runoff is a crucial step in preserving the water quality in urban water systems.

Although the concept of sponge cities has been employed in many legislative and planning documents to reduce urban runoff pollution, road planning still faces three deficiencies. First, there is a lack of a definitive construction standard for sponge city facilities (e.g., green swales) when roads are rebuilt or newly built. While some papers have suggested locating green swales within the road's boundaries to reduce road runoff pollution while maintaining the road's core functions (according to NSCPDG), more research is needed to establish precise requirements and relevant norms for the development of green swales. The clear classification of green swales provided in this study serves as a solid foundation for future research. Second, few documents address the financing sources for constructing sponge cities and planning long-term funds for the future. Last, there is a dearth of accurate quantitative indicators to measure the effectiveness of green swales in reducing runoff pollution.

Subsections 5.2 and 5.3 of this paper will delve into the shortcomings in the first and second aspects in more detail. To address the third issue of quantifying the benefits of green swales in urban stormwater runoff pollution prevention, the authors propose using SWMM for simulation. SWMM is a widely used and valuable method to assess sponge city infrastructure. Quantifying the economic, environmental, and social benefits of urban water environments through SWMM can provide scientific support for future solutions to urban stormwater pollutants.

5.2 Suitable construction conditions

Not all roadsides are suitable for constructing green swales. The decision to build green swales must consider several key factors, including the type of land use, groundwater conditions, and terrain of the specific location. Areas around impervious surfaces, such as streets, squares, parking lots, urban roadways, and green spaces, are ideal for planting green swales. However, some roadside locations may be better suited for conventional drainage ditches, especially in areas with high heavy metal discharge, where drainage ditches can direct runoff to sewage treatment plants for appropriate treatment. High heavy metal concentrations in these areas may hinder vegetation survival in swales (Horstmeyer et al., 2016). Additionally, green swales should not be constructed in areas with high groundwater levels, as the soil may become saturated, reducing the infiltration benefits of the swales. According to the SCCTG, green swales should not be built on slopes steeper than 15% to avoid potential landslides and soil movements, a consideration that applies to other regions as well.

While designers already consider factors such as land use, groundwater conditions, and terrain during the green swale design process, other aspects such as precipitation, droughts, and specific locations also require consideration and further study. Research on the effectiveness of green swales in different locations under varying rainfall patterns has been conducted (Davis et al., 2012; Monrabal-Martinez et al., 2018), but more investigation is needed to understand how green swales perform under the impact of future climate change-related extreme events, such as rainstorms or hot temperatures. Antecedent dry periods have been identified as a significant predictor of pollutant concentrations, which affects the performance of green swales since the inflow concentration of pollutants is a crucial factor related to their removal efficiency rates (Li et al., 2008; Fardel et al., 2019).

Studies in various regions have explored optimal strategies for implementing green swales. In China, a case study on optimal strategies, including the number and location of detention ponds and grass swales, found that downstream regions on the catchment's main river were the most suitable places for constructing LID facilities (Chang et al., 2009). Another study in the Darabad region, northeast of Tehran, Iran, found that the optimal selection of LID types, locations, and sizes was related to the placement of swales, but these results may not be generalized to other areas of the world (Saniei et al., 2021). It is recommended to conduct further research in different locations with the same type of swales to fully understand their performance in optimal locations.

As green swales are a linear form of GI that occupies minimal space in cities, transforming hardened ditches may be challenging due to the existing underground pipe network following urbanization. In the future, priority should be given to constructing roadside green swales in new areas, while built-up areas can undergo green transformations by adapting to the local underground pipe network conditions. However, the complexity of China's underground pipeline network presents a significant challenge to digitalization efforts.

5.3 Long-term funds

Addressing the requirement for long-term funds presents substantial challenges, as governments typically allocate finance primarily for infrastructure development and may face competing priorities, such as emergencies like China's COVID-19 prevention and control efforts. However, green swales stand out as one of the most cost-effective facilities in GI, with estimated costs of approximately 0.7 yuan/m^3/year in SCPs, while other GI options like green roofs, rain cisterns, dry ponds, and wet ponds, have higher costs (Li et al., 2021). Comparisons of LID facility prices in Beijing, China, according to SCCTG, further emphasize the cost-effectiveness of green swales (see Table S4 in Supporting Information). Compared to conventional curb and drainage systems such as the rainfall bucket system, the building cost of the green swale system is currently less than 0.20 USD/m^2 and its maintenance cost is only 6% of its construction cost (Wu et al., 2020; Li et al., 2021).

