Quantitative assessment of urban green infrastructure performance in runoff regulation and its economic valuation (case study: Tehran)

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Abstract

This study aims to quantitatively assess the performance of existing green infrastructure in Tehran in regulating urban runoff and to estimate the economic value of this ecosystem service using an integrated framework based on remote sensing, geographic information systems, the runoff curve number model, and economic valuation. Environmental indices, including the Green Infrastructure Index, Normalized Difference Vegetation Index, and Normalized Difference Built-up Index, as well as land-use data, were derived from remote sensing data. Runoff volume under existing urban conditions was then estimated using the SCS-CN model, and the role of green infrastructure in reducing runoff was quantified by comparing existing conditions with a hypothetical scenario without the effect of green infrastructure. The results showed that the mean Green Infrastructure Index for Tehran was 0.271. The runoff volume generated under existing conditions was calculated at 26.59 million cubic meters, while existing green infrastructure was able to regulate approximately 1.47 million cubic meters of runoff. The economic value of this ecosystem service was estimated at approximately USD 2.34 million using a transferred, unadjusted coefficient. The results show that Tehran's urban green infrastructure, in addition to its environmental role, has measurable hydrological and economic functions and can serve as an effective strategy for sustainable runoff management and greater urban resilience.

Keywords: Economic Valuation, Ecosystem Services, Remote Sensing, Runoff Regulation, Tehran, Urban Green Infrastructure

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1.Introduction

Rapid urbanization in recent decades has brought about extensive changes in the spatial structure of cities and has become one of the most important factors altering the natural water cycle in urban environments (Amani-Beni et al., 2019). The expansion of impervious surfaces such as buildings, streets, and parking lots has reduced rainfall infiltration, increased surface flow velocity, reduced groundwater recharge, and intensified the risk of inundation and urban flooding (Hou et al., 2020; Saeedi et al., 2022). These challenges are more pronounced in large, densely developed cities, especially in arid and semi-arid climates, because the combination of prolonged dry periods and short, intense rainfall events places additional pressure on urban water management systems (Lizárraga-Mendiola et al., 2017; Saeedi & Goodarzi, 2020). Under these conditions, conventional approaches based on gray infrastructure, such as channels, drainage networks, and flood control

structures, cannot on their own address the new complexities arising from climate change and urban development (Aghili Mahabadi et al., 2022). In recent years, urban green infrastructure and nature-based solutions have therefore attracted considerable attention from researchers and urban planners as complementary, sustainable approaches to enhancing urban resilience. Recent studies show that, in addition to improving urban environmental quality, green infrastructure provides a range of ecosystem services, including runoff regulation, urban heat island mitigation, improved air quality, greater biodiversity, and a better quality of life for residents (Yao et al., 2025).

Urban green infrastructure is defined as a planned network of natural and semi-natural spaces intended to preserve ecological processes and provide environmental services within the urban fabric. Unlike conventional green spaces, which are designed primarily for aesthetic or recreational purposes, green infrastructure is multifunctional and can serve hydrological, ecological, and social roles simultaneously (Choi et al., 2021). One of its most important regulating services is the control of surface runoff through increased infiltration, temporary water storage, reduced flow velocity, and increased evapotranspiration (Zubelzu et al., 2020). Recent studies show that the type, structure, and spatial distribution of green elements directly affect the extent of ecosystem services they provide, and that measuring green space area alone cannot reveal their actual performance (Saeedi et al., 2022). Recent approaches have therefore moved toward developing composite indices such as the Green Infrastructure Index, which can represent different land-cover characteristics, vegetation conditions, and ecological functioning within a unified spatial framework (Dvornikov et al., 2025).

Remote sensing and geographic information systems have become important tools for monitoring and evaluating urban green infrastructure at large scales. Satellite data make it possible to derive environmental indices with broad spatial coverage and suitable revisit intervals and to detect spatial variation in urban ecological conditions without extensive field surveys. Recent studies emphasize that remote sensing has become increasingly important for identifying green cover, mapping ecosystem services, and supporting urban planning decisions (Di Palma et al., 2024).

