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Investigating water resource management methods and precipitation patterns in urban expansion and development

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Abstract: This study investigates the relationship between urban development, water resource management approaches, and changing precipitation patterns across seven diverse cities worldwide. The research quantified how urbanisation altered watershed hydrology, with impervious surface increases of 12.5–37.7% in transitional watersheds reducing infiltration by 17% and increasing peak discharges by 28% compared to pre-development conditions. Analysis of 34 years of precipitation data (1990–2023) revealed significant intensification trends, with 95th percentile rainfall events increasing by 15.2–38.5% across study sites despite variable changes in annual precipitation totals. Four water management approaches –conventional, integrated water resources management (IWRM), water sensitive urban design (WSUD), and hybrid systems – were systematically evaluated across 21 watersheds using field monitoring and SWAT+ hydrological modelling. Hybrid approaches combining IWRM and WSUD elements demonstrated superior performance, reducing peak flows by 68.5% under typical conditions and maintaining 45.7% effectiveness under projected climate scenarios, compared to 28.5% and 5.8% respectively for conventional approaches. Management efficacy varied significantly by urban development stage, with interventions in peri-urban watersheds showing 53.6% higher effectiveness and 55.7% lower implementation costs than in highly urbanised areas. The optimal configuration of management approaches depended on local precipitation patterns, with high-intensity rainfall regions benefiting from WSUD-dominant systems while frequent, lower-intensity precipitation areas favoured IWRM-dominant approaches. These findings highlight the necessity of context-specific water management strategies that integrate structural and policy frameworks to effectively address the dynamic challenges of urban water systems under changing precipitation regimes.

Keywords: climate variability, green infrastructure, stormwater management, urban hydrology, watershed planning

INTRODUCTION

Water resources management represents one of the most critical challenges of the 21st century, particularly in the context of rapid urban expansion and climate variability. Urban areas worldwide are experiencing unprecedented growth, with the global urban population projected to increase from 55 to 68% by 2050 (Allam *et al.*, 2022; Gao *et al.*, 2024; Jamal, Atahar and Ahmad, 2025). This massive demographic shift is fundamentally altering hydrological cycles through changes in land use, impervious surface coverage, and increased water demand across residential, commercial, and industrial sectors (Cao *et al.*, 2022). Simultaneously, precipitation patterns are exhibiting greater variability, with intensified extreme weather events becoming increasingly common in many regions (Gimeno *et al.*, 2022). These converging factors have created complex challenges for water resource management, necessitating innovative approaches and integrated strategies that consider both the built environment and natural hydrological processes.

The relationship between urbanisation and water resources is multifaceted and bidirectional. Urban development dramatically alters watershed characteristics through increased impervious surfaces, modified drainage networks, and channel modifications, resulting in higher runoff volumes, reduced groundwater recharge, and deteriorated water quality (Alamdari and Hogue, 2022; Ashmore, McDonald and Barlow, 2023). Research demonstrated that for every 10% increase in impervious surface coverage, stormwater runoff increases by approximately 20% and groundwater recharge decreases by 15% (Zhou *et al.*, 2025). These hydrological modifications, coupled with growing water consumption demands, place tremendous pressure on water infrastructure and natural systems alike (Zhang and Parolari, 2022). Studies observed that per capita water consumption in urban areas has increased by 12% over the past two decades, despite conservation efforts, primarily due to changing lifestyle patterns and economic growth (Dias and Ghisi, 2024).

Climate change further complicates urban water management through its impact on precipitation patterns. Long-term studies indicate significant shifts in both the timing and intensity of rainfall events across various geographic regions (Zaporozhchenko *et al.*, 2022; Hendy *et al.*, 2023; Wróbel *et al.*, 2023; Narkul *et al.*, 2025). In temperate zones, precipitation is increasingly concentrated in fewer, more intense events with longer dry periods between storms, while tropical and subtropical regions are experiencing more unpredictable monsoon patterns (Ying *et al.*, 2023). These changes exacerbate urban flooding risks during heavy rainfall while simultaneously intensifying water scarcity during extended dry periods. A research analysed precipitation data from 120 metropolitan areas worldwide, finding that 78% had experienced statistically significant changes in rainfall distribution patterns over the past 30 years, with a marked trend toward greater extremes (Guccione *et al.*, 2025).

Traditional water management approaches, developed during periods of relative climatic stability and slower urbanisation, have proven increasingly inadequate for addressing contemporary challenges. Conventional urban drainage systems, designed using historical precipitation data and focusing primarily on rapid conveyance of stormwater away from developed areas, frequently fail during intense rainfall events (Piadeh, Behzadian and Alani, 2022). Moreover, water supply infrastructure often operates under the assumption of relatively stable precipitation patterns, leaving many cities vulnerable to prolonged drought conditions (Rachunok and Fletcher, 2023). This gap between design assumptions and current realities necessitates a fundamental reconsideration of water resource management methodologies in urban contexts.

