

Urban flood risk under climate change: modeling and LID-based solutions

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Urban flooding is an escalating threat driven by climate change, rapid urbanization, and altered land use patterns, resulting in increased impervious surfaces and disrupted hydrological cycles. Globally, flood risks have intensified due to rising temperatures and shifting precipitation patterns. Urban populations continue to grow, increasing the vulnerability and exposure of cities to flood hazards. In India, urban centers face frequent flood disasters with significant economic and social impacts. This study reviews recent advances in urban flood modeling, focusing on climatic and land-use influences, with applications of models such as PCSWMM, HEC-HMS, and coupled 1D-2D hydrodynamic approaches. Climate scenarios from IPCC's latest reports and urban growth projections are integrated to assess future flood risks. Additionally, flood mitigation strategies, including Low Impact Development (LID) practices like detention ponds, permeable pavements, and green roofs, are evaluated for their effectiveness in reducing flood peaks and volumes. Case studies from Indian cities demonstrate the critical need for sustainable urban water management and adaptive infrastructure to enhance resilience against the increasing threat of urban floods induced by climatic and anthropogenic factors.

Keywords: *Urban Flooding, Climate Change Modeling, Hydrological Modeling, Flood Risk Assessment, Low Impact Development (LID)*

Introduction

The increasing risk of urban flooding is primarily attributable to a combination of climatic shifts, modifications in land usage, and anthropogenic actions. Rapid urban expansion worldwide has intensified flood risks (Grimm et al., 2008), while rising temperatures and shifting monsoon patterns also contribute to the increased incidence of floods (Solomon et al., 2007). In a stable climate system without human influence, extreme temperature events typically recur every decade; however, with global warming projected to rise by 1.5°C, 2°C, and 4°C, there will be corresponding increases in rainfall and temperature globally (IPCC, 2023). Rapidly growing economies, especially Annex I countries experiencing accelerated urbanization, face amplified vulnerability to floods, leading to substantial human and economic losses (Highfield and Brody, 2013). In India, urban centers have witnessed numerous flood disasters severely impacting the nation's economy (Patankar, 2015). The number of natural hazards has increased from 1900 to the present. Floods are one of the major natural hazards that occur frequently. The global population is expected to exceed eight billion people in 2022. By 2022, the population of cities is expected to account for 56.9% of the total population. The urban area ratio of the general region increased by approximately 7.92%, from 12.17% in 2022 to 20.09% in 2052. The globe may anticipate adding over 1.5 billion urban areas during the next 15 years, and three billion more by 2050. Urban regions currently house 55% of the global population, which is anticipated to increase to 68% by 2050 (IPCC, 2023).

