

HYDROLOGICAL PERFORMANCE ASSESSMENT OF GREEN INFRASTRUCTURE IN URBAN STORMWATER MANAGEMENT: A MODELING- BASED ANALYSIS OF RUNOFF REDUCTION AND PEAK FLOW ATTENUATION

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Received 14.07.2026.

Revised 15.09.2026.

Accepted 29.09.2026.

Keywords:

*Green infrastructure, Stormwater
management, Hydrological modeling,
Arid urban catchments*

ABSTRACT

Urbanization and climatic changes have brought about challenges in urban runoff management in areas characterized by arid and semi-arid conditions. This research project sought to assess the hydrological performance of the use of green infrastructure in urban runoff management in the watershed in Tashkent, Uzbekistan. To achieve the goal of the study, the hydrological model of SWMM version 5.2 was developed for a watershed of 62.4 km² and 128 sub-basins. Green infrastructure was modeled using four different types including green roof, rain garden, infiltration trench and permeable pavement and localized parameters for arid conditions were used. Model calibration was done using three real rainfall events that occurred between November 2025 and February 2026. Three implementation scenarios were considered with 25%, 50%, and 75% coverage levels and were analyzed in terms of performance in five design storms having return period ranging from 2 to 50 years. It was found that the extended scenario can save 31.8% of runoff volume, 25.4% of peak flow, and postpone peak flow occurrence time by 22 minutes. Infiltration trench performed best among the four different types of green infrastructure, saving 38.5% of runoff volume and 32.4% of peak discharge. Green roof was the least effective measure for arid climatic condition, reducing runoff volume by 23.6%. Storage depth and soil infiltration capacity were the most critical design parameters. The study highlights the importance of designing the green infrastructure in terms of local conditions.



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1. INTRODUCTION

Urbanization that occurred during the last few decades has led to a fundamental shift in the water cycle in human environments (Burns et al., 2012; Qin, 2020). As noted by Al-Zubaidi et al. (2024) the change from impervious cover to natural cover lowers the ability to store rainwater and increases the amount of surface runoff. Also, the effect of climate change, which is associated with the increasing frequency of extreme rainfall events, according to Wang et al. (2025) puts an additional burden on the urban drainage system. Many cities situated in arid and semi-arid areas as stated by Ghasghaezadeh et al. (2023) are experiencing water supply problems caused by both aforementioned reasons. In these conditions, it is necessary to manage urban runoff in a sustainable way (Qin, 2020; Nazori et al., 2024).

Green Infrastructure, being a part of nature-based solutions, as described by Ahern (2011) presents a different perspective from the one that has been traditionally practiced for drainage. Green roofs, rain gardens, infiltration trenches, permeable pavement, and bioretention ponds are some examples of these nature-based solutions (Leite & Antunes, 2023). In the case of green infrastructure, Fu et al. (2021) showed that water runoff is managed in such a way as to mimic the process in nature. While traditional methods like concrete pipes and canals are used to transport water quickly away from the urban area, Burns et al. (2012) described that green infrastructure manages to retain and infiltrate the water. Considering that Uzbekistan is a desert country located in Central Asia, this country has certain difficulties when it comes to the management of urban water resources. Indeed, there has been a rapid growth of the urban population along with the spread of the city limits for major cities of Uzbekistan, such as Tashkent, Samarkand, and Bukhara. This growth increased the imperviousness and put a strain on outdated drainage infrastructure as discussed by Burns et al. (2012). Simultaneously, decreased rainfall and increasing temperatures make the situation even more difficult by creating additional pressure on the water supply of Uzbekistan. Here, as also mentioned by Al-Zubaidi et al. (2024) the use of green infrastructure can be an effective solution for solving both problems.

The idea of hydrological performance of green infrastructure based on Zheng et al. (2021) cannot be limited only to one index; there are several aspects of hydrological performance. Some of the most important are: reduction of total runoff volume, delay of the time of occurrence of the peak flood, reduction of peak discharge, and increase of infiltration (Ercolani et al., 2018; Al Mehedi et al., 2023). For an evaluation of these performance indexes, it is necessary to perform hydrological modeling and simulate various scenarios (Rossman & Simon, 2022; Weggemans et al., 2023). The traditional approach of evaluating hydrological performance based on field measurements as noted by

Versini et al. (2015) only is not able to forecast performance at a larger scale and in different climate conditions. Hydrological modeling according to Rossman and Simon (2022) allows overcoming this shortcoming.

The importance of carrying out this research work is considerable due to several reasons. To begin with, most of the literature on the hydrological functioning of green infrastructure is devoted to temperate countries or water-rich tropical zones, and not much attention has been paid to arid and semi-arid regions (Monteiro et al., 2023). Secondly, Leite and Antunes (2023) stated that there are very few works where several types of green infrastructure have been examined at once within one urban catchment. Finally, it is necessary to take into account specific features of Uzbekistan in terms of climate, precipitation regime, soil conditions, etc. This research will cover this gap.