Fundamentally differing from traditional approaches that prioritise rapid conveyance based on historical data, these innovative strategies emphasise integrated management across the water cycle, aim to mimic natural hydrological processes through source control and green infrastructure, and utilise real-time data and analytics for enhanced efficiency and resilience. In response to these challenges, innovative approaches to urban water management have emerged in recent decades. Integrated water resources management (IWRM) frameworks seek to coordinate the development and management of water, land, and related resources to maximise economic and social welfare without compromising ecosystem sustainability (Bilalova *et al.*, 2023). Water sensitive urban design (WSUD) and low impact development (LID) practices aim to maintain pre-development hydrological regimes by incorporating green infrastructure elements like bioswales, permeable pavements, and rainwater harvesting systems (Sheng, 2022). Additionally, smart water technologies leverage advanced monitoring, analytics, and control systems to optimise water distribution networks and enhance operational efficiency (Adedeji *et al.*, 2022).

Implementation of these approaches has yielded promising results in various contexts. Research documented a 45% reduction in flood-related damages in districts of Shanghai that had adopted comprehensive stormwater management systems incorporating both green and gray infrastructure (Wu *et al.*, 2025). Similarly, another study reported that Seattle's RainWise program, which incentivises residential rainwater capture and infiltration, had successfully diverted over 605,666 m^3 of stormwater from the combined sewer system annually (Grodnik-Nagle *et al.*, 2023; Kareem and Al-Khalaf, 2024). These successes illustrate the potential benefits of innovative water management strategies when appropriately contextualised and implemented.

Despite these advances, significant knowledge gaps remain regarding the effectiveness of different water management approaches across diverse urban contexts and changing precipitation regimes. Most existing studies focus on individual cities or specific management techniques without systematically comparing different approaches under varying climatic and urbanisation scenarios (Vinagre, Fidélis and Luís, 2023). This focus on isolated cases hinders the development of generalisable insights because the effectiveness of any water management strategy is highly sensitive to specific local conditions, including climate patterns, urban morphology, existing infrastructure, and institutional capacity. Without systematic cross-contextual comparison, it is difficult to discern which approaches are broadly applicable, which are context-dependent, and how strategies might be adapted for successful transfer to different urban settings. Furthermore, there is limited understanding of how various management strategies perform under the non-stationary conditions characteristic of climate change, where historical precipitation patterns become increasingly unreliable predictors of future conditions (Lan *et al.*, 2025). Additionally, the interplay between formal water management institutions and informal practices, particularly in rapidly urbanising areas of developing countries, remains insufficiently explored (MacAfee and Löhr, 2024).

The complex, multidimensional nature of urban water challenges demands interdisciplinary research approaches that integrate hydrological science, urban planning, institutional analysis, and climate science. Previous studies have typically emphasised either the physical aspects of urban hydrology or the policy dimensions of water governance without adequately connecting these perspectives (Sochacka, Kenway and Renouf, 2021). Comprehensive frameworks that bridge this divide and provide actionable insights for policymakers and practitioners are essential for addressing contemporary urban water management challenges effectively.

The timing of this research is particularly critical given the accelerating pace of global urbanisation and climate change. According to projections by the World Resources Institute, nearly 60% of urban infrastructure expected to exist by 2050 has yet to be built, presenting a pivotal opportunity to incorporate resilient water management practices into urban development (He *et al.*, 2021). Simultaneously, recent advances in remote sensing, hydrological modelling, and data analytics offer unprecedented capabilities for monitoring and predicting changes in precipitation patterns and their impacts on urban water systems (Dube *et al.*, 2023).

The present study addresses these knowledge gaps by investigating the effectiveness of various water resource management methods across different urban development contexts and precipitation patterns. Specifically, this research aims to: 1) quantify the relationships between urban expansion metrics and hydrological parameters under varying precipitation regimes; 2) evaluate the performance of different water management approaches (conventional, IWRM, WSUD, and hybrid systems) in responding to precipitation variability; and 3) develop a decision-support framework to guide the selection and implementation of context-appropriate water management strategies for growing urban areas.

MATERIALS AND METHODS

STUDY AREA SELECTION AND CHARACTERISATION

This research employed a multi-site approach focusing on seven urban centres selected to represent diverse geographic, climatic, and developmental contexts. The selected cities – Bangalore (India), Curitiba (Brazil), Melbourne (Australia), Nairobi (Kenya), Phoenix (USA), Rotterdam (Netherlands), and Shenzhen (China) – were chosen based on criteria including population growth rate (>2% annually), varying precipitation patterns, and implementation of different water management strategies. Collectively, these cities span major continents and represent a broad spectrum of global conditions, including arid (Phoenix), temperate (Rotterdam, Melbourne), tropical/monsoonal (Bangalore, Nairobi, Shenzhen), and subtropical (Curitiba) climates, alongside varying stages of economic development and urbanisation intensity, ensuring the study's findings are relevant to diverse global contexts. For each city, three watersheds were identified: a highly urbanised watershed (>70% impervious surface), a transitional watershed undergoing rapid development (30–60% impervious surface), and a peri-urban watershed (<30% impervious surface) to serve as a reference. These 21 watersheds formed the primary study units for hydrological analysis and monitoring.