One of the most important applications of green infrastructure is urban runoff management. Land-use change and the expansion of impervious surfaces have increased the runoff coefficient and shortened the time of concentration, thereby increasing the likelihood of urban flash floods (Young et al., 2009). By increasing water retention capacity, green infrastructure elements such as parks, green spaces, urban gardens, green roofs, and permeable surfaces can reduce part of the hydrological load on a city. Various hydrological models have been developed to quantify this function. Among them, the U.S. Soil Conservation Service Curve Number (SCS-CN) method is one of the most widely used in urban studies because of its simplicity, compatibility with land-use data, and applicability in GIS (Soulis & Valiantzas, 2012). The model makes it possible to translate land-surface characteristics into quantitative runoff estimates and can be used to compare different urban development scenarios or scenarios with and without green infrastructure (Mishra & Singh, 1999).

2.Theoretical and Empirical Background

Studies in recent decades have described green infrastructure as a functional network of natural and semi-natural elements capable of simultaneously providing several ecosystem services in urban environments. Benedict and McMahon were among the first researchers to propose green infrastructure as a planning framework for connecting natural elements and maintaining ecological functions (Benedict & McMahon, 2006). Many subsequent studies have shown that green

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infrastructure can play an important role in mitigating the negative effects of urban development, increasing resilience to climate change, and improving urban environmental quality.

Ecosystem services provided by green infrastructure include regulating, supporting, cultural, and provisioning services. Runoff regulation and urban flood risk reduction are among its most important functions in densely developed cities. In recent years, the concept of nature-based solutions has become closely linked to green infrastructure (Fang et al., 2024). This approach emphasizes using natural processes to address urban challenges and, unlike conventional engineering solutions, seeks to meet environmental, economic, and social objectives simultaneously. Studies have shown that developing green infrastructure reduces climate hazards such as flooding and urban heat and generates considerable cultural and psychological value through ecosystem service provision (Saeedi et al., 2025; Shokri Biarargh & Nematimehr, 2019; Summers & Vivian, 2018).

Runoff control is one of the most important ecosystem services provided by green infrastructure. Numerous studies have shown that elements such as urban parks, rain gardens, green roofs, and permeable surfaces can contribute effectively to runoff control through temporary water storage, increased infiltration, and reduced peak discharge. For example, researchers have shown that sustainable surface water management systems can complement conventional drainage networks (Jia et al., 2015). A review also found that small-scale green infrastructure can reduce runoff volume and the pollutants transported by surface flow (Liu et al., 2017).

Rainfall–runoff models are necessary to quantify the hydrological effects of green infrastructure. The SCS-CN method estimates runoff generation potential based on the relationship between land-cover type, soil hydrological conditions, and rainfall amount (Mishra & Singh, 1999). This method has been used in various studies to examine the effects of land-use change, urban development, and different runoff management scenarios.

Despite a growing body of research on the role of green infrastructure in reducing runoff, several gaps remain. A substantial share of earlier studies focused only on measuring green space area or evaluating vegetation indices and did not establish a quantitative relationship between the actual condition of existing green infrastructure, the reduction in runoff volume, and the economic value of this ecosystem service. Moreover, many studies assessed green infrastructure performance at the city scale without combining remote sensing data, hydrological modeling, and economic valuation. Recent studies emphasize the need for integrated frameworks that can evaluate the multidimensional performance of green infrastructure from ecological, hydrological, and economic perspectives (Khalili et al., 2024).

Tehran, one of the largest metropolitan areas in the Middle East, is a suitable case for examining this issue. Rapid physical expansion, increased building density, reduced permeable surfaces, and a semi-arid climate have exposed the city to serious runoff management challenges (Yalveh et al., 2025). Although Tehran has a network of parks, urban green spaces, and natural elements, the spatial distribution and hydrological performance of these elements have rarely been evaluated quantitatively within an integrated framework. Understanding the actual capacity of Tehran's existing green infrastructure to provide runoff regulation services can therefore inform urban planning, flood management, and the development of nature-based solutions.

Accordingly, the main objective of this study is to develop an integrated framework based on remote sensing, hydrological modeling, and economic valuation to assess the role of existing green infrastructure in regulating Tehran's urban runoff. The ultimate objective is to estimate the economic value of the runoff regulation service provided by urban green infrastructure. The

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principal innovation of this study is the simultaneous integration of spatial analysis using remote sensing, hydrological modeling, and economic valuation to assess the actual performance of existing green infrastructure at the metropolitan scale.