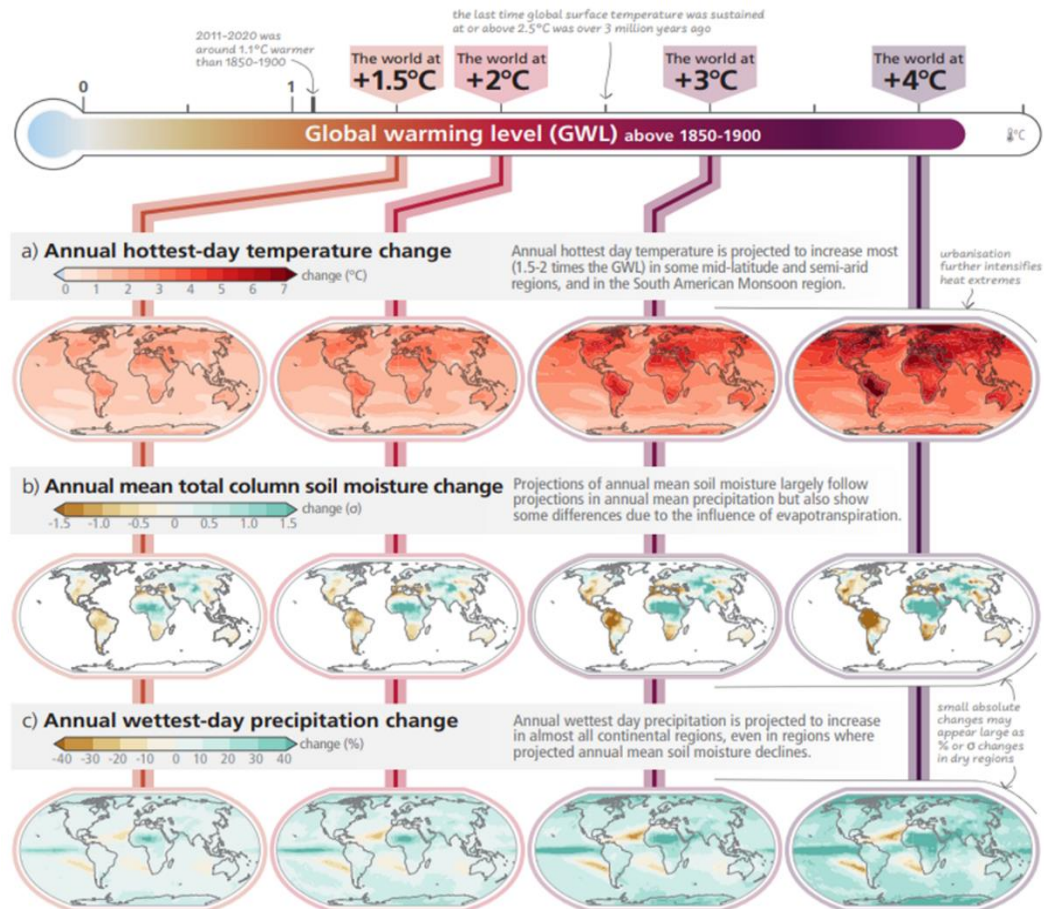


Figure 1. Projected changes of Annual temperature, soil moisture and precipitation at different global warming levels

Floods are defined as an increase in water level along a river stream or on the shoreline that induces the inundation of normally dry land. In India, 12% of the land area and approximately 5161 urban local bodies are vulnerable to floods. Every year, flood events occurring due to climatic frontiers alone incur losses of 3 billion US dollars to the Indian economy, which is 10% of the worldwide economic losses due to floods.

Impact of urbanization and LULC on flooding

Urbanization significantly impacts natural surfaces within cities, primarily through changes in land use and an increase in impervious surfaces. These changes affect hydrological processes by shortening the time it takes for water to travel through a watershed, while also increasing the volume, peak flow, and total discharge of runoff. As urban areas develop, the natural balance of hydrology is disrupted, leading to altered patterns of peak flow distribution and modifying the timing and size of both low flows and flood events. Key components such as base flow, interflow, and evaporation tend to decline under urbanization, whereas surface runoff, streamflow, and peak discharges escalate, resulting in heightened flood risks and altered water availability dynamics in urban catchments (Rezaei et al., 2019).

