

From grey to green: Eco-friendly urban drainage for resilient and sustainable cities

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Abstract

Rapid urbanization has become a key driver of socioeconomic development and improved living standards, yet it simultaneously places severe pressure on urban infrastructure systems, particularly drainage networks that are often outdated and undersized. The expansion of impermeable surfaces reduces natural infiltration, leading to increased stormwater runoff, frequent urban flooding, and declining water quality. Conventional grey drainage infrastructure, dominated by rigid pipe networks and storm sewers, offers limited short-term flood control but is increasingly inadequate, costly, and environmentally unsustainable under intensified rainfall patterns driven by climate change. These challenges highlight the urgent need for adaptive and eco-friendly urban drainage solutions. This study systematically reviews the transition from grey to green drainage systems and evaluates their contribution to urban resilience and sustainability. Using a systematic literature review (SLR) methodology, peer-reviewed articles and conference papers published between 2000 and 2025 were collected from Scopus, Web of Science, ScienceDirect, and Google Scholar. A rigorous three-stage screening process was applied, followed by structured data extraction and thematic synthesis. The review demonstrates that nature-based solutions, including Sustainable Urban Drainage Systems (SuDS), Low-Impact Development (LID), and green infrastructure, effectively replicate natural hydrological processes by slowing, storing, and infiltrating stormwater at its source. Measures such as permeable pavements, rain gardens, green roofs, and constructed wetlands significantly reduce flood risk while delivering co-benefits, including groundwater recharge, urban cooling, pollution reduction, and biodiversity enhancement. The integration of smart technologies, including IoT-based monitoring and real-time control, further strengthens system adaptability and performance. Overall, the findings highlight eco-friendly drainage as a critical component of resilient, inclusive, and sustainable urban development, particularly for cities facing rapid urbanization and climate change pressures.

Keywords: Climate change adaptation; Green infrastructure; Low-Impact Development (LID); Sustainable Urban Drainage Systems (SuDS); Urban flood resilience

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INTRODUCTION

Urbanization is a key driver of socio-economic progress, significantly transforming cities and communities, influencing infrastructure, social dynamics, economic development, and the overall urban environment (Kaiser, 2023). Rapid urbanization reshapes land use and infrastructure, driving development aimed at enhancing living standards and overall urban quality of life (Stokes & Seto, 2019). By 2050, nearly 70% of the global population is projected to reside in urban areas, intensifying challenges such as transportation congestion, heightened energy demand, strained water resources, inefficient waste management, and the pressing need for sustainable, climate-resilient, and environmentally responsible infrastructure (Ma & Huang, 2021; United Nations, 2019).

Urbanization drives economic growth and better living standards, but simultaneously places immense pressure on infrastructure systems, particularly drainage networks, which often remain inadequate and vulnerable (Shrivastava et al., 2018; Sukanya & Tantia, 2023). Urban flooding and waterlogging are among the most visible and destructive consequences of inadequate drainage systems in developing countries. Climate change projections indicate that, in the near future, stormwater management systems in urban environments will struggle to meet performance expectations, as future climatic conditions deviate significantly from historical patterns and design assumptions (Bibi & Kara, 2023).

Cities in South Asia, such as Kathmandu in Nepal and Mumbai and Chennai in India, face recurring urban flooding during monsoon seasons, as heavy rains overwhelm outdated drainage networks (Pradhan-Salike & Pokharel, 2017). Conventional “grey” infrastructure, comprising underground concrete pipes and storm sewers, has traditionally focused on diverting stormwater quickly to rivers or oceans. While this approach provides short-term relief, it is costly to construct and maintain, environmentally unsustainable, and increasingly inadequate in addressing the escalating intensity of stormwater runoff linked to urban sprawl and climate change (Roozbahani

et al., 2020). Similarly, climate change significantly impacts urban quality of life by altering rainfall patterns and increasing the frequency of extreme hydrological events, such as droughts and floods. Intensified rainfall poses particular risks to highly urbanized areas, where sealed surfaces amplify runoff volumes and peak flows. Existing stormwater drainage systems are often inadequate to handle these increased flows, resulting in urban flooding that threatens infrastructure, property, and public safety (Przestrzelska et al., 2024).

Urbanization degrades land structures through hardened surfaces, reducing infiltration and increasing runoff, which heightens the frequency and severity of urban flooding during rainfall events (D. Liu et al., 2020; Ren et al., 2018). Urban resilience is essential for addressing the challenges posed by rapid urbanization and environmental changes. The present urban population growth trend emphasizes the urgent need for resilient, adaptive, and sustainable urban planning strategies (Kapucu et al., 2024).