3.Methodology

3.1.Study Area

This study was conducted in Tehran, one of the largest and most densely populated metropolitan areas in the Middle East. Rapid urban development, an increase in impervious surfaces, a decline in vegetation cover, and changes in natural drainage patterns have made surface runoff management more challenging in the city. The study area was defined using the official municipal boundary of Tehran. This boundary served as the main analysis extent and was used to clip all spatial data. The study area covers approximately 63,068 hectares, equivalent to 630.68 square kilometers. The overall research framework comprised four main stages: deriving environmental indices from remote sensing data, developing the Green Infrastructure Index, modeling urban runoff, and estimating the economic value of the runoff control ecosystem service.

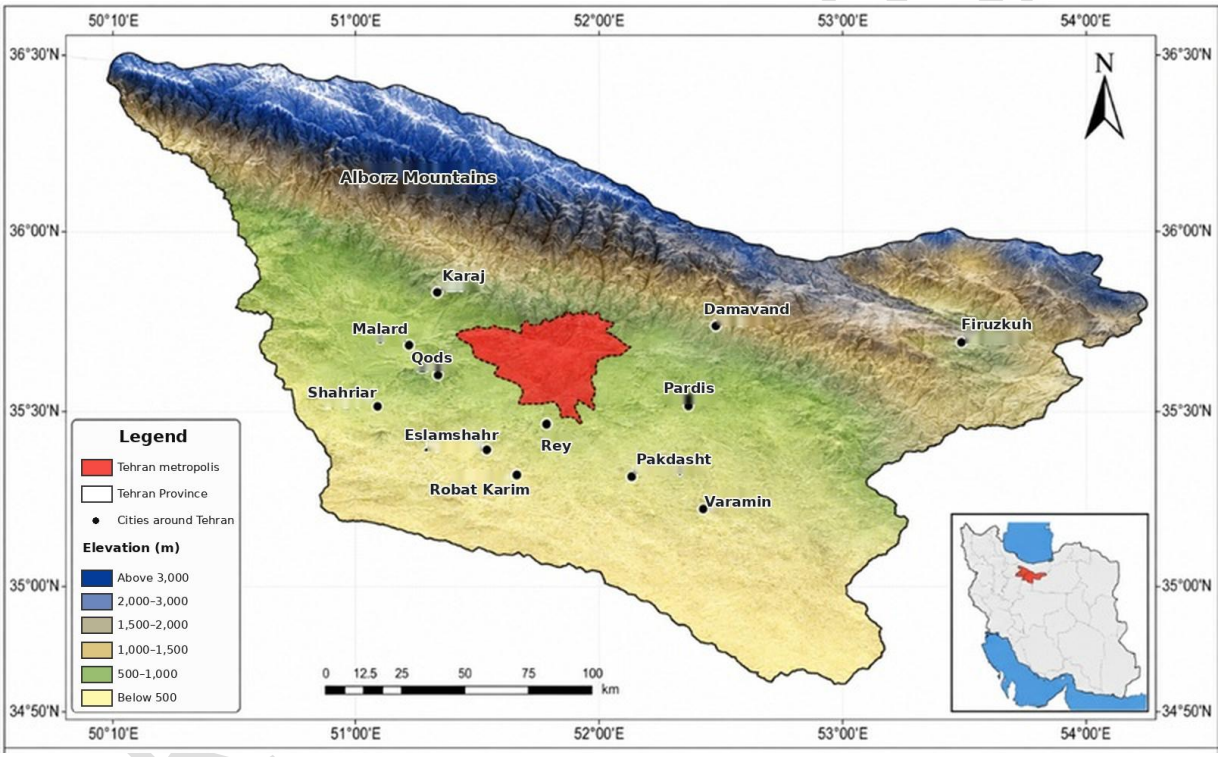


Figure 1. Study area and location of Tehran within the region examined.

3.2.Research Method

As shown in Figure 2, the workflow began by defining the study area and acquiring land-cover data, satellite imagery, and rainfall data. After preprocessing in Google Earth Engine, the Green Infrastructure Index was calculated and the layers required for hydrological analysis were transferred to Python. Two scenarios were then defined: current land-cover conditions and a change in runoff curve numbers for selected pixels. Runoff depth and volume were estimated for both scenarios under the same rainfall using the curve number method. The outputs were compared to quantify the runoff regulation service, and its monetary equivalent was estimated using a transferred replacement cost coefficient. Finally, the numerical consistency of the outputs was checked, and the results were presented in maps and tables.

