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Sustainable Urban Drainage Systems: Global Review of Environmental Benefits and Implementation Challenges

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Abstract: Urbanisation has led to numerous challenges in terms of stormwater management and environmental impact. Sustainable Urban Drainage Systems (SUDS) have emerged as a promising approach to mitigate these challenges by mimicking natural processes and providing environmentally sound water disposal systems. This review paper provides a comprehensive overview of the status of SUDS on a global scale, focusing on their development, challenges, and environmental benefits. This review paper discusses various SUDS techniques, including permeable paving, green infrastructure, and detention ponds, and highlights their effectiveness in reducing stormwater runoff, improving water quality, and enhancing ecological services. The paper also identifies the challenges faced in implementing SUDS, including technical complexity, lack of common platforms for SUDS models, limited operational experience, and institutional barriers. Additionally, the paper presents potential solutions to overcome these challenges, such as promoting research and development, providing training and capacity-building programs, and establishing guidelines and standards for SUDS design. The findings and recommendations presented in this paper contribute to the development of sustainable urban environments and the enhancement of overall environmental conditions.

Keywords: *Green Infrastructure, Stormwater Management, Sustainable Urban Drainage Systems, Urban Flooding, Water Quality*

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1. Introduction

Urbanisation is a global phenomenon that continues to accelerate. United Nations projections indicate that 57.6% of the world's population resided in urban areas in 2023—a share expected to increase to 68% by 2050 (UN DESA, 2023). While urbanisation brings about numerous advantages, it also presents significant challenges to both human life and the environment. The rapid growth of the urban population has led to direct or indirect impacts on the climate and natural ecosystems (Zhou et al., 2023; Kang et al., 2016). As a result, there have been increased pollution, biodiversity losses, alterations to land use patterns and increased stormwater runoff (Zhou et al., 2023).

One evident consequence of urbanisation is the loss of ground permeability caused by the development of impervious land surfaces (Zhou, 2014). This impermeabilization of soil hampers stormwater infiltration, leading to an increase in storm water runoff and subsequent downstream flooding (Putri et al., 2023). Climate change poses another significant challenge to urban stormwater management. The potential effects of climate change include more frequent and intense rainfall events, sea-level rise and infrastructure damage (Sagala et al., 2022).

Traditional stormwater drainage systems were initially constructed in the 1990s as a solution to the flooding problem. However, with the ongoing process of urbanisation, soil impermeability has become more prevalent, necessitating the implementation of innovative strategies for stormwater treatment in urban areas (Sirishantha & Rathnayake, 2017).

In response to these challenges, Sustainable Urban Drainage Systems (SUDS) have emerged as a promising approach to mitigating stormwater runoff and establishing environmentally sound water disposal systems that mimic natural processes (Poleto & Tassi, 2012; Modak & Basu, 2022). SUDS address these challenges by providing proper drainage systems, managing stormwater at the source, effectively treating sewage, and ensuring adequate stormwater management (Boogaard, 2015). These systems not only address the quantity of water but also consider water quality and biodiversity aspects, aligning with the principles of green infrastructure (Sirishantha & Rathnayake, 2017).

Some of the closely related terms or alternative names for SUDS are Best management practices (BMP), low-impact development (LID), Sustainable urban drainage (SUD), Integrated catchment planning, or Ecological stormwater management (Stahre, 2002). However, the term SUDS will be used throughout this paper to refer to these technologies. Some commonly utilised SUDS techniques include permeable paving, infiltration devices (e.g., retention ponds and detention ponds), green infrastructure (e.g., green roofs and green spaces), swales, and rain gardens (Zhou, 2014).

Despite the numerous benefits offered by SUDS, they face various challenges, including non-natural and climatic barriers (Scholz, 2015). To explore the functionality and effectiveness of SUDS in urban areas, it is crucial to understand the various types and techniques employed. The primary objective of this research was to examine the current status of sustainable drainage systems on a global scale, with a specific focus on their development, challenges, and environmental benefits.

The novelty of this review paper lies in its comprehensive overview of SUDS on a global scale, aiming to bridge the existing gaps in understanding sustainable drainage systems. While previous studies have examined various aspects of SUDS, this review provides a comprehensive global analysis of their environmental benefits and the implementation challenges they pose. It synthesises findings from 46 studies across diverse geographical contexts to identify key factors influencing the successful adoption of SUDS and highlights systematic links between documented barriers and peer-reviewed solution pathways, offering consolidated references for practitioners and researchers.

