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Performance Evaluation of Urban Storm-Water Drainage System Under Extreme Rainfall: A Systematic Review

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Abstract

Urban storm-water drainage systems (USDS) face new challenges associated with the intensification of rainfall extremes because of climate change and urbanization. This systematic review evaluates the efficiency of traditional and innovative storm-water management systems under conditions of rainfall extremes based on the evidence from 25 peer-reviewed studies and case studies published from 2000 to 2026. The methodology used in this review is aligned with the PRISMA guidelines and involves systematic literature searches in the following databases: ScienceDirect, Web of Science, PubMed, Google Scholar, and specialized databases. Major findings include the inefficiency of conventional grey infrastructure built under stationary climate assumptions because of the forecasted rainfall intensification by 20-80%, which outmatches the design capabilities. Green infrastructure (e.g., rain gardens, permeable pavements, sustainable urban drainage systems) demonstrates strong performance with regard to runoff reduction (15-50%) and peak flow reduction, however, it faces scalability and maintenance problems. The integration of artificial intelligence (AI) and green infrastructure is identified as a revolutionary approach, allowing for real-time adaptive management and predictive optimization. Comparing conventional and hybrid drainage systems allows identifying that hybrid systems provide 18% of cost reduction and 50% lower detention volume. The case studies (examples of implementation of hybrid drainage systems) from Malmö, New York City, Ann Arbor, and Changsha are discussed in details. Nevertheless, there is still a considerable gap in the literature concerning standard performance evaluation metrics, long-term maintenance guidelines, and the integration of the non-stationary climate into the design criteria. This review provides recommendations for urban planners and researchers to improve the performance of storm-water systems in the changing climate conditions.

Keywords: Urban storm-water drainage systems; extreme rainfall; climate change adaptation; green infrastructure; artificial intelligence;

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1. Introduction

Storm-water management has been identified as one of the most prominent infrastructure problems of the 21st century, which combines climate change, rapid urbanization, and the deterioration of drainage systems. Intensification of rainfall extremes as a consequence of climate change generates sharper hydrograph peaks, mobilizing the contamination and overwhelming the drainage systems that were designed in the era of the stationary climate (Intergovernmental Panel on Climate Change (IPCC), 2023). As it is noted by the IPCC (2023), the short-duration rainfall extremes are projected to increase in most regions that have significant consequences for the urban flood risk management and public safety (National Academies of Sciences, Engineering, and Medicine, 2019).

The following figure shows a chart showing the impact of climate change to the need for adaptive and sustainable solutions

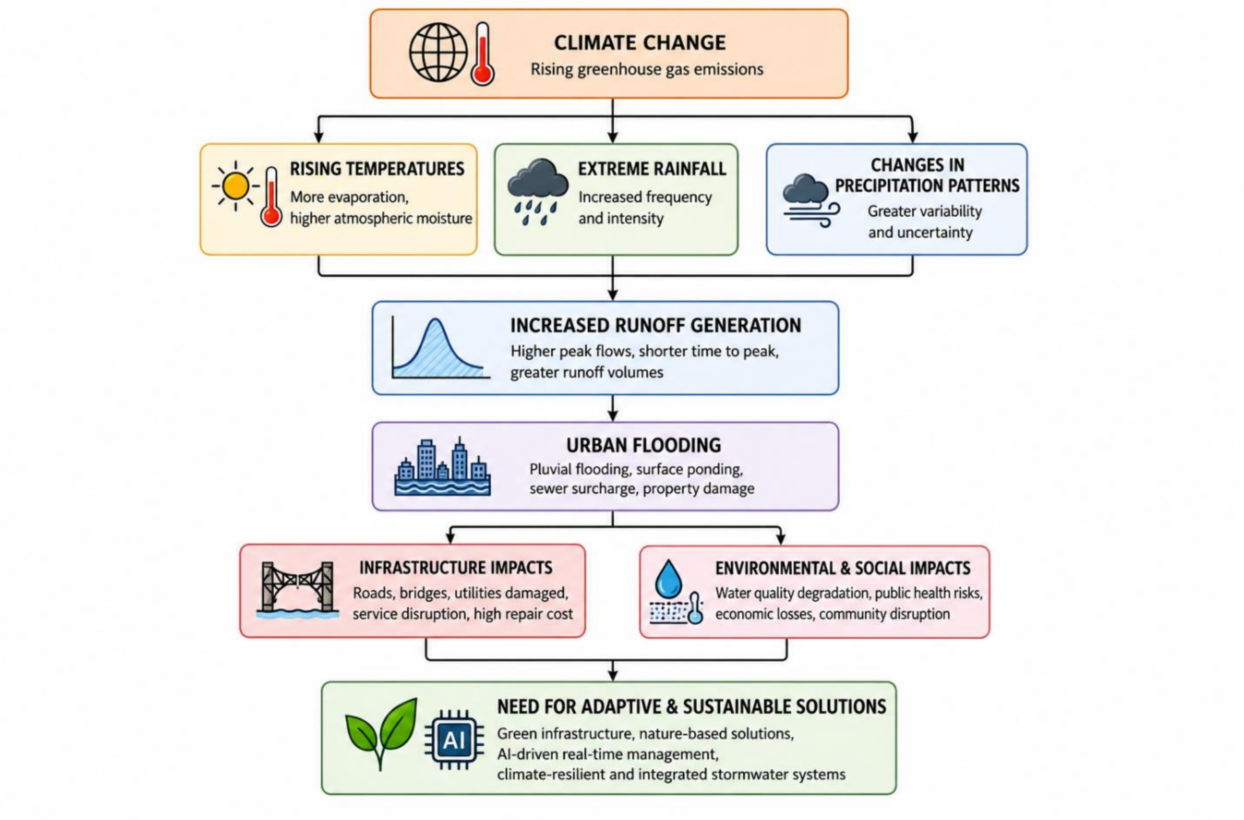

Figure 1: Climate Change → Urban Flooding Conceptual Framework

Urban storm-water drainage systems (USDS) are municipal infrastructures that should rapidly collect runoff and ensure efficient surface drainage with the aim of decreasing urban flood risks (Butler, Digman, Makropoulos, & Davies, 2018). However, the effectiveness of traditional USDS designed according to historical intensity-duration-frequency (IDF) curves is currently questioned due to the climate change (Zhou, Leng, Su, & Ren, 2021). The intensification of rainfall extremes and the precipitation variability surpass the capabilities of existing systems resulting in pluvial flooding, with adverse consequences, such as transportation disruption, economic damage, and secondary disasters that threat public safety (National Academies of Sciences, Engineering, and Medicine, 2019).

Fast urbanization in China resulted in the increased exposure to flood hazards. There has been a 13.39% reduction in the urban flood regulation service since 1977 until 2018 (Luo & Zhang, 2021). The expansion of the urban area changes the landscape that influences the hydrological cycle with the removal of vegetation and soil compaction, thus raising flood risk due to the increased surface runoff and decreased infiltration. At the same time, the climate change increases the urban flood risk because of the significant shifts in precipitation regimes and the increase in the frequency and intensity of extreme events (Intergovernmental Panel on Climate Change (IPCC), 2023).

Traditionally, the storm-water management was associated with grey infrastructure – networks of pipes, channels, and detention basins, which aimed at water collection (Butler, Digman, Makropoulos, & Davies, 2018). These systems are efficient in the water removal, however, they ignore the sustainability aspect and fail to capture storm-water as a resource (Wong & Brown, 2009). The fast drainage typical for the traditional systems decreases surface collection time and can result in increased downstream flooding (Fletcher, Andrieu, & Hamel, 2013).

Green infrastructure (GI) represents a new approach to the storm-water management (United States Environmental Protection Agency (EPA), 2021). The GI, which includes rain gardens, permeable pavements, green roofs, and bioretention systems, imitates the natural hydrological process with the goal to reduce the runoff volume, increase infiltration, and improve the water quality (Fletcher, Andrieu, & Hamel, 2013). Nonetheless, the implementation of the green infrastructure is associated with certain problems of scalability, maintenance, and the cost, which limits its wide-scale use in the urban environment (United States Environmental Protection Agency (EPA), 2024).

The integration of artificial intelligence (AI) with the green and grey infrastructure represents a new adaptive approach to the storm-water management. The AI can transform the existing approaches with help of the tools, such as the U.S. Environmental Protection Agency's (EPA's) Storm-water Management Model (SWMM) (Rossman, 2022), machine learning algorithms, and real-time control system that can be used to design, predict flooding scenarios and manage storm-water dynamically (Kerkez, Glaser, Bales, & Meadows, 2016); (Abdel-Aal, Elshorbagy, & Soliman, 2024). Although there is an abundance of research on GI and AI independently, their integration has not been explored in storm-water management literature (Mullapudi, Wong, & Kerkez, 2020).