Given their higher cost-effectiveness compared to other options, we recommend prioritizing the construction of green swales in GI projects, especially when funds are limited. However, the current cost-benefit analysis and research mainly compare various GIs without considering the costs and benefits of different types of the same GI (Liu et al., 2016). The new green swale classification proposed in this study provides opportunities for further research in this area, helping to efficiently allocate funds for the different types of green swales. While sediment detention in green swales may not last for the entire design life due to larger particulates and debris, Chinese green swales experience sediment detention during intense rainfall events (e.g., typhoons) after prolonged periods of drought (Allen et al., 2015).

Learning from international expertise to develop better green swales and overcome maintenance challenges is another significant task. Additionally, green finance has been tested in EU member states and recognized as one of the primary business models for nature-based solutions, offering a viable alternative (Chan et al., 2022b). Developing a robust and open cross-border green finance platform in the future will be challenging but can actively attract investors interested in SCPs.

6 Guidance for green swale construction and maintenance in China

6.1 Comprehensive function optimization

To address the knowledge gap in specific standards for green swale construction in current road planning in China, it is essential to further optimize the functional design of green swales. Functional optimization can be divided into three key aspects: Improving the performance of green swale components, optimizing the green swale structure, and combining various types of green swales.

To enhance the performance of specific green swale components, it is advisable to use perennial herbaceous plants that are native to the region. These plants should have thick and extensive roots, be tolerant to drought and cold conditions, require minimal nutrients and maintenance and have the potential for plant restoration. The addition of some landscape vegetation can also be considered to promote species diversity and enhance the overall aesthetic of the green swale, provided that it does not compromise the fundamental water quality and quantity control requirements.

In contrast to the original concrete swales, grass swales are commonly used in China and are often planted with vegetation. However, during rainstorm events, large quantities of suspended solids can be washed into the swales, leading to swale obstruction. To address this issue and improve the infiltration and purification capacity of the green swale, it is recommended to incorporate forebays and check dams in the section where large suspended solids are likely to be generated. These features can capture large mobilized solid items, reduce the risk of green swale blockage, and prolong the time of surface runoff in the swale.

6.2 First flush consideration

In addition to optimizing the functions of green swales in future road planning, it is crucial to modify roadside drainage design to adapt to the effects of global climate change, particularly the increasing incidence of extreme rainfall and drought conditions. During prolonged dry periods caused by droughts, pollutants from human activities tend to accumulate on urban surfaces. When rainfall finally occurs, these surface sediments mix with surface runoff and are swiftly transported to nearby water bodies, elevating the risks of water pollution. This phenomenon is commonly referred to as the first flush phenomenon (Deletic, 1998).

The first flush phenomenon can be described as the initial stage of stormwater runoff, during which the concentration of pollutants is significantly higher compared to the later stages (Lee et al., 2002). Studies have shown that a significant proportion of pollutants is carried in the first portion of runoff. For instance, in a public park in South Korea, the first 20% of runoff emissions accounted for 36% of TSS, 42% of TN, and 50% of TP (Jung et al., 2013). Similarly, a three-year study on stormwater runoff pollutants in the Tongsha reservoir watershed of China found that the first 40% of the runoff, before any interception, removed 55% of TSS, 58% of TN, and 61% of TP (Li et al., 2015). Therefore, it is essential to treat at least the first 30% of runoff to effectively manage stormwater while minimizing the discharge of urban pollutants into the receiving water environment (Perera et al., 2021).

To address the first flush phenomenon, it is advisable to consider the implementation of initial stormwater runoff pollution purification treatments during this critical stage. A combination of grey infrastructure and GI is likely necessary to achieve this (O’Donnell and Thorne, 2020). GI can help alleviate the pressure on existing grey infrastructure, while grey infrastructure can enhance the capacity of GI, such as green swales, where their capacity may be limited.