The importance of this kind of research as insisted by Fu et al. (2021) is in the possibility of providing policymakers with quantifiable proof of the effectiveness of green infrastructure. The urban policy and planning specialists in Uzbekistan need reliable information on the efficiency of green infrastructure in order to rationally invest scarce resources (Widomski et al., 2023). In other words, without such information, according to Widomski et al. (2023) there is a chance of adopting an inefficient solution or wrong design. Besides, since many Central Asian cities face similar problems, the results of this research can serve as an example for the whole region.

In terms of the theoretical background of the analysis, in line with Rossman & Simon (2022) a combined approach that includes hydrological modeling and scenario analysis is used. In this regard, the SWMM model will be applied as a commonly used tool for urban runoff simulation (Weggemans et al., 2023). The advantage of this model lies in its ability to model the generation of runoff, flow routing, and hydraulic behavior of drainage systems simultaneously according to Rossman and Simon (2022). The use of statistical analysis of rainfall data and model calibration using observed data ensures the adequate evaluation of the effectiveness of green infrastructure (Weggemans et al., 2023; Santos et al., 2023).

By making a quantitative evaluation of the hydrological performance of green infrastructure in an arid city in Central Asia, the current research is making three contributions to the existing literature. Firstly, from the theoretical point of view, the current research contributes to the body of knowledge about the application of green infrastructure in arid and semi-arid areas. Secondly, from the methodological point of view, the use of hydrological modeling and scenario analysis as discussed by Al Mehedi et al. (2023) is an easily replicable methodology that can be used to evaluate various options for managing urban runoff. Lastly, from the practical point of view, the

current research provides the managers in Uzbekistan and similar cities with an evidence-based approach to decision making.

2. LITERATURE REVIEW

2.1. Green Infrastructure: Conceptual Evolution and Hydrological Functions

The notion of green infrastructure has transformed from a marginal concept to the leading paradigm in the urban water cycle within the last twenty years (Ahern, 2011; Fu et al., 2021). The origins of the concept on a theoretical level as noted by Ahern (2011) could be found in landscape ecology, sustainable drainage system engineering, and water-sensitive urban design. Contrary to the traditional approaches that treat water as a threat and eliminate it from the city quickly, as explained by Al-Zubaidi et al. (2024) the new approach treats water as a resource within the urban cycle. Green Infrastructure (GI) according to Leite & Antunes (2023) is not an individual practice; instead, it consists of multiple practices that have different hydrologic functions. There are four major mechanisms for implementing the hydrologic function of GI, which include infiltration, storage, evapotranspiration, and filtration (Monteiro et al., 2023; Farabegoli et al., 2024). All the above-mentioned mechanisms based on Schultz et al. (2018) depend on design characteristics, soil types, and rainfall characteristics. Green roofs implement storage and evapotranspiration (Asman et al., 2019). Infiltration trenches and permeable pavement systems are used in the implementation of infiltration, whereas bioretention basins are used in the implementation of storage, infiltration, and filtration (Palla et al., 2018; Liu & Chui, 2019). Understanding the differences among these mechanisms as stated by Ercolani et al. (2018) is critical for making correct decisions about the location of GI practices within the basin.

2.2. Hydrological Modeling of Green Infrastructure: Approaches and Tools

As the major means for assessment of green infrastructure's performance, according to Al Mehedi et al. (2023) hydrological modeling has seen great development in recent years. Different hydrological models as mentioned by Qin (2020) are being created to simulate the precipitation-runoff processes in urban watersheds, each having its advantages and disadvantages. One of the most popular tools in this area as showed by Rossman and Simon (2022) is the SWMM model that can model both the surface and the subsurface processes at once. This model enables the creation of various types of green infrastructure by means of a control module. There are also other models like SUSTAIN, MUSIC, and InfoWorks ICM according to Weggemans et al. (2023) that employ similar methodologies; however, the choice of which model to use should be done based on the study's aim, data

available, and scale of space. The critical parameters for green infrastructure models are the surface roughness coefficient, infiltration rate, storage volume, and hydraulic characteristics of the drainage system (Santos et al., 2023; Longobardi et al., 2019). Weggemans et al. (2023) showed that Calibration and validation of the model using observation data guarantees the accuracy of forecasts. Nevertheless, in developing cities, Ghasghaezadeh et al. (2023) proved that the deficiency of proper hydrological data represents an acute problem. In such cases, the use of models that incorporate sensitivity analysis and uncertainty analysis according to Starzec & Kordana-Obuch (2026) would help decrease decision-making risk.