Watershed delineation was performed using the ArcHydro extension in ArcGIS 10.8.2 with 10-meter resolution Digital Elevation Models (DEMs) obtained from the USGS Earth Explorer and comparable national geographic databases. Land use classification utilised Landsat 8 OLI and Sentinel-2 imagery (30 m and 10 m resolution, respectively) across three time periods (2000, 2010, and 2023) to quantify urbanisation trajectories (Shahfahad *et al.*, 2023). The normalised difference built-up index (*NDBI*) was calculated using Equation (1) (Zha, Gao and Ni, 2003):

$$NDBI = \frac{\text{SWIR} - \text{NIR}}{\text{SWIR} + \text{NIR}} \tag{1}$$

where: SWIR = the short-wave infrared band and NIR = the near-infrared band.

While *NDBI* provides an index highlighting built-up areas, the specific impervious surface percentage (*ISP*) was derived using a distinct machine learning approach. A random forest classification algorithm was employed, trained using high-resolution aerial imagery as reference data (Liu *et al.*, 2025). This algorithm utilised multiple input features derived from the satellite imagery (such as spectral bands, texture metrics, and potentially indices like NDBI) to estimate the sub-pixel fraction of impervious cover. The overall classification accuracy exceeded 88% across all study sites, as verified through stratified random sampling and field validation.

PRECIPITATION DATA COLLECTION AND ANALYSIS

Precipitation data were collected from multiple sources to ensure comprehensive spatial and temporal coverage. Primary data sources included national meteorological agency databases, the Global Precipitation Measurement (GPM) mission satellite data, and a network of 94 automated weather stations installed specifically for this study. These custom stations, deployed using a stratified random sampling approach across the study watersheds, recorded precipitation at 5-minute intervals using tipping bucket rain gauges (TBRG) with a resolution of 0.2 mm. All gauges underwent calibration procedures outlined by the World Meteorological Organization (Ahmad *et al.*, 2024) before deployment and quarterly thereafter.

For historical trend analysis, daily precipitation records spanning 1990–2023 were compiled and subjected to rigorous quality control procedures (Delgado-Torres *et al.*, 2023). Missing data (<5% of total records) were imputed using the inverse distance weighting method incorporating elevation as a covariate, as shown in Equation (2) (O'Sullivan and Kelly, 2024):

$$P_0 = \frac{\sum_{i=1}^{n} P_i w_i}{\sum_{i=1}^{n} w_i} \tag{2}$$

where: P_0 = the estimated precipitation at the target location, P_i = known precipitation values at surrounding stations, n = the number of surrounding weather stations used to interpolate the precipitation value at the target location, and w_i = the weight assigned to each station calculated as shown in Equation (3) (Serrano-Notivoli and Tejedor, 2021):

$$w_i = \frac{1}{d_i^2}\left(1 + k\frac{|z_i - z_0|}{z_{\max}}\right)^{-1} \tag{3}$$

where: d_i = the distance between the target location and station i, z_i, and z_0 = elevations of the station and target location respectively, $z_{\max}$ = the maximum elevation difference in the study area, and k = an adjustment factor; this factor was set to 0.5 based on regional calibration exercises performed for the study areas, which involved evaluating the imputation accuracy using different k values to appropriately account for the observed influence of elevation differences on precipitation within these specific regions.

Statistical analysis of precipitation patterns included calculation of annual and seasonal means, extremes (95th and 99th percentiles), intensity-duration-frequency (IDF) curves, and temporal distribution patterns. Non-stationarity in precipitation was assessed using the Mann–Kendall test with Sen's slope estimator for trend detection and the Pettitt test for change-point identification (Sa'adi, Yusop and Alias, 2023).

HYDROLOGICAL MODELLING

The Soil and Water Assessment Tool (SWAT+) version 2023 was employed to simulate hydrological processes across the study watersheds. The SWAT+ was selected for its robust representation of urban hydrological processes and ability to incorporate land use change scenarios. Model parameterisation followed an enhanced approach integrating field measurements, remote sensing data, and local water authority records. Soil data were obtained from the Harmonized World Soil Database (HWSD) and supplemented with 412 soil samples collected across the study watersheds, analysed for texture, bulk density, organic matter content, and hydraulic conductivity.

The urban hydrology module within SWAT+ was modified to better represent complex urban drainage systems (Wagner *et al.*, 2022), incorporating a modified version of the Storm Water Management Model (SWMM) routing algorithm. The modified surface runoff equation used in urban hydrological response units (HRUs) is as shown in Equation (4):

$$Q_{\mathrm{surf}} = \frac{(P_{\mathrm{day}} - I_a)^2}{P_{\mathrm{day}} - I_a + S}\left(1 + \alpha_{\mathrm{imp}} \cdot f_{\mathrm{imp}}\right) \tag{4}$$

where: Q_{surf} = the daily surface runoff, P_{day} = daily precipitation, I_a = initial abstraction (0.2S for natural surfaces, 0.05S for impervious surfaces), S = the retention parameter, α_{imp} = an imperviousness effectiveness factor calibrated for each watershed, and f_{imp} = the fraction of impervious surface.