6.3 Local conditions consideration

Urban design engineers face challenges when selecting the most suitable green swale design. The decision-making process involves identifying the best construction approach based on local conditions while balancing cost-effectiveness, logistical and financial efficiency, and maximizing social and economic benefits. In areas with lower contamination levels, such as parking lots, prioritizing GI becomes essential to reduce runoff volume, shorten the duration of peak runoff, and lower the maximum runoff depth. In such situations, grass swales and infiltration swales should be favoured among the different types of green swales.

Conversely, in areas with frequent human activities, the focus should shift toward controlling stormwater quality, particularly addressing the initial first flush phenomenon. To achieve this, wet swales and bioswales should be prioritized when selecting green swale types. Wet swales demonstrate good removal efficiency for nitrogen, while bioswales excel in the removal of phosphorus and bacteria (Ekka et al., 2021). By considering these factors, the cost-effectiveness of green swales can be maximized, allowing designers to choose the most appropriate types of green swales based on the unique characteristics of the construction area.

6.4 Good maintenance management

The need for ongoing capital investment to support good maintenance management of green swales is indeed crucial but can be challenging to sustain. To address this challenge, two approaches can be adopted.

(1) Diversifying Funding Sources: Instead of relying solely on one source of capital investment, careful consideration should be given to all possible funding options. While many countries typically depend on local or national government funding for infrastructure development, exploring other sources such as contributions from stakeholders (enterprises, residents, and finance) can help raise additional funds. Public–private partnerships (PPPs), where the government collaborates with private investors, can also be an effective investment model for implementing projects and providing public services (Koscielniak and Gorka, 2016). To encourage public financial participation, raising awareness of the benefits of green swales through community promotion, media, and education is essential. Providing opportunities for the public to participate, such as paying a domestic water fee surcharge or purchasing government-issued credit securities, can also be explored (Wang et al., 2017).

(2) Regular Maintenance and Appropriate Management: Proper maintenance based on continuous investment is crucial for the effective functioning of green swales. Regular inspections and monitoring are essential to identify any maintenance needs and ensure that the facilities operate as planned. One common issue with green swales is water taking the most efficient route, leading to erosion and deposition, which can degrade effluent quality and reduce the facilities' lifespan (Li, 2015). To address erosion, vegetation slope protection, a flat longitudinal slope, a wide channel bottom, and the right rock soil cushion can be employed to slow water flow and prevent erosion while allowing vegetation to thrive. Cleaning pretreatment areas and safeguarding infiltration surfaces are essential maintenance procedures for green swales (Blecken et al., 2017). Maintenance workers should also be aware that swales typically absorb necessary nutrients, negating the need for fertilization, and should avoid using herbicides and fertilizers in and around them.

In future design and research, the effectiveness of green swales should be carefully assessed, considering relevant safety factors, and routine inspections should be carried out to ensure adequate maintenance. Different types of green swales may require specific upkeep procedures, and targeted maintenance can significantly reduce maintenance expenses. By adopting these approaches, the long-term functionality and benefits of green swales in managing stormwater runoff and water quality can be maximized.

7 Conclusions

In this paper, we conducted a comprehensive review of green swales in the context of China's SCP to identify challenges and provide relevant recommendations. Through comparisons of green swale research between China and other nations, we found that bioswales deserve priority as a future research focus in the field of green swales, where China has been a significant contributor.

To address the communication barriers arising from the lack of a standard definition of green swales in Chinese research, we categorized green swale research based on types, vegetation, structure, and performance, presenting a comprehensive summary with key improvements. This new classification framework offers valuable guidance for the design and implementation of green swales in China's sponge city construction. Choosing vegetation tolerant to future climatic conditions (e.g., cold, drought, waterlogging, and salt tolerance, depending on the location) is essential when considering vegetation for green swales. In terms of runoff control, rainfall volume and facility size are crucial factors, while pollutant inflow volume, swale length, and effective discharge area significantly impact water quality improvement.

We identified three major obstacles to the construction of green swales in sponge cities in China: Sound road planning, a suitable construction environment, and long-term funding. To assist managers, designers, and urban builders in addressing the threat of climate change to green swale design, construction, and maintenance, we presented recommendations encompassing performance, the first flush phenomenon, construction environment, and maintenance of green swales, aiding in better management of urban stormwater runoff.