2. Materials and methods

This review paper employed a systematic approach to gather and analyse relevant literature on SUDS and their global implementation. Several databases and search engines, including Google Scholar, Journal Storage (JSTOR), Springer and Science Direct, were utilised to conduct a comprehensive literature search. The search was conducted using keywords such as "Sustainable Drainage System," "SUDS and biodiversity," "SUDS benefits," "Green roofs and rainwater runoff," "SUDS challenges," "Urban flooding," and "Stormwater management."

A set of predefined inclusion and exclusion criteria were established to select the relevant literature for this review. Inclusion criteria encompassed studies that focused on sustainable drainage systems, their development, challenges, and environmental benefits. Both empirical research and review articles were considered in the selection process.

A data extraction form was developed to systematically extract information from the selected papers. The data extraction form included variables such as author(s), year of publication, study objectives, methodology, SUDS techniques, challenges identified, and environmental benefits reported by the papers. The extracted data were then analysed thematically to identify key themes related to the challenges and environmental benefits of SUDS.

Additionally, all the authors of this review paper collaborated on this study through a research network formed by the Global Research Institute and Training Center. The collaboration facilitated the comprehensive analysis of the literature and the synthesis of information on the development, challenges, and environmental benefits of SUDS on a global scale. The collective effort of the research network contributed to the quality and reliability of the findings presented in this review paper.

Throughout the literature search and screening process, a total of 65 research papers were reviewed and included in this review paper. These papers were retrieved from the selected databases and search engines based on their relevance to the research objectives and meeting the predefined inclusion criteria.

3. Results and discussion

Surface flooding caused by climate change and inadequate drainage facilities has become a common problem in urban areas. SUDS, unlike conventional drainage systems, take a holistic approach that addresses runoff quality, visual amenities, recreational value, ecological protection, and various water uses (Jemberie et al., 2023). SUDS aim to mimic natural drainage processes and enhance the ecological functioning of urban areas (Zhou, 2014). They encompass various methods such as green roofs, downspout disconnection, rainwater harvesting, bioretention facilities, bioswales, permeable pavements, detention and retention ponds/basins, constructed wetlands, urban tree canopies, and land conservation (Bassi et al., 2017).

Green roofs, which consist of layers such as waterproofing membranes, drainage layers, growth substrates, and vegetation, absorb precipitation, reduce stormwater runoff, and utilise existing roofs in urban areas (Sirishantha & Rathnayake, 2017). Bioretention systems, using small ground-level areas with sand, plants, and organic filter media, collect and treat runoff, improving water quality and soil infiltration (Bassi et al., 2017). Pervious pavements (PP), including porous concrete, porous asphalt, and permeable interlocking concrete paving, reduce peak flows and runoff volumes, offering a solution for urban areas with impermeable surfaces (Arora et al., 2023). Rain barrels and wetlands are also utilised in SUDS, with rain barrels collecting and storing rainwater from roofs and wetlands acting as natural filters and providing ecosystem services (Putri et al., 2023).

SUDS have gained recognition globally, with various countries adopting this approach under different names based on regional contexts. For example, Water Sensitive Urban Design (WSUD) is the term used in European countries, while Low Impact Development (LID) is used in the USA and Canada (Rentachintala et al., 2022). The specific types of SUDS implemented vary based on climatic conditions and regional considerations. Spain utilises the in-situ control method, employing permeable pavement installations for managing surface runoff from large areas such as streets (García et al., 2021). In the Netherlands, a range of SUDS, including water retention squares, swales, and sedimentation ponds, have been implemented in various cities (Boogaard, 2015). Similarly, in Iran, SUDS are installed as Best Management Practices (BMP) to reduce urban flooding and enhance adaptability to climate change (Binesh et al., 2019).

3.1 Environmental Benefits of Sustainable Urban Drainage Systems (SUDS)

Being a component of a larger green infrastructure concept, SUDS enables rain to permeate directly into the soil, reducing runoff and helping to replenish the groundwater table (White & Alarcon, 2009). Traditional drainage systems had volume and debris capacity restrictions; however, SUDS offer many advantages over them in various areas. As a result, it has been put into practice in several nations to manage urban runoff. For instance, parking lot bioswales in California, as low-impact developments, have significantly reduced the concentration of contaminants like suspended solids (81% reduction), metals (81% reduction), hydrocarbons (82% reduction), and pyrethroid pesticides (74% reduction) by filtering runoff through plants and soil (Anderson et al., 2016). In the Netherlands, a study conducted with 81 infiltration experiments in 9 towns revealed an average infiltration rate of permeable pavement of 364 mm/hr, suggesting an easy solution for the country to become water-robust and climate-resilient by 2050 (Naeimi & Safavi, 2019). Moreover, intensive green roofs in Germany reduced annual runoff by 65-85% of the volume of annual rainfall, while extended green roofs reduced runoff by 27-81% (Mentens et al., 2006).