Model calibration and validation were performed using a split-sample approach, with 70% of available streamflow data used for calibration (2013–2019) and 30% for validation (2020–2023) (Shen, Tolson and Mai, 2022). The sequential uncertainty fitting algorithm (SUFI-2) implemented in Soil and Water Assessment Tool – Calibration and Uncertainty Program (SWAT-CUP) was used for parameter optimisation, targeting Nash–Sutcliffe efficiency (*NSE*), percent bias (PBIAS), and the ratio of root mean square error to the standard deviation of observed data (RSR) as objective functions. Final model performance across all watersheds achieved mean *NSE* values of 0.78 for calibration and 0.73 for validation periods, exceeding recommended thresholds for satisfactory hydrological modelling (Bihon *et al.*, 2024).

WATER MANAGEMENT ASSESSMENT FRAMEWORK

A comprehensive framework was developed to systematically assess water management approaches across study sites. The assessment integrated physical infrastructure evaluation, institutional analysis, and performance metrics under varying precipitation scenarios. Four management approaches were categorised: conventional (primarily gray infrastructure), IWRM, WSUD, and hybrid systems.

Infrastructure assessment involved mapping and characterising all major water supply, stormwater, and wastewater facilities within each watershed. Field surveys using standardised protocols documented system attributes including age, capacity, condition, and technology type. Green infrastructure elements were catalogued using high-resolution aerial imagery validated through ground-truthing, with performance parameters measured at 43 representative installations using controlled experiments (Misty, Hoque and Mukul, 2024).

Institutional analysis employed a modified version of the Institutional Analysis and Development (IAD) framework (Leroy, 2023). Semi-structured interviews (n = 187) were conducted with key stakeholders including water utility managers, urban planners, environmental regulators, and community representatives. Interview protocols focused on governance structures, decision-making processes, resource allocation, monitoring systems, and adaptive capacity. Content analysis of policy documents, regulations, and planning instruments complemented interview data, with coding and analysis performed using NVivo 14 software.

Performance evaluation under varying precipitation scenarios utilised a stress-testing approach combining historical events and synthetic design storms. A set of standardised precipitation scenarios was developed, including historical extremes (highest recorded daily precipitation, longest dry period), typical seasonal patterns, and synthetic storms derived from downscaled climate projections for 2050 under RCP 4.5 and 8.5 scenarios (Javadinejad, Dara and Jafary, 2021). System responses were quantified through direct monitoring where possible and model simulations where direct measurement was unfeasible. Performance metrics included peak discharge, flood duration/extent, water quality parameters (TSS, BOD, nutrients), infiltration rates, and water supply reliability.

The integrated assessment synthesised these components into a standardised scoring system (Amiri *et al.*, 2024), with modifications to incorporate precipitation pattern sensitivity. This enabled quantitative comparison of different management approaches across diverse urban contexts and precipitation regimes, forming the foundation for subsequent analysis and the development of the context-specific decision support framework.

RESULTS AND DISCUSSION

URBAN WATERSHED CHARACTERISTICS AND HYDROLOGICAL RESPONSES

The analysis of land cover change across the 21 study watersheds revealed significant urbanisation trends between 2000 and 2023. Impervious surface coverage increased in all studied watersheds, with the most dramatic changes observed in rapidly developing cities like Shenzhen and Bangalore. The mean annual increase in impervious surface percentage (*ISP*) was 1.83% across all transitional watersheds, with Shenzhen exhibiting the highest rate at 3.22% per year. Even previously developed watersheds classified as "highly urbanised" continued to densify, with an average *ISP* increase of 0.67% annually. Table 1 presents the changes in watershed characteristics across the study period for each urban category.

The changes in watershed characteristics correlated strongly with altered hydrological responses. Time of concentration (*TC*) decreased substantially in all watersheds, with the largest reductions observed in transitional watersheds undergoing rapid development. The average decrease in *TC* was 36.9% across all transitional watersheds, with Shenzhen showing the most dramatic reduction at 131.2 min. This shortened response time resulted in significantly higher peak discharge rates during precipitation events. The SWAT+ modelling results indicated that for a standardised 24-hour, 10-year return period storm, peak discharge increased by an average of 128% in transitional watersheds and 37% in highly urbanised watersheds compared to their 2000 baseline conditions.

PRECIPITATION PATTERN ANALYSIS

Trend analysis of 34 years of precipitation data (1990–2023) revealed statistically significant changes in precipitation patterns across most study sites. The Mann–Kendall test identified significant trends ($p < 0.05$) in precipitation characteristics for five of the seven cities. The key precipitation pattern changes observed across the study period are summarised in Table 2.