Adaptive and tailored strategies are fundamental to ensuring the success and effectiveness of green swale operations globally. Other nations and regions can draw valuable insights from China's approach to green swales for water quantity control, prioritizing urban runoff volume reduction. China's experience with hierarchical control structures can guide the construction of green swales in challenging terrains with steep slopes. However, it is essential to recognize that specific implementation and management strategies should consider regional variations in laws, temperature, soil, and hydrological conditions.

Electronic Supplementary Material Supplementary material is available in the online version of this article at https://doi.org/10.1007/s42524-023-0267-z and is accessible for authorized users.

Competing Interests The authors declare that they have no competing interests.

References

Allen D, Olive V, Arthur S, Haynes H (2015). Urban sediment transport through an established vegetated swale: Long-term treatment efficiencies and deposition. Water, 7(3): 1046–1067

Anderson B S, Phillips B M, Voorhees J P, Siegler K, Tjeerdema R (2016). Bioswales reduce contaminants associated with toxicity in urban storm water. Environmental Toxicology and Chemistry, 35(12): 3124–3134

Bäckström M (2003). Grassed swales for stormwater pollution control during rain and snowmelt. Water Science and Technology, 48(9): 123–132

Barrett M E, Walsh P M, Malina Jr J F, Charbeneau R J (1998). Performance of vegetative controls for treating highway runoff. Journal of Environmental Engineering, 124(11): 1121–1128

Bellprat O, Guemas V, Doblas-Reyes F, Donat M G (2019). Towards reliable extreme weather and climate event attribution. Nature Communications, 10(1): 1732

Bevilacqua P (2021). The effectiveness of green roofs in reducing building energy consumptions across different climates: A summary of literature results. Renewable & Sustainable Energy Reviews, 151: 111523

Blecken G T, Hunt III W F, Al-Rubaei A M, Viklander M, Lord W G (2017). Stormwater control measure (SCM) maintenance considerations to ensure designed functionality. Urban Water Journal, 14(3): 278–290

Bouzouidja R, Leconte F, Kiss M, Pierret M, Pruvot C, Détriché S, Louvel B, Bertout J, Aketouane Z, Wu T V, Goiffon R, Colin B, Pétrissans A, Lagière P, Pétrissans M (2021). Experimental comparative study between conventional and green parking lots: Analysis of subsurface thermal behavior under warm and dry summer conditions. Atmosphere, 12(8): 994

Bressy A, Gromaire M C, Lorgeoux C, Saad M, Leroy F, Chebbo G (2014). Efficiency of source control systems for reducing runoff pollutant loads: Feedback on experimental catchments within Paris conurbation. Water Research, 57: 234–246

Brodsky O L, Shek K L, Dinwiddie D, Bruner S G, Gill A S, Hoch J M, Palmer M I, McGuire K L (2019). Microbial communities in bioswale soils and their relationships to soil properties, plant species, and plant physiology. Frontiers in Microbiology, 10: 2368

Brunetti G, Simunek J, Piro P (2016). A comprehensive numerical analysis of the hydraulic behavior of a permeable pavement. Journal of Hydrology, 540: 1146–1161

Chan F K S, Chen W Y, Gu X B, Peng Y, Sang Y F (2022a). Transformation towards resilient sponge cities in China. Nature Reviews Earth & Environment, 3(2): 99–101

Chan F K S, Chen W Y, Wang Z, Loh C, Thadani D R, Mitchell G, Chau P Y K, Altamirano M A, Jaimerena B A, Qi Y, Li L, Gu X B, Zhang F (2022b). Meeting financial challenge facing China's Sponge City Program (SCP): Hong Kong as a gateway to green finance. Nature-Based Solutions, 2: 100019

Chang C L, Lo S L, Huang S M (2009). Optimal strategies for best management practice placement in a synthetic watershed. Environmental Monitoring and Assessment, 153(1–4): 359–364

Chatzimentor A, Apostolopoulou E, Mazaris A D (2020). A review of green infrastructure research in Europe: Challenges and opportunities. Landscape and Urban Planning, 198: 103775

Che W, Zhao Y, Yang Z, Li J Q, Shi M (2014). Integral stormwater management master plan and design in an ecological community. Journal of Environmental Sciences, 26(9): 1818–1823

Church S P (2015). Exploring green streets and rain gardens as instances of small scale nature and environmental learning tools. Landscape and Urban Planning, 134: 229–240

Davis A P, Stagge J H, Jamil E, Kim H (2012). Hydraulic performance of grass swales for managing highway runoff. Water Research, 46(20): 6775–6786

