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Resilient Cities through Integrated Drainage: Bridging Hydraulics, GIS, and Nature-Based Strategies

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ABSTRACT

Urban drainage systems are essential for managing stormwater, mitigating flood risks, and sustaining urban resilience, especially under pressures from rapid urbanization, climate change, and increasing impervious surfaces. Traditional drainage networks, primarily designed for efficient wastewater conveyance, often fail under extreme rainfall events and high hydraulic demand, highlighting the need for integrated, adaptive solutions. This review synthesizes recent advancements in urban drainage planning, emphasizing the use of hydraulic modeling, optimization techniques, GIS, and Remote Sensing to assess network performance, predict flood inundation, and improve resilience. Methodologies including SWMM-based hydraulic simulations, one- and two-dimensional runoff modeling, and heuristic optimization algorithms enable accurate representation of flow dynamics, iterative network design, and cost-effective pipe sizing, while spatial datasets derived from high-resolution DEMs, satellite imagery, and precipitation products support precise mapping of impervious surfaces, catchment characteristics, and flood-prone zones. The novelty of this work lies in its integrated evaluation of conventional and smart drainage strategies, highlighting hybrid approaches that combine physical modeling, geospatial analysis, and optimization to enhance hydraulic efficiency, environmental sustainability, and adaptive capacity. Key findings demonstrate that smart and nature-based solutions such as green roofs, permeable pavements, bioswales, and sponge city initiatives significantly reduce peak runoff, pollutant loads, and carbon emissions while improving system resilience. The review provides evidence-based recommendations for cost-effective, environmentally sustainable, and climate-resilient urban drainage planning, offering a comprehensive framework for future research and practical implementation in modern cities.

Keywords

Urban drainage, Storm water management, Hydraulic modeling, GIS, Remote sensing, Optimization, Green infrastructure.

Highlights

- Integrated hydraulic and geospatial approaches improve drainage resilience.
- Smart and nature-based solutions reduce flooding and environmental impact.
- Hybrid modeling offers cost-effective, sustainable urban water management.

Introduction

The evolution of urban drainage systems demonstrates a continuous adaptation to technological advances, population growth, and environmental challenges, progressing from basic sanitation and flood protection in ancient civilizations around 3000 BC to modern integrated water management [1-3]. Early open channels in Mesopotamian and Indus Valley cities prioritized hygiene, while Roman covered sewers introduced organized networks emphasizing public health [4,5]. Industrialization and rapid urban expansion increased runoff volumes and peak flows by 1.5 to 10 times, reducing infiltration and evapotranspiration [6-8]. Conventional grey infrastructure efficiently conveyed stormwater but disrupted natural hydrology and transported over 600 pollutants, including heavy metals, nutrients, and emerging contaminants [9-11]. Smart drainage systems integrate real-time monitoring, data-driven management, and green infrastructure such as permeable pavements, bioswales, and green roofs to enhance infiltration, storage, and water quality, reflecting Water Sensitive City principles [12-14]. The transition from combined sewer systems, which mix stormwater and sanitary sewage and risk overflows during heavy rainfall, to separate sewer systems, which isolate flows for improved treatment and pollutant reduction, highlights a shift toward sustainable, resilient, and adaptive urban drainage [15-17]. Together, these developments mark the progression from localized, reactive systems to proactive, integrated, and environmentally sensitive urban water management [18,19].

Sewer network design has evolved through the integration of hydraulic modelling and optimization techniques to ensure both reliable system performance and cost efficiency [20,21]. Hydraulic approaches, based on fundamental fluid mechanics and continuity equations, employ methods such as the Manning equation, Saint Venant equations, and SWMM simulations to accurately represent flow dynamics under varying hydrological conditions, including complex phenomena like backwater effects, pressurized flow, and reverse flow [22-24]. These models generate time-series data on flow rate, velocity, and depth, allowing iterative calibration to satisfy hydraulic constraints [25,26]. Complementing this, optimization techniques, initially formulated through linear, nonlinear, and dynamic programming and more recently through heuristic and artificial intelligence methods such as genetic algorithms, particle swarm optimization, and ant colony optimization, aim to determine optimal pipe diameters, slopes, and layouts while minimizing construction costs [27,28]. Hybrid approaches that integrate hydraulic simulation with optimization algorithms enhance design accuracy by combining realistic flow representation with cost minimization [29,30]. While hydraulic modelling provides high-fidelity evaluation of system performance, optimization methods offer flexible, scalable, and near-optimal solutions for complex, large-scale networks [1]. Together, these complementary strategies form the foundation for a two-stage sewer network design approach, enabling iterative refinement of parameters to satisfy hydraulic and economic constraints while addressing the increasing complexity of modern urban drainage systems [2,3].