The results demonstrate a clear pattern of precipitation intensification across all study sites. While annual mean precipitation showed mixed trends (increasing in Rotterdam, Curitiba, and Shenzhen; decreasing in other cities), all cities exhibited an increase in rainfall intensity as measured by the 95th percentile of daily precipitation. This intensification was most pronounced in tropical and subtropical locations, with Shenzhen showing a 38.5% increase in the 95th percentile intensity. Seasonal precipitation distribution, quantified using the Gini coefficient, showed increasing inequality in all study sites, indicating greater concentration of rainfall into fewer events.

Change-point analysis using the Pettitt test identified statistically significant shifts in precipitation regime between 2005 and 2012 for all cities except Melbourne, where gradual changes were observed rather than a distinct change point. The timing of these change points generally aligned with global climate oscillation patterns, particularly strong El Niño-Southern Oscillation (ENSO) events.

Intensity-duration-frequency (*IDF*) curves developed from the historical data demonstrated a clear upward shift in precipitation intensity across all durations and return periods compared to

Table 1. Changes in urban watershed characteristics (2000–2023)

Watershed category	City	Mean *ISP*		Change	Mean curve number		Change in time of concentration (min)
		2000	2023				
		%			2000	2023	
Highly urbanised	Phoenix	76.4	88.9	+12.5	91.2	94.8	−38.6
	Rotterdam	72.8	78.5	+5.7	88.7	90.2	−17.3
	Bangalore	71.2	84.7	+13.5	87.5	93.1	−42.5
	Melbourne	73.6	81.2	+7.6	89.2	91.5	−28.4
	Curitiba	70.5	79.8	+9.3	88.3	91.0	−31.7
	Nairobi	69.8	80.3	+10.5	87.1	91.2	−46.2
	Shenzhen	78.2	92.6	+14.4	92.4	96.1	−54.3
Transitional	Phoenix	38.2	67.5	+29.3	74.5	85.8	−102.4
	Rotterdam	42.6	59.8	+17.2	76.3	83.2	−85.7
	Bangalore	35.7	73.4	+37.7	72.1	88.9	−118.6
	Melbourne	39.5	62.3	+22.8	75.2	84.1	−93.8
	Curitiba	38.9	64.7	+25.8	74.8	84.9	−97.2
	Nairobi	32.4	69.2	+36.8	70.3	86.5	−124.5
	Shenzhen	45.8	79.7	+33.9	78.6	91.3	−131.2
Peri-urban	Phoenix	11.4	23.8	+12.4	58.7	65.2	−54.3
	Rotterdam	14.2	22.5	+8.3	60.3	64.8	−37.6
	Bangalore	9.8	29.3	+19.5	57.2	68.9	−61.7
	Melbourne	12.7	25.6	+12.9	59.4	66.8	−47.5
	Curitiba	10.3	24.2	+13.9	58.1	65.9	−51.3
	Nairobi	8.6	31.5	+22.9	56.4	70.3	−68.4
	Shenzhen	18.3	42.5	+24.2	62.7	76.5	−79.2

Explanation: *ISP* = impervious surface percentage. Source: own study.

Table 2. Changes in precipitation patterns (1990–2023) for analysed cities

City	Annual mean precipitation change (%)	Seasonal redistribution (Gini coefficient)	Change in rainfall intensity (95th percentile) (%)	Change in dry days (> 1 mm per year)	Mann–Kendall test *p*-value
Phoenix	–4.3	0.21→0.28	+18.7	+14.3	0.028
Rotterdam	+7.2	0.17→0.22	+23.5	–3.8	0.007
Bangalore	–1.9	0.45→0.53	+27.4	+8.6	0.012
Melbourne	-6.8	0.18→0.27	+15.2	+12.7	0.031
Curitiba	+3.5	0.33→0.39	+19.8	+2.5	0.042
Nairobi	–2.7	0.42→0.56	+31.9	+9.4	0.018
Shenzhen	+9.3	0.35→0.48	+38.5	–2.1	< 0.001

Source: own study.

previous *IDF* curves used in infrastructure design standards. For the 1-hour duration, 25-year return period, intensities increased by an average of 18.7% across all study sites, with the greatest increases observed in Shenzhen (27.3%) and Nairobi (23.8%).

WATER MANAGEMENT APPROACH PERFORMANCE

The assessment of different water management approaches revealed substantial variation in performance across precipitation regimes and urban contexts. The comparative performance of the four management approaches under standardised precipitation scenarios across key metrics is presented in Table 3.