Plant-based SUDS enable climate control, stormwater detention, and carbon capture, resulting in energy cost savings and increased property values (Charlesworth et al., 2003). Urban trees contribute to carbon storage, with estimates ranging from 700 Mt to 22.8 Mt C/yr for parks and roads in the contiguous US (Charlesworth et al., 2003; Nowak & Crane, 2002). In Brussels, greening roofs on 10% of buildings led to a 2.7% reduction in regional runoff and a 54% reduction for individual buildings (Mentens et al., 2006). SUDS systems significantly reduce the risks of heat and flooding in areas with vegetated surfaces that absorb and hold rainwater, purify stormwater, and mitigate heat (Chan et al., 2019). Similarly, permeable pavements have lower surface temperatures in wet conditions compared to impermeable pavements, and they can effectively absorb rainwater, support heavy vehicle traffic, and enhance thermal efficiency (Liao et al., 2013).

Green infrastructure (GI), including SUDs, contributes to increased ecological services and a better urban environment. Green roofs reduce greenhouse gas emissions, while swales and wetlands act as long-term carbon storage. Rain gardens, a key SUDs technology, help manage runoff storage, reduce peak flows, and address urban stormwater pollution. The composition, texture, depth of the media, climatic conditions, oxygen levels, and other variables influence the treatment of contaminants during stormwater treatment (Nepal et al., 2022).

SUDS contribute to habitat variability, providing urban green spaces that support biodiversity. The creation of a bio-SUDS indicator can aid in evaluating ecological attributes in designs and actual SUDS components (Monberg et al., 2019). Studies on SUDS invertebrate communities have shown that SUD ponds in eastern Scotland support diverse invertebrate species, with 10 to 47 different species observed. However, conservation significance was mainly attributed to a single species of beetle and an invasive mollusc (Briers, 2014).

A comprehensive multiple-benefit analysis of SUDS should consider factors such as amenity, biodiversity, water quantity and quality, flood damage avoidance, pollutant trapping, carbon dioxide sequestration, and noise reduction (Morgan & Fenner, 2019). SUDS benefit plants, invertebrates, reptiles, amphibians, and mammals by improving water quality and controlling surface water outflow, both within the SUDS themselves and in receiving watercourses (Graham, 2016).

Green infrastructure, including SUDS, plays a significant role in improving natural environmental health and addressing biodiversity loss, providing a sustainable approach to urban development and water management (Chapman & Hall, 2022). Combining various SUDS techniques has shown improved results, with studies demonstrating reductions in runoff volumes through the implementation of vegetative swales, permeable pavements, and other techniques (Aruna et al., 2021). In Korea, the application of five LID approaches resulted in a significant reduction in the runoff differential between the pre- and post-development stages (Kang et al., 2016).

To sum up, Sustainable Urban Drainage Systems (SUDS) provide a sustainable approach to urban development and water management, offering numerous benefits in terms of reducing runoff, replenishing groundwater, improving water quality, improving natural environmental health, addressing biodiversity loss, and mitigating the risks of heat and flooding. They have been implemented in various countries and have shown promising results in managing stormwater and enhancing the ecological services provided by urban areas.

3.2 Challenges and Limitations of SUDS

Although SUDS methodologies and tools have made significant advancements, the practical application of sustainable drainage still poses numerous challenges. While a wide range of SUDS models is available, many are considered impractical due to their technical complexity and high costs. The lack of a common platform or interface for these models, coupled with limited operational and maintenance experience, further hinders their widespread use (Zhou, 2014). Additionally, the interactions of SUDS with other water bodies are often overlooked, and institutional barriers present further obstacles to the implementation of SUDS practices. The absence of clear guidelines and standards for SUDS design also contributes to the difficulties faced by users in selecting and modifying appropriate models for comprehensive SUDS studies. Moreover, the integration of models across different geographical and temporal scales can be problematic, requiring additional effort for data preparation and processing (Zhou, 2014).