Stormwater drainage and urban flooding represent a critical challenge at the intersection of urban hydrology, infrastructure planning, and disaster risk management, particularly under rapid urbanization and climate change [4,5]. Pluvial flooding caused by intense rainfall frequently overwhelms conventional drainage systems, which are often designed using historical precipitation data and are unable to accommodate future variability, resulting in increased flood frequency, duration, and severity [6,7]. Advanced hydrological and hydraulic modeling tools, including SWMM, PCSWMM, MIKE URBAN, StormCAD, and GIS-based frameworks, have become essential for simulating rainfall-runoff processes, drainage network performance, and flood inundation, with coupled one- and two-dimensional models offering improved prediction of overland flow dynamics [8-10]. Impervious surfaces arising from urban expansion significantly exacerbate flooding by reducing infiltration and increasing runoff volumes and peak discharges, necessitating upgrades to drainage systems and increased infrastructure costs [11,12]. Studies integrating climate change projections from Regional Climate Models, low-impact development interventions such as permeable pavements, green roofs, detention systems, and deep stormwater tunnels demonstrate the importance of adaptive, resilient, and site-specific approaches [13-15]. Collectively, these findings underscore the need for integrated stormwater management frameworks that combine modeling, sustainable design, and planning strategies to mitigate urban flooding risks under evolving climatic and urban conditions [16,17].

Geographic Information Systems (GIS) and Remote Sensing (RS) play a pivotal role in urban drainage modeling by providing high-resolution spatial datasets that address the scarcity of ground observations, particularly in developing regions [18,19]. RS-derived data, including IMERG precipitation products, ALOS PALSAR DEMs, and Sentinel-2 land use/cover imagery, enable accurate extraction of key parameters such as slope, imperviousness, elevation, and drainage patterns, which are critical for runoff estimation and hydraulic simulation [20-22]. Case studies from Gurugram, Dhaka, Lahore, and the Zhujiang Delta demonstrate that integrating GIS and RS with hydrological models such as SWMM and MIKE SWMM allows simulation of rainfall-runoff processes, flood susceptibility mapping, and evaluation of drainage system resilience under climate change and urbanization scenarios [23-25]. Spatial mapping using GPS and ArcGIS facilitates precise geolocation, visualization, and analysis of drainage networks, flood-prone areas, and infrastructure vulnerabilities, supporting targeted interventions [26-28]. Advanced techniques, including multi-criteria decision analysis, machine learning models, and scenario-based planning, further enhance predictive accuracy and enable assessment of mitigation measures such as low-impact development and infiltration basins [29,30]. Collectively, the integration of GIS, RS, and hydrological modeling provides a robust, data-driven framework for urban drainage assessment, flood risk management, and climate-resilient infrastructure planning [1,2].

This study addresses the evolving challenges of urban drainage and flood management under rapid urbanization and climate change by integrating conventional hydraulic design, smart drainage strategies, and geospatial analysis [3-5]. Utilizing advanced methodologies, including SWMM-based hydraulic modeling, AI-driven optimization, and GIS/Remote Sensing techniques, the research systematically evaluates network performance, runoff dynamics, and flood risk across diverse urban catchments [6-8]. The novelty of this work lies in its combined approach, linking physical modeling with geospatial datasets and resilience-oriented planning, while also highlighting the environmental implications, including potential CO_2 emissions from infrastructure development [9-11]. Results demonstrate the critical influence of impervious surfaces, network configuration, and climate variability on flood susceptibility, while illustrating the effectiveness of hybrid green-grey solutions and optimization-guided design in enhancing system reliability, reducing pollutant loads, and improving sustainability [12-14]. These findings provide a comprehensive framework for adaptive, cost-effective, and environmentally responsible urban drainage planning, establishing a foundation for future research on carbon mitigation and green infrastructure interventions [15-17].

Evolution of Urban Drainage Systems

The historical evolution of urban drainage systems reflects the changing priorities of human settlements, transitioning from basic waste removal to complex, integrated water management frameworks [31-33]. In ancient civilizations (circa 3000 BC), drainage systems were primarily designed for sanitation and flood protection, often using open channels and rudimentary sewers, as seen in early Mesopotamian and Indus Valley cities [34,35]. During the Roman era, significant engineering advancements introduced covered sewers and organized drainage networks, emphasizing public health and urban hygiene [36,37]. However, in the post-Roman and early industrial periods, rapid urban growth outpaced infrastructure development, leading to unsanitary conditions and waterborne diseases [38,39]. The 19th and early 20th centuries marked the emergence of centralized sewer systems under the “Sanitary City” concept, focusing on efficient conveyance of wastewater away from populated areas [40,41]. Quantitatively, urban expansion during industrialization significantly altered hydrological processes, reducing infiltration and evapotranspiration while increasing runoff volumes and peak flows [42,43]. Studies indicate that urbanization increased runoff peaks by 1.5 to 10 times for short return periods, highlighting the hydrological impact of impervious surfaces and engineered drainage [44]. This historical trajectory demonstrates how urban drainage evolved from localized, function-specific systems to large-scale, engineered networks, ultimately setting the foundation for modern sustainable approaches. Therefore, understanding this historical progression reveals that urban drainage systems have continuously adapted in response to technological capabilities, population pressures, and environmental challenges [31].

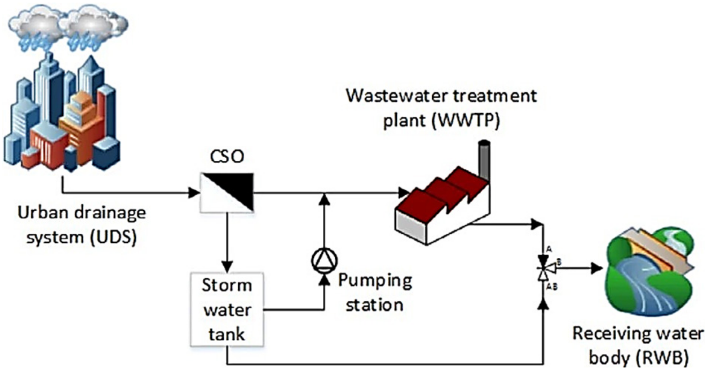

Figure 1: Urban Drainage System [44].