This systematic review aims at closing the gap in the literature by providing a comprehensive framework of performance evaluation of storm-water systems under the conditions of rainfall extremes. Although some studies have evaluated certain technologies or specific case studies in the past, it is important to develop an overall comparison of conventional, green, and hybrid systems according to some standardized performance metrics (Chang, Franczyk, & Kim, 2021). In this systematic review, peer-reviewed studies, government reports, and case studies will be reviewed in order to identify the performance of

USDS under extreme rainfall, best practices and research priorities to enhance the urban flood resilience.

2. Methodology of the Systematic Review

The systematic review was conducted according to the guidelines of the Cochrane Handbook for Systematic Reviews of Interventions (Higgins et al., 2019) and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). According to the Cochrane Handbook, systematic review is defined as an identification and synthesis of all empirical evidence that meets the predetermined criteria to answer a certain question. It implies having well-defined objectives, eligibility criteria, reproducible methodology, comprehensive searches, validity assessment of the studies, and systematic synthesis of results (Higgins et al., 2019).

The following figure shows the PRISMA flow diagram for the systematic review methodology used.

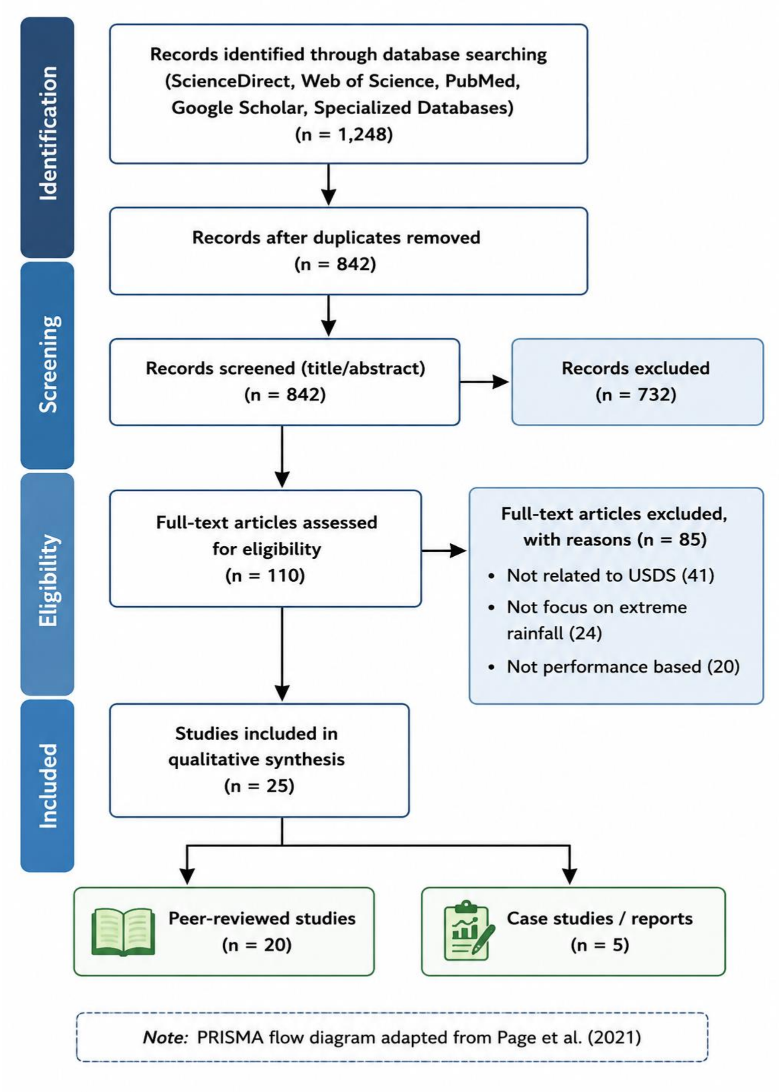

Figure 2: PRISMA Flow Diagram

The research question was formulated using the PICO framework (Higgins et al., 2019): How do urban storm-water drainage systems (conventional, green, hybrid, and AI-integrated) perform under extreme rainfall events in terms of flood mitigation, cost-effectiveness, and resilience across different urban contexts and climate scenarios?

A comprehensive search has been conducted in multiple databases and specialized sources to ensure broad coverage. The following databases have been searched:

- Primary Academic Databases: ScienceDirect, Web of Science Core Collection, PubMed Central, Google Scholar, Scopus

- Specialized Systematic Review Registries and Databases: PROSPERO, Campbell Collaboration, EPPI-Centre, DoPHER

- Specialized Storm-water and Climate Resources: SRDR (AHRQ), What Works Clearinghouse, Climate-ADAPT (European Environment Agency, 2024)

Inclusion and Exclusion Criteria were also considered as part of the systematic review.

The Inclusion Criteria involved: publications from 2000 till 2026; peer-reviewed articles, conference papers, government reports, and documented case studies; studies on urban storm-water management in urban or peri-urban catchments; reports on performance metrics (flood mitigation, runoff reduction, water quality improvement, cost-effectiveness); consideration of extreme rainfall events, climate change scenarios, or non-stationary climate; English-language publications or those with comprehensive English translation

The Exclusion Criteria involved: rural or agricultural drainage studies; opinion articles, editorials, or commentaries; lack of quantitative performance metrics; duplicate publications reporting the same data.

Although the review prioritized high-impact peer-reviewed literature, relying solely on academic literature can cause missing valuable information found in the grey literature, such as technical white papers, municipal reports, non-English publications (Higgins et al., 2019). Inclusion of such materials in future reviews can reveal new challenges and opportunities in the field of storm-water management. Moreover, heterogeneity of the study design, metrics, and reporting standards across the included studies limits the feasibility of meta-analysis.

3. Challenges, Barriers, and Research Gaps

Although the integration of the storm-water management has great potential, some barriers prevent its implementation. One of the main barriers is the interoperability of AI systems and green infrastructure. Current technologies lack standardized protocols of integration of AI-driven systems with green infrastructure, such as rain gardens or permeable pavements (Kerkez, Glaser, Bales, & Meadows, 2016); (Abdel-Aal, Elshorbagy, & Soliman, 2024). Besides, many AI solutions require a lot of data for their proper functioning, which is unavailable in regions with the low availability of monitoring or sensor network (Mullapudi, Wong, & Kerkez, 2020). The complex and computationally demanding nature of AI systems also acts as a barrier to its adoption, especially for municipalities with limited resources.

The use of AI technologies and the construction of green infrastructure is associated with high initial costs. Implementation of the AI system usually requires investment in computing resources, sensors, and skilled employees (Kerkez, Glaser, Bales, & Meadows, 2016). The installation of green infrastructure, such as permeable pavements or green roofs, is expensive and unaffordable, especially in resource-constrained environments (United States Environmental Protection Agency (EPA), 2021). Maintaining the balance between cost-effectiveness and sustainability is a continuous problem for urban planners (Wong & Brown, 2009). The maintenance costs of sustainable drainage systems are approximately twice higher than the costs of conventional sewer systems (Malmö Stad, 2018). Open storm-water systems can accumulate trash and canals need maintenance. Costs may also incur from granite block destruction. However, good drainage can save from the flood damages thus making economic sense (Malmö Stad, 2018).

The maintenance of green infrastructure is essential for its functioning (United States Environmental Protection Agency (EPA), 2021). The integration of AI adds the complexity to the maintenance of hybrid systems, thus putting pressure on the resources (Rafiei Emam & Mishra, 2021). Maintenance routines, such as vacuum sweeping of permeable pavements and media rejuvenation in bioretention are frequently identified as major controls of performance, however, there is a significant lack of consistency in the maintenance reporting, thus preventing performance transfer across climate and urban development (Fletcher, Andrieu, & Hamel, 2013).

There were some critical gaps in the literature need to be filled that include:

- Standardized performance metrics: The absence of performance metrics that can be applied in different contexts hinders the comparability and evidence-based decision-making (Chang, Franczyk, & Kim, 2021).

- Non-stationary design framework: The integration of the non-stationary rainfall into the design storms and continuous simulations is inconsistent; many assets are sized according to mean and not peak-dominated regimes (Zhou, Leng, Su, & Ren, 2021).

- Long-term performance monitoring: The high-frequency monitoring to capture peaks and first-flush is necessary, however, sub-hourly autosamplers and in-situ sensors are rarely used, thus limiting the first-flush and peak estimations (Kerkez, Glaser, Bales, & Meadows, 2016).

- Public health risks integration: Although short-duration rainfall intensification causes hydraulic challenges, comprehensive studies that link storm-water quality dynamics with health risks are limited (National Academies of Sciences, Engineering, and Medicine, 2019).

- Climate-resilient design standards: The development and implementation of non-stationary IDF curves and climate-resilient design standards are urgent; studies showed that design intensities may need to be increased by 20-80% to account for the climate change (Zhou, Leng, Su, & Ren, 2021).

- Multi-objective optimization: The research on the optimization of green infrastructure facilities in terms of size, placement, and interconnections is needed; current studies focus only on the spatial coverage (United States Environmental Protection Agency (EPA), 2024).