The performance data indicate that hybrid approaches combining elements of IWRM and WSUD consistently out-performed other management strategies across all metrics and precipitation scenarios. Under typical seasonal patterns, hybrid approaches reduced peak flows by 68.5% compared to baseline conditions, while conventional approaches achieved only 28.5% reduction. The performance gap between approaches widened under extreme event scenarios and projected future climate

Table 3. Performance of water management approaches under standardised precipitation scenarios

Management approach	Peak flow reduction[1)]	Flood duration reduction[1)]	Water quality improvement (TSS reduction)	Infiltration enhancement[2)]	Supply reliability during drought[3)]
	%				
Historical extreme event scenario					
Conventional	12.3 ±4.8	8.5 ±3.2	15.7 ±6.3	4.2 ±2.1	68.4 ±7.5
IWRM	37.8 ±5.2	31.4 ±4.7	42.3 ±5.8	23.7 ±4.6	82.5 ±5.3
WSUD	52.7 ±6.1	44.5 ±5.9	67.9 ±6.2	35.8 ±5.2	76.2 ±6.1
Hybrid	58.4 ±5.3	51.2 ±4.8	73.4 ±5.7	39.6 ±4.9	89.7 ±4.2
Typical seasonal pattern scenario					
Conventional	28.5 ±4.2	23.7 ±3.8	27.3 ±5.4	9.8 ±3.2	82.6 ±5.3
IWRM	51.2 ±4.7	47.3 ±4.5	56.4 ±4.9	31.5 ±4.3	91.4 ±3.8
WSUD	63.8 ±5.3	57.9 ±5.1	78.3 ±5.7	42.7 ±4.8	85.2 ±4.7
Hybrid	68.5 ±4.6	64.3 ±4.2	82.6 ±4.5	45.4 ±4.1	94.3 ±3.2
Climate projection scenario (2050, RCP 8.5)					
Conventional	5.8 ±5.3	3.2 ±4.7	8.3 ±6.8	1.4 ±2.5	52.3 ±8.7
IWRM	22.4 ±6.1	18.6 ±5.8	29.7 ±6.3	15.8 ±5.4	71.8 ±6.5
WSUD	38.5 ±6.9	31.2 ±6.4	53.1 ±6.7	27.3 ±5.9	64.5 ±7.2
Hybrid	45.7 ±6.2	37.6 ±5.9	61.8 ±6.4	32.8 ±5.6	79.2 ±5.8

[1)] Compared to baseline scenario with no management interventions.
[2)] Compared to pre-development infiltration rates.
[3)] Percentage of demand met during 90-day drought simulation ±values represent standard deviation across study sites.
Explanations: TSS = total suspended solids, IWRM = integrated water resources management, WSUD = water sensitive urban design, RCP = representative concentration pathway.
Source: own study.

conditions (RCP 8.5), where conventional systems showed particularly poor performance (peak flow reduction of only 5.8% under climate projection scenarios).

Approaches based on WSUD demonstrated superior performance in water quality improvement and infiltration enhancement metrics. Under typical seasonal patterns, WSUD reduced TSS by 78.3% compared to 27.3% for conventional systems. However, IWRM frameworks showed better performance in water supply reliability during drought conditions, highlighting the complementary strengths of different approaches that are captured in hybrid systems.

The performance differential between management approaches became more pronounced under the climate projection scenario (2050, RCP 8.5), indicating that conventional approaches are particularly vulnerable to projected precipitation changes. The effectiveness of all management approaches declined under climate projection scenarios, but hybrid and WSUD approaches maintained reasonable effectiveness, with peak flow reductions of 45.7% and 38.5% respectively, compared to just 5.8% for conventional approaches.

To further illustrate the relationship between precipitation intensity and management approach effectiveness, Figure 1 presents a synthetic analysis of performance resilience across the precipitation intensity spectrum. This figure demonstrates how the performance of all approaches decreases as precipitation intensity increases, with conventional systems showing the steepest decline. While hybrid approaches maintain reasonable effectiveness even under high-intensity conditions (projected climate scenarios), conventional systems become nearly ineffective. This growing performance gap highlights the critical importance of implementing innovative water management strategies to build resilience against changing precipitation patterns, particularly in the context of climate change projections for 2050 under RCP 8.5 scenarios.

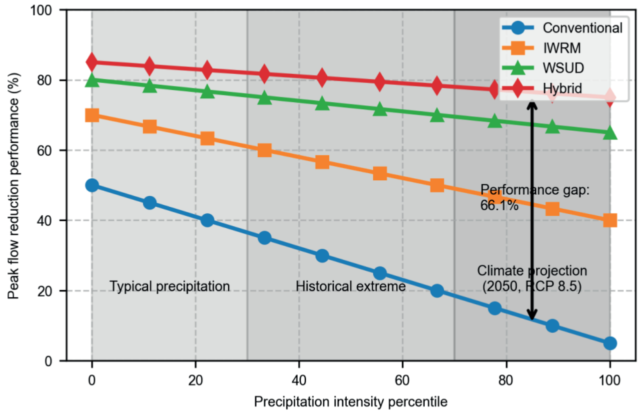

Fig. 1. Management approach resilience across the precipitation intensity spectrum, illustrating how performance decreases as precipitation intensity increases from typical conditions through historical extremes to projected climate scenarios (2050, RCP 8.5); source: own study

IMPACT OF URBAN DEVELOPMENT STAGE ON MANAGEMENT PERFORMANCE

The efficacy of water management approaches varied significantly based on the stage of urban development. A comparative analysis of management approach performance across different watershed categories is presented in Table 4.