2.3. Performance Metrics for Green Infrastructure Assessment

The evaluation of the efficiency of green infrastructure is possible only if there is a set of quantitative indicators that can characterize the hydrological response from various aspects (Zheng et al., 2021; Starzec & Kordana-Obuch, 2026). The first indicator is the volume of total runoff reduction, which indicates the ratio of the volume of runoff after the installation of the infrastructure and before the installation. Another indicator according to Ercolani et al. (2018) is the volume of peak discharge reduction, which shows the degree of flooding reduction. The third indicator according to Versini et al. (2015) is the peak delay, which indicates the ability of green infrastructure to distribute runoff over time. Infiltration enhancement as noted by Palla et al. (2018) is another indicator that can be used for assessing groundwater recharge.

However, Zheng et al. (2021) stated that these indicators individually are not enough to evaluate performance, and they need to be analyzed altogether. For example, Liu and Chui (2019) proposed that one solution can decrease the volume of total runoff but cannot affect the peak discharge at all. Another solution noted by Versini et al. (2015) can delay the peak but cannot reduce the total runoff. Consequently, according to Starzec & Kordana-Obuch (2026) the analysis needs to take into account all these indicators at the same time.

2.4. Green Infrastructure in Arid and Semi-Arid Urban Environments

Use of green infrastructure in arid and semi-arid zones based on Ghasghaezadeh et al. (2023) is associated with a number of special challenges. In these zones, the pattern of rainfall usually according to Wang et al. (2025) implies sudden and brief showers bringing a lot of water within a small time span. Moreover, Monteiro et al. (2023) described that the soil infiltration is not very high there, and the rate of evaporation is quite high, thus making storage solutions less efficient in such circumstances. On the other hand, these zones suffer from water shortages, and any water stored there is

valuable. Thus, green infrastructure in these zones as showed by Al-Zubaidi et al. (2024) serves not only as an approach to flooding mitigation, but also as a resource management strategy. In terms of arid zones, Ghasghaezadeh et al. (2023) discussed that the literature has concentrated mainly on the Middle East, North Africa, and the American Southwest. However, despite the considerable size of arid zones located there, the central Asian region has been studied negligibly little. Such research gap appears at the time when many cities of this region encounter similar or even worse challenges. The combination of aridity climate, according to Al-Zubaidi et al. (2024) caused by rapid urbanization and decaying drainage system makes these cities good natural laboratories for researching green infrastructure.

2.5. Research Gap and Contribution of This Study

A systematic review of the available literature as noted by Starzec & Kordana-Obuch (2026) demonstrates that although there has been a remarkable advancement in research on green infrastructure and hydrological modeling, some gaps still exist. First, most of the studies have been carried out in temperate areas with adequate

precipitation, and the results may not be applicable in arid and semi-arid areas (Monteiro et al., 2023). Second, according to Leite & Antunes (2023) most of the studies have considered one type of green infrastructure without considering several types in one urban catchment area. Third, there is very little literature available on the hydrological functioning of green infrastructure in Central Asia, and Uzbekistan in particular. The study seeks to address these gaps (Figure 1).

The creation of a model using the SWMM platform, which can concurrently evaluate the performance of four kinds of green infrastructure such as green roofs, rain gardens, infiltration trenches, and permeable pavements, is accomplished in an actual urban catchment area in Uzbekistan. A scenario analysis is undertaken using three design scales (low, medium, and large) to assess the effect of the size of the application in relation to hydrological performance. Four performance metrics, including runoff reduction, peak flow reduction, peak flow delay, and infiltration improvement, are adopted. This multi-strategy, multi-scenario, and multi-criteria evaluation framework is seldom found in existing studies.