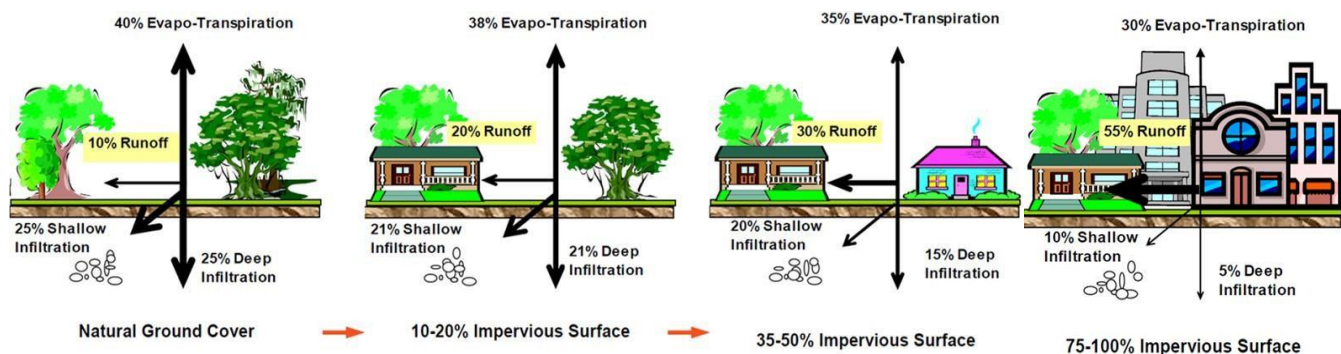


Figure 2. Impact of urbanization and LULC on flooding

As imperviousness increases, water infiltration decreases and runoff increases. In densely populated areas, more than half of the rainfall is only a portion of what it was originally. It causes flooding and reduces deep infiltration, thereby lowering groundwater levels in wetlands and wells.

1. Impact of climate change on flooding

Floods in cities do not occur as discrete, isolated incidents. They exist as part of the larger urban context, causing landslides and interacting with other concurrent dangers, such as cyclone storm surges or tsunamis. Increases in mean atmospheric temperatures are among the projected consequences of climate change. An increase in air temperature increases the volume of water that the atmosphere can hold, making more water accessible for precipitation. Large cities can act as "heat islands," increasing the air temperature in a specific area. The ensuing microclimate could enhance the amount and severity of rainfall in metropolitan regions. Global warming is likely to increase both the intensity and incidence of extreme weather events (Hu et al., 2024).

2. Flood modeling

The process of simulating/predicting water level, flood depth, and flow velocity using mathematical or hydrodynamic models. Hydrodynamic Models replicate the flow of water by solving equations based on physical laws. Depending on the geographical representation of the floodplain, models can be classified into the following categories:

2.1. 1D flood modeling

One-dimensional (1D) flood models simplify floodplain flow by assuming it occurs along a single main axis, typically aligned with the river's centerline. This approach is appropriate in cases where the flow direction predominantly follows a linear path, such as within river channels, and when broader dimensional complexity is unnecessary or computational resources are limited. In 1D models, the floodplain flow is treated as an extension of the channel flow, with flow velocity and water depth averaged across cross-sections perpendicular to the flow direction. This simplification enables efficient modeling of flood dynamics over elongated areas but may miss lateral variations in flow characteristics.

2.2. 2D Flood modeling

Two-dimensional (2D) flood models, in contrast, simulate floodplain flow across a grid or mesh covering the floodplain surface. These models assume that the vertical water depth dimension is smaller relative to horizontal dimensions, allowing the flow to be represented by depth-averaged velocities in two horizontal directions. Utilizing a digital elevation model (DEM), 2D models dynamically calculate water depths and velocities at multiple points across the floodplain surface, capturing complex flow patterns over wide and irregular areas. This approach provides a more detailed and realistic representation of flood behaviour, especially where flow spreads in multiple directions, such as in broad floodplains, urban areas, or topographically complex landscapes.

2.3. Coupled 1D-2D flood modeling

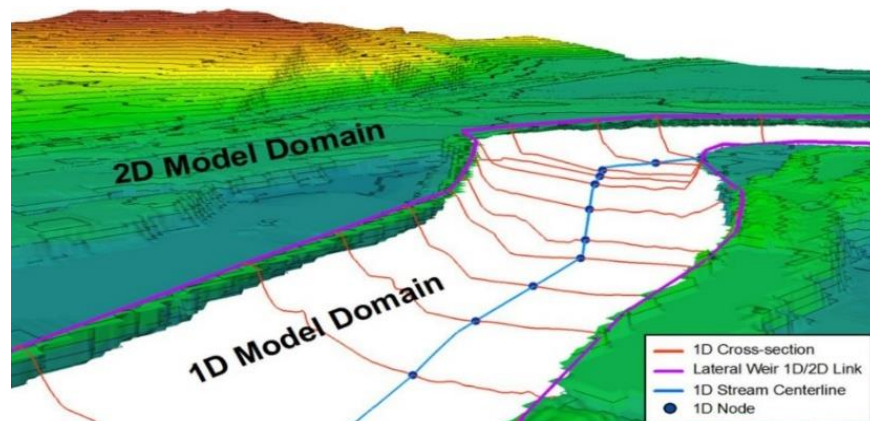


Figure 3. 1D model of the river channel coupled with a 2D model of the floodplain