4. Understanding Extreme Rainfall Events and Climate Change Impacts

The short-duration rainfall extremes represent the greatest challenge to the urban drainage systems (Intergovernmental Panel on Climate Change (IPCC), 2023). The intensification of rainfall results in the sharper hydrograph peaks that mobilize contaminations early in the storm, thus shifting the risks from chronic to episodic (Fletcher, Andrieu, & Hamel, 2013). The update of IDF methods consistently indicated the increase in the sub-hourly intensity that governs first-flush pollutant export (Zhou, Leng, Su, & Ren, 2021). The non-stationarity of rainfall statistics undermines the validity of the historical design assumptions for flood and water-quality protection (Butler, Digman, Makropoulos, & Davies, 2018). Non-stationarity may lead to the invalidation of stationary IDF curves derived from historical data (Zhou, Leng, Su, & Ren, 2021).

The climate projections suggest the increase in the frequency and intensity of the rainfall extremes because of the climate change (Intergovernmental Panel on Climate Change (IPCC), 2023). In a study on urban drainage challenges in South-Central China, (Bao, Wang, Li, & Chen, 2025) predicted the 32% increase in 24-hour rainfall depth for the 200-year return period in the period from 2040s to 2060s under RCP8.5. However, this intensification is not uniform for different return periods. Short-return-period rainfall extremes (2-10 years) have little change, while long-return-period rainfall extremes (≥20 years) experience significant increase. This difference shows that thermodynamically-driven extreme convection, highly responsive to the atmospheric warming, dominates rare and intense rainfall extremes (Intergovernmental Panel on Climate Change (IPCC), 2023).

This intensification is consistent with the global trends. For instance, (Rosenberg, et al., 2010) found that a 50-year return period rainfall in Washington State intensified by 37% within 25 years and became an 8.4-year rainfall event. Similarly, (He, Zhang, Liu, & Wang, 2022) projected that the 100-year floods could become 5- or 10-year events in the Yellow River basins in case of 4 degrees warming.

The following table shows projected changes in extreme rainfall intensity under climate change scenarios

Table 1: Projected Changes in Extreme Rainfall Intensity Under Climate Change Scenarios

Region	Return Period	Historical Intensity (mm/h)	Projected Intensity (mm/h)	Timeframe	Scenario	Source
South-Central China	200-year	Baseline	+32% increase	2040s-2060s	RCP8.5	(Bao, Wang, Li, & Chen, 2025)
Washington State	50-year	Baseline	+37% (became 8.4-year event)	25-year period	Historical	(Rosenberg, et al., 2010)

Yellow River Basin	100-year	Baseline	Equivalent to 5-10 year event	4°C warming	Projected	(He, Zhang, Liu, & Wang, 2022)
Sweden (Southern)	Annual	Baseline	+15-20%	End of century	RCP8.5	Climate-ADAPT
China (National)	Design rainfall	Baseline	+20-80% required increase	Future	Climate-adjusted	Zhou et al. (2021)

Source: Author

Urbanization amplifies flood risk through several factors. Rapid conversion of porous soils to impervious surfaces disturbs hydrologic cycles through the loss of vegetation and compaction of the soil (Fletcher, Andrieu, & Hamel, 2013) resulting in increased flood risk through higher surface runoff, decreased infiltration and shorter concentration times (Butler, Digman, Makropoulos, & Davies, 2018). (Luo & Zhang, 2021) report 13.39% decrease in China's flood regulation ecosystem service from 1977 to 2018 due to changes in land use, which signals increased flood risk. Combined effect of urbanization and climate change forms compound risk which is larger than the sum of the individual risks (National Academies of Sciences, Engineering, and Medicine, 2019). Urban sprawl affects the pattern of land use with a growth in construction land in many Chinese cities of 3.2% annually since 2010 and reduction of peri-urban green spaces and agricultural lands of 15-20% (Luo & Zhang, 2021). Changes in land use contribute to amplifying volumes of surface runoff and flood peaks beyond those predicted only taking into account climate factors.

Coinciding with the increase in rainfall, urbanization calls for reconsideration of the conventional approach to designing urban storm-water drainage systems (USDS), as current practices rely on stationary design IDF curves (Zhou, Leng, Su, & Ren, 2021). Recent research shows that there may be a need to increase design intensities by 20-80% across China taking into account climate change (Zhou, Leng, Su, & Ren, 2021) with huge infrastructure investments needed as drainage systems developed based on historical rainfalls become increasingly inefficient. Hydraulic modeling proves direct transition of increased rainfall intensity to increased flood risks. For a 100-year event in a South-Central China watershed, (Bao, Wang, Li, & Chen, 2025) demonstrate that the area where ponding depth is expected to exceed 300-500 mm grows by 21% and the area corresponding to the most severe floods (ponding depth of >500 mm) increases from 1.38% to 1.62% of the watershed. From climate forcing to hydrologic impacts, the process highlights the principal danger the increased precipitation poses for current urban drainage systems (Intergovernmental Panel on Climate Change (IPCC), 2023).

5. Performance Assessment of Conventional Storm-water Drainage Systems

Current USDS are usually designed to collect storm-water runoff in the shortest possible way and carry it away to receive waters in order to avoid flooding (Butler, Digman, Makropoulos, & Davies, 2018). The systems consist of networks of pipes, pits, detention basins which are developed using historical IDF curves. According to Wong and Brown (2009), conventional drainage systems offer no possibilities to preserve storm-water as a resource because the main purpose of the systems is to get rid of runoff as quickly as possible.

First, there is a major limitation in terms of the assumption of USDS stationarity. The current design is based on rainfall characteristics over a certain period ignoring time changes in rainfall and assuming hydrological variables are stationary (Zhou, Leng, Su, & Ren, 2021), which becomes increasingly irrelevant under the climate change scenario since numerous studies show trends in extreme rainfall intensity (Intergovernmental Panel on Climate Change (IPCC), 2023); (Rosenberg, et al., 2010).

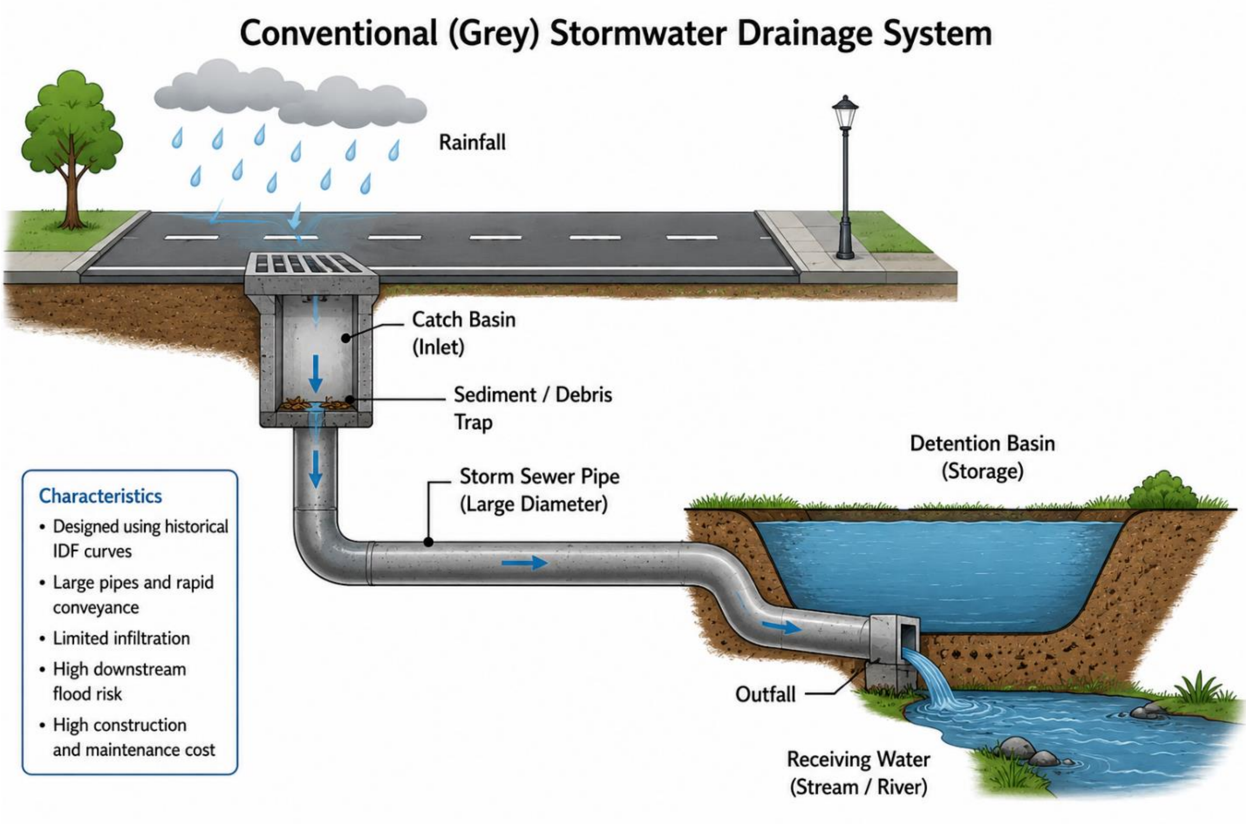

Figure 3: Conventional Storm-water Drainage System

Performance assessment of conventional USDS under the condition of extreme events reveals certain systematic weaknesses. Hydraulic modeling suggests that the drainage systems designed based on historical climate data will be increasingly overwhelmed by future extreme events (Bao, Wang, Li, & Chen, 2025). The risk of flooding from future rainfall will be able to exceed the historical risk of one level; for example, the risk of floods from future 5-year events will be equal to the risk of historical 10-year events (Zhou, Leng, Su, & Ren, 2021). Urban drainage capacity in the Xiao Zhai area of Xi'an is insufficient and shows limited adaptability to evolving climatic conditions; the number of overloaded manholes and the total volume of flood are expected to increase by 19.3-44.8% and 171-716%, respectively, from future rainfall with a 20-year return period (Bao, Wang, Li, & Chen, 2025). Areas of high flood risk are mainly characterized by urban location with adverse topography and high population density.