The United Nations estimates that over 4.2 billion people currently reside in cities, with urban populations projected to reach nearly 6 billion by 2041 (Kuddus et al., 2020). This rapid growth, coupled with urban sprawl, has intensified environmental challenges such as heightened pollution, biodiversity loss, the urban heat island effect, and depletion of natural resources, all of which threaten ecological balance and urban sustainability (Grzegorzek et al., 2023). The increasing sealing of urban areas reduces infiltration, causing excessive surface runoff. Existing stormwater drainage systems often fail to manage the higher flows, heightening the risk of urban flooding and endangering residents and infrastructure (Ogunkan & Ogunkan, 2025).

Urban flooding has increasingly been recognized as a natural disaster with severe environmental, social, and economic impacts, particularly in cities worldwide. Key contributing factors include rapid urban growth, climate change-induced variations in rainfall intensity, and inadequately designed or insufficient urban drainage systems, which fail to manage excess water effectively, leading to property damage, threats to human life, and environmental degradation (Hassan et al., 2022; M. Wang et al., 2017; Q. Zhou et al., 2019). Urban development with increased impervious surfaces alters hydrology, reduces response time, and heightens flood risk by limiting infiltration and accelerating runoff (J. Wang et al., 2020). Current practices reveal significant gaps, particularly the insufficient integration of climate change mitigation and adaptation measures within infrastructure planning and management (Ahmadi et al., 2025). Urban resilience provides a contemporary approach to enhancing urban sustainability, emphasizing the adaptability, robustness, and interconnectedness of infrastructure systems to withstand social, environmental, and economic challenges (Xie et al., 2020).

Sustainable Urban Drainage Systems (SuDS) mark a paradigm shift in stormwater management, providing holistic, nature-based solutions to address flooding, water quality, and broader urban water challenges (Monachese et al., 2024). Rapid urbanization and escalating climate change impacts create an urgent demand for transformative, sustainable approaches to urban water management, ensuring resilience, efficiency, and long-term environmental protection (Srivastava, 2020). This study addresses the critical question of designing eco-friendly urban drainage through an extensive literature review. The findings of this research are expected to provide not only academic contributions to the fields of sustainable infrastructure and urban resilience but also practical guidelines for policymakers, planners, and engineers working in resource-constrained environments.

METHODS

This study adopts a rigorous literature review to examine the transition from conventional grey drainage systems to eco-friendly urban drainage solutions and their role in enhancing urban resilience and sustainability. A comprehensive review of peer-reviewed journal articles and conference papers was conducted using major academic databases, including Scopus, Web of Science, and Google Scholar. Relevant literature was identified using carefully selected keywords such as “eco-friendly urban drainage,” “Sustainable Urban Drainage Systems (SuDS),” “Low-Impact Development (LID),” “green infrastructure,” “urban flooding,” “climate change adaptation,” and “urban resilience.” The collected studies were systematically screened, evaluated, and analyzed to synthesize existing knowledge and identify key research trends and gaps. Inclusion criteria focused on studies addressing urban stormwater management, nature-based drainage solutions, climate resilience, and ecosystem services. Articles lacking methodological clarity, empirical relevance, or peer-review status were excluded. Key information was systematically extracted, including study objectives, geographic context, methodological approaches, drainage typologies, performance indicators, and reported benefits and limitations. Additionally, articles that were not directly related to urban drainage systems or did not address resilience and sustainability

were excluded to preserve the review's thematic coherence. Together, these inclusion and exclusion criteria ensured that the studies were high-quality and relevant to the objectives of this research.

RESULTS

Urban drainage networks play a vital role in mitigating damage from extreme weather events, particularly as rainfall patterns continue to shift (Monachese et al., 2024). The growing frequency of flood events has resulted in substantial socioeconomic losses and adverse environmental impacts worldwide (Barredo et al., 2012). Urban areas face heightened flood risks due to altered land surfaces and changes in hydrological processes driven by human activities (Guan et al., 2016). During intense rainfall, drainage systems are often overwhelmed, as inflows exceed their designed capacity, resulting in urban flooding (Falconer et al., 2009).

Impact of Climate Change on Urbanization

Climate change significantly impacts urban water systems, increasing runoff and flooding risks (Willems et al., 2012). Studies indicate design intensities may rise 20–80%, creating severe capacity challenges for existing drainage systems designed for fixed return periods (Ekström et al., 2005). Alongside climate pressures, urbanization exacerbates runoff by increasing impervious surfaces, altering land cover, and reducing vegetative areas, raising peak flows and pollution levels (Mailhot & Duchesne, 2010). Rapid economic-driven land modifications, such as replacing natural surfaces with pavements and clearing ponds, further degrade water quality and increase vulnerability to flood hazards, demanding integrated, adaptive, and sustainable urban drainage solutions (Arora & Reddy, 2013).

Sustainable Urban Infrastructure

Sustainability is broadly defined as meeting the needs of the present without compromising the ability of future generations to meet their own needs. It is a multidisciplinary concept spanning engineering, economics, social, and environmental sciences, and forms the basis of the emerging, evolving field of sustainable urban infrastructure research (Ferrer et al., 2018). Urban sustainability extends this principle to cities, emphasizing a balance between social, economic, environmental, cultural, and ecological dimensions. While there is consensus on its importance, approaches to achieving it vary depending on geographic, political, financial, and institutional contexts (Finco & Nijkamp, 2001).