The transition from conventional to smart drainage systems represents a critical shift in urban water management, driven by the need for resilience, sustainability (Figure 1), and efficiency under changing climatic and urban conditions [32-34]. Conventional drainage systems were primarily based on grey infrastructure, including pipes, culverts, and channels, designed to rapidly convey stormwater away from urban areas to prevent flooding [36]. While effective in the short term, these systems significantly disrupted the natural hydrological cycle by increasing runoff volume, accelerating flow velocity, and reducing groundwater recharge [36,37]. Empirical evidence shows that urban runoff not only increases in quantity but also carries over 600 identified chemical pollutants, including heavy metals, nutrients, and emerging contaminants such as pharmaceuticals [38,39]. Additionally, conventional systems lack adaptability, making them vulnerable to extreme rainfall events intensified by climate change [40]. In contrast, smart drainage systems integrate real-time monitoring, data-driven decision-making, and decentralized green infrastructure such as permeable pavements, bioswales, and green roofs [41-43]. These systems aim to mimic natural processes by enhancing infiltration, evapotranspiration, and storage, thereby reducing peak flows and improving water quality [44]. Qualitatively, this shift reflects a move from reactive flood control to proactive, integrated water resource management aligned with Water Sensitive Cities (WSC) principles [31,32]. Hence, the evolution toward smart drainage systems signifies a transformative approach that enhances urban resilience, ecological sustainability, and adaptive capacity in modern cities [33,34].

The development and comparison of combined and separate sewer systems illustrate a fundamental evolution in urban drainage design, particularly in addressing hydraulic capacity and water quality challenges [35,36]. Combined sewer systems (CSS), widely adopted during the industrial era, were designed to transport both stormwater and sanitary sewage through a single network, offering cost-effective infrastructure during early urban expansion [37,38]. However, these systems become inefficient during heavy rainfall, leading to combined sewer overflows (CSOs) when flow exceeds approximately 1.5 to 6 times the dry weather flow [39,40]. Such overflows discharge untreated mixtures of stormwater and sewage into receiving waters, often containing pollutant concentrations that exceed those of typical wastewater, especially during the first flush [41,42]. This poses significant environmental and public health risks due to contaminants such as suspended solids, nutrients, and emerging chemicals [43]. In response, separate sewer systems (SSS) were developed to isolate stormwater from sanitary sewage, enabling more efficient wastewater treatment and reducing overflow risks [44]. Quantitatively, separate systems improve pollutant removal efficiency and reduce contamination loads entering natural water bodies, while also facilitating the integration of sustainable stormwater management practices [31,32]. Despite higher initial costs and infrastructure complexity, SSS offer greater long-term benefits in terms of environmental protection and system resilience [33,34]. Therefore, the shift from combined to separate sewer systems highlights a critical advancement in urban drainage, emphasizing the importance of sustainable design, pollution control, and adaptive infrastructure in contemporary urban environments [36,37].

Sewer Network Design Approaches

The application of hydraulic models in sewer network design constitutes a fundamental approach for accurately representing flow dynamics and ensuring compliance with hydraulic constraints (Table 1) [45,46]. Classical formulations such as the Manning equation have long been employed to determine pipe diameter and slope based on flow velocity and discharge under steady flow assumptions [47,48]. However, the increasing complexity of urban drainage systems has led to the adoption of advanced simulation tools, most notably the Storm Water Management Model (SWMM), developed in 1971 and subsequently refined [49,50]. SWMM integrates hydrological and hydraulic processes by representing sub catchments as nonlinear reservoirs and simulating pipe flow using the one-dimensional Saint Venant equations, thereby enabling the analysis of unsteady and non-uniform flow conditions [51]. Through simulation, time series of flow rate, velocity, and depth are generated for each pipe segment, allowing iterative adjustments to satisfy constraints such as minimum and maximum velocity, allowable depth-to-diameter ratios, and slope limitations [52]. For example, when the simulated flow depth exceeds acceptable limits, pipe diameters are recalculated using Manning-based relationships, while slope adjustments are made to ensure velocity remains within thresholds that prevent sedimentation or erosion [53]. Furthermore, SWMM enables the simulation of complex hydraulic conditions such as backwater effects, reverse flow, and pump operations, significantly improving design reliability compared to simplified methods [54]. The integration of these hydraulic models within iterative design frameworks allows for systematic refinement of sewer network parameters until all constraints are satisfied [45,46]. Therefore, hydraulic modelling approaches provide a scientifically rigorous and physically consistent foundation for sewer network design by capturing real flow behavior and system interactions [47-49].