While 1D models are computationally efficient and effective at representing flow in confined channels and linear networks, they often lack precision in capturing detailed floodplain flow patterns. Conversely, 2D models offer superior detail over floodplains but demand greater computational resources and can struggle with accurately simulating flow

through narrow channel structures like bridges or sluices. To leverage the strengths and mitigate the weaknesses of both methods, coupled 1D-2D models have been developed. These hybrid models simulate channel flow using 1D equations, while floodplain flow is represented with 2D modeling, allowing for detailed flood propagation over wide areas with lower computational costs than a fully 2D model. This approach can accurately depict the interaction between channelized flow and overbank flow, capturing important hydraulic structures and floodplain dynamics with balanced computational efficiency (Figure 3).

3. Climate model

A climate model serves as a mathematical illustration of the physical events that govern the climate. Climate modeling is a method used to simulate the numerous factors that cause climate change. The simulation was performed by characterizing the climatic system using basic physical rules. The model consists of a sequence of equations expressing these laws. Climate models can be slow and expensive to use, even on faster computers, and the findings are merely estimates. The goal is to comprehend the processes and forecast the consequences of these alterations and interactions. It is necessary to simplify how the components of the climate system interact with each other, causing feedback, which in turn requires a large amount of computation to simulate. The solutions begin with an initialized state and study the consequences of modifications to various components of the climate system. The boundary conditions and solar radiation were determined using observational data; however, because the data were incomplete, intrinsic uncertainty occurred (Bagheri & Liu, 2024).

Types of climate models

- ✓Energy Balance Models (EBMs) – 1D
- ✓Radiative Convective (RC) Models- 1D
- ✓Statistical Dynamical (SD) Models -2D
- ✓Global Circulation Models (GCMs)- 3D

4. Global circulation models/ global climate model (GCMs)

Global Circulation Models (GCMs), also known as Global Climate Models, simulate the three-dimensional dynamics of the atmosphere and oceans. These models typically feature higher vertical resolution relative to horizontal resolution in their computational grids, enabling them to represent atmospheric and oceanic processes across different layers of the Earth system. GCMs can include Atmospheric GCMs (AGCMs), Oceanic GCMs (OGCMs), or coupled Atmosphere-Ocean GCMs (AOGCMs). They solve a complex system of nonlinear equations representing physical laws (e.g., conservation of momentum, thermodynamics) through numerical methods based on sequential time-stepping at spatial grid points worldwide.

Despite their global scope, GCM outputs are limited in spatial resolution, generally spanning tens to hundreds of kilometres, which constrains their ability to capture regional or local climate details. This limitation motivates the application of downscaling techniques, which bridge the gap between coarse GCM outputs and finer-scale climate information needed for impact assessments. Downscaling methods include statistical approaches, which use historical observations to establish empirical relationships to GCM outputs, assuming these relationships remain stable over time. This approach is computationally efficient but can be less accurate if changing climate dynamics alter these relationships.

As an alternative, Regional Climate Models (RCMs) provide dynamically downscaled climate data by embedding a higher-resolution model within boundary conditions supplied from GCMs. RCMs typically operate at grid resolutions of 50 km or finer, dramatically enhancing the representation of localized climatic phenomena influenced by topography, land cover, and water bodies. This higher spatial resolution enables RCMs to resolve small-scale features such as mountain ranges, lakes, or urban heat islands, offering more precise regional climate projections. However, RCMs require significant computational resources, limiting their routine use for very long-term or multiple scenario simulations. The increased complexity and data demands necessitate careful model configuration and validation to ensure reliability in climate impact studies and policy formulation (Zhou et al., 2018).