Green Infrastructure

Green infrastructure addresses runoff control, pollutant removal, and carbon storage in urban water systems, yet research remains limited on optimizing facility design, structure, and long-term effectiveness to enhance performance and urban environmental sustainability (Zhu et al., 2025). Green infrastructure promotes smart land conservation through large-scale planning and integrated action. It considers landscapes from parcels to regions, balancing ecological, social, and economic uses to optimize benefits for both nature and people (Grădinaru & Hersperger, 2019). Unlike grey infrastructure, which relies solely on engineered systems, green infrastructure utilizes vegetation, soils, and natural processes to manage water, enhance air quality, and support biodiversity. Eco-friendly drainage, a subset of green infrastructure, provides environmental, economic, and social benefits, aligning development with sustainability by integrating ecological functions into urban growth and resilience strategies (Esra-Zannat et al., 2024).

Urban Resilience

Resilience is a multi-dimensional concept. In engineering, it denotes the ability to absorb disturbances and recover rapidly, while in socio-ecological systems, it reflects the capacity to adapt and achieve a new, desirable equilibrium after disruption (DeCaro et al., 2025). Urban resilience refers to a city's capacity to withstand, adapt to, and recover from shocks and stresses while maintaining essential functions and well-being (Cao, 2023). It involves responding to natural disasters, climate change, economic crises, and infrastructure failures through proactive planning and adaptive strategies (Dahal et al., 2025). By recognizing cities as interconnected systems, urban resilience aims to minimize impacts, enhance recovery, and foster sustainable, inclusive, and long-term urban development (Beilin & Wilkinson, 2015).

Resilience is a key concept in climate change adaptation, describing a city's capacity to withstand, recover from, and adapt to shocks and stresses, particularly those caused by climate change, ensuring long-term urban sustainability (D. Kim & Lim, 2016). Resilience enables cities to maintain development despite climate change, requiring both short-term disaster risk mitigation and long-term capacity-building to respond effectively to systemic transformations and ensure sustainable urban growth and stability (Satterthwaite & Dodman, 2013). Building resilience demands a transformative approach to urban planning and management that addresses growing complexity and uncertainty, enabling cities to adapt effectively to future challenges (Wilkinson et al., 2010). Effective management combines structural measures, such as levees and retention basins, with non-structural approaches, such as zoning, sustainable land use, early warning, and emergency planning (Moon et al., 2024). Utilizing GIS and advanced modeling enhances risk assessment and strategy design, while stakeholder participation ensures inclusive, adaptive, and context-specific flood resilience solutions for sustainable urban development (Bullen & Miles, 2024). Incorporating climate projections, such as changing precipitation, sea-level rise, and storm intensity, enables adaptive, robust flood management, improving both urban resilience and the long-term sustainability and livability of cities. Key elements of urban resilience encompass multiple interrelated dimensions that enable cities to withstand, adapt to, and recover from various shocks and stresses (Cao, 2023). They are:

- **Robust infrastructure:** It is fundamental, requiring well-designed and maintained systems such as resilient transportation networks, reliable energy grids, water and sanitation systems, and communication networks that continue to function effectively during crises (Galasso et al., 2022).
- **Diverse and inclusive communities:** They are equally important, where social cohesion, community engagement, and efforts to address inequalities strengthen support networks, enabling residents to collaborate and assist one another during emergencies (Rijal, 2023).
- **Resource efficiency and sustainability** are essential for urban resilience, enabling cities to reduce their ecological footprint and strengthen their capacity to respond to environmental changes. This involves promoting renewable energy, sustainable transportation, efficient water and waste management, and the development of green spaces (Shamsuddin, 2020).

Ecosystem Services Framework

Rapid urban expansion intensifies pressure on ecosystem services, straining natural resources and reducing cities' capacity to sustain environmental balance (Romero-Duque et al., 2020). Urban regions often lack sufficient green and blue spaces, which are further threatened by rising population density (Gunawardena et al., 2017). Preserving and enhancing green-blue infrastructure (GBI) is vital for mitigating climate change impacts in cities. GBI supports water treatment, reduces runoff, and offers social and psychological benefits. Urban ponds and wetlands, as key GBI elements, significantly sustain hydrological cycles (Kati & Jari, 2016).