Optimization techniques in sewer network design have been extensively developed to achieve cost-effective solutions while maintaining hydraulic performance under strict constraints [50,51]. Since the late 1960s, the sewer design problem has been formulated as an optimization problem in which the objective is to minimize total construction cost while determining optimal pipe diameters, slopes, and sometimes network layout [52,53]. Early approaches relied on exact methods such as linear programming, nonlinear programming, and dynamic programming, but these methods faced significant computational challenges due to the complexity and scale of sewer systems [54]. The problem is widely recognized as a non-deterministic polynomial time problem characterized by non-convexity, multimodality, and mixed discrete-continuous variables, particularly because pipe diameters are selected from commercially available discrete sizes [45,46]. To address these challenges, heuristic and artificial intelligence based methods such as genetic algorithms, ant colony optimization, particle swarm optimization, simulated annealing, and cellular automata have been introduced [47-49]. These approaches provide near-optimal solutions with significantly reduced computational effort, with studies showing that heuristic methods can reduce computational time to less than ten percent of that required by traditional

Table 1: Sewer Network Design Approaches and Optimization Techniques [45-54].

Criterion	Hydraulic Modelling Approaches	Optimization Techniques using AI and Heuristics
Primary Purpose	To simulate physical behavior of flow within sewer systems under varying hydrological conditions	To determine the most cost effective and efficient sewer network configuration under given constraints
Core Principle	Based on physical laws of fluid mechanics and continuity equations	Based on mathematical optimization, search algorithms, and iterative improvement
Key Methods Used	Manning equation, Saint Venant equations, SWMM simulation	Linear programming, nonlinear programming, dynamic programming, genetic algorithms, ant colony optimization, particle swarm optimization, simulated annealing, cellular automata
Type of Analysis	Deterministic and physics based simulation	Stochastic, heuristic, and evolutionary search based analysis
Input Requirements	Topography, rainfall data, flow characteristics, pipe roughness, boundary conditions	Cost functions, constraints, design variables such as pipe diameter and slope, initial feasible solutions
Output Generated	Flow rate, velocity, water depth, hydraulic grade line, system performance under dynamic conditions	Optimal or near optimal pipe sizes, slopes, layout configurations, and total system cost
Handling of Complexity	Accurately models complex hydraulic conditions such as backwater effects, pressurized flow, and reverse flow	Handles combinatorial and large scale optimization problems efficiently but may simplify hydraulic processes
Computational Demand	Moderate, depends on simulation complexity and time steps	High for exact methods, significantly reduced for heuristic methods often less than ten percent of exact approaches
Accuracy	High accuracy due to real physical representation of system behavior	Moderate to high accuracy depending on algorithm and integration with simulation models
Flexibility	Limited flexibility without integration with optimization tools	Highly flexible and adaptable to different problem formulations and constraints
Limitations	Requires iterative calibration and may not directly optimize cost	Does not always guarantee globally optimal solution and may depend on initial conditions
Strength	Provides realistic and reliable system performance evaluation	Provides efficient and scalable solutions for cost minimization and design optimization
Practical Application	Used for validating and simulating sewer network performance	Used for designing optimal sewer systems under economic and operational constraints

optimization techniques while maintaining comparable solution quality [50,51]. In addition, hybrid approaches that integrate hydraulic simulation tools such as SWMM with optimization algorithms further enhance design accuracy by combining realistic flow simulation with cost minimization strategies [52,53]. Despite these advancements, most methodologies separate layout design from hydraulic design to reduce complexity, which may limit achieving global optimality [54]. In conclusion, optimization techniques have significantly advanced sewer network design by offering flexible, efficient, and scalable solutions capable of addressing the inherent complexity of modern drainage systems [45-54].

Stormwater Drainage and Urban Flooding

Stormwater drainage and urban flooding represent a critical intersection of urban hydrology, infrastructure design, and disaster risk management, particularly under the pressures of climate change and rapid urbanization [54-56]. Pluvial flooding caused by intense rainfall overwhelming drainage systems has emerged as a dominant urban hazard due to inadequate infrastructure planning and limited integration between stormwater management and flood mitigation strategies [57,58]. Traditional drainage systems, often designed using historical rainfall data, are insufficient to accommodate future variability in precipitation patterns, resulting in increased flood frequency, duration, and severity [59-61]. Modeling-based assessments using tools such as SWMM and MIKE URBAN indicate substantial increases in flooding nodes and inundation extents under projected climate scenarios (Table 2) [62,63]. For example, in Delhi catchments, flooded nodes are expected to rise from 2–6 to as high as 51 under future conditions [64]. Urban flood management is further complicated by uncertainties in rainfall patterns, infrastructure limitations, and socio-economic vulnerabilities [65,66]. Advanced solutions such as deep stormwater tunnels, detention systems, and optimization-based design approaches have shown potential; however, their effectiveness depends on site-specific factors, including geomorphology and financial feasibility [66,67]. These studies emphasize the necessity of integrated, adaptive, and resilience-based stormwater management frameworks to mitigate urban flooding risks under evolving climatic and urban conditions [53,55].