5. Climate change scenarios

These scenarios were provided by the IPCC for projecting future climatic conditions based on the global warming level up to the year 2100 (IPCC, 2023).

5.1 Representative concentration pathway (RCP)

The IPCC uses a Representative Concentration Pathway (RCP) to track greenhouse gas concentrations rather than emissions. Four paths were utilized for climate modeling and research for the IPCC's Fifth Assessment Report (AR5) in 2014. The paths describe various climate futures contracts, all of which are deemed feasible depending on the amount of greenhouse gases (GHG) generated in the future. The RCPs were originally named RCP2.6, RCP4.5, RCP6.0, and RCP8.5 after the potential range of radiative forcing levels in 2100 (2.6, 4.5, 6, and 8.5 W/m²). They are consistent estimates of the radiative forcing components intended to be used as feed for climate modeling, pattern scaling, and atmospheric chemical modeling (IPCC, 2023).

5.2 Shared socioeconomic pathways SSPs

Climate change scenarios for expected worldwide socioeconomic shifts up to 2100 are specified in the IPCC's Sixth Assessment Report on Climate Change, published in 2021. They are used to estimate greenhouse gas emissions projections under various climate strategies

6. Studies on urban flood modeling

Kumar and Umamahesh (2024) analyzed the effects of climate change and urban sprawl on the drainage infrastructure of Zones XII, IV, and V in Hyderabad, India. Their methodology integrated a Markov chain framework with a 1D-2D PCSWMM model to assess flood risks generated by extreme precipitation (1-10 days), which was modeled under four SSP scenarios using CMIP6 GCMs (EC-Earth3-Veg, MPI-ESM-1-2-HR, and MPI-ESM-1-2-LR). Precipitation data was downscaled with the MCPG model, while urban expansion was forecasted using an MC-CA model. Findings indicated more intense rainfall under the EC-Earth3-Veg model, a 6.1% reduction in vegetation, and a 29.06% growth in urban cover by 2075. These changes are projected to expand flood hazard zones, particularly for rainfall events lasting one day or longer. Anuthaman et al. (2023) investigated the influence of Land Use and Land Cover (LULC) change on flooding in Chennai's Adyar watershed. The study focused on this rapidly urbanizing area, which is highly susceptible to floods due to climatic and anthropogenic changes. By analyzing LULC shifts between 2005 and 2015, the researchers projected flood scenarios for 2030 and 2050 using a coupled HEC-HMS and HEC-RAS model. The results forecast a 6% growth in built-up areas and a 74% probability of more intense precipitation by 2050, leading to a projected 19.4% and 60.4% increase in flood depth by 2030 and 2050, respectively. The study proposes constructing flood carrier canals along the downstream river reach as the most effective mitigation strategy. Kumar et al. (2022) assessed climate change implications for urban flooding in two Delhi watersheds: the Jahangirpuri drain and Qudesia Nallah catchments. Utilizing future rainfall projections from Regional Climate Models (RCMs) and a calibrated hydraulic model, the study compared flooding under historical (1990-2016) and future (RCP 4.5, 2021-2100) scenarios. The analysis revealed a substantial rise in flooded areas; the number of flooded nodes increased from 2-6 to 11-51 in the Qudesia Nallah and from 12-43 to 42-91 in the Jahangirpuri drain. The research concludes that future extreme rainfall will cause flooding equivalent to current 20-year events, providing critical information for municipal flood planning.