- **Regulating services:** Wetlands provide crucial hydrological functions, supporting ecosystem services such as groundwater recharge, nutrient cycling, water purification, erosion control, and sediment regulation (Berlin & Handley, 2007). A key service is flood regulation, where wetlands reduce flood peaks, extend return periods, augment low flows, and moderate runoff. Wetlands act as "nature's age-old method of flood control" due to their capacity for both short- and long-term water storage (Kadykalo & Findlay, 2016).
- **Provisioning services:** Currently, about 47% of the global population experiences water scarcity for at least one month annually, and by 2050, nearly six billion people will face clean water shortages (Rahman, 2021). Climate change exacerbates this crisis by intensifying floods, droughts, salinity, and drainage congestion (Mirza, 2011). Rainwater harvesting (RWH) is increasingly recognized as a sustainable solution. In rural areas, it provides safe drinking water where groundwater is contaminated by arsenic (Alim et al., 2021) or fluoride (Alim et al., 2020). In urban contexts, RWH reduces mains water demand by supplying non-potable uses such as toilet flushing, laundry, and garden irrigation (Santos et al., 2020). It also supports stormwater management, flood mitigation (Jamali et al., 2020), pollutant removal, and aquifer recharge (Huang et al., 2021), contributing to sustainable water security and resilience.
- **Cultural services:** Green roofs and urban wetlands enhance aesthetic value and recreational opportunities (Vourdoubas, 2024). Wetlands are vital biodiversity hotspots, yet they remain among the most endangered ecosystems worldwide (J. Zhou et al., 2020). Their ecological sensitivity and adaptability

foster remarkable diversity, shaped by factors such as origin, location, water and chemical regimes, dominant species, and soil-sediment characteristics, making them crucial for sustaining global ecological balance (Bassi et al., 2014).

- Supporting services: Green infrastructure improves biodiversity and soil health (Buzzard et al., 2021). Soil health refers to the soil's capacity to function as a living ecosystem, supporting vital hydrologic and ecological processes effectively (Yoder et al., 2022). Green infrastructure in agriculture supports agroforestry, conservation buffers, precision farming, and regenerative soil practices, improving soil health, water retention, and biodiversity while reducing microclimatic impacts, fostering sustainable farming systems and long-term environmental resilience (Ogwu & Kosoe, 2025).

Applying the ecosystem services framework ensures that eco-friendly drainage is not viewed narrowly as a flood control measure but as a multifunctional urban system that contributes to overall sustainability (Costadone & Zhang, 2025)

Challenges of the Conventional Urban Drainage System

Urban drainage systems have long served as essential infrastructure for managing stormwater and wastewater (Chocat et al., 2007). However, designing effective systems remains challenging, especially under climate change and urbanization, which increase the frequency and severity of urban flooding, threatening global cities' resilience and sustainability (Huong & Pathirana, 2013). Conventional drainage systems focus on rapidly conveying runoff through sewer networks to nearby water bodies, treating water as a nuisance (Chocat et al., 2007). They are primarily designed for flood prevention, but they often neglect water quality, amenities, and recreational benefits. Researchers have criticized these systems for long-term unsustainability, citing pollution from combined sewer overflows, high environmental disruption, and reliance on costly, rigid structural measures like concrete pipes (Li et al., 2013; Roy et al., 2008). Their fragmented expansion further limits adaptability to changing conditions (Sieker et al., 2008). With climate change and urbanization intensifying flooding and water quality challenges, conventional drainage expansion struggles to meet sustainability criteria, highlighting the need for more resilient, flexible, and environmentally friendly alternatives (Hellström et al., 2000; Pradhan-Salike & Pokharel, 2017).

Eco-Friendly Drainage Systems

Eco-friendly drainage systems, also known as Sustainable Urban Drainage Systems (SuDS), Low-Impact Development (LID), or green stormwater infrastructure, are innovative approaches that mimic natural hydrological processes (Srishantha & Rathnayake, 2017). Unlike conventional drainage focused on quick water removal, eco-friendly systems promote infiltration, evapotranspiration, and decentralized runoff management (Pachouri et al., 2025). Materials like pervious concrete enhance infiltration, swales enable biofiltration and biodiversity, and coconut or natural fibre-reinforced slabs improve durability (Awolusi et al., 2024). Using recycled aggregates conserves resources, lowers emissions, and enhances the sustainability and resilience of urban drainage infrastructure (Bhattarai & Bhattarai, 2023). Together, these sustainable approaches offer cost-effective and environmentally responsible alternatives to conventional drainage systems, thereby fostering resilient urban environments and promoting long-term ecological balance and effective stormwater management (Manickam & Pandulu, 2025). Common examples include:

- Permeable pavements: Permeable pavements enable rainwater infiltration, reducing surface runoff and mitigating flooding (Chinchella et al., 2025). Permeable pavement systems (PPS) play a vital role in managing stormwater runoff, mitigating flooding, and improving water quality by retaining and removing pollutants. Their implementation supports eco-friendly urban environments, enhances green infrastructure, and delivers practical, environmental, and financial benefits, contributing to sustainable and resilient urban ecosystems (Tota-Maharaj et al., 2024).
- Rain gardens and bioswales: Vegetated depressions capture and filter stormwater, reducing runoff and improving water quality. Increasing urbanization and climate change intensify the need for such innovative, nature-based stormwater management solutions (Kõiv-Vainik et al., 2022). Rain gardens, as nature-based solutions, play a vital role in regulating hydrology, improving water quality, and enhancing ecosystem services within urban environments (M. Wang et al., 2024). Rain gardens enhance urban landscapes by integrating ecological, aesthetic, and social functions. They create visually appealing, resilient spaces, improving stormwater management while enriching urban life quality and supporting

sustainable, multifunctional urban environments (Utami et al., 2022). They enhance visual diversity and appeal while improving urban functionality. Through thoughtfully designed layouts and diverse plantings, rain gardens not only manage runoff but also enrich residents' quality of life, providing ecological, social, and visual value to urban landscapes and promoting multifunctional green infrastructure (Pirotti et al., 2022).