Table 2: Performance Comparison of Conventional vs. Hybrid Drainage Systems

Parameter	Conventional System	Hybrid System	Improvement
Pipe sizes	Larger diameters required	Smaller diameters sufficient	Reduced material consumption
Detention basin volume (10% AEP)	1785.60 m³	738 m³	>50% reduction
Detention basin volume (5% AEP)	2239 m³	943 m³	>50% reduction
Maximum outflow rate (10% AEP)	0.034 m³/s	0.032 m³/s	Lower peak discharge
Peak overflow (minor storms)	6.8 L/s	~0 L/s	Near elimination
Peak overflow (5% AEP)	12.2 L/s	~0 L/s	Significant reduction
Installation ost(10% AEP)	$603,170	$494,660	18% reduction
Installation cost (5% AEP)	$637,630	$521,170	18% reduction
Material consumption	Higher	Lower	Reduced environmental impact
Downstream impact	Higher	Lower	Better ecological outcomes

Source: Author

There are substantial economic consequences of the inefficiency of the conventional USDS. For example, the total cost of installation of conventional USDS for 10% and 5% AEP events in Pipers Crest development in South Australia is $603,170 and $637,630, respectively (United States Environmental Protection Agency (EPA), 2024). On the other hand, the installation cost of the hybrid USDS, which includes WSUD elements, makes $494,660 and $521,170 correspondingly, which is approximately 18% less for both cases (Wong & Brown, 2009). The major cost factor of conventional USDS is higher volume of detention basin with conventional detention volume being 1,785.60 m³ (10% AEP) and 2,239 m³ (5% AEP) comparing to 738 m³ and 943 m³ for hybrid systems with over 50% decrease in the volume of detention and corresponding cost savings.

Another important but often overlooked factor of conventional USDS is aging of the infrastructure. Many storm-water drainage systems are approaching or exceeding their 50-100-year design lifespan, which means they lack the ability to withstand increasing frequency and intensity of storms (National Academies of Sciences, Engineering, and Medicine, 2019). Aging infrastructure complicates the challenge posed by climate change, as old systems may show lower hydraulic capacity due to sedimentation, corrosion, or decay (Butler, Digman, Makropoulos, & Davies, 2018). Furthermore, conventional USDS are prone to failures in case of extreme weather conditions. The peak overflow for conventional systems ranges from 6.8 L/s to 12.2 L/s for 10% and 5% AEP events, respectively, suggesting high risks of localized flooding and overloads (United States Environmental Protection Agency (EPA), 2024). Hybrid systems show almost zero peak overflows, which indicates much higher safety margin for both minor and major storm events.

6. Green Infrastructure and Sustainable Urban Drainage Systems

Green infrastructure represents various nature-based solutions aimed at storm-water management by mimicking natural hydrological cycle (Fletcher, Andrieu, & Hamel, 2013). Such systems reduce storm-water runoff through interception, evapotranspiration, infiltration and detention and represent more environmentally friendly alternative to grey systems (United States Environmental Protection Agency (EPA), 2021)

The following figure shows green infrastructure components and hydrologic functions

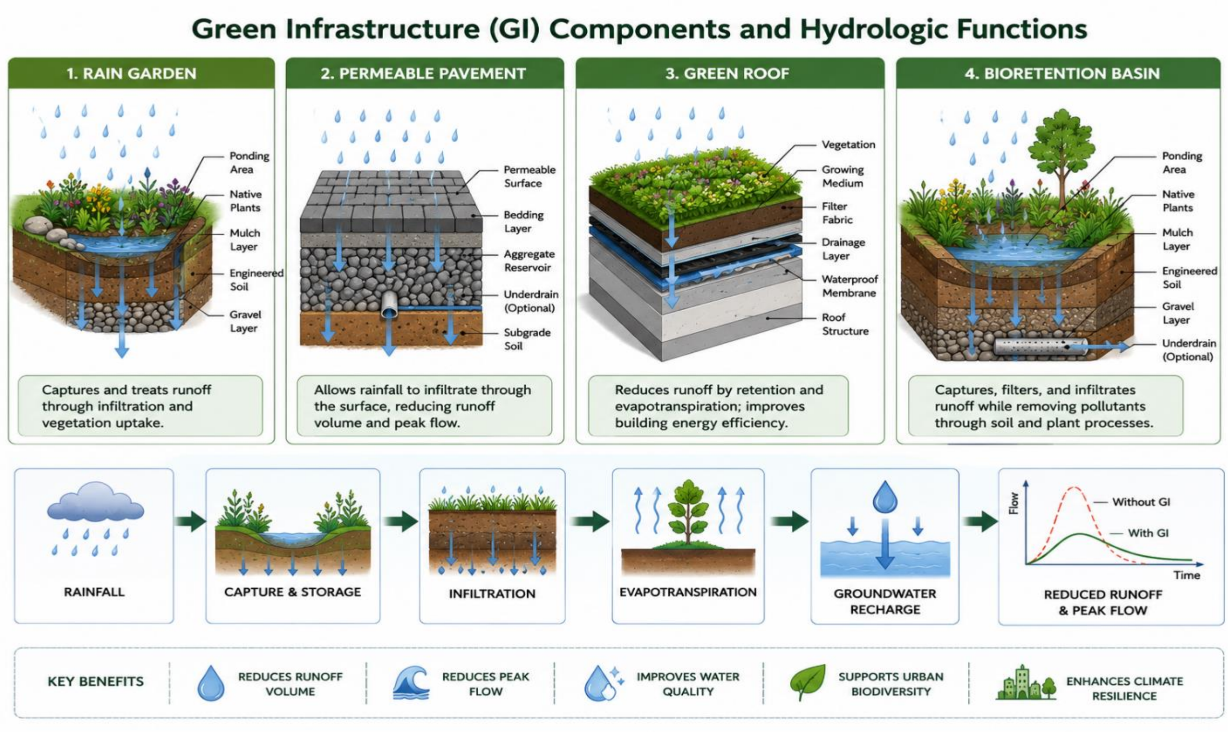

Figure 4: Green Infrastructure Components

The main types of GI include:

Rain gardens and bioretention basins: Depressions with vegetation collecting and treating storm-water runoff through filtration, infiltration and biological uptake (United States Environmental Protection Agency (EPA), 2021). Rain gardens in New York City absorbed 130-143 million gallons of storm-water between 1990 and 2015, proving effectiveness of the practice even in dense urban areas (United States Environmental Protection Agency (EPA), 2021). In Cincinnati, strategically placed rain gardens at the bottom of slopes detained 50% of inflow and delayed overflow by 5.5 hours under the conditions of heavy rainfall.

Permeable pavements: Pavements which allow runoff to seep into soil and infiltrate due to pores in pavement, which reduces runoff volume and filters contaminants (Fletcher, Andrieu, & Hamel, 2013). Evaluation of 40 permeable pavement sites in several states revealed that concrete grid pavers have the highest infiltration rates – approximately 4.9 cm/h without maintenance and 8.6 cm/h with maintenance (United States Environmental Protection Agency (EPA), 2021).

Green roofs: Roofs covered with vegetation providing insulation, water storage and reduction of urban heat island effect (Malmö Stad, 2018). Green roofs can be cooler by 4°C compared to conventional roofs; in Augustenborg, 11,000 m² of green roofs were installed, including 2,100 m² for public housing and 9,000 m² for the Botanical Roof Garden (Malmö Stad, 2018).

Rain barrels and cisterns: Decentralized storm-water storage systems collecting storm-water for later use. The limitations of the method include contamination risks. In New Jersey, evaluation of twelve rain barrels attached to one roof revealed that the water is not potable due to presence of E. coli, although it is suitable for agriculture since low zinc, lead and coliform levels were detected (United States Environmental Protection Agency (EPA), 2021).