Das and Sahoo (2025) evaluated the combined impact of land use and climate change on urban flooding in the Extended Bhubaneswar Development Authority zone, India. Climate effects were analyzed using the CMIP6 NorESM2-MM model under SSP 4.5, comparing a baseline period (1985-2014) with future intervals (2015-2050, 2051-2070, 2071-2100). IDF curves indicated rising rainfall intensities. Urban growth, projected via the MOLUSCE plugin in QGIS, predicted impervious surfaces would expand from 51.28% to 81.12% within the municipality and from 16.37% to 34.52% in the extended zone by 2100. SWMM simulations showed increased surface runoff, while HEC-RAS mapping indicated greater flood depths, rising from 0.752 m to 1.18 m for a 100-year event, elevating risk in areas like Nuagaon and Lingipur. These findings are vital for crafting targeted mitigation strategies. Avashia and Garg (2020) studied the influence of land use change on urban flooding for 42 Indian cities under current conditions and future climate scenarios. A hybrid classification technique was applied to Landsat imagery from 1990-2017 to evaluate land-use patterns. A flooding event database, compiled from newspaper archives, was used with a logistic mixed-effects model to project future flooding under three RCPs (2.6, 4.5, 8.5) and urban development scenarios. Results underscore the critical role of preserving green, open, and blue spaces in mitigating flood risk. Flooding events were significantly lower under RCP 2.6 compared to RCPs 4.5 and 8.5, which showed similar high risks. The study advocates for Indian cities to pursue sub-2°C warming goals and adopt integrated spatial planning for resilience.

Table 1 summarizes significant urban flood modeling research from around the world. The listed studies employ a variety of hydrological and hydrodynamic models, such as global hydrological models, SWMM, HEC-RAS, LISFLOOD-FP, InfoWorks ICM, GLOFRIS, and dynamic statistical models. The collective findings reveal considerable escalations in flood risk and consequences driven by climate change (e.g., RCP8.5), urbanization, sea-level rise, and

extreme weather. Key innovations featured in this research involve the merger of advanced climate projections with hydrological frameworks, the use of high-resolution rainfall data, integrated river and urban flood simulations, large-scale risk mapping at pan-European and global levels, and the accounting for tidal and storm surge influences. The knowledge derived from these studies is broadly applicable for improving flood risk evaluation and designing resilient urban systems.

Table 1. Studies on urban flood modelling

Reference	Model Used	Location	Result	Innovation in the study
Arnell & Gosling (2016)	Global hydrological model	Global	Flood risk increases significantly under RCP8.5 scenario; hotspots in Asia and Africa	Integration of CMIP5 climate projections with hydrological models
Miller and Hutchins (2017)	SWMM	Houston, USA	Increased precipitation extremes lead to 35% higher flood frequency	High-resolution rainfall data integrated with storm water models
Lugeri et al. (2010)	HEC-RAS	Central Europe	Riverine and pluvial flooding expected to intensify	Combined river and urban flood modeling
Jongman et al. (2014)	LISFLOOD-FP	Europe	Economic losses from urban flooding could triple by 2080	Pan-European risk mapping under socio-economic and climate scenarios
Yan et al. (2016)	InfoWorks ICM	Shanghai, China	Sea-level rise and urbanization double flood depth	Dynamic modeling of sea-level rise + storm surge impacts
Poussin et al. (2015)	GLOFRIS	Europe	Risk increases disproportionately in northern cities	First large-scale analysis combining hazard + exposure
Moftakhari et al. (2017)	Dynamic statistical models	New Orleans, USA	Nuisance flooding increases 10-fold by 2100	Incorporation of tidal non stationarity
Alfieri et al. (2017)	Global hydrological model	Global	Urban floods may displace 50M by 2080	Global-scale projections combining hydrology + exposure
Mahmood et al., 2025	Multi-model ensemble	Global	Urban flood model accuracy limited by operational constraints	Review highlights potential of ensemble approaches
Zhang et al., 2025	Exposure mapping + hydrological	Global South	Urban flood exposures increasing fastest in Global South	High-res global exposure mapping using new datasets
Bagheri et al., 2024	Remote sensing + hydrodynamics	Multiple cities	Climate change amplifies intensity/extent of urban flooding	Combines remote sensing observations with modeling for flood mapping
Rosenzweig et al., 2021	Urban ecosystem models	USA (multi-city)	Accurate urban flood models improve risk reduction	Numerical models capturing details of city infrastructure