- **Green roofs:** Growing awareness of environmental sustainability and human impacts has made eco-friendly practices a key focus for researchers, urban planners, and architects (İnan, 2019). Green roofs, also known as living or vegetated roofs, mitigate the adverse effects of urbanization by integrating vegetation and layered growing media on building rooftops. They enhance stormwater management, regulate temperature, improve air quality, support biodiversity, and elevate urban aesthetics, offering an economical and sustainable solution for environmentally resilient cities (Ismail et al., 2018; Romali et al., 2023). These roofs play a vital role in reducing stormwater runoff by retaining precipitation and facilitating evapotranspiration, while also contributing to cooler indoor temperatures during summer (Gregoire & Clausen, 2011). Essential design inputs include land use, basin conditions, rainfall, and evapotranspiration potential (Versini et al., 2016). Although initial construction costs are high, green roofs prove economical over time, offering both environmental and economic benefits, making them a sustainable solution for urban stormwater management (Oberndorfer et al., 2007).
- **Constructed wetlands:** Engineered ecosystems that store, filter, and gradually release stormwater (Marques & Mandrak, 2024). Constructed wetlands (CWs) are physical structures resembling canals, designed with impermeable bases and populated by wetland plants (Vymazal, 2022). CW systems may include filter media that provide a suitable environment for plant growth. Macrophytes and other plants in CWs transfer oxygen to the substrate, support microbial growth around roots, and facilitate wastewater decomposition (Kataki et al., 2021). By combining physical, chemical, and biological processes, CWs effectively treat wastewater, enhance nutrient removal, and promote ecological balance, making them a sustainable and nature-based solution for urban and rural water management (Majid et al., 2025). CWs offer sustainable, low-cost water treatment while enhancing aesthetics. Using filters like sand, corals, or membranes, they capture particles, support microbial decomposition, and enable effective purification based on wastewater characteristics and reuse goals (Sombei et al., 2025). This cost-effective, technically feasible approach effectively treats polluted water, integrating physical, chemical, and biological processes to promote ecological balance and provide an efficient solution for urban and rural wastewater management (Fuentes-López et al., 2018).
- **Rainwater harvesting systems:** Rainwater harvesting systems capture and store rainwater for domestic or industrial use (García-Ávila et al., 2023). In addition to flood prevention, these systems contribute to groundwater recharge, reduce urban heat islands, and improve air quality, making them highly suitable for climate adaptation strategies in developing countries (Faiz et al., 2024). The eco-friendly rainwater detention system proved structurally safe, meeting strength standards, with no heavy metals or organic compounds detected in leaching tests. It poses no risk to soil or groundwater. It is economically feasible, with construction and life cycle costs approximately 30% and 58% lower than conventional polyethylene infiltration tanks, demonstrating enhanced safety, environmental friendliness, and cost-effectiveness, indicating its potential as a superior alternative for field applications (H. Kim et al., 2022). Rainwater harvesting addresses rising water demand while reducing stormwater runoff, flood risks, soil erosion, and groundwater depletion (Rahaman et al., 2019). It improves water quality and storage, offering a simple, economical, and eco-friendly solution where surface or groundwater is limited (Pala et al., 2021).

Climate Change Adaptation

In today's interconnected world, climate change amplifies risks, as sustainable development relies on delicate interactions that can be disrupted by the unintended consequences of development activities (Ogwu, 2019). Global climate change increases the frequency of extreme events, making it urgent for cities to strengthen adaptation measures to protect infrastructure, communities, and ecosystems from escalating climate-related risks (Pei et al., 2022). "Climate change response strategies have evolved from prevention and mitigation in the 1970s, through mitigation focus in the 1980s, to adaptation, which is now widely recognized as essential for resilience.

Originating in ecology, adaptation is now central to climate research and global change science.” (Doria et al., 2009; O’Brien, 2012).