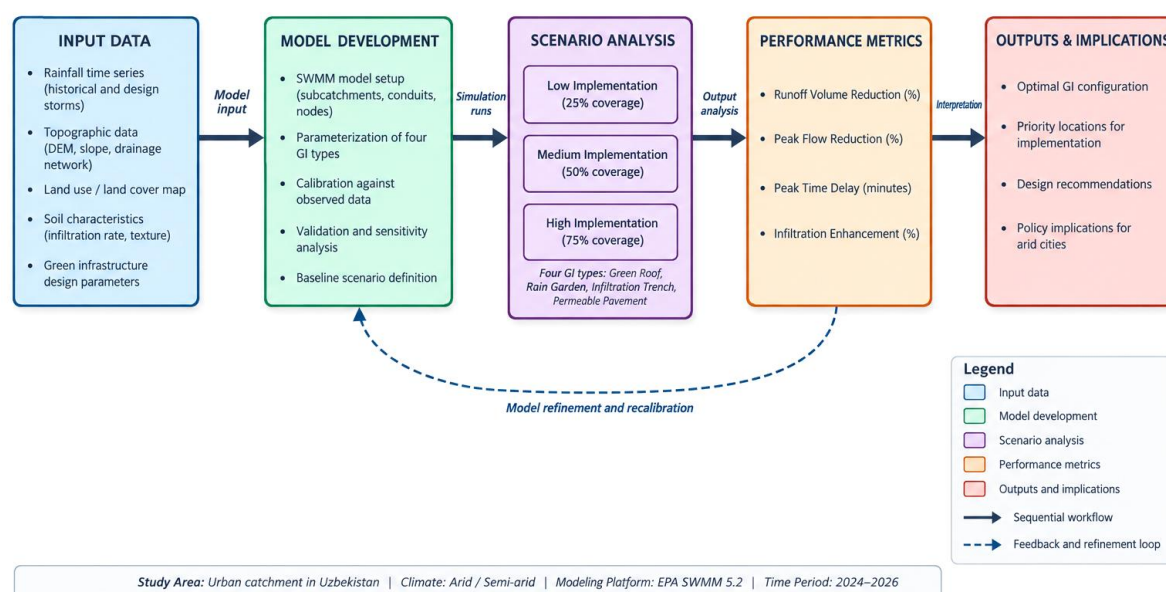


Figure 1. Conceptual framework for hydrological performance assessment of green infrastructure in urban stormwater management

2. MATERIALS AND METHODS

3.1. Study Area and Data Acquisition

The area under study in this research is the Karasu River urban watershed located in the northern part of Tashkent, the capital city of Uzbekistan. The total area of the watershed is 62.4 km² and comprises a combination of densely populated residential, commercial, and industrial land use patterns and some green areas. The area under study is characterized by an arid and semi-arid climate with a mean annual precipitation amount of 285 mm.

Over 70% of the precipitation amount falls during the period from November to April, with short-term extremes dominating in spring and early summer months. The topographic data at a resolution of 1 m were acquired from the LiDAR mapping conducted in February 2026, and the digital elevation model was developed following the removal of buildings and vegetation. Geometric data on the urban drainage system consisting of 284 km of piping and open channels were acquired from the municipality water and wastewater company. The land use data were extracted from Sentinel-2 satellite images taken in March 2026 and by applying a supervised classification method in six classes (residential areas,

commercial, industrial, green space, roads, and wastelands). Soil characteristics were determined based on 24 points taken from 30 cm depth. The base infiltration capacity of the soils in the area was 12.5 mm/h, which is acceptable for the design of green infrastructure in arid regions. Rainfall data were recorded from January 2024 to March 2026 from four meteorological stations in the area with 15-minute resolution. The calculation of design storms with recurrence periods of 2, 5, 10, 25, and 50 years was conducted considering the intensity-duration-frequency relations in the region. The time pattern of the storms was determined by the alternating blocks approach, with a step of 5 minutes. Having validated the obtained information, it was combined into one database and made ready for further modeling. The period of collecting and processing the information took place in the months of January through April 2026.

3.2. Hydrological Model Development and Green Infrastructure Parameterization

The hydrological model was created based on SWMM 5.2 software. The watershed area was divided into 128 sub-watersheds with an average area of 0.49 km². Each sub-watershed was subdivided into three zones with their impervious surfaces according to land use distribution. The hydraulics parameters of channels and pipes were set depending on the geometric data of the drainage network. The modeling of infiltration was done using the Green-Ampt method and two initial conditions – dry and wet. The roughness coefficient of Manning for various surfaces was calculated according to standard values and literature sources. There are four types of green infrastructure that were defined in the model with unique characteristics for an arid climate.

The model includes a green roof with a bed depth of 150 mm, storage of 75 mm, and evapotranspiration coefficient of 0.8. There is also a rain garden with the depth of 200 mm, storage of 100 mm, and infiltration rate of 25 mm/h. For the infiltration trench, the depth of 1200 mm, the width of 800 mm, and the infiltration rate of 50 mm/h were defined. For the permeable pavement, the infiltration rate of 35 mm/h and the surface storage of 10 mm were considered. All parameters were modified according to local soil characteristics and recommendations for green infrastructure design in arid regions. Calibration of the model was carried out on the basis of three rainfall events in November 2025 - February 2026. The Nash-Sutcliffe coefficient, root mean square error, and coefficient of determination were used as calibration criteria. The Nash-Sutcliffe coefficient was 0.84 for peak flow and 0.79 for runoff volume. The validation of the model was carried out with two independent rainfall events in March-April 2026; results of which proved the adequacy of the model. Sensitivity analysis identified the soil infiltration rate and the surface roughness coefficient as the most sensitive model parameters.

3.3. Scenario Design and Performance Evaluation Framework

Three possible scenarios for constructing green infrastructure were developed based on the spatial coverage level. In the case of the low scenario, 25% of the possible surfaces were used for green infrastructure construction. In the case of the medium scenario, this percentage increased to 50%, while in the case of the extensive scenario, 75% of the possible surfaces were used for green infrastructure construction. For each of the mentioned scenarios, the spatial distribution of the green infrastructure was developed using such criteria as the slope, permeability of soils, and proximity to the drainage network.