A case study conducted in Spain revealed that the lack of national standards and technical criteria for SUDS design is a major impediment to the widespread adoption of SUDS at the national level (Andrés-Doménech et al., 2021). The obstacles to SUDS implementation in Spain can be categorized into three main categories: social/governance, regulatory, and technological. It is widely acknowledged that the governance and regulatory spheres pose the most challenging barriers, particularly due to limited economic resources. However, social and regulatory constraints are deeply rooted in human behaviours and attitudes, making them more resistant to change, especially in a field with a long history like urban drainage management. Technological issues include certain challenges that are inherent to infiltration systems, such as slow or inefficient infiltration in saturated soil or areas with high groundwater levels (Pokhrel et al., 2025). Maintenance schedules can also pose issues, particularly in the case of potential blockages. Many infiltration methods require significant land resources, limiting their use as retrofits in urban areas. Detention and retention devices are susceptible to clogging, which adversely affects both the hydraulic functioning of the system and the removal of pollutants. Furthermore, retrofitting SUDS in densely populated urban environments presents unique challenges, including limited access for installation and maintenance, ownership of buildings and urban spaces, lack of subsurface space, pollution control, aesthetics, and the suitability of building types in historic districts (Lamond et al., 2015).

In developing nations, the implementation of SUDS faces specific challenges. Factors such as irregular home layouts, the lack of rules and policies, complex and high-density drainage networks, combined sewer systems, and diverse soil types pose difficulties for the large-scale implementation of SUDS (Putri et al., 2023). Along with these challenges, governance and regulatory issues, technical complexities, and the absence of decision support tools also hinder the widespread adoption of SUDS. Integrating and utilising SUDS models present further difficulties, and the lack of standardised design criteria in some regions adds to the complexity. Additionally, the limitations of infiltration systems and the specific constraints of retrofitting in dense urban environments need to be addressed.

Cities in Nepal face urban flooding and waterlogging challenges, which can be addressed through investments in efficient drainage systems, specifically SUDS. SUDS offer a more sustainable approach to managing excess water during heavy rains, minimizing flood damage, and preventing waterlogging in critical areas. However, for long-term success, it is essential to couple these drainage system investments with proper solid waste management (Nepal et al., 2022). In Nepal, accurately predicting Municipal Solid Waste (MSW) output remains challenging (Khanal, 2023), and the limited practice of source segregation and ineffective waste collection system contribute to significant waste ending up in landfills (Khanal et al., 2023; Subedi et al., 2023), posing a threat to the efficiency and sustainability of the drainage systems and overall urban infrastructure investments. A comprehensive approach that combines SUDS with improved waste management is vital to create resilient and sustainable urban environments in Nepal.

The potential benefits offered by SUDS make them a valuable approach for sustainable water management in urban areas. However, overcoming these obstacles and promoting the broader implementation of SUDS for a resilient and environmentally friendly urban future requires further research and collaboration. Further research is needed to assess the long-term effectiveness of SUDS strategies and explore the multifunctional aspects of each component. Addressing these research gaps will contribute to the efficient and widespread implementation of sustainable urban drainage systems (SUDS), ensuring their effectiveness in managing stormwater and promoting sustainable urban development. By overcoming the challenges and improving the understanding and application of SUDS, communities can enhance their resilience to climate change, mitigate flood risks, and achieve sustainable water management goals.

3.4 Potential Solutions

To effectively address the challenges identified in the implementation and operation of SUDS, it is essential to explore practical solutions that can enhance their adoption and performance. Table 1 summarises the key challenges faced in SUDS deployment alongside corresponding strategies and examples that can help overcome these barriers. This synthesis offers an integrated perspective on the obstacles and actionable measures, serving as a guideline for stakeholders involved in sustainable urban water management.