Urban runoff modeling is essential for understanding, predicting, and managing stormwater dynamics within rapidly urbanizing environments [56-58]. Contemporary research employs advanced hydrological and hydraulic modeling tools, including SWMM, PCSWMM, MIKE URBAN, StormCAD, and GIS-based frameworks, to simulate rainfall-runoff processes, drainage network performance, and flood inundation patterns [59-61]. These models integrate one-dimensional and two-dimensional approaches, providing accurate representations of surface and subsurface flow interactions [62,63]. Coupled one-dimensional and two-dimensional models demonstrate improved capability in capturing flood extents and overland flow dynamics, particularly in peri-urban catchments [64,65]. Subgrid and rain-on-grid modeling techniques offer efficient alternatives for large-scale or data-limited regions, reducing computational complexity while maintaining reasonable accuracy [65,66]. Climate change projections derived from Regional Climate Models, such as CORDEX, are increasingly incorporated into these models to simulate future flood scenarios under varying return periods [67]. Sensitivity analyses further identify critical parameters including imperviousness, Manning’s roughness coefficient, and depression storage, which strongly influence runoff and flooding outcomes [54,55]. Despite their robustness, these models face challenges related to data availability, calibration, and uncertainty quantification [56,57]. Urban runoff modeling has therefore evolved into a sophisticated and indispensable tool for flood risk

Table 2: Case Studies on Stormwater Drainage and Urban Flooding [54-67].

Study Focus	Location	Methodology / Tools Used	Key Findings
Climate change impact on urban flooding	Delhi, India (Qudesia Nallah & Jahangirpuri)	SWMM integrated with RCM (CORDEX)	Flooded nodes increased significantly under projected scenarios; two-year storms may resemble current twenty-year storm impacts
Stormwater control measures	Peri-urban catchment (unspecified)	Coupled one-dimensional and two-dimensional modeling	Rain tanks and infiltration trenches were effective for five- to twenty-year storms
Runoff coefficient and drainage design	Dammam, Saudi Arabia	StormCAD with GIS integration	Increased runoff coefficient elevated discharge, velocity, and construction costs by two to three times
Urban flood modeling	West Bengal, India	SWMM and MIKE URBAN	Two-dimensional modeling improved flood extent prediction; detention ponds reduced peak flow
Urbanization and climate change impacts	Robe Town, Ethiopia	PCSWMM with RCM projections	Flooding volume increased by up to 67.4 percent under combined urbanization and climate change scenarios
Flood modeling with limited data	Dakar outskirts, Senegal	ATHYS platform	Efficient flood prediction with reduced data and computational requirements
Deep stormwater tunnels	Seoul, South Korea	3D OpenFOAM simulation	Smaller culvert diameters improved flow stability; air pockets reduced tunnel efficiency
Sponge city / Low Impact Development effectiveness	China (unspecified city)	SWMM and PCSWMM	LID significantly reduced runoff but was less effective during extreme storms
Sustainable drainage	India (general)	Conceptual and planning frameworks	Emphasized the need for integrated, city-specific drainage strategies

assessment, supporting evidence-based decision-making and the design of resilient stormwater infrastructure systems [60,61].

Impervious surfaces significantly influence urban flooding and stormwater drainage, reflecting the consequences of rapid land-use transformation [60,61]. Urbanization converts natural landscapes into built environments characterized by roads, rooftops, and pavements, which reduce infiltration capacity and substantially increase surface runoff volumes and peak discharge rates [62,63]. Empirical and modeling studies demonstrate that even modest increases in impervious area can lead to substantial rises in runoff; for example, a ten percent increase in imperviousness can elevate runoff by up to fifty percent, while higher levels may result in increases exceeding three hundred percent [63-65]. This escalation affects key design parameters of stormwater drainage systems, including outfall discharge, flow velocity, and lag time, often resulting in doubled or tripled infrastructure costs under intensified urbanization scenarios [66,67]. Impervious surfaces also reduce groundwater recharge and enhance pollutant transport, further exacerbating environmental degradation [54,55]. Altered runoff coefficients necessitate the redesign and upgrading of existing drainage networks to accommodate higher hydraulic loads [56,57]. Low Impact Development strategies, such as permeable pavements, green roofs, and infiltration trenches, provide effective mitigation measures, although performance varies with storm intensity and spatial implementation [58,59]. The proliferation of impervious surfaces is a primary driver of urban flooding, highlighting the importance of sustainable urban planning and adaptive drainage design to manage increasing hydrological pressures [60-67].

GIS and Remote Sensing in Urban Drainage

The role of Geographic Information Systems (GIS) and Remote Sensing (RS) in urban drainage modeling is fundamentally rooted in their capacity to generate high-resolution spatial datasets that compensate for the scarcity of ground-based observations, particularly in developing regions [68-70]. In the context of urban drainage systems (UDS), RS-derived datasets such as IMERG precipitation products, ALOS PALSAR Digital Elevation Models (DEMs), and Sentinel-2 land use/land cover (LULC) imagery provide critical inputs for hydrological analysis (Table 3) [71,72]. These datasets enable the extraction of key parameters including slope, elevation, imperviousness, and drainage patterns, which are essential for accurate runoff estimation and hydraulic simulation [73-75]. The Gurugram case study demonstrates how half-hourly IMERG data (0.1° resolution) effectively replaced sparse rain gauge data, enabling detailed simulation of pluvial flooding scenarios [76]. Similarly, LULC classification through satellite imagery allows identification of impervious surfaces, which directly influence runoff coefficients and peak discharge [77]. In Dhaka and Zhujiang Delta studies, multitemporal satellite imagery revealed significant urban expansion and corresponding increases in runoff depth and flood susceptibility [78,79]. Furthermore, SAR and Landsat imagery have been widely applied for flood mapping due to their ability to capture data under varying weather conditions. GIS-based flood susceptibility mapping integrates multiple thematic layers such as elevation, slope, drainage density, and proximity to streams to identify high-risk zones with high accuracy (e.g., 88.3% in recent studies). These approaches highlight how RS and GIS collectively enable continuous, large-scale, and precise environmental monitoring. Therefore, the integration of spatial datasets derived from RS within GIS frameworks significantly enhances the reliability and applicability of urban drainage assessments in data-scarce environments, ultimately improving flood risk management and infrastructure planning [67,68].