Sustainable Urban Drainage Systems (SUDS) have proved to be efficient in removing particulates and associated pollutants in storm-water with performance decreasing under the condition of high inflow and aging (Fletcher, Andrieu, & Hamel, 2013). Performance is highly situational and variable over time since hydraulic overload during brief and intense periods results in bypass while aging and clogging affect media properties and flow paths, thus reducing the removal performance of SUDS exactly when pollutant pulses are the greatest (United States Environmental Protection Agency (EPA), 2024).

Table 3: Performance Metrics of Green Infrastructure Types Under Extreme Rainfall

GI Type	Runoff Reduction	Peak Flow Attenuation	Water Quality Improvement	Maintenance Requirement	Scalability
Rain Gardens	50-90% of events	5.5-hour delay	Moderate (sediment, nutrients)	Medium (annual weeding)	Moderate
Permeable Pavements	50-80%	Significant	High (filtration)	High (vacuum sweeping)	High
Green Roofs	40-60%	Moderate	Low	Medium	Low (structural limits)
Rain Barrels	10-30%	Minimal	N/A (storage only)	Low	High
Bioretention Basins	60-90%	High	High (multiple pollutants)	Medium-High	Moderate

Constructed Wetlands	70-95%	Very High	Very High	High	Low (space required)
Infiltration Trenches	50-80%	Moderate	Moderate	Medium	Moderate

Source: Author

The main factors to consider in urban storm-water management are cost and scalability. The advantage of rain barrels is low cost and decentralization of water management, however, the methods suffer from maintenance issues and contamination. Permeable pavements provide substantial runoff reduction and filtration benefits, however, high initial cost and technical issues may prevent wide implementation in resource-limited settings (Fletcher, Andrieu, & Hamel, 2013). AI can help with cost-saving and scalability through identification of cost-sharing opportunities, prediction of maintenance needs and simulation of materials performance (Rafiei Emam & Mishra, 2021). In the case of green infrastructure, one should balance upfront investments with costs of flood damages avoided which may be quite high. In the case of Augustenborg, the SEK 200 million (~€24 million) physical improvement expenses were compensated by the costs of avoided flood damage, as Augustenborg did not suffer from the flood-damage during the extreme event (such as a 50-year rainfall event in 2007 which resulted in flooding in Malmö) (Malmö Stad, 2018) 4. Case Study: Augustenborg, Malmö

Augustenborg is an example of successful implementation of SUDS (Malmö Stad, 2018). The Augustenborg area in Malmö used to face the problem of annual flooding since it had an inappropriate drainage system which could not withstand rainwater runoff, household wastewater and pressure coming from other parts of the city. During 1998-2002, the process of regeneration included building of sustainable urban drainage systems with 6 km of water channels and ten retention ponds (Malmö Stad, 2018). The storm-water management system channels rainwater from roofs, streets and car parks through visible trenches, ditches, ponds and wetlands. Green roofs were installed in all post-1998 developments and added to existing building amounting to 11,000 m² of existing buildings (Malmö Stad, 2018). The aim of the system was to manage a 15-year rainfall event with the goal to handle 70% of storm-water from roofs and sealed areas in the open system (Malmö Stad, 2018). The results of the project were impressive. The problem of flooding was solved after the implementation. Despite the occurrence of 50-year rainfall event in 2007 which caused extensive flooding in Malmö, Augustenborg remained safe (Malmö Stad, 2018). In 2014, the neighborhood has avoided significant flood damages during heavy rainfall event with over 100 mm of rainfall per 6 hours. It is estimated that 90% of storm-water from rooftops and impervious surfaces is handled in the open system, and annual total runoff is reduced by about 20% compared to conventional system due to evapotranspiration from trenches and retention ponds (Malmö Stad, 2018).

Table 4: Cost Comparison of Storm-water Management Approaches

Infrastructure Type	Initial Cost (Relative)	Maintenance Cost (Annual)	Lifetime (Years)	Cost-Effectiveness
Conventional Drainage	High	Low	50-100	Low under climate change
Hybrid (Conventional + WSUD)	Moderate	Moderate	50+	High (18% cost reduction)
Rain Gardens	Low-Moderate	Low-Medium	20-30	High for small catchments
Permeable Pavements	High	Medium-High	20-40	Moderate-High
Green Roofs	High	Medium	30-50	Moderate
Retention Ponds	High	High	30-50	Moderate
AI-Enhanced Green Infrastructure	Very High	Medium	Varies	Potentially high

Source: Author

7. Integration of Artificial Intelligence and Smart Technologies

The opportunities of artificial intelligence for the improvement of urban storm-water management are vast (Abdel-Aal, Elshorbagy, & Soliman, 2024). Tools such as EPA's Storm-water Management Model (SWMM) (Rossman, 2022) and advanced machine learning algorithms can help in optimizing infrastructure design, prediction of flood scenarios and real-time storm-water management (Kerkez, Glaser, Bales, & Meadows, 2016). AI modeling tools are capable of analyzing collected data in order to create realistic digital simulation which becomes increasingly accurate with data accumulation (Rafiei Emam & Mishra, 2021).

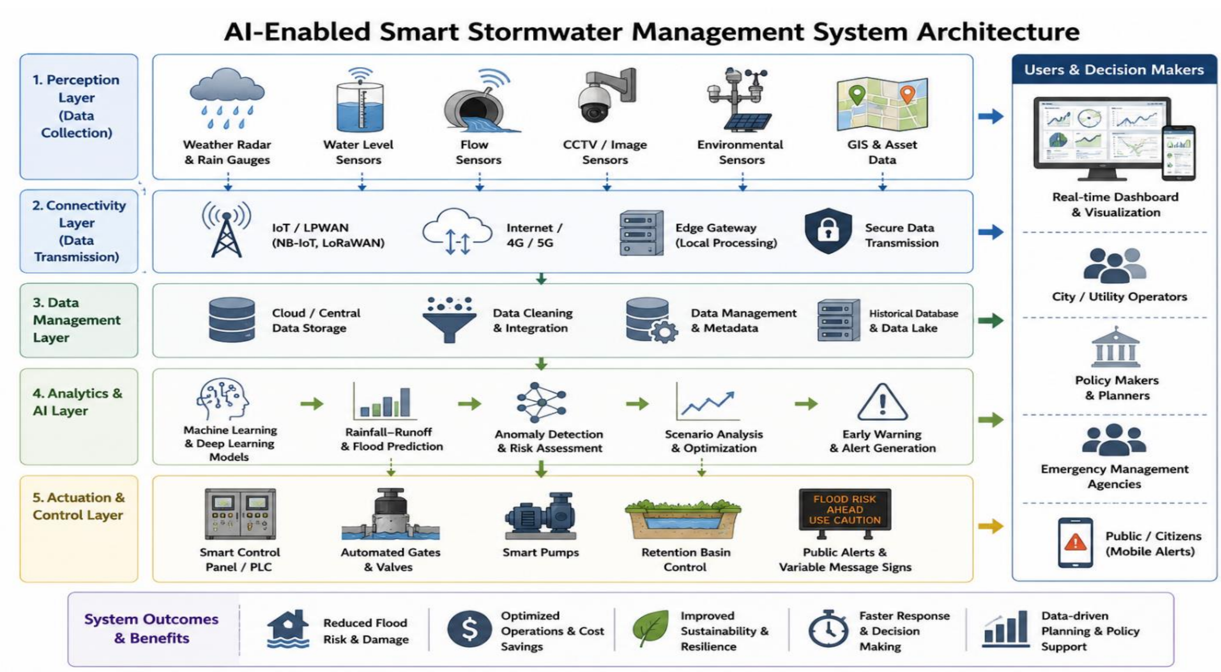

Figure 5: AI Smart Storm-water Management Architecture

AI-based modeling tools in storm-water management include:

- Hydrologic and hydraulic modeling: Analysis of water movement in drainage systems with regard to data on runoff, evaporation, infiltration and pipe size.

- Water quality modeling: Analysis of runoff pollutants in order to predict contamination and response.

- Floodplain and green infrastructure modeling: Creating a digital simulation of floodplains to predict water movement over the basins.

- Climate change modeling: Prediction of weather patterns and environmental changes to incorporate climate variability into storm-water management.

AI-based real-time systems improve storm-water management by allowing for dynamic reaction to environment conditions (Kerkez, Glaser, Bales, & Meadows, 2016). In Ann Arbor, Michigan, wireless sensors and control valves have helped in reducing runoff flow to 0.15 m^3/s which outperformed static infrastructure (Mullapudi, Wong, & Kerkez, 2020). The real-time system uses deep neural network which is trained with reinforcement learning by giving rewards and penalties for effective and ineffective storm management, respectively. The results of single-basin experiments show that the system allows for the effective reduction of runoff, and the more restrictive constraints result in better performance.