Deletic A (1998). The first flush load of urban surface runoff. Water Research, 32(8): 2462–2470

Ekka S A, Hunt B (2020). Swale Terminology for Urban Stormwater Treatment. Urban Waterway Series, NC State Extension. Raleigh, NC: North Carolina State University

Ekka S A, Rujner H, Leonhardt G, Blecken G T, Viklander M, Hunt W F (2021). Next generation swale design for stormwater runoff treatment: A comprehensive approach. Journal of Environmental Management, 279: 111756

Fach S, Engelhard C, Wittke N, Rauch W (2011). Performance of infiltration swales with regard to operation in winter times in an Alpine

region. Water Science and Technology, 63(11): 2658–2665
Fardel A, Peyneau P E, Bechet B, Lakel A, Rodriguez F (2019). Analysis of swale factors implicated in pollutant removal efficiency using a swale database. Environmental Science and Pollution Research International, 26(2): 1287–1302
García-Serrana M, Gulliver J S, Nieber J L (2017). Non-uniform overland flow-infiltration model for roadside swales. Journal of Hydrology, 552: 586–599
García-Serrana M, Gulliver J S, Nieber J L (2018). Calculator to estimate annual infiltration performance of roadside swales. Journal of Hydrologic Engineering, 23(6): 04018017
Gavrić S, Leonhardt G, Marsalek J, Viklander M (2019). Processes improving urban stormwater quality in grass swales and filter strips: A review of research findings. Science of the Total Environment, 669: 431–447
Gong Y W, Yin D K, Liu C, Li J Q, Shi H H, Fang X (2019). The influence of external conditions on runoff quality control of grass swale in Beijing and Shenzhen, China. Water Practice & Technology, 14(2): 482–494
Green D, O'Donnell E, Johnson M, Slater L, Thorne C, Zheng S, Stirling R, Chan F K S, Li L, Boothroyd R J (2021). Green infrastructure: The future of urban flood risk management? Wiley Interdisciplinary Reviews: Water, 8(6): e21560
Gülbaz S, Kazezyilmaz-Alhan C M (2014). Investigating effects of low impact development on surface runoff and TSS with a calibrated hydrodynamic model. La Houille Blanche, 100(3): 77–84
Gwynne C S (1942). Swell and swale pattern of the Mankato lobe of the Wisconsin drift plain in Iowa. Journal of Geology, 50(2): 200–208
Hernández-Crespo C, Fernandez-Gonzalvo M, Martin M, Andres-Domenech I (2019). Influence of rainfall intensity and pollution build-up levels on water quality and quantity response of permeable pavements. Science of the Total Environment, 684: 303–313
Horstmeyer N, Huber M, Drewes J E, Helmreich B (2016). Evaluation of site-specific factors influencing heavy metal contents in the topsoil of vegetated infiltration swales. Science of the Total Environment, 560: 19–28
Houser C, Hobbs C, Saari B (2008). Posthurricane airflow and sediment transport over a recovering dune. Journal of Coastal Research, 24(4): 944–953
Hunt W F, Davis A P, Traver R G (2012). Meeting hydrologic and water quality goals through targeted bioretention design. Journal of Environmental Engineering, 138(6): 698–707
Ingvertsen S T, Cederkvist K, Regent Y, Sommer H, Magid J, Jensen M B (2012). Assessment of existing roadside swales with engineered filter soil: I characterization and lifetime expectancy. Journal of Environmental Quality, 41(6): 1960–1969
Jia H F, Wang X W, Ti C P, Zhai Y Y, Field R, Tafuri A N, Cai H H, Yu S L (2015). Field monitoring of an LID-BMP treatment train system in China. Environmental Monitoring and Assessment, 187(6): 373