Spatial mapping using GPS and ArcGIS constitutes a critical methodological component in urban drainage studies by enabling precise geolocation, visualization, and analysis of drainage infrastructure and flood-prone areas [70,71]. GPS technology facilitates the accurate collection of field data, including coordinates of drainage networks, flood extents, and sampling locations, which are subsequently processed within GIS platforms such as ArcGIS for spatial analysis [72-74]. In the Saraswati River study, GPS-based field sampling combined with ArcGIS and Google Earth Engine enabled detailed mapping of river trajectories and water quality parameters across 27 locations [75,76]. Similarly, topographic mapping and flood channel identification in the Mashhad basin study were conducted using spatial datasets to locate suitable sites for stormwater infiltration basins [77,78]. ArcGIS tools support the development of Digital Terrain Models (DTMs), slope analysis, and spatial overlays, which are essential for understanding runoff pathways and flood propagation [79]. The integration of classified remote sensing imagery further enhances mapping accuracy by distinguishing between roofs, paved surfaces, and permeable land using advanced image processing techniques such as edge detection. Additionally, spatial mapping facilitates the identification of infrastructure vulnerabilities, as demonstrated in erosion-risk studies where roads, bridges, and drainage systems were overlaid with hazard maps. This enables planners to prioritize critical zones for intervention. The ability of GIS to visualize complex spatial relationships and integrate multiple datasets makes it indispensable for urban hydrological assessments [67,68]. Hence, spatial mapping using GPS and ArcGIS provides a robust framework for accurate data acquisition, visualization, and decision-making in urban drainage management, ensuring more targeted and effective flood mitigation strategies [70-72].

The integration of GIS and Remote Sensing with hydrological models such as SWMM represents a transformative advancement in simulating and evaluating urban drainage system performance under varying environmental conditions [73-75]. Hydrological models require detailed inputs related to rainfall, catchment characteristics, and drainage network configurations, which are efficiently derived from GIS and RS datasets [76,77]. In the Gurugram study, SWMM was successfully employed using RS-derived inputs to simulate both functional and structural failure scenarios, revealing that climate change poses a greater individual threat while its combination with urbanization significantly reduces system resilience [78,79]. Similarly, in Lahore, the integration of GIS with SWMM and rainfall modeling techniques such as Log-Pearson Type III distribution and Alternating Block Method enabled the generation of design hyetographs in data-scarce conditions, leading to accurate flood risk assessment. The Mashhad basin study also utilized MIKE SWMM to simulate rainfall–runoff processes and evaluate hydraulic performance, identifying critical conduits and testing mitigation measures such as infiltration basins. Furthermore, GIS-based Multi-Criteria Decision Analysis (MCDA) and machine learning models such as Outlier Robust Extreme Learning Machine (ORELM) have been integrated to enhance flood susceptibility prediction and future scenario analysis under climate change projections [68-70]. These integrated approaches allow simulation of complex interactions between land use changes, rainfall variability, and drainage capacity [71,72]. Consequently, the coupling of GIS and RS with hydrological models not only improves simulation accuracy but also supports scenario-based planning and resilience assessment [73-75]. In conclusion, such integration provides a comprehensive and data-driven framework for evaluating urban drainage systems, enabling informed decision-making for sustainable and climate-resilient urban infrastructure development [76-79].

Discussions and Recommendations

The reviewed literature highlights that urban drainage systems have evolved significantly, transitioning from basic sanitation-focused designs to complex, integrated frameworks that address flood mitigation, environmental protection, and resilience under climate change [1-6,31-34]. Historical analyses indicate that conventional drainage systems, while effective in conveying stormwater, are increasingly inadequate in coping with intensified rainfall, urban expansion, and impervious surface proliferation [54-58]. Modeling studies using SWMM, MIKE URBAN, and PCSWMM consistently show that urbanization exacerbates peak runoff, increases flooding frequency, and reduces groundwater recharge, necessitating the adoption of adaptive and integrated stormwater management strategies [54-58,68-72]. Furthermore, the comparison of combined and separate sewer systems emphasizes the environmental and operational advantages of separate networks, particularly in reducing pollutant loads, preventing combined sewer overflows, and facilitating sustainable stormwater practices [31-54]. These findings underscore the critical need for proactive planning that incorporates hydrological modeling, real-time monitoring, and risk assessment to optimize hydraulic performance and environmental outcomes [68-79].

Spatial analysis through GIS and Remote Sensing emerges as an indispensable tool in addressing data scarcity and enhancing drainage system planning [68-79]. Case studies from Gurugram,

Table 3: Case Studies on GIS and Remote Sensing in Urban Drainage and Flood Assessment [73-82].