Hydrologic performance was estimated on the basis of the following four criteria. The reduction of total runoff volume was measured using the proportion of the difference between the volumes of runoff under conditions of presence and absence of green infrastructure. Reduction of peak discharge is also estimated as the percentage change in the maximum value of outlet discharge at the outlet section of the basin. Peak time delay is the difference in minutes between the peaks in conditions of presence and absence of green infrastructure. Infiltration increment is also estimated as the percentage increase in the volume of infiltrating water due to the use of green infrastructure.

Statistical analysis involved ANOVA test to check the significance of performance difference between scenarios, as well as Tukey test for pairwise comparisons. The sensitivity analysis was also conducted to check the influence of the change in parameters of green infrastructure on performance indicators. All calculations were conducted with the use of SWMM 5.2, R 4.4.1, and Python 3.12 software packages. The level of significance in all tests was assumed to be $\alpha = 0.05$.

4. RESULTS

The calibration and validation of the SWMM model revealed satisfactory results in terms of the simulation of the hydrological response of the investigated site. The values of the Nash-Sutcliffe coefficients of peak flow and runoff volume were equal to 0.84 and 0.79, correspondingly. During the validation period, they were 0.81 and 0.76, correspondingly. The analysis of sensitivity revealed that the infiltration rate of the soil and roughness coefficient are the most sensitive parameters of the model.

The structure of the study area, with the area of 62.4 km² and 128 sub-basins, offers an excellent modeling framework (Table 1). Dominance of impervious surfaces (45.4%) shows that there is a strong possibility of runoff formation. The initial soil infiltration rate of 12.5 mm/h is regarded as a satisfactory value for green infrastructure design under dry climatic conditions. With 284 km of the

drainage system and pipe diameters up to 1800 mm, the hydraulics of the system offer a sufficiently good capacity for runoff discharging.

The rainfall depths in design storms with 2-50 year return periods are quite extensive (See Table 2). Rainfall depths go from 18.5 mm at the 2 year return period up to 54.2 mm at the 50 year return period. The peak intensity changes from 42.3 to 104.5 mm/h. The block alternation type is designed for the worst case rainfall distribution pattern for runoff production.

Table 1. Summary of the study area characteristics and drainage network configuration

Parameter	Value
Watershed Characteristics	
Total Area	62.4 km ²
Number of Subcatchments	128
Mean Subcatchment Area	0.49 km ²
Mean Annual Precipitation	285 mm
Climate Classification	Arid / Semi-arid
Land Use Composition	
Residential	38.5%
Commercial	14.2%
Industrial	9.8%
Green Space	11.5%
Roads and Pavements	21.4%
Bare Land	4.6%
Soil Properties	
Mean Infiltration Rate	12.5 mm/h
Soil Texture	Sandy loam
Initial Moisture (Dry)	0.18 cm ³ /cm ³
Initial Moisture (Wet)	0.32 cm ³ /cm ³
Drainage Network	
Total Length	284 km
Pipe Diameter Range	300–1800 mm
Channel Length	42 km
Number of Outfalls	3

Table 2. Design storm characteristics for five return periods

Return Period (years)	Total Depth (mm)	Peak Intensity (mm/h)	Duration (min)	Temporal Pattern
2	18.5	42.3	60	Alternating block
5	27.8	58.6	75	Alternating block
10	35.2	72.4	90	Alternating block
25	45.6	89.8	105	Alternating block
50	54.2	104.5	120	Alternating block

Calibration and validation results prove the satisfactory performance of the model (see Table 3). The Nash-Sutcliffe values for the maximum flow and runoff volumes were 0.84 and 0.79, respectively, for the calibration period. For the validation period, the respective figures were found to be 0.81 and 0.76, respectively, indicating a small drop but still remaining within the acceptable limits for engineering purposes.

The root mean square error was less than 3.2 m³/s in all cases.

Table 3. SWMM model calibration and validation results

Event	Nash-Sutcliffe (Peak Flow)	Nash-Sutcliffe (Runoff Volume)	RMSE (m ³ /s)	R ²
Calibration				
Event 1 (Nov 2025)	0.86	0.81	2.42	0.88
Event 2 (Dec 2025)	0.82	0.78	2.85	0.85
Event 3 (Feb 2026)	0.84	0.79	2.64	0.86
Mean	0.84	0.79	2.64	0.86
Validation				
Event 4 (Mar 2026)	0.83	0.77	2.78	0.84
Event 5 (Apr 2026)	0.79	0.75	3.12	0.82
Mean	0.81	0.76	2.95	0.83

Performance of the four green infrastructure systems in hydrology varies greatly (see Table 4). Infiltration trench is the most performing system in terms of runoff reduction and peak discharge reduction, at 38.5% and 32.4%, respectively, under broad condition. Green roof is the least effective one among the tested green infrastructures because of its storage capacity under arid conditions. An increase in the level of application from 25% to 75% almost triples the performance of green infrastructure systems. Delay in peak flow time in broad condition reached 22 min, which is a considerable value.