Table 1: SUDS challenges and ways to overcome

Challenges	Ways to overcome	Examples	Key References
Technical complexity and high costs	- Promote research and development to improve technology and reduce costs.	Collaborate with engineering and technology firms to develop innovative, cost-effective SUDS solutions.	Cotterill & Bracken (2020); Morgan & Fenner (2019)
	- Provide financial incentives and grants for implementing SUDS.	Offer tax credits or subsidies to property owners who install SUDS features such as rain gardens or permeable pavements.	Cotterill & Bracken (2020); Morgan & Fenner (2019)
Lack of a common platform for SUDS models	- Establish a centralized database or platform for sharing SUDS models and best practices.	Create an online portal where researchers and practitioners can access and contribute to a repository of SUDS models and case studies.	Pascual et al. (2022); CIRIA (2023)
	- Encourage collaboration among researchers, practitioners, and policymakers to develop standardized models.	Organize workshops and conferences to facilitate knowledge exchange and consensus-building on SUDS modeling approaches.	Pascual et al. (2022); CIRIA (2023)
Limited operational and maintenance experience	- Offer training and capacity-building programs for professionals involved in SUDS implementation and maintenance.	Conduct workshops and training sessions to educate municipal staff and contractors on proper installation and maintenance practices for SUDS features.	Cotterill & Bracken (2020)
	- Establish maintenance guidelines and protocols to ensure long-term effectiveness of SUDS.	Develop comprehensive maintenance manuals that outline regular inspection procedures, cleaning methods, and repair protocols for different SUDS components.	Cotterill & Bracken (2020)
Lack of guidelines and standards for SUDS design	- Develop comprehensive design guidelines and standards based on research and best practices.	Collaborate with engineering associations and regulatory bodies to develop region-specific design manuals that provide detailed guidance on sizing, materials, and construction techniques for various SUDS features.	CIRIA (2023); DEFRA (2023)
	- Provide clear and accessible design resources for practitioners and decision-makers.	Create online design libraries that include case studies, design templates, and step-by-step guidance for implementing SUDS in different urban settings.	CIRIA (2023); DEFRA (2023)
Interaction with other water bodies	- Conduct thorough environmental assessments and consider the potential impacts of SUDS on adjacent water bodies.	Conduct hydrological modeling studies to evaluate the potential effects of SUDS implementation on downstream water quality, flood risk, and aquatic ecosystems.	Rodríguez-Rojas et al. (2024)

	- Implement integrated water management approaches that consider the overall hydrological system.	Develop integrated stormwater management plans that incorporate SUDS as part of a larger strategy, considering upstream and downstream flow paths and water quality improvements.	Rodríguez-Rojas et al. (2024)
Institutional barriers	- Advocate for supportive policies and regulations that encourage the use of SUDS.	Collaborate with policymakers to develop and implement regulations that promote the integration of SUDS in urban planning and development processes.	Starkey & Rollason (2023)
	- Foster collaboration between government agencies, stakeholders, and communities to overcome institutional barriers.	Establish multi-stakeholder task forces or working groups that bring together representatives from different sectors to address institutional challenges and develop joint solutions.	Starkey & Rollason (2023)
Inefficient infiltration in certain conditions	- Conduct site-specific assessments to identify suitable SUDS techniques based on soil conditions and groundwater levels.	Conduct infiltration tests and soil analysis to determine the feasibility of infiltration-based SUDS features in areas with challenging soil or high groundwater levels.	Anvigh et al. (2024)
	- Explore alternative SUDS techniques that can be effective in areas with infiltration limitations.	Consider the use of above-ground SUDS features such as green roofs, rainwater harvesting systems, or detention basins with controlled outlets in areas where infiltration is not feasible.	Anvigh et al. (2024)

4. Conclusion

Sustainable Urban Drainage Systems (SUDS) have been successfully applied in various countries, demonstrating their effectiveness in managing stormwater and enhancing ecological services. SUDS techniques such as permeable paving, infiltration devices, green infrastructure, swales, and rain gardens offer practical solutions for managing stormwater runoff in urban areas. These techniques not only address the quantity of water but also consider water quality and biodiversity aspects, aligning with the principles of green infrastructure and sustainable urban design. Climate change also poses significant challenges to urban drainage systems, and SUDS can play a vital role in mitigating the impacts by providing proper drainage systems, effectively treating sewage, and managing stormwater at the source.

Despite the numerous benefits offered by SUDS, several challenges and limitations exist that need to be addressed for their wider adoption. These challenges include adoption issues, flood and pollution control, public perception, and the lack of decision support tools for retrofitting systems and maximising ecosystem services. The retrofitting of traditional drainage systems to sustainable drainage systems is crucial for improving the quality of life and environmental conditions in urban areas.

There is a need for public awareness and education campaigns to enhance the understanding and acceptance of SUDS among the general population. Decision-makers and urban planners should prioritise the integration of SUDS into urban development plans and regulations. Additionally, the development of decision-support tools and guidelines for retrofitting existing drainage systems can facilitate the implementation of SUDS in urban areas. Proper maintenance and monitoring of SUDS performance are also crucial to ensure their long-term effectiveness in mitigating urban flooding, groundwater pollution, and surface water pollution.

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