Study Area / City	Objective / Focus	Methods / Tools	Key Findings / Outcomes
Gurugram, India	Evaluate Urban Drainage System (UDS) resilience under climate change and urbanization	SWMM modeling, Remote Sensing: IMERG (precipitation), ALOS PALSAR (DEM), Sentinel-2 (Land Use/Cover)	Climate change poses greater threat than urbanization individually; combination significantly reduces UDS resilience; 11/25 conduits non-resilient; highlights utility of remote sensing for developing countries
Mashhad, Iran (East Eghbal basin)	Simulation and evaluation of urban drainage; flood control	MIKE SWMM, rainfall-runoff simulation, hydraulic response evaluation	Six conduits had difficulties handling stormwater; three natural storm infiltration basins proposed; noticeable reduction in flooding after interventions
Dhaka, Bangladesh	Assess impact of urbanization on stormwater runoff and drainage	GIS, Remote Sensing (panchromatic imagery, DTM), hydrologic data	Assessed inundation extent under current and future urbanization; modified DTM to predict future flood spread
Zhujiang Delta, China	Link urban growth to surface runoff changes	Remote Sensing: Landsat TM, GIS analyses, SCS runoff model	Uneven urban growth increased annual runoff depth by 8.10 mm; highly urbanized areas more prone to flooding; urbanization reduced max storage capacity
Two case studies, unspecified	Integrate planned urban drainage with GIS for design & simulation	Open-source tools (Auto Numbering, Get Elevation, Excel2GIS), GIS platform, drainage design software	Improved accuracy, reduced prep time, better visualization of hydraulic results on urban master plan
Lesser Zab River Basin (LZRB), Iraq/Iran	Assess erodibility and flash flood hazard; prioritize sub-basins	Morphometric analysis, hydrological data, hazard mapping	Upper sub-basins produce higher runoff; 18 sub-basins moderate to low risk; 29 sub-basins low possibility of flash flooding
Unspecified region	Flood susceptibility mapping and risk assessment	Weighted Overlay Analysis (WOA), Analytic Network Process (ANP), RS & GIS, ORELM (MATLAB)	Flood susceptibility map developed with 88.3% accuracy; elevation, slope, distance from stream main risk factors; projected future flood areas under climate change scenarios
Lahore, Pakistan	Evaluate drainage capacity under urbanization & climate change	SWMM modeling, GIS, LPT-III distribution, Alternating Block Method (ABM)	Existing system inadequate for 2-year storm; 60% area inundated; low-impact development suggested to improve infiltration and reduce runoff
King Talal Dam vicinity, Jordan	Flood hazard mapping	Remote Sensing (RS), GIS, AHP weighting, weighted sum overlay	Flood risk zones identified; lower elevation and proximity to streams main factors; robust framework for disaster mitigation
Global urban areas review	Nature-based solutions and Sustainable Urban Drainage Systems (SUDSs) for climate adaptation	Systematic literature review, PRISMA, bibliometric and co-occurrence analysis	Highlighted gaps in standardizing design and performance monitoring of SUDSs; emphasized NbSs as a viable strategy for urban resilience