The use of digital twins – virtual models of the physical system powered by real-time data – opens huge opportunities of integrating AI with green infrastructure (Rafiei Emam & Mishra, 2021). These models allow performing scenario tests in order to assess resilience of the system prior to implementation. Applied to green roofs, digital twins help in simulating the performance of the infrastructure under different weather conditions in order to maximize water retention and minimize urban heat island effect (Rafiei Emam & Mishra, 2021). AI-based climate models, such as CMIP5 and CMIP6, can downscale global climate data in order to predict future weather in the area and inform about the best location and design of green infrastructure to prevent floods in future (Bao, Wang, Li, & Chen, 2025). The Change Factor Approach (CFA) represents climate change with precipitation statistics variables in order to predict extreme precipitation and estimate runoff variation in future (Bao, Wang, Li, & Chen, 2025).

The main promise of AI in storm-water management is integration with green infrastructure (Abdel-Aal, Elshorbagy, & Soliman, 2024). The current approaches often treat AI and green infrastructure innovations separately, while combination of the two provides many opportunities for optimization (Kerkez, Glaser, Bales, & Meadows, 2016).

The applications of AI-assisted green infrastructure can comprise:

• Rain Gardens: Real-time sensors can monitor the inflow levels and forecast maintenance scheduling to prevent overload of the system due to excessive rainfall. Predictive algorithms can process hydrological information and define the best places to install the rain gardens to maximize their efficiency in urban settings (Abdel-Aal, Elshorbagy, & Soliman, 2024).

• Permeable Pavements: Simulation of material behavior in the variable environment can assist in informed decision making regarding the installation and maintenance of pavements (Rafiei Emam & Mishra, 2021).

• Rain Barrels: Smart systems can monitor water quality and optimize its usage making the collection systems automated and efficient. Real-time sensors can monitor water quality and give notifications about water contamination (Kerkez, Glaser, Bales, & Meadows, 2016).

Table 5: AI Integration Opportunities for Green Infrastructure

GI Component	AI Application	Expected Benefit	Implementation Complexity
Rain Gardens	Predictive placement algorithms	20-30% efficiency increase	Medium
Permeable Pavements	Material performance simulation	Optimized material selection	Medium
Rain Barrels	Water quality monitoring sensors	Contamination risk reduction	Low-Medium
Green Roofs	Digital twin performance simulation	15-25% retention improvement	High
Retention Ponds	Real-time level control	30-50% capacity optimization	High
Detention Basins	NSGA-II pump optimization	71% efficiency improvement	High
Whole System	Deep neural network control	<0.15 m^3/s peak flow	Very High

Source: Author

8. Comparative Analysis of Approaches to Storm-water Management

Conventional storm-water systems compared to hybrid ones are inferior in terms of performance and cost effectiveness (United States Environmental Protection Agency (EPA), 2024). Hybrid drainage systems with WSUD elements were shown to perform better than conventional storm-water systems in the Pipers Crest case study (Wong & Brown, 2009). The size of pipes used in the hybrid system was less in contrast to the conventional system, and a greater number of smaller pipes were used. The volume of the detention basin in the hybrid system was less than half of the volume of the basin in the conventional system (738 m^3 vs. 1,785.60 m^3 for 10% AEP events), showing land and cost savings (United States Environmental Protection Agency (EPA), 2024). More importantly, hybrid systems have better safety, as for the conventional storm-water system peak overflows ranged from 6.8 L/s to 12.2 L/s for 10% and 5% AEP events, while for the hybrid storm-water system it was close to zero, which indicates the absence of peak overflows and decreased risks of floods and upwelling at pits during major rainfall events. Maximum outflow rates from the detention basin at 10% AEP were 0.034 and 0.032 m^3/s for the two systems, and both were much lower than the pre-development peak flow of 0.045 m^3/s.

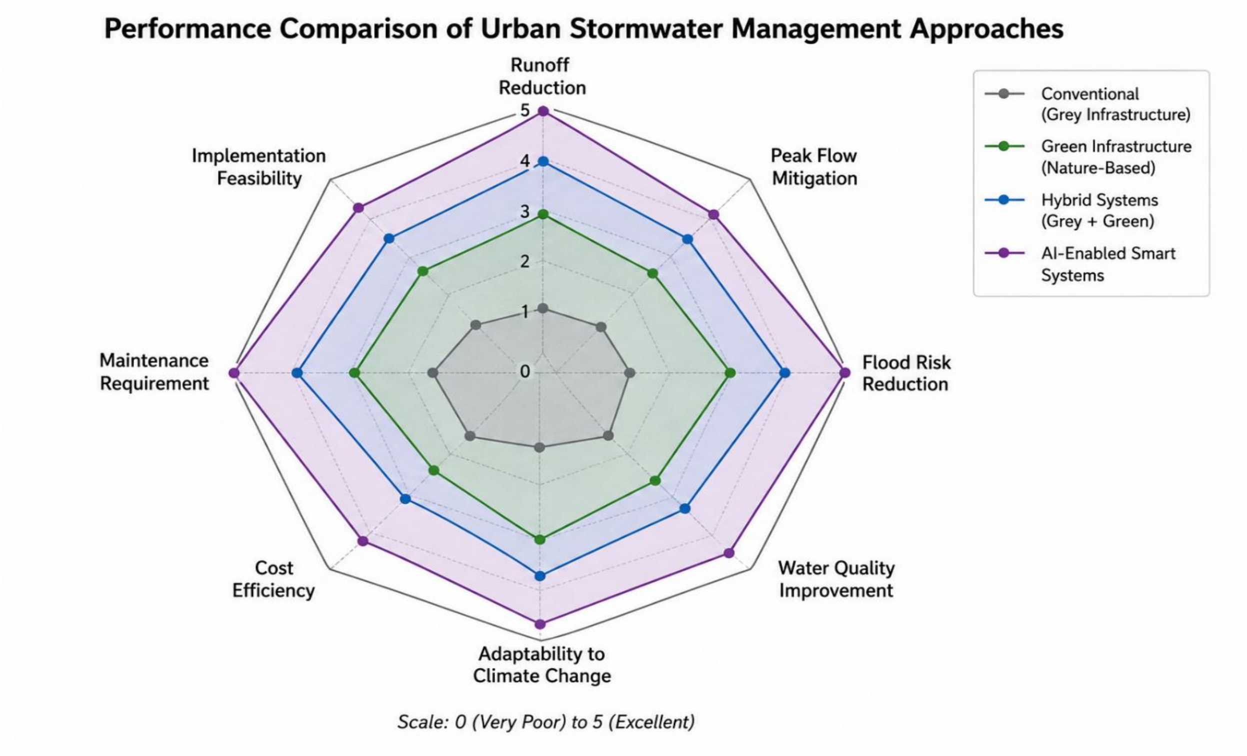

Figure 6: Conventional storm-water systems compared to hybrid ones

The comparison of green and grey infrastructure suggests that the two types of infrastructure have different advantages and disadvantages (Fletcher, Andrieu, & Hamel, 2013). Grey storm-water infrastructure is good at quickly removing the water and usually requires less per-unit maintenance (Butler, Digman, Makropoulos, & Davies, 2018). It does not have co-benefits for the environment and does not solve water quality issues. Green infrastructure has a number of benefits such as runoff reduction, water quality improvement, microclimate regulation, biodiversity maintenance, and aesthetic improvement (United States Environmental Protection Agency (EPA), 2021). There is an impressive potential of green infrastructure to mitigate the flood risks: according to the analyses conducted in New York City, community storm-water gardens absorbed 130–143 million gallons of storm-water between 1990 and 2015 (United States Environmental Protection Agency (EPA), 2021). In Cincinnati, rain gardens detained roughly half of all inflows and prevented 90% of rainfall events from generating runoff into the combined sewer system (United States Environmental Protection Agency (EPA), 2021). The problems related to the green infrastructure include land availability and maintenance costs; it was estimated that sustainable drainage systems have maintenance costs roughly twice higher than the costs of conventional sewer systems because of debris accumulation and regular cleaning of open channels (Malmö Stad, 2018). Despite increased maintenance costs, the open drainage system implemented in Augustenborg was assessed as more sustainable than the conventional sewer system from the perspective of technical, environmental, economical, and social sustainability (Malmö Stad, 2018). The best storm-water management strategies integrate conventional, green, and AI approaches (Wong & Brown, 2009). Hybrid storm-water systems combining grey infrastructure with nature-based solutions benefit from synergetic effects that surpass the sum of the benefits of its parts

(Chang, Franczyk, & Kim, 2021). Green-grey-blue systems provide multilayered protection against floods. The combination of updated grey infrastructure standards with nature-based SUDS solutions is a powerful solution to mitigate the increased risks of floods brought about by climate change by addressing current drainage capacity limitations and future climate adaptability (United States Environmental Protection Agency (EPA), 2024). When integrated with green infrastructure, AI will help to increase the efficiency, scalability, and adaptability of storm-water management approaches to allow them to mitigate urban floods and promote sustainability in the long term (Abdel-Aal, Elshorbagy, & Soliman, 2024). Evaluation of different approaches to storm-water management under climate change scenarios will help to gain crucial insights into urban planning. Studies conducted in the Xiao Zhai area based on CMIP6 projections show that the risks of floods from future rainfall are raised by one level as compared to historic flood risk, i.e. future 5-year rainfall events equal to the historic 10-year rainfall events (Bao, Wang, Li, & Chen, 2025). Green infrastructure can be considered as an effective way to manage the more frequent 1-, 5-, and 10-year events resulting from climate change (Chang, Franczyk, & Kim, 2021). Modeling of the Blue River Watershed showed that LID practices made the surrounding infrastructure resistant to climate change-related weather events. The addition of a 150-foot riparian buffer and proper green infrastructure resulted in the decrease of peak inflow, total volume, and flood extent for 1-, 5-, and 10-year events; the flood extent for smaller events decreased by about 8%, while there were almost no changes in larger 100-year events (United States Environmental Protection Agency (EPA), 2024). Spatial analysis shows that there is correlation between flood risks and resilience ranging from 0.49 to 0.63, which means that there are high risks and low resilience in vulnerability hot spots where priority actions are needed (Chang, Franczyk, & Kim, 2021). Thoughtful planning of grey-green rainwater facilities in these regions can lead to improved resilience of the rainwater systems to 0.67–0.95 under climate change (Chang, Franczyk, & Kim, 2021).