Low-Impact Development (LID)

LID practices offer a nature-based solution to stormwater challenges by replicating natural hydrological processes (T. Liu et al., 2021). They reduce peak runoff, enhance infiltration, and retain stormwater through interventions like permeable pavements, bio-retention cells, green roofs, and rain gardens, collectively minimizing flood risks, improving water quality, and promoting sustainable urban water management (Fletcher et al., 2015). LID techniques reduce impervious surfaces, encourage natural infiltration, and integrate water management with landscaping (Ghodsai et al., 2020). Originally popularized in the United States, LID principles are increasingly applied in Asia and Africa, where they are adapted to local contexts with limited resources (Sehrawat & Shekhar, 2025). While LID techniques are effective under normal conditions, their efficiency decreases during extreme rainfall due to excess runoff (Pour et al., 2020). Enhancing resilience requires integrating green infrastructure retrofitting, dynamic stormwater management, and hybrid drainage solutions (Dong et al., 2017). Retrofitting with vegetated swales and green streets improves infiltration, while smart retention basins with real-time sensors optimize water storage (Zhu, 2024). Additionally, mitigating the urban heat island effect through cool roofs and reflective pavements reduces surface runoff and enhances stormwater absorption in dense urban areas (Kumar et al., 2024).

Sustainable practice in urban areas

Sustainable urban practices are crucial for tackling challenges posed by rapid urbanization, climate change, and resource depletion (James, 2024). With over half the global population living in cities, adopting sustainable development strategies is increasingly vital for environmental protection, resource efficiency, and resilient urban growth. It ensures the efficient use of vital resources such as water, energy, and materials (Chandratreya, 2024). By reducing waste and promoting resource recovery, cities can minimize their ecological footprint while strengthening resilience against resource scarcity (Zarei, 2020). Adopting sustainable practices helps protect natural ecosystems, enhance biodiversity, and improve air and water quality (H.-Y. Liu et al., 2021). Initiatives like urban forests and green roofs absorb stormwater, filter pollutants, and create habitats for wildlife (Tzoulas et al., 2007). Sustainable infrastructure investments bring long-term economic advantages (Meng et al., 2024). Cities benefit from higher property values, reduced energy costs, and improved public health, all of which contribute to stronger, more resilient local economies (Haughton & Hunter, 2004). Sustainable urban development prioritizes equity, ensuring that all residents have access to essential services, green spaces, and healthy environments (Dsouza et al., 2023). This inclusive approach fosters community engagement and enhances quality of life (De Haas et al., 2021). Integrating climate resilience into urban planning helps cities adapt to extreme weather events and rising sea levels (Ugah et al., 2025). These practices reduce vulnerabilities and enhance metropolitan areas' ability to withstand future challenges (Emekci, 2024). Furthermore, sustainable urban practices promote healthier lifestyles by encouraging active transportation, reducing pollution, and ensuring access to green spaces (Dmitrović et al., 2025).

Future Directions and Adoptive Strategies

Water supply and sewage systems are vital components of urban infrastructure, delivering essential services (Asghari et al., 2023). Yet, climate change and urban flooding increase their vulnerability, posing significant challenges to the reliability, efficiency, and resilience of urban water management and threatening community well-being (Nipa & Kermanshachi, 2020). Urban flooding threatens sewage systems, with heavy rainfall, storm surges, and poor drainage causing sewage plant inundation and combined sewer overflows, compromising infrastructure and increasing contamination risks, which pose serious public health hazards (Hou et al., 2021).

Along with rapid urbanization, the growth of impervious surfaces, such as roads, buildings, and parking areas, amplifies stormwater runoff, increases flood risks, and highlights the urgent need for resilient and sustainable urban drainage solutions (Bartos & Kerkez, 2021; Shaibu et al., 2025). Growing urbanization, climate change, and escalating pressure on natural resources make sustainable urban water management critical (Shah et al., 2025). Ensuring a reliable water supply demands integrated approaches that optimize water use, improve efficiency, and address challenges across the entire water cycle for long-term urban resilience and sustainability (Shaibu et al.,

2025). Rapid urbanization and climate change intensify the need for innovative urban water management approaches, ensuring resilient, efficient, and sustainable water systems for growing cities (Siddique, 2021). Urban expansion and growing populations intensify flooding and water pollution (Miller & Hutchins, 2017). Increased hardened surfaces from urbanization degrade land structure, reducing infiltration and drainage, which elevates the risk and frequency of urban flooding during rainfall events (D. Liu et al., 2020; Ren et al., 2018).

Traditional urban drainage systems struggle to cope with extreme rainfall and rapid urbanization, leading to flooding and water pollution. Innovative solutions are essential to enhance their efficiency, resilience, and sustainability, ensuring safer and more environmentally responsible urban water management (Harahap et al., 2024). Prioritizing green infrastructure in underserved communities helps cities reduce historical disparities in green space and water access, improve environmental quality, and promote social equity, fostering healthier, more inclusive, and sustainable urban environments (Noe et al., 2020). Integrated Urban Water Management (IUWM) models are essential for informed decision-making in complex urban water systems, linking stormwater, wastewater, and drinking water sectors (Mosleh & Negahban-Azar, 2021).