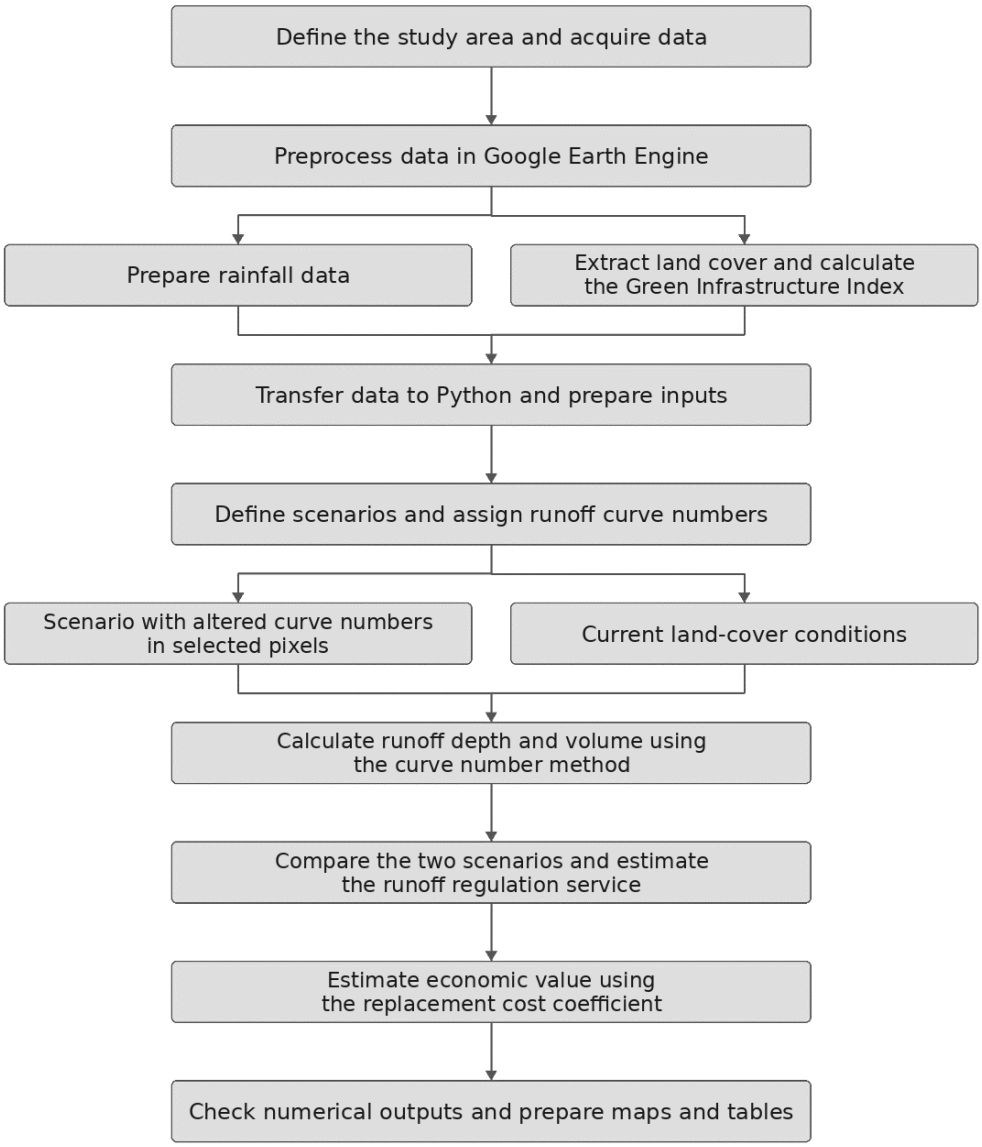


Figure 2. Research workflow for estimating the runoff regulation service and its monetary equivalent

This study used remote sensing, climate, and spatial data to assess the capacity of urban green infrastructure to control runoff. The data comprised a land-use map, the Green Infrastructure Index, the NDVI vegetation index, the NDBI built-up index, CHIRPS rainfall data, and the boundary of Tehran's urban area. Table 1 summarizes the characteristics of the data used. All raster data were first standardized in terms of coordinate system, spatial extent, cell size, and NoData values. For area and volume calculations, all layers were transformed to UTM Zone 39N (EPSG:32639). The data were then clipped to the Tehran city boundary so that all analyses were performed only within the urban area of Tehran.