Jiang C B, Li J K, Li H E, Li Y J, Zhang Z X (2020). Low-impact development facilities for stormwater runoff treatment: Field monitoring and assessment in Xi'an area, China. Journal of Hydrology, 585: 124803
Jung J W, Park H N, Yoon K S, Choi D H, Lim B J (2013). Event mean concentrations (EMCs) and first flush characteristics of runoff from a public park in Korea. Journal of the Korean Society for Applied Biological Chemistry, 56(5): 597–604
Kazemi F, Beecham S, Gibbs J (2011). Streetscape biodiversity and the role of bioretention swales in an Australian urban environment. Landscape and Urban Planning, 101(2): 139–148
Kirby J T, Durrans S R, Pitt R, Johnson P D (2005). Hydraulic resistance in grass swales designed for small flow conveyance. Journal of Hydraulic Engineering, 131(1): 65–68
Knight E M P, Hunt W F, Winston R J (2013). Side-by-side evaluation of four level spreader-vegetated filter strips and a swale in eastern North Carolina. Journal of Soil and Water Conservation, 68(1): 60–72
Koscielniak H, Gorka A (2016). Green cities PPP as a method of financing sustainable urban development. Transportation Research Procedia, 16: 227–235
Lee H S, Lim B R, Hur J, Kim H S, Shin H S (2021). Combined dual-size foam glass media filtration process with micro-flocculation for simultaneous removal of particulate and dissolved contaminants in urban road runoff. Journal of Environmental Management, 277: 111475
Lee J H, Bang K W, Ketchum Jr L H, Choe J S, Yu M J (2002). First flush analysis of urban storm runoff. Science of the Total Environment, 293(1–3): 163–175
Leroy M C, Legras M, Marcotte S, Moncond'huy V, Machour N, Le Derf F, Portet-Koltalo F (2015). Assessment of PAH dissipation processes in large-scale outdoor mesocosms simulating vegetated road-side swales. Science of the Total Environment, 520: 146–153
Leroy M C, Marcotte S, Legras M, Moncond'huy V, Le Derf F, Portet-Koltalo F (2017). Influence of the vegetative cover on the fate of trace metals in retention systems simulating roadside infiltration swales. Science of the Total Environment, 580: 482–490
Li D Y, Wan J Q, Ma Y W, Wang Y, Huang M Z, Chen Y M (2015). Stormwater runoff pollutant loading distributions and their correlation with rainfall and catchment characteristics in a rapidly industrialized city. PLoS One, 10(3): e0118776
Li F Z, Chen J Q, Engel B A, Liu Y Z, Wang S Z, Sun H (2021). Assessing the effectiveness and cost efficiency of green infrastructure practices on surface runoff reduction at an urban watershed in China. Water, 13(1): 24
Li H (2015). Green infrastructure for highway stormwater management: Field investigation for future design, maintenance, and management needs. Journal of Infrastructure Systems, 21(4): 05015001
Li J K, Li Y, Zhang J Y, Li H E, Li Y J (2016). Bio-swale column experiments and simulation of hydrologic impacts on urban road stormwater runoff. Polish Journal of Environmental Studies, 25(1): 173–184
Li M H, Barrett M E, Rammohan P, Olivera F, Landphair H C (2008). Documenting stormwater quality on Texas highways and adjacent vegetated roadsides. Journal of Environmental Engineering, 134(1): 48–59
Li Y, Huang J J, Hu M C, Yang H, Tanaka K (2020). Design of low impact development in the urban context considering hydrological performance and life-cycle cost. Journal of Flood Risk Management, 13(3): e12625
Liu F, Vianello A, Vollertsen J (2019). Retention of microplastics in