5. Studies on flood mitigation measures

Rapid urbanization has altered the initial hydrological changes in cities and increased the percentage of impermeable areas. Consequently, there is an increased demand for urban water management, such as an increase in the overall risk of urban flooding (Yang et al., 2013). Due to the rise in extreme weather conditions caused by climate change, this scenario is likely to worsen soon (Hu et al., 2017). Antiquated urban rainfall management techniques have proven to be ineffective in certain dangerous situations, such as the 2018 severe rainstorms in western Japan. A sponge city plan was developed in China to address this issue, reduce floods, and enhance water quality (Xia et al., 2017). Building a new metropolitan area concept for flood control, known as a "sponge city," entails boosting ecological structures and drainage networks. Kochi is one of the metropolitan areas that must deal with the problem of rising sea levels. The Greater Cochin Development Authority (GCDA), a government agency mandated to plan the Kochi Corporation and its suburban areas, is charting a course of action to make Kochi the first sponge city in Kerala. The Union government's' sponge city mission will cover 15 urban local bodies of Andhra Pradesh under this initiative, and this plan will rejuvenate 64 water bodies in these 15 cities.



Detention pond



Porous Pavements



Grass swales



Infiltration trench,



Rain garden



Green roof

Figure 6. Low impact design structures

Emerging from North America, the concept of Low Impact Development (LID) is a strategic approach to land management that works in concert with natural systems to treat stormwater at its source. It has become a fundamental component of the sponge city initiative. By emphasizing the infiltration, filtration, storage, evaporation, and detention of runoff, LID techniques effectively mimic a watershed's original hydrologic cycle before urban development. This capacity to promote urban sustainability has captured the attention of planners, designers, and policymakers, who are keenly interested in how LID elements alter hydrological processes. Research consistently shows that implementing LID principles profoundly influences water balance and flood mitigation, notably affecting peak discharge rates, time-to-peak lag, total stormwater volume, and the ratio of precipitation that becomes surface runoff. Zope et al. (2017) assess urban flooding in the Poisar River catchment (20.19 km²) in Mumbai, India, by analyzing land use-land cover (LULC) changes from 1966 to 2009 using toposheets and satellite images. Built-up areas increased from 16.64% to 44.08%, whereas open spaces decreased from 43.09% to 7.38%. Flood assessment was carried out using HEC-HMS, HEC-RAS, and GIS-based models to evaluate floodplain extent and hazards. The results showed a 2.6% to 20.9% increase in peak discharge due to LULC changes, with detention ponds reducing peak discharge by up to 34.5% for higher return periods. Floodplain extent increased by 14.22% to 42.5% from 1966 to 2009, but detention ponds reduced the flood extent by 4.5% to 7.7%. This study highlights the effectiveness of detention ponds in mitigating flood risks and provides valuable flood maps for urban planning and disaster mitigation. The integration of hydrological models with GIS and remote sensing is effective for flood management.

Garg et al. (2018) studied the overexploitation of water resources, which has led to critical scarcity, shifting water management into a "take-make-use-dispose" model. In response, rainwater harvesting offers a sustainable solution within the Circular Economy (CE). In drought-prone Iran, water shortages have increased the need for alternative approaches to water conservation. This study evaluated a low-impact development (LID) scenario in Soltan Abad, Iran, using bioretention, subsurface infiltration, rainwater cisterns, and porous pavements. The results show that these LIDs can manage 60% of annual rainfall-runoff, reducing water stress by reusing rainwater and recharging groundwater, thereby supporting a circular economy. Baltaci and Kalin (2024) evaluated two Low Impact Development (LID) practices, rain barrels and permeable pavements, in a coastal Alabama watershed. The EPA SWMM model was calibrated with 2014-2015 data to identify flood-prone areas using design storms with return periods of 1-100 years. The results showed that LIDs reduced runoff (1-24%), peak flow (18-25%), and water depth (5-15%), helping restore natural flow regimes. However, their effectiveness decreased with longer storm return periods, and rain barrels were the most cost-effective and impactful solution. These studies highlight the potential of LID measures to mitigate flood risks across diverse urban settings. Table 2 represents a various Low Impact Development (LID) practices applied across multiple cities and countries to mitigate urban flood risks. These studies evaluate different LID techniques such as detention ponds, porous pavements, green roofs, infiltration trenches, rain gardens, and retention tanks. The impacts of these practices on flood peak reduction, runoff volume, and overall flood management are highlighted. Notably, the