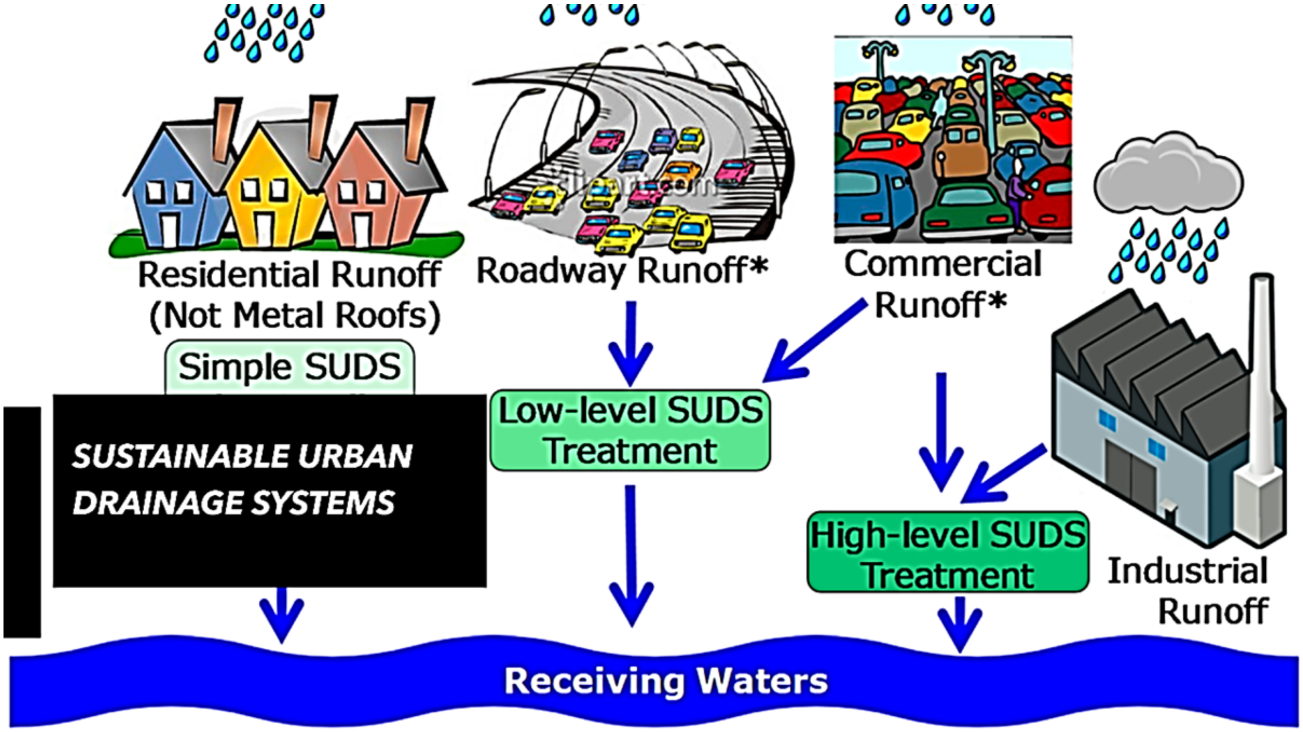

Figure 2: Sustainable Urban Drainage System.

Dhaka, Lahore, and the Zhujiang Delta demonstrate that RS-derived datasets, combined with GIS-based hydrological modeling, improve the accuracy of flood mapping, urban runoff estimation, and resilience assessment [68-79]. The integration of machine learning, multi-criteria decision analysis, and scenario-based modeling further enables predictive evaluation of drainage performance under future climate and land-use changes [79]. These approaches allow urban planners to identify high-risk zones, prioritize interventions, and simulate the effectiveness of mitigation measures such as low-impact development, detention systems, and sponge city initiatives [54,62,78,79]. The consistent observation across studies is that the coupling of geospatial tools with hydraulic models enhances decision-making, particularly in data-limited contexts, and supports sustainable and resilient urban infrastructure development [68-79].

Based on the reviewed literature, several key recommendations emerge to enhance the design, management, and sustainability of urban drainage systems. Urban drainage planning should integrate conventional and smart drainage approaches, combining grey infrastructure with decentralized green and nature-based solutions such as permeable pavements, bioswales, green roofs, and sponge city initiatives to balance hydraulic efficiency, ecological sustainability, and reduction of CO_2 emissions [54,55,62,78,79]. Hydraulic modeling and optimization tools should be systematically applied to assess network performance, refine pipe sizing, and reduce construction and operational costs [45-53,68-72]. The widespread use of GIS and Remote Sensing should be promoted to enable accurate mapping, flood risk assessment, and scenario-based planning [68-79]. Urban flood management should adopt a resilience-oriented and holistic perspective that considers climate projections (Figure 2), impervious surface impacts, and socio-economic vulnerabilities to ensure adaptive, cost-effective, and environmentally sustainable interventions [54-58,78,79]. Future research should prioritize hybrid approaches that integrate hydraulic simulation, AI-based optimization, and geospatial analysis to enhance predictive accuracy, operational reliability, and long-term sustainability, including the quantification and mitigation of the carbon footprint associated with urban drainage infrastructure [54,68-79].

Conclusions

Urban drainage systems have undergone a significant evolution, transitioning from rudimentary open channels and localized waste removal methods to sophisticated, integrated networks that combine conventional grey infrastructure with smart, data-driven approaches. Historical analysis highlights that engineering innovations, population growth, and urbanization have continuously shaped drainage design, with combined and separate sewer systems reflecting efforts to balance cost, hydraulic performance, and environmental protection. The literature emphasizes that conventional systems, while effective for rapid conveyance, are increasingly insufficient under extreme rainfall and climate change scenarios, necessitating the adoption of adaptive, resilient, and integrated approaches.

Hydraulic modeling and optimization techniques have emerged as essential tools for modern sewer network design. The integration of

SWMM-based simulations, one-dimensional and two-dimensional hydraulic models, and AI-driven heuristic optimization provides accurate representations of flow dynamics, allowing iterative design adjustments to satisfy velocity, depth, and slope constraints while minimizing construction and operational costs. These approaches not only enhance system reliability but also facilitate the evaluation of green and hybrid interventions, demonstrating the importance of linking physical modeling with optimization frameworks for sustainable urban drainage planning.

Geospatial technologies, particularly GIS and Remote Sensing, have proven critical for urban drainage assessment, especially in data-scarce environments. High-resolution DEMs, land use/land cover classification, and satellite precipitation datasets enable precise mapping of impervious surfaces, catchment characteristics, and flood-prone zones, while supporting scenario-based simulations of urbanization and climate impacts. Integrating these spatial datasets with hydrological models enhances predictive accuracy, informs flood mitigation strategies, and allows identification of priority areas for infrastructure improvement. Furthermore, these tools facilitate the evaluation of the environmental and sustainability aspects of drainage systems, providing insights into runoff, pollutant transport, and resilience under changing climatic conditions.

Overall, this review highlights that effective urban drainage management requires a multi-dimensional and integrated approach. Combining conventional and smart drainage techniques, optimization-based design, and GIS/Remote Sensing analysis allows for cost-effective, resilient, and environmentally sustainable solutions. The findings underscore the importance of adopting green infrastructure and nature-based solutions to mitigate flooding, reduce pollutant loads, and minimize carbon emissions associated with urban water systems. Future research should focus on hybrid methodologies that link hydraulic modeling, optimization, and geospatial analysis with environmental and climate metrics to support adaptive planning, improve sustainability, and advance the development of resilient urban water management frameworks.

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