Sustainable Urban Drainage Systems (SUDS) provide integrated solutions for managing urban stormwater by replicating natural hydrological processes to reduce flooding, improve water quality, and support ecosystems (Butler et al., 2008). By combining features such as permeable pavements, green roofs, and rain gardens, they adapt to local conditions (Almeida et al., 2023). Despite proven benefits, adoption faces challenges such as limited awareness, high costs, and regulatory barriers (Çaldağ & Gökalp, 2025). Strengthening collaboration, policy support, and research on long-term performance and socio-economic impacts is vital for enhancing urban resilience and sustainability (Monachese et al., 2024). Participatory governance is a key pillar of urban resilience and sustainability, fostering inclusive decision-making and community engagement in city planning and management (Renn & Klinke, 2013). A participatory approach fosters stakeholder collaboration, ensuring local needs and priorities are effectively addressed for sustainable and inclusive urban planning (Kapucu, 2006).

Existing drainage systems could not handle increased inundation in simulated scenarios, leaving the city vulnerable to flooding and damage to property and infrastructure. Implemented LIDs reduced peak runoff, flood magnitude, and flooded junctions under urbanization and climate change, while combining mitigation measures offered greater overall flood reduction (Bibi & Kara, 2023). Climate change is projected to significantly impact urban hydrological processes, with peak stormwater runoff and flooding volumes expected to rise substantially throughout the 21st century, intensifying urban water management challenges (Mohammed et al., 2021; Willems et al., 2012). Implementing multiple LID types is essential to mitigate flood risks, especially in heavily impacted urban areas (Binesh et al., 2019). However, resilient systems like LIDs alone cannot fully mitigate inundation without proper drainage infrastructure; hence, urban drainage systems must be redesigned to address the compounded impacts of rapid urbanization and climate change (Jenkins et al., 2017). To address the challenges of conventional drainage systems, eco-friendly or nature-based approaches offer a promising alternative (Soni et al., 2025). Often referred to as SuDS, Low-LID, or green infrastructure, these systems mimic natural hydrological processes by slowing, storing, and infiltrating stormwater at or near its source (Chen & Chui, 2025). This system includes rain gardens, permeable pavements, green roofs, and constructed wetlands, which reduce flood risks while providing co-benefits such as groundwater recharge, improved water quality, urban cooling, and enhanced biodiversity (Palermo et al., 2023). Among these, bioretention systems, permeable pavements, green roofs, swales, and constructed wetlands are the most widely implemented and scalable worldwide (Dutta et al., 2021). Furthermore, smart SuDS, enhanced with IoT sensors, adaptive controls, and real-time monitoring, improve efficiency, adaptability, and scalability, enabling advanced, data-driven urban water management solutions (Allende-Prieto et al., 2024).

Urban resilience studies emphasize diverse, interdisciplinary approaches that actively engage communities. A key focus is fostering collaborative networks and multi-stakeholder partnerships, recognized as essential for building adaptive, inclusive, and robust urban systems capable of responding effectively to social, environmental, and infrastructural challenges (Zeng et al., 2022). Green infrastructure offers a sustainable solution to climate change and urban flooding. By integrating permeable surfaces, green roofs, and strategically placed urban green spaces, stormwater runoff is managed effectively, enhancing water absorption, reducing flood risks, and providing natural buffers to protect urban areas (Dharmarathne et al., 2024).

DISCUSSION

Adaptation Strategies for Sustainable Urban Drainage System Management

Infrastructure Modifications for Climate Resilience

Urban infrastructure is highly vulnerable to climate change, particularly to urban flooding (Mishra & Sadhu, 2023). Enhancing resilience requires strategic modifications to critical facilities, including elevating foundations above anticipated flood levels to maintain operational continuity (Keller, 2025; Tirpak et al., 2021). Complementing these strategies, green infrastructure offers a sustainable solution by incorporating permeable surfaces, green roofs, and urban green spaces (Mihalakakou et al., 2023). These features absorb stormwater, manage runoff, and act as natural buffers, collectively reducing flood risks and enhancing urban climate resilience while supporting environmental sustainability (Dharmarathne et al., 2024).

Community Involvement

Community involvement is essential for achieving comprehensive urban resilience (Khotimah et al., 2025). Engaging local populations helps identify unique challenges, ensures decision-making reflects diverse needs, and enables the development of tailored, effective solutions that enhance social, environmental, and infrastructural resilience (Kapucu et al., 2021). Achieving transdimensional urban resilience requires engaging diverse stakeholders, including government, the private sector, community groups, and academia. Collaboration ensures coordinated efforts toward common goals, addresses disparities affecting vulnerable populations, and integrates interdisciplinary and participatory perspectives (Kapucu et al., 2024).

Green Infrastructure and Sustainable Urban Planning

Developing climate-resilient cities requires environmentally friendly infrastructure and sustainable urban planning (Bica & Tucan, 2021). Key strategies include avoiding construction in flood-prone areas, preserving natural drainage, adopting mixed-use zoning, promoting compact design, and prioritizing public transportation to reduce emissions and urban heat islands (Dharmarathne et al., 2024). Green roofs absorb stormwater and provide shade, while permeable surfaces allow rainwater infiltration, easing drainage strain (Akter & Rain, 2025). Strategically placed urban green spaces, such as parks and gardens, act as natural flood buffers, enhance aesthetics, and support resident well-being (Foster et al., 2011). Urban resilience focuses on ecological preservation, economic stability and diversification, and robust infrastructure, enabling cities to protect themselves and respond effectively to emergencies (Meerow et al., 2016).