Table 6: Comparative Effectiveness of Storm-water Management Approaches Under Different Rainfall Scenarios

Rainfall Scenario	Conventional Grey	Green Infrastructure	Hybrid System	AI-Enhanced Hybrid
< 2-year return period	Effective	Highly effective	Highly effective	Highly effective
2-10 year return period	Moderately effective	Effective	Highly effective	Highly effective
10-50 year return period	Limited effectiveness	Moderately effective	Effective	Highly effective
50-100 year return period	Ineffective	Limited effectiveness	Moderately effective	Effective
> 100 year return period	Ineffective	Ineffective	Limited effectiveness	Moderately effective
Climate change (long-term)	Ineffective (stationarity failure)	Potentially effective	Effective with updates	Most adaptive

Source: Author

9. Case Studies of Successful Implementation

Multiple case studies were analyzed that had successful implementation. The figure below shows the locations of the case studies.

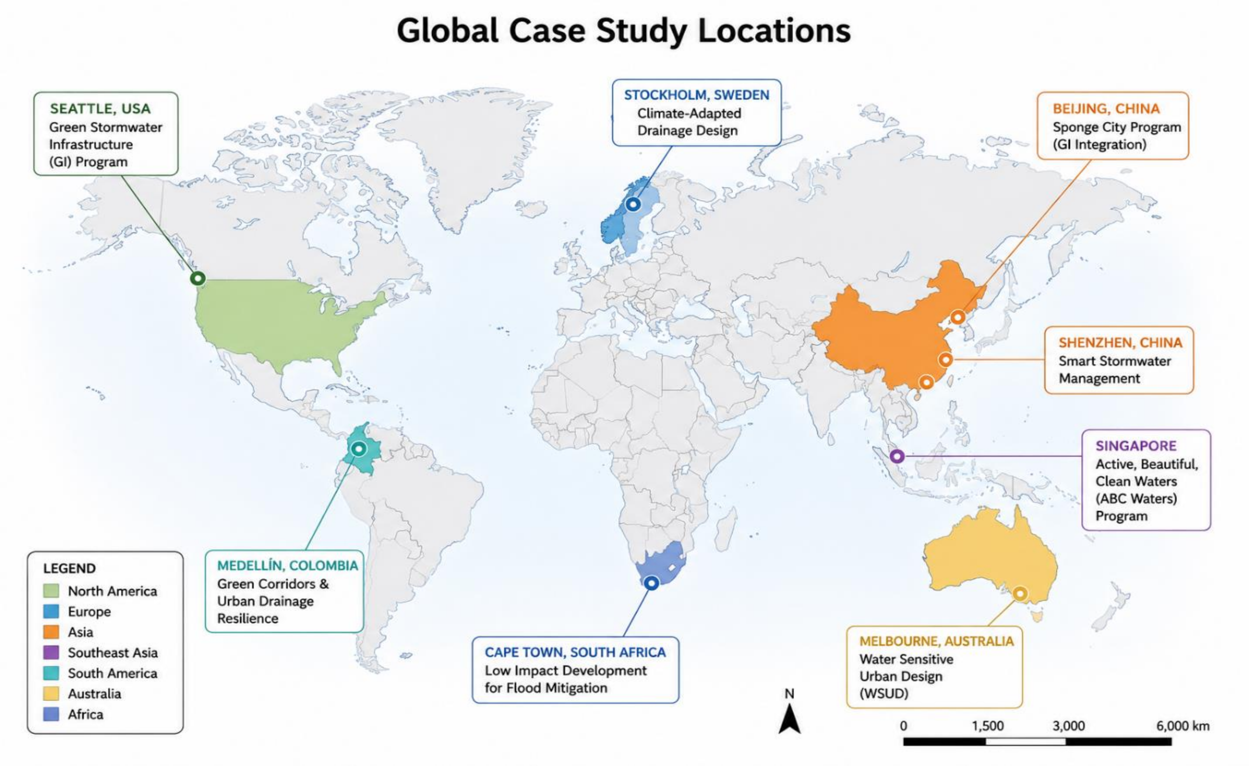

Figure 7: Global Case Study Locations

The example of Augustenborg, Malmö: SUDS transformation shows how the integration of SUDS can change the fate of the urban area prone to flooding (Malmö Stad, 2018). After the area was regenerated between 1998 and 2002, the place successfully managed several extreme rainfall events that brought floods to other parts of Malmö.

Success factors include: leadership of the Malmö Service Department and MKB housing company; active involvement of the stakeholders, including residents, local businesses, schools, and research institutions; delegation of the authority from the city to the district level allowing for quick decision making; collaboration during project management; about one fifth of tenants participated in dialogue meetings (Malmö Stad, 2018)

Measurable outcomes expected are: 90% of storm-water from rooftops and impervious surfaces is diverted to open systems; 20% of decrease in the total annual runoff volume; successful management of 50-year rainfall event (2007) and 100+ mm rainfall event in 6 hours (2014); zero combined sewer overflow; creation of three local companies and related employment opportunities; Investment of SEK 200 million (~€24 million); flood damage avoidance (Malmö Stad, 2018)

The example of community rain gardens in New York City shows how green infrastructure can be scaled up in the urban environment (United States Environmental Protection Agency (EPA), 2021). According to the analyses, between 1990 and 2015 the community storm-water gardens absorbed 130–143 million gallons of storm-water in 52.5 inches of rainfall (United States Environmental Protection Agency (EPA), 2021).

The Ann Arbor example shows how AI can help to implement real-time storm-water management (Kerkez, Glaser, Bales, & Meadows, 2016); (Mullapudi, Wong, & Kerkez, 2020). The watershed was equipped with wireless sensors and control valves feeding data to deep neural networks trained via reinforcement learning (Mullapudi, Wong, & Kerkez, 2020).

Finding at the Ann Arbor example show: single-basin systems are able to reduce runoff flow to below 0.15 m^3/s; systems with more exact performance constraints have better performance; batch-normalized neural networks are necessary for multi-basin systems; larger systems require more complex sensor and AI systems; multi-basin systems are superior to uncontrolled systems especially during high-intensity rainfall (Mullapudi, Wong, & Kerkez, 2020)

The Changsha example shows how to apply an integrated assessment framework to evaluate USDS resilience under future climate scenarios (Bao, Wang, Li, & Chen, 2025). The framework included dynamic climate downscaling using the WRF model, non-stationary frequency analysis via GEV distribution and 1D-2D coupled hydraulic modeling using InfoWorks ICM (Bao, Wang, Li, & Chen, 2025).

Projected outcomes of Changsha example are: 32% increase in 24-hour rainfall depth for 200-year return period in the 2060s; 17% increase in the area with ponding depth >500 mm for 100-year event; 21% increase in the area with 300–500 mm ponding depth; recommendation to upgrade design standards to at least 10-year return period using climate-adjusted IDF curves (Bao, Wang, Li, & Chen, 2025)

10.Discussion and Implications for Policy and Practice

It is found that there are substantial pollutant export and flood risks during short and intense rainstorms when the first minutes of runoff bear disproportionate loads (Fletcher, Andrieu, & Hamel, 2013). Bioretention, wetlands, and detention systems were proven to attenuate flows and reduce concentration during moderate storms in various regions (United States Environmental Protection Agency (EPA), 2021). Still, there is some performance degradation in these systems during hydraulic overloading, short-circuiting, or aged media (Fletcher, Andrieu, & Hamel, 2013). The major finding of this review is the conclusion that there is the dynamic coupling between peak-driven mobilization, asset failure modes under stresses, and human exposure by non-stationary rainfall (Zhou et al., 2021; (Intergovernmental Panel on Climate Change (IPCC), 2023).

Climate-resilient storm-water management should be evaluated using metrics sensitive to peaks and pulses, designed for performance under plausible future short-duration intensities, and explicitly linked to exposure reduction objectives (Chang, Franczyk, & Kim, 2021).