results demonstrate substantial reductions in peak flow rates and runoff volumes, with some studies reporting peak flow reductions as high as 92%. This collection of research showcases the effectiveness and cost-efficiency of various LID measures in diverse urban contexts, providing valuable insights for sustainable flood mitigation planning.

Table 2. Studies on the effectiveness of LID practices in the reduction of flood peak and volume

Source	LID Implementation	Location	Outcome
Li et al., 2019	Detention pond	SA city, China	Peak flow rate was reduced by nearly 92%.
Palermo et al., 2020	Porous Pavements, Green roof	Paola, Italy	Achieved reductions in runoff and peak flow of up to 45.8% and 54.3%, respectively.
Zhang et al., 2020	Retention tank, grass swales, green roof	Beijing, China	Resulted in a 48.59% decrease in runoff volume and a 67.29% decline in peak flow rate.
Ghodsi et al., 2020	Porous Pavements, Infiltration trench, vegetated swales, Bioretention pond	North-eastern Tehran, Iran	Flood volume was reduced by up to 18%.
Eckart et al., 2018	Porous Pavements, Infiltration trench, Bioretention pond	Ontario, Canada	The infiltration trench was identified as the most cost-effective LID for reducing flood peaks.
Tredway & Havlick, 2017	Porous Pavements, Rain garden, Stream Naturalization	Colorado, USA	Runoff reduced by 18.8% (Porous Pavements), 4.7% (Rain Garden), 12.3% (Stream Naturalization), and 32.7% when combined.
Ahmed et al., 2017	Infiltration trench	Johor, Malaysia	Peak flow was successfully reduced within a range of 17.5% to 20.95%.

Conclusion

Urban flooding has become a growing concern, especially in developing regions like India, due to the combined impacts of climate change and rapid urban expansion. Employing Markov chain-driven methods for detailed land use forecasting supports more accurate urban flood assessments, urban design, and informed policy actions. The expansion of cities and increasingly variable weather patterns contribute to heightened flood risks, as increased areas of impermeable surfaces and unpredictable rainfall intensify surface runoff. Advanced forecasting and simulation tools such as climate models, the Markov Chain Precipitation Generator, PCSWMM, and HEC-HMS play vital roles in anticipating flood events. Incorporating Low Impact Development (LID) practices, including features like permeable pavements and green roofs, is effective in lessening flood impacts by controlling stormwater runoff. For communities to better withstand flood hazards linked to shifts in climate and land use, urban planners and policymakers should emphasize improving stormwater infrastructure, protecting natural water retention zones, and adopting sustainable drainage systems to strengthen overall resilience.

Way forward

Future research should focus on improving flood risk assessments by utilizing long-term data from rain gauge stations for better downscaling accuracy. Incorporating hydrological models like lumped, semi-distributed, and distributed models will help account for regional rainfall variability in flood projections. Feasibility studies on canal construction in metropolitan areas should be conducted to manage flood risks effectively. Additionally, non-structural methods, such as forestry interventions, should be explored alongside traditional solutions. Integrating Low Impact Development (LID) infrastructure and sustainable drainage systems will enhance urban flood resilience, while the development of smart flood monitoring systems can improve flood forecasting. Active community and stakeholder engagement is essential for successful flood mitigation and urban sustainability.

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AI tool usage declaration

No AI tools have been used in manuscript preparation. Grammarly software is used to correct grammatical errors.

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