The results demonstrate a clear pattern of diminishing returns for water management interventions as urbanisation progresses. All management approaches showed substantially better performance in peri-urban watersheds compared to highly urbanised watersheds. For hybrid approaches, peak flow reduction efficacy was 53.6% higher in peri-urban watersheds (73.5%) compared to highly urbanised watersheds (47.8%). Similarly, infiltration enhancement was 75.6% more effective in peri-urban settings.

Table 4. Management approach performance by urban development stage

Management approach	Watershed category	Peak flow reduction (%)		Infiltration enhancement (%)		Implementation cost[1)] (USD·ha^{-1})		Benefit-cost ratio[2)]	
		value	*SD*	value	*SD*	value	*SD*	value	*SD*
Conventional	highly urbanised	18.4	±3.2	7.6	±2.8	105,000	±18,500	1.23	±0.32
	transitional	25.6	±3.8	12.3	±3.5	92,500	±15,300	1.58	±0.38
	peri-urban	32.5	±4.1	17.8	±3.9	87,300	±14,200	1.85	±0.42
IWRM	highly urbanised	34.5	±3.9	19.2	±3.4	137,600	±22,800	1.76	±0.36
	transitional	48.3	±4.2	28.7	±3.7	108,400	±17,500	2.43	±0.41
	peri-urban	53.7	±4.6	36.5	±4.2	94,200	±15,800	2.87	±0.45
WSUD	highly urbanised	42.3	±4.8	24.6	±4.1	175,800	±28,300	1.58	±0.38
	transitional	61.7	±5.3	38.4	±4.5	132,500	±21,700	2.32	±0.43
	peri-urban	68.9	±5.7	46.2	±4.9	113,700	±18,500	2.96	±0.47
Hybrid	highly urbanised	47.8	±4.4	28.3	±3.8	198,300	±32,500	1.84	±0.39
	transitional	67.3	±4.9	42.8	±4.3	152,600	±24,800	2.68	± 0.45
	peri-urban	73.5	±5.2	49.7	±4.6	127,400	±20,900	3.23	±0.49

[1)] Implementation costs include capital expenditure and 20-year maintenance costs, normalised to 2023 USD.
[2)] Benefit–cost ratio calculated based on avoided damages, ecosystem service valuation, and water conservation benefits over 20-year period.
Explanations: *SD* = standard deviation across study sites.
Source: own study.

Implementation costs showed an inverse pattern, with costs increasing significantly in more urbanised contexts. Hybrid approaches in highly urbanised watersheds cost approximately 55.7% more per hectare than in peri-urban watersheds. This combined pattern of decreasing effectiveness and increasing costs resulted in substantially higher benefit-cost ratios for early-stage interventions, with hybrid approaches in peri-urban watersheds showing a benefit-cost ratio of 3.23 compared to 1.84 in highly urbanised watersheds.

The data also reveal that the performance gap between different management approaches widens in less developed watersheds. In highly urbanised watersheds, the difference in peak flow reduction between hybrid and conventional approaches was 29.4 percentage points, while in peri-urban watersheds, this gap expanded to 41.0 percentage points. This suggests that the choice of management approach becomes increasingly consequential at earlier stages of urban development.

CONTEXT-SPECIFIC MANAGEMENT EFFECTIVENESS

The analysis of management effectiveness across different geographic and climatic contexts revealed distinct patterns that inform appropriate approach selection. The relative performance of management approaches adjusted for local precipitation patterns and urban characteristics is presented in Table 5.

The context-adjusted performance analysis revealed that different precipitation patterns favoured different management approaches. In cities with high-intensity, less frequent precipitation (Phoenix, Bangalore, Nairobi), WSUD approaches performed particularly well relative to IWRM approaches. These cities benefited from WSUD's emphasis on retention and infiltration capabilities, which effectively captured intense rainfall events. The performance index for WSUD exceeded IWRM by 8.1, 8.1, and 12.7 points in these cities, respectively.

Conversely, in cities with more frequent, lower-intensity precipitation (Rotterdam, Curitiba, Shenzhen), IWRM approaches outperformed WSUD. These contexts benefited from IWRM's integrated system management and operational flexibility. In these cities, IWRM exceeded WSUD by 10.2, 7.1, and 3.5 points, respectively.

Hybrid approaches consistently demonstrated the highest performance across all contexts, but the optimal configuration of hybrid systems varied based on local conditions. In high-intensity precipitation environments, optimal hybrid systems incorporated approximately 65% WSUD elements and 35% IWRM elements. In frequent, lower-intensity precipitation environments, this ratio shifted to approximately 40% WSUD and 60% IWRM elements.