Integrating Smart Technologies

Integrating smart technologies, such as IoT, for real-time monitoring optimizes resource use, reduces operational inefficiencies, and enables more efficient, responsive, and sustainable management of urban water systems. To address challenges like resource scarcity, urbanization, environmental degradation, and climate change, sustainable infrastructure is essential, emphasizing social justice, economic viability, environmental stewardship, and resilience against shocks and disruptions (Kapucu et al., 2024).

Sustainable infrastructure requires a holistic approach, balancing environmental, social, and economic factors throughout its lifecycle from planning and construction to operation, maintenance, and recycling (Firoozi et al., 2025). Recent years have seen increased focus on linking infrastructure development with sustainability goals (Popescu et al., 2023). Governments, institutions, and communities prioritize investments to reduce emissions, improve energy efficiency, advance social equity, and build climate-resilient communities, driven by awareness, incentives, technology, and the push for a low-carbon, resource-efficient economy (Awasthi et al., 2024). Raising public environmental awareness is vital to ensuring a clean, healthy environment. Green infrastructure effectively addresses urban challenges, including improving air quality, managing stormwater, and reducing urban heat. Unlike traditional gray infrastructure, which relies on concrete and pipes, it harnesses vegetation and natural processes to deliver multiple benefits. By mitigating stormwater runoff that carries pollutants and sediments, green infrastructure protects water quality, enhances ecosystem health, and promotes sustainable urban development for resilient and livable cities (Rodrigues et al., 2023).

Major Findings

The review highlights that rapid urbanization and climate change have significantly intensified stormwater management challenges, particularly in developing cities where outdated drainage systems exacerbate flooding and waterlogging risks. Conventional “grey” infrastructure focused on rapid stormwater conveyance through pipes and sewers has proven costly, environmentally unsustainable, and inadequate under changing rainfall patterns. In contrast, SuDS, LID, and eco-friendly drainage approaches offer resilient, cost-effective, and nature-based alternatives that mimic natural hydrological processes.

Green infrastructure, including permeable pavements, rain gardens, green roofs, constructed wetlands, and rainwater harvesting systems, effectively reduces surface runoff, enhances infiltration, improves water quality, and promotes biodiversity. These systems also deliver co-benefits such as groundwater recharge, carbon sequestration, microclimate regulation, and enhanced urban aesthetics. The integration of ecological design into urban development supports multifunctional urban systems, thereby improving environmental performance and livability.

The study emphasizes the role of the ecosystem services framework, which broadens the perception of urban drainage from mere flood control to a multifunctional system contributing to sustainability, health, and well-being. Regulating, provisioning, cultural, and supporting services derived from green-blue infrastructure strengthen cities’ adaptive capacity and ecological resilience. Additionally, integrating smart technologies such as IoT-based monitoring and adaptive control enhances the efficiency and responsiveness of SuDS under dynamic climate conditions.

Urban resilience requires a holistic approach combining robust infrastructure, resource efficiency, and inclusive governance. Community engagement, policy support, and interdisciplinary collaboration are critical for successful implementation. Future strategies should prioritize green retrofitting, climate-responsive planning, and hybrid drainage solutions that combine traditional and nature-based systems. Overall, adopting eco-friendly, adaptive, and participatory drainage management can transform cities into resilient, sustainable, and environmentally balanced urban systems.

CONCLUSION

Urban water and drainage systems are increasingly vulnerable to the compounded impacts of climate change and rapid urbanization, which exacerbate flooding, water pollution, and public health risks. Traditional drainage infrastructure, designed for historical rainfall patterns, struggles to cope with extreme precipitation and the expansion of impervious surfaces, leading to reduced infiltration and increased runoff. SuDS and LIDs offer innovative, nature-based alternatives that replicate natural hydrological processes to mitigate floods, enhance water quality, and restore urban ecosystems. IUWM frameworks further strengthen urban resilience by linking stormwater, wastewater, and potable water sectors to optimize efficiency and sustainability. However, limited awareness, regulatory barriers, and high implementation costs hinder widespread adoption. Strengthening policy frameworks, promoting participatory governance, and integrating smart technologies such as IoT-based monitoring can enhance system performance and sustainability. Policymakers must prioritize green infrastructure investment, ensure equitable access in underserved areas, and foster interdisciplinary collaboration among governments, researchers, and communities. Future directions should focus on long-term performance evaluation, socio-economic impact assessment, and adaptive design approaches that harmonize ecological preservation, social equity, and technological innovation to build resilient, sustainable, and inclusive urban water systems.

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