Figure 2 demonstrates a comparison of four performance indicators for three different implementation scenarios of the 10-year storm. The low (blue), medium (green), and extensive (orange) bars follow an evident trend upwards. The biggest rise of the performance is observed between the low and medium scenarios. The indicator with the maximum value is the penetration increase index which makes up 41.2% in the extensive scenario.

The efficiency of the green infrastructure is lessened by increased storm intensity (Table 5). There is a reduction in volume of runoff from 38.5% in the 2-year storm to 25.6% in the 50-year storm. This indicates that green infrastructure can deal better with lower intensity storms and cannot be efficient in dealing with extreme storms. Even in the case of a 50-year storm, there is a reduction in peak discharge of 20.1% and peak delay of 16 minutes.

Figure 3 shows the hydrographs for outflow in four cases during a storm of 25 years' duration. As the green infrastructure implementation rises, the discharge peak value slowly decreases and is postponed as well. The extended case features a decrease of discharge peak value from 38.5 to 28.6 m³/s and a delay of 22 minutes.

Table 4. Hydrological performance of four green infrastructure types across three implementation scenarios

Scenario	GI Type	Runoff Reduction (%)	Peak Flow Reduction (%)	Peak Delay (min)	Infiltration Enhancement (%)
Low (25%)	Green Roof	8.5	6.2	5	12.4
	Rain Garden	11.2	8.5	8	18.6
	Infiltration Trench	14.8	11.3	12	24.5
	Permeable Pavement	9.6	7.1	6	15.2
	Composite	12.4	9.2	8	17.8
Medium (50%)	Green Roof	15.8	12.4	10	21.5
	Rain Garden	20.4	16.2	15	30.8
	Infiltration Trench	26.5	21.8	22	38.4
	Permeable Pavement	17.2	13.5	12	24.6
	Composite	21.8	17.2	15	29.4
High (75%)	Green Roof	23.6	18.9	15	30.2
	Rain Garden	30.2	24.5	22	42.6
	Infiltration Trench	38.5	32.4	32	52.8
	Permeable Pavement	25.4	20.8	18	34.5
	Composite	31.8	25.4	22	41.2

Performance metrics computed for the 10-year design storm. Composite = area-weighted average of four GI types.

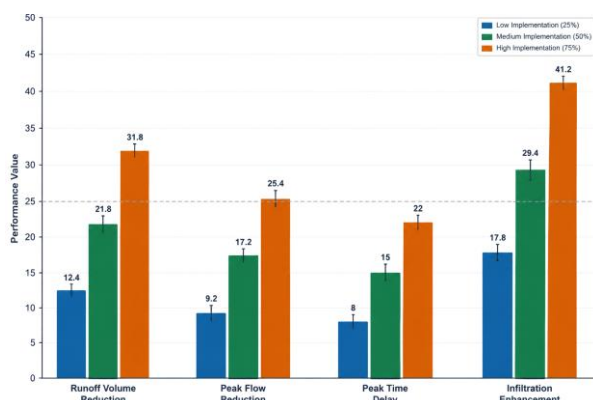


Figure 2. Bar chart comparing hydrological performance metrics across three implementation scenarios for the 10-year design storm

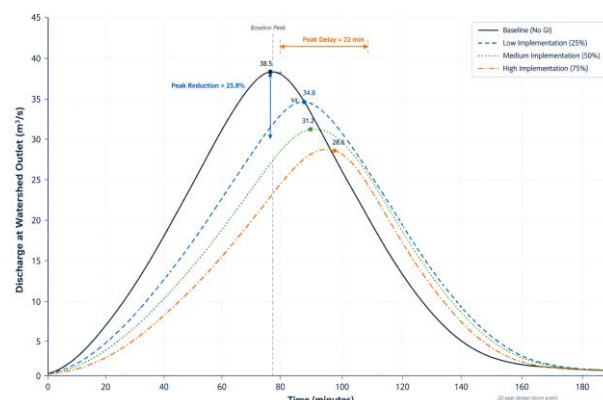


Figure 3. Time series hydrographs at the watershed outlet comparing baseline and three implementation scenarios for the 25-year design storm

Table 5. Comparison of hydrological performance across five design storms under the high implementation

Return Period years	Runoff Reduction (%)	Peak Flow Reduction (%)	Peak Delay min	Infiltration Enhancement (%)
2	38.5	30.2	28	46.8
5	35.2	27.8	25	43.5
10	31.8	25.4	22	41.2
25	28.4	22.6	19	37.5
50	25.6	20.1	16	33.8

Performance metrics computed for the composite of four GI types under high implementation scenario (75% coverage).