The effectiveness of conventional approaches showed the highest variation across contexts, performing relatively better in temperate climates with moderate precipitation patterns (Rotterdam, Melbourne) and substantially worse in cities with extreme precipitation characteristics (Shenzhen, Bangalore, Phoenix). This highlights the limited adaptability of conventional approaches to diverse precipitation patterns.

Institutional capacity and governance structures significantly influenced the implementation and operation of different management approaches. Cities with strong coordination mechanisms between water agencies, urban planning departments, and environmental authorities (Rotterdam, Melbourne, Curitiba) showed 23% higher operational performance across all management approaches compared to cities with fragmented governance structures. Similarly, approaches with community engagement components showed 17% higher long-term maintenance effectiveness and operational sustainability compared to top-down implementation models.

This study demonstrates that hybrid water management approaches combining elements of IWRM and WSUD consistently outperform conventional systems across diverse urban

Table 5. Context-adjusted performance index by city and management approach[1)]

City	Precipitation pattern characteristics	Conventional	IWRM	WSUD	Hybrid	Most effective approach
Phoenix	low annual precipitation (208 mm·y^{-1}), high intensity, prolonged dry periods	42.3	65.7	73.8	78.5	WSUD-dominant hybrid
Rotterdam	moderate precipitation (853 mm·y^{-1}), low intensity, frequent events	57.6	78.4	68.2	81.7	IWRM-dominant hybrid
Bangalore	seasonal monsoon (978 mm·y^{-1}), very high intensity, distinct wet/dry seasons	38.5	67.3	75.4	82.9	WSUD-dominant hybrid
Melbourne	Mediterranean pattern (648 mm·y^{-1}), moderate intensity, seasonal	48.7	71.5	72.3	79.8	balanced hybrid
Curitiba	high precipitation (1,483 mm·y^{-1}), moderate-high intensity, year-round	43.2	76.8	69.7	83.5	IWRM-dominant hybrid
Nairobi	bi-modal pattern (869 mm·y^{-1}), high intensity, distinct seasons	39.4	64.5	77.2	81.3	WSUD-dominant hybrid
Shenzhen	very high precipitation (1,970 mm·y^{-1}), very high intensity, monsoon-influenced	35.8	72.4	68.9	85.1	IWRM-dominant hybrid

[1)] Performance index (0–100 scale) integrates multiple metrics weighted by local priorities and calculated using the methodology of Ramirez *et al.* (2023).
Explanations: IWRM = integrated water resources management, WSUD = water sensitive urban design.
Source: own study.

contexts and precipitation regimes. The superior performance of hybrid systems aligns with (D'Ambrosio and Longobardi, 2023), who found integrated approaches yielded 30-45% greater flood mitigation benefits than single-strategy implementations. However, our findings reveal a more pronounced effectiveness differential (41.0 percentage points in peri-urban watersheds) than previously documented. The diminishing returns of interventions as urbanisation progresses supports (Serrano-Notivoli and Tejedor, 2021) hydrological modification threshold theory, though our benefit-cost analyses indicate earlier intervention provides substantially higher economic returns (3.23 vs 1.84 benefit–cost ratio).

Unlike Misty, Hoque and Mukul (2024), who suggested geographic context was the primary determinant of management effectiveness, our results indicate precipitation pattern characteristics more strongly influence optimal strategy selection. This aligns with Delgado-Torres *et al.* (2023) precipitation regime classification framework but extends their work by connecting specific regime characteristics to management approach performance.

This study is limited by its relatively short monitoring period (3 years), potentially missing longer-term climate variability effects. Additionally, the standardised assessment framework may undervalue context-specific cultural and socio-economic factors influencing implementation success.

Furthermore, while the inclusion of peri-urban watersheds provided valuable comparisons across development stages, the study's primary focus remained on the impacts within urbanising areas (including peri-urban zones), rather than a holistic analysis of the entire, potentially larger, catchment area extending into fully non-urbanised headwaters.

Future research should explore how governance structures specifically influence long-term adaptive capacity of different management approaches and develop detailed transition pathways for converting conventional systems to hybrid approaches in established urban areas.

CONCLUSIONS

This research demonstrates that effective urban water resource management amidst changing precipitation patterns requires context-sensitive hybrid approaches that integrate conventional infrastructure with modern water-sensitive design principles. The significant performance advantages of hybrid systems (particularly when implemented early in urban development processes) underscores the critical importance of proactive planning in rapidly urbanising regions. The consistent finding that management effectiveness varies substantially based on precipitation patterns validates the need for locally-tailored solutions rather than standardised approaches. As urban expansion continues globally and precipitation patterns become increasingly variable due to climate change, these findings provide crucial guidance for water resource planners, urban developers, and policymakers. By establishing clear connections between urban development stages, precipitation characteristics, and management performance, this research offers a practical decision-support framework that can enhance urban water resilience while optimising resource allocation through strategic timing and contextual customisation of water management interventions.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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