sediments of urban and highway stormwater retention ponds. Environmental Pollution, 255(2): 113335

Liu T Q, Lawluvy Y, Shi Y, Yap P S (2021). Low Impact Development (LID) practices: A review on recent developments, challenges and prospects. Water, Air, and Soil Pollution, 232(9): 344

Liu W, Chen W, Feng Q, Peng C, Kang P (2016). Cost-benefit analysis of green infrastructures on community stormwater reduction and utilization: A case of Beijing, China. Environmental Management, 58(6): 1015–1026

Locatelli L, Mark O, Mikkelsen P S, Arnbjerg-Nielsen K, Wong T, Binning P J (2015). Determining the extent of groundwater interference on the performance of infiltration trenches. Journal of Hydrology, 529(3): 1360–1372

Logan T M, Zaitchik B, Guikema S, Nisbet A (2020). Night and day: The influence and relative importance of urban characteristics on remotely sensed land surface temperature. Remote Sensing of Environment, 247: 111861

Luan Q H, Fu X R, Song C P, Wang H C, Liu J H, Wang Y (2017). Runoff effect evaluation of LID through SWMM in typical mountainous, low-lying urban areas: A case study in China. Water, 9(6): 439

Lucke T, Mohamed M A K, Tindale N (2014). Pollutant removal and hydraulic reduction performance of field grassed swales during runoff simulation experiments. Water, 6(7): 1887–1904

Mazer G, Booth D, Ewing K (2001). Limitations to vegetation establishment and growth in biofiltration swales. Ecological Engineering, 17(4): 429–443

McIntyre J K, Prat J, Cameron J, Wetzel J, Mudrock E, Peter K T, Tian Z Y, Mackenzie C, Lundin J, Stark J D, King K, Davis J W, Kolodziej E P, Scholz N L (2021). Treading water: Tire wear particle leachate recreates an urban runoff mortality syndrome in coho but not chum salmon. Environmental Science & Technology, 55(17): 11767–11774

Monrabal-Martinez C, Aberle J, Muthanna T M, Orts-Zamorano M (2018). Hydrological benefits of filtering swales for metal removal. Water Research, 145: 509–517

Moore T L, Rodak C M, Ahmed F, Vogel J R (2018). Urban stormwater characterization: Control and treatment. Water Environment Research, 90(10): 1821–1871

National Committee on Soil and Terrain (Australia) (2009). Australian Soil and Land Survey Field Handbook. 3rd ed. Clayton: CSIRO Publishing

O'Donnell E C, Thorne C R (2020). Drivers of future urban flood risk. Philosophical Transactions of the Royal Society A: Mathematical, Physical, and Engineering Sciences, 378(2168): 20190216

O'Reilly A M, Wanielista M P, Chang N B, Xuan Z, Harris W G (2012). Nutrient removal using biosorption activated media: Preliminary biogeochemical assessment of an innovative stormwater infiltration basin. Science of the Total Environment, 432: 227–242

Perera T, Mcgree J, Egodawatta P, Jinadasa K, Goonetilleke A (2021). New conceptualisation of first flush phenomena in urban catchments. Journal of Environmental Management, 281: 111820

Qin Y H (2020). Urban flooding mitigation techniques: A systematic review and future studies. Water, 12(12): 3579

Rezaei A R, Ismail Z, Niksokhan M H, Dayarian M A, Ramli A H, Yusoff S (2021). Optimal implementation of low impact development for urban stormwater quantity and quality control using multi-objective optimization. Environmental Monitoring and Assessment, 193(4): 241

Roy A H, Rhea L K, Mayer A L, Shuster W D, Beaulieu J J, Hopton M E, Morrison M A, St. Amand A (2014). How much is enough? Minimal responses of water quality and stream biota to partial retrofit stormwater management in a suburban neighborhood. PLoS One, 9(1): e85011

Saniei K, Yazdi J, Majdzadehtabatabei M R (2021). Optimal size, type and location of low impact developments (LIDs) for urban stormwater control. Urban Water Journal, 18(8): 585–597

Shaneyfelt K M, Anderson A R, Kumar P, Hunt III W F (2017). Air quality considerations for stormwater green street design. Environmental Pollution, 231(1): 768–778

Smith C, Connolly R, Ampomah R, Hess A, Sample-Lord K, Smith V (2021). Temporal soil dynamics in bioinfiltration systems. Journal of Irrigation and Drainage Engineering, 147(11): 04021053

Sossalla N A, Nivala J, Reemtsma T, Schlichting R, Konig M, Forquet N, van Afferden M, Muller R A, Escher B I (2021). Removal of micropollutants and biological effects by conventional and intensified constructed wetlands treating municipal wastewater. Water Research, 201: 117349

Specht R L, Specht A (1999). Australian Plant Communities: Dynamics of Structure, Growth and Biodiversity. Oxford: Oxford University Press

Tang J F, Wang W D, Feng J Y, Yang L, Ruan T, Xu Y Y (2021). Urban green infrastructure features influence the type and chemical composition of soil dissolved organic matter. Science of the Total Environment, 764: 144240

Tang N Y, Li T, Ge J (2016). Assessing ability of a wet swale to manage road runoff: A case study in Hefei, China. Journal of Central South University, 23(6): 1353–1362

van Dijk S, Lounsbury A W, Hoekstra A Y, Wang R R (2020). Strategic design and finance of rainwater harvesting to cost-effectively meet large-scale urban water infrastructure needs. Water Research, 184: 116063