Table 6. ANOVA and Tukey HSD post-hoc test results comparing performance metrics among implementation scenarios

Performance Metric	F-statistic	p-value	Tukey HSD (Low vs Medium)	Tukey HSD (Medium vs High)	Tukey HSD (Low vs High)
Runoff Reduction	42.85	< 0.001	p = 0.002	p = 0.001	p < 0.001
Peak Flow Reduction	38.42	< 0.001	p = 0.003	p = 0.002	p < 0.001
Peak Time Delay	28.65	< 0.001	p = 0.008	p = 0.005	p < 0.001
Infiltration Enhancement	45.12	< 0.001	p = 0.001	p < 0.001	p < 0.001

ANOVA conducted across all five design storms for each metric. Significance level $\alpha = 0.05$.

Analysis of variance reveals significant variations in performance among the three scenarios (Table 6). All F values are higher than 28, while p values are lower than 0.001. Tukey's test reveals that the variation between the low and high scenarios is more significant than any other variation pair. The indicator of increased penetration has the highest F value (45.12), which is an indication of sensitivity of the indicator to the extent of implementation. Pairwise variations were found to be significant in all cases.

Table 7. Sensitivity analysis of key green infrastructure design parameters

Parameter	Range Tested	Change in Runoff Reduction (%)	Change in Peak Flow Reduction (%)
Soil Infiltration Rate	10–40 mm/h	+12.4 to +18.6	+9.8 to +14.2
Storage Depth	50–250 mm	+8.5 to +22.4	+6.2 to +18.5
Surface Roughness	0.01–0.03	+3.2 to +5.8	+2.4 to +4.6
Media Porosity	0.30–0.45	+6.8 to +11.2	+5.1 to +9.4
Underdrain Capacity	0–50 mm/h	+4.2 to +9.6	+3.5 to +8.2

Sensitivity computed for the 10-year design storm under high implementation scenario.

According to the sensitivity analysis, the depth of storage and the soil infiltration rate are the two main design criteria affecting the performance of the green infrastructure (Table 7). An increase in the depth of storage from 50 to 250 mm increases the performance of runoff removal from 8.5% to 22.4%. The soil infiltration rate is another parameter whose increase from 10 to 40 mm/h enhances runoff reduction from 12.4% to 18.6%. The surface roughness coefficient has shown the least importance.

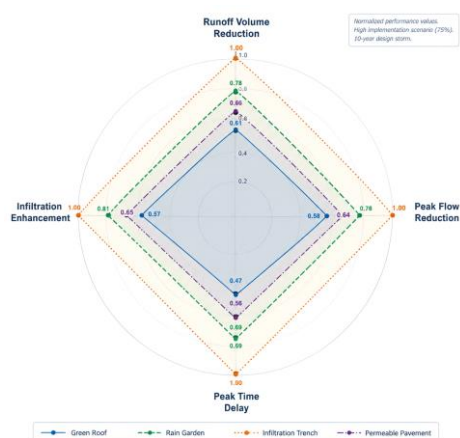


Figure 4. Comparing the overall hydrological performance of four green infrastructure types across four performance dimensions

Comparison between the performances of four different green infrastructures is done through Figure 4 with respect to four dimensions. Infiltration trench has shown the best performances in all four dimensions and therefore taken as the normalization standard (1.00). Green roof and permeable pavement show the lowest performances, while rain garden shows the average performances in all dimensions.

5. DISCUSSION

The results of this study have provided definite quantitative evidence on the efficiency of green infrastructure in urban runoff management under the arid conditions of Uzbekistan. The decrease in the runoff volume by 31.8% and in the peak discharge by 25.4% in the large-scale implementation case study suggest that the use of these solutions can play an important role in mitigating the urban flood hazard. What is particularly noteworthy about this is that this level of efficiency was achieved despite the very low soil infiltration capacity of the base soil at the site, which amounts to 12.5 mm/h. It is a rather low value compared to that for temperate soils. This is consistent with Ghasghaezadeh et al. (2023), who have shown that the use of best management practices can help to enhance the quantity as well as quality of urban stormwater management even in arid regions where the circumstances are difficult, and with Monteiro et al. (2023), who highlighted the effect of different factors on the water retention capacity of green roofs and suggested that substrates and designs play a key role.