The following figure shows the climate-resilient storm-water framework and its subcategories.

Figure 8: Climate-Resilient Storm-water Framework

Policy recommendation would offer a huge impact such as:

- Update Design Standards: The urban storm-water and public health policies should recognize the short-duration extreme rainfall as one of the major reasons of flood risk and infrastructure failure and, therefore, require climate-adjusted, non-stationary IDF curves (Zhou et al., 2021; (Intergovernmental Panel on Climate Change (IPCC), 2023). The priorities should be given to regions with the highest rate of flood risks increase, especially low-lying and highly urbanized regions.
- Implement Performance-Based Standards: The regulatory frameworks should move from prescriptive designs to performance-based standards considering the event-scale dynamics, including the event-scale monitoring at drinking-water intakes, critical outfalls, and high-use recreational sites (U.S. EPA, 2024; (Butler, Digman, Makropoulos, & Davies, 2018).
- Integrate Green-Grey Infrastructure: The standards should require risk-based placement and sizing of green-grey treatment trains in high exposure, flood-prone catchments with asset management requirements for sediment and media renewal, inspection frequency, and contamination disposal (Wong & Brown, 2009; U.S. EPA, 2021).
- Harmonize Water Regulations: Sanitation, storm-water, and drinking water regulations should be harmonized so that the chemical and microbial standards, advisory thresholds, and risk assessment benchmarks would be applied to storm-water-wastewater corridors (National Academies of Sciences, Engineering, and Medicine, 2019).
- Support Community Engagement: The policies should favor affordable green-grey combinations that minimize exposure to open drains and contaminated flood waters with the surveillance connecting water quality, storm metrics, and health indicators (Malmö Stad, 2018).

The results of this review have implications for the urban planning practice. The predicted increase in rainfall intensity and flood risks makes it evident that USDS design based on stationary IDF curves is inadequate (Zhou, Leng, Su, & Ren, 2021). In order to increase the resilience of cities, it is recommended to urgently update USDS design standards to at least 10-year return period using climate-adjusted, non-stationary IDF curves (Bao, Wang, Li, & Chen, 2025). Besides the upgrading of grey infrastructure, the deeper integration of SUDS into the sponge city concept is crucial (Fletcher, Andrieu, & Hamel, 2013). SUDS can complement traditional drainage infrastructure helping to reduce surface runoff, enhance infiltration, and mitigate peak flow and, thus, reducing the load on upgraded USDS. The combination of updated grey infrastructure standards and nature-based solutions provides the more robust and multilayered defense against increased flood risks (Chang, Franczyk, & Kim, 2021).

This review has some limitations. The reliance on the peer-reviewed literature might result in exclusion of perspectives provided in the grey literature such as government reports or technical white papers (Higgins et al., 2019). Including the latter in future reviews can provide additional insights. Almost all of the evidence comes from the English-language publications, which might result in the exclusion of the important works in other languages. Short-duration extremes, pathogens, microplastics, and risk assessment endpoints are understudied, especially in low-income cities (National Academies of Sciences, Engineering, and Medicine, 2019). The heterogeneity of study designs, metrics, and storm characterization methods used in the selected articles made a formal meta-analysis and pooling impossible (Higgins et al., 2019). These factors probably underestimate risks and uncertainties in the areas of high exposure and poor data coverage, thus, limiting the applicability of the conclusions made in the literature review to other climates and infrastructures.

11.Future Research Roadmap

The following figure provides a summary of the future roadmap for urban storm-water management towards climate-resilient, smart and sustainable.

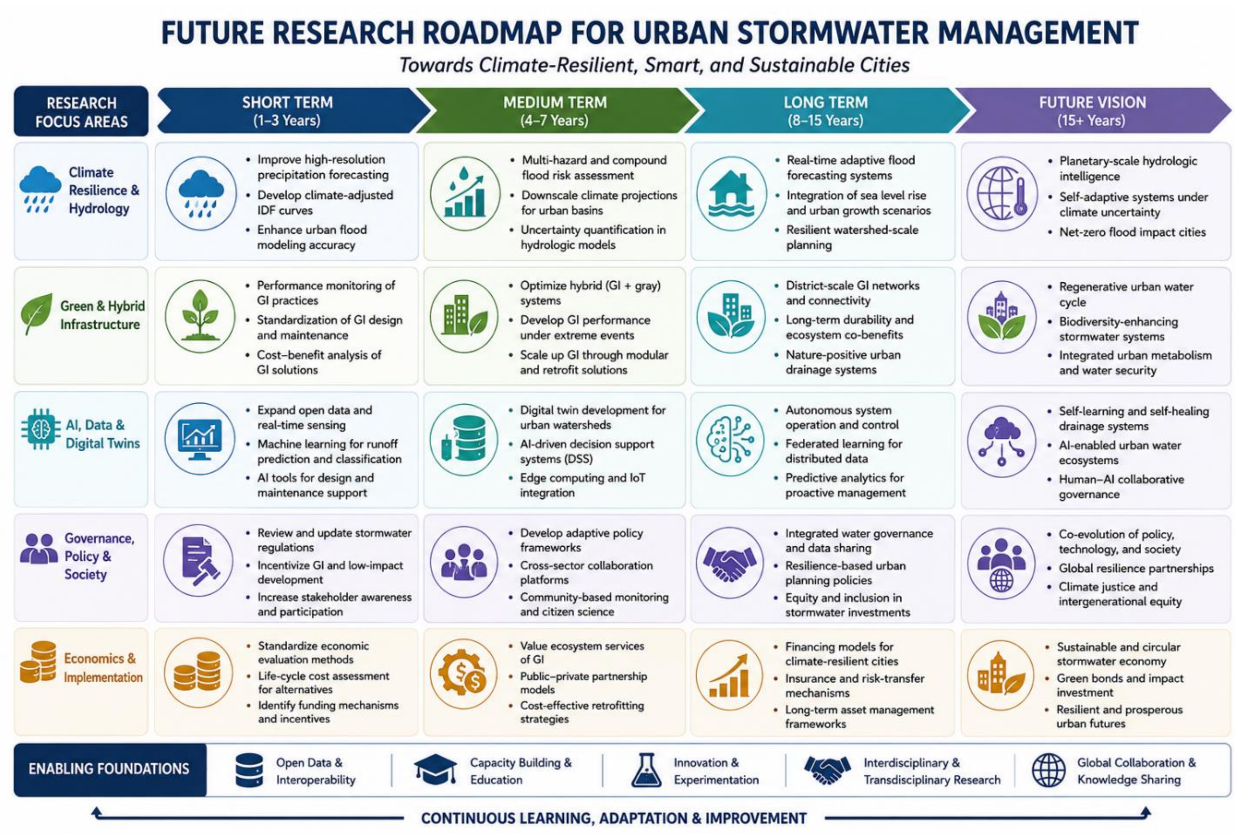

Figure 9: Future Research Roadmap

12.Conclusion

The management of urban storm-water poses substantial risks to the environment and human health With the traditional USDS reaching the end of the lifecycle, the challenges of flooding and environmental degradation will only grow stronger. Urban development must become sustainable with minimizing impermeable surfaces and preserving ecological equilibrium. Modern USDS combining green infrastructure and AI allows making a leap forward and solving flood risks. This systematic review shows that the intensification of short-duration extremes due to climate change challenges the conventional, stationary-design assumptions. The expected 20–80% increase in the design rainfall intensities in many regions requires urgent update of engineering standards and planning.

Green infrastructure, which imitates natural hydrology, maintains the functions of watershed and enables environmentally responsible urban development. The successful examples of implementation such as Augustenborg, Malmö, show that properly designed SUDS are able to withstand extreme events such as 50-year and 100-year rainfall events. However, the problem of scalability and maintenance exists and requires further innovation. AI applications simplify storm-water management starting from planning up to real-time operations. Through simulation of storm-water behavior and optimization of infrastructure design, AI increases the efficiency and adaptability, with real-time AI systems being even superior to the static human-made management and paving the way to smart cities. The integration of green infrastructure and AI is the major innovation in storm-water management. This hybrid solution solves the immediate problems and builds the climate resilience in the long term.

The solutions powered by AI, trained to adapt to environmental changes, will be useful for sustainable and efficient storm-water management in the future. Further research in the field should focus on expanding the hybrid models, improving predictive abilities and addressing the scalability and cost issues. Some priority directions are the development of standardized high-frequency monitoring protocol, investigating the mixture toxicity and microplastics fate in extreme hydraulics, integrating quantitative microbial risk assessment and dynamic non-stationary design, and longitudinal evaluation of SUDS aging and maintenance triggers in various urban forms and climates. With these advances, the potential of green infrastructure and AI in storm-water management will become enormous and redefine the field, bringing more resilient, sustainable, and climate-adaptive cities. The integrated assessment framework used in this review, including dynamic climate downscaling, non-stationary extreme value analysis, and high-resolution hydraulic modeling, shows notable flexibility of application to diverse geographical, climatic, and urban conditions, making it a useful tool for global urban flood risk assessment.

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