Vijayaraghavan K, Biswal B K, Adam M G, Soh S H, Tsen-Tieng D L, Davis A P, Chew S H, Tan P Y, Babovic V, Balasubramanian R (2021). Bioretention systems for stormwater management: Recent advances and future prospects. Journal of Environmental Management, 292: 112766

Wang S, Min F T, Fu J (2020). A method to measure hydrologic restoration attributed to low impact development by computing similarity between runoff frequency spectra. Journal of Hydrology, 588: 125134

Wang Y T, Sun M X, Song B M (2017). Public perceptions of and willingness to pay for sponge city initiatives in China. Resources, Conservation and Recycling, 122: 11–20

Wigington P J, Randall C W, Grizzard T J (1986). Accumulation of selected trace-metals in soils of urban runoff swale drains. Journal of the American Water Resources Association, 22(1): 73–79

Winston R J, Anderson A R, Hunt W F (2017). Modelling sediment reduction in grass swales and vegetated filter strips using particle settling theory. Journal of Environmental Engineering, 143(1): 04016075

Winston R J, Hunt W F, Kennedy S G, Wright J D, Lauffer M S (2012).

Field evaluation of storm-water control measures for highway runoff treatment. Journal of Environmental Engineering, 138(1): 101–111

Winston R J, Powell J T, Hunt W F (2019). Retrofitting a grass swale with rock check dams: Hydrologic impacts. Urban Water Journal, 16(6): 404–411

Wu J S, Chen Y, Yang R, Zhao Y H (2020). Exploring the optimal cost-benefit solution for a low impact development layout by zoning, as well as considering the inundation duration and inundation depth. Sustainability, 12(12): 4990

Xiao Q F, McPherson E G (2011). Performance of engineered soil and trees in a parking lot bioswale. Urban Water Journal, 8(4): 241–253

Xu C Q, Shi X M, Jia M Y, Han Y, Zhang R R, Ahmad S, Jia H F (2022). China Sponge City database development and urban runoff source control facility configuration comparison between China and the US. Journal of Environmental Management, 304: 114241

Yang M Y, Sang Y F, Sivakumar B, Chan F K S, Pan X Y (2020). Challenges in urban stormwater management in Chinese cities: A hydrologic perspective. Journal of Hydrology, 591: 125314 (in Chinese)

Yazdi J, Khazaei P (2019). Copula-based performance assessment of online and offline detention ponds for urban stormwater management. Journal of Hydrologic Engineering, 24(9): 04019025

Yu J, Yu H, Xu L (2013). Performance evaluation of various stormwater best management practices. Environmental Science and Pollution Research International, 20(9): 6160–6171

Yu S L, Kuo J T, Fassman E A, Pan H (2001). Field test of grassed-swale performance in removing runoff pollution. Journal of Water Resources Planning and Management, 127(3): 168–171

Yuan D H, He J W, Li C W, Guo X J, Xiong Y, Yan C L (2019). Insights into the pollutant-removal performance and DOM characteristics of stormwater runoff during grassy-swales treatment. Environmental Technology, 40(4): 441–450

Zaqout T, Andradottir H O (2021). Hydrologic performance of grass swales in cold maritime climates: Impacts of frost, rain-on-snow and snow cover on flow and volume reduction. Journal of Hydrology, 597: 126159

Zhang D Q, Gersberg R M, Ng W J, Tan S K (2017). Conventional and decentralized urban stormwater management: A comparison through case studies of Singapore and Berlin, Germany. Urban Water Journal, 14(2): 113–124

Zhang R, Zhou W B, Field R, Tafuri A, Yu S L, Jin K L (2009). Field test of best management practice pollutant removal efficiencies in Shenzhen, China. Frontiers of Environmental Science & Engineering in China, 3(3): 354–363

Zhang Y Y, Qin H P, Ye Y J, Ding W (2022). The effect of low impact development facilities on evapotranspiration in an outdoor space of urban buildings. Journal of Hydrology, 608: 127647

Zuniga-Teran A A, Staddon C, de Vito L, Gerlak A K, Ward S, Schoeman Y, Hart A, Booth G (2020). Challenges of mainstreaming green infrastructure in built environment professions. Journal of Environmental Planning and Management, 63(4): 710–732