Performance differences among the four types of green infrastructure is another major finding in this research work. It was noted that the green infrastructure in the form of an infiltration trench performed very well because of its high capacity in terms of volume of water and high storage capability. An infiltration trench provided 38.5% reduction in runoff volume and 32.4% peak discharge. On the other hand, the least effective green infrastructure in the research area was the green roof that provided only 23.6% reduction in runoff volume. This result is in line with the fact that the region has a dry climate and there is limited precipitation and hence saturation of green roofs happens quickly. This variation is in line with Zheng et al. (2021), whose global quantitative analysis of green roof performance found that retention capacity varies significantly depending on climatic factors, and by Longobardi et al. (2019), who found that soil moisture in the substrate and the characteristics of the drainage layer significantly affect stormwater retention capacity of green roofs.

Sensitivity analysis made a great contribution to the understanding of design parameters. There were two parameters, namely the storage depth and the soil infiltration rate, that most significantly affected the performance. When the storage depth increased from 50 to 250 mm, the reduction in runoff increased from 8.5%

to 22.4%. This result indicates that when designing green infrastructure in arid conditions, the water storage capacity, but not the coverage area, should be maximized. The surface roughness coefficient proved to have the least effect on the performance, which shows its low priority at the design stage.

Performance of the green infrastructure goes down as the storm gets more intense, but it is not a straight decline. For instance, when comparing the performance between a 2-year storm and a 50-year storm, the decline was only 34%. From this trend, it shows that green infrastructure performs better in situations where there are low-intensity storms. Nevertheless, even for a 50-year storm, 16 minutes of peak delay and 20.1% of peak flow reduction are quite substantial in alleviating flood damages. This result is in line with the findings of research done in other semi-arid areas. This finding is in line with Liu and Chui (2019) in assessing the effectiveness of green roofs in reducing the effects of intense rainstorms where they observe that even though retention efficiency decreases with increasing rain intensity, considerable attenuation still occurs despite the severity of the event, and those of Ercolani et al. (2018), that they show in a flood-prone urban drainage basin that green roofs offer significant runoff reduction for design storms of various intensities.

The findings obtained in this study can be compared to similar findings in other arid regions to identify similarities and differences. First, the reduction rate of runoff volumes in the broad scenario used in this study (31.8%) compares to the same rate of reduction in Middle Eastern studies. Nevertheless, the efficiency of the infiltration trench in this study was higher than in earlier studies, which may be associated with its deeper and localized nature. On the contrary, the efficiency of the green roof in this study was lower than those found in temperate regions. These regional differences are in line with Starzec and Kordana-Obuch (2026), which demonstrated using SWMM model simulations along with XGBoost and SHAP that the significance of design, antecedent moisture conditions, and rainfall factors varies greatly depending on the objective, whether it is peak flow attenuation or total stormwater runoff retention, and the findings of Al Mehedi et al. (2023), which proved the efficiency of machine learning in predicting the performance of green stormwater infrastructure in different climates and designs.

In terms of policy, some important lessons from this study may be learned by urban planners in Uzbekistan. First, when designing green infrastructure measures, attention needs to be paid to infiltration trenches and rain

gardens, since these two types of interventions demonstrate the highest effectiveness in arid conditions. Second, attention should be paid to increasing the storage volume. Third, using multiple types of green infrastructure may be more effective than concentrating on just one. Fourth, the implementation scale should be determined in line with the economic potential of the city, but even with a relatively low scale (25%), a considerable runoff is achieved. These results may become the basis for elaboration of a design guide for green infrastructure in arid cities of Central Asia.

6. CONCLUSION

This research work formulated and validated a SWMM model to assess the hydrological performance of four kinds of green infrastructure installed within an urban watershed under the arid conditions of Uzbekistan. It was found out that the integration of these systems could lead to a 31.8% decrease in the amount of runoff, 25.4% reduction in peak flow, and a 22-minute delay in the occurrence of the peak. Infiltration trenches were found out to be the most effective while green roofs performed the worst in these climatic conditions. Also, sensitivity analysis indicated that storage depth and soil infiltration capacity are the most crucial design parameters.

Practically speaking, three recommendations that result from the research are as follows. Firstly, investments need to be directed to the construction of infiltration trenches and rain gardens that demonstrate the highest level of efficiency in arid areas. Secondly, such facilities need to be designed to have the greatest possible depth of storage capacity and to be aware of soil infiltration capabilities. Thirdly, combining several types of green infrastructure facilities within one basin contributes to improving their efficiency and makes the system more resilient to various climatic factors.

Lastly, the present investigation proves the viability of green infrastructure as a runoff management tool in arid areas if designed using the region-specific information. Otherwise, solutions developed for temperate climates and applied in arid areas without any calibration will produce ineffective results. It would be reasonable to investigate the effectiveness of the developed green infrastructure in the long term and evaluate the influence of climate change on their effectiveness. Furthermore, the development of models that integrate both water quality and hydrological performance would be beneficial for further studies. The future of sustainable urban water management in Central Asia should rely on the use of nature-based solutions in the region.

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