Table 1. Data used in the study

Application in the study	Type and native spatial resolution	Time period or version	Data source	Data used	No.
Preparing the land-cover map through temporal compositing, calculating class areas, and defining vegetation scenarios	Raster; 10 m	2024	Ready-to-use Dynamic World V1 product in Google Earth Engine	Land cover and land-cover class probabilities	1

Application in the study	Type and native spatial resolution	Time period or version	Data source	Data used	No.
Calculating the Normalized Difference Vegetation Index (NDVI)	Raster; 10 m for red and near-infrared bands	2024	Sentinel-2 image collection in Google Earth Engine; the exact collection identifier should be entered as specified in the code	Sentinel-2 multispectral imagery	2
Examining daily rainfall, supplying model rainfall for the selected day, and calculating total rainfall over the preceding five days	Raster; 0.05°, approximately 5 km	2024; selected day: January 11; antecedent rainfall: January 6–10	CHIRPS Daily; UCSB-CHG/CHIRPS/DAILY collection in Google Earth Engine	Daily rainfall	3
Identifying soil groups C and D in the study area and assigning CN based on the combination of soil and land cover	Raster; approximately 250 m	Version 2.0; independent of the land-cover year	HiHydroSoil v2.0; hydrologic soil group layer in the public Earth Engine-hosted collection	Hydrologic soil group (HSG)	4
Calculating runoff under existing conditions and vegetation conversion scenarios, and analyzing sensitivity to CN and antecedent moisture	Derived raster; 10 m² computational grid	Corresponding to 2024 land cover; reference condition: AMC II	Produced in this study by combining land cover, HSG, and reference CN values	Runoff curve number (CN) map	5

CHIRPS rainfall data have a spatial resolution of approximately 5 km and do not resolve rainfall variation at the neighborhood or urban parcel scale. In this implementation, the spatial maximum of the input rainfall raster was extracted and applied as a uniform rainfall value throughout the computational domain. The 10 m computational grid therefore represents the scale at which land-surface characteristics are represented and runoff is calculated; it does not imply that independent rainfall data are available at that scale. Under uniform rainfall, spatial variation in estimated runoff in this framework results from differences in land-surface parameters.

Runoff was calculated using a rainfall scenario defined from the maximum daily rainfall raster for the study period. Annual total rainfall was excluded from these calculations. In the Python implementation, the spatial maximum of the input raster was extracted and applied uniformly to compare land-cover scenarios. This rainfall selection alone does not reconstruct an actual event occurring concurrently across the study area, and no specific event date is inferred from it. The annual rainfall layer was reported solely to describe rainfall conditions in the study area and was not used to calculate the runoff volumes presented. The runoff volume, runoff regulation service, and its monetary equivalent therefore apply to the rainfall scenario examined and are not annual values.

Spectral indices derived from Sentinel-2 satellite imagery were used to assess environmental conditions in Tehran. NDVI was calculated to examine vegetation conditions and the intensity of urban vegetation activity. This index is calculated using Equation 1.

Equation 1:

$$NDVI=(NIR-Red)/(NIR+Red)$$

where NIR is near-infrared band reflectance and Red is red band reflectance. Higher NDVI values indicate denser vegetation and a greater capacity to retain water, increase infiltration, and reduce

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surface runoff. NDBI was also calculated using Equation 2 to assess the intensity of urban development and the extent of built-up surfaces.

Equation 2:

NDBI=(SWIR-NIR)/(SWIR+NIR)

Higher NDBI values indicate a greater extent of urban impervious surfaces. The Green Infrastructure Index was normalized to a range of zero to one by combining information on vegetation, built-up areas, and land-surface characteristics. Higher values indicate greater green infrastructure capacity to provide runoff regulation services. The index was calculated by combining three components: normalized NDVI, the sum of the probabilities of the trees, grass, and crops classes in Dynamic World, and the complement of the built-class probability. The temporal median of each probability band was first calculated for the study period. NDVI was rescaled to the range from zero to one using fixed bounds of −0.2 and 0.8, and values outside this range were clipped. The Green Infrastructure Index was then obtained using the set of expressions in Equation 3.

Equation 3:

$$N = clip(\frac{(NDVI + 0.2)}{1.0}.0.1)$$

$$V = median(p_trees) + median(p_grass) + median(p_crops)$$

$$B = median(p_built)$$

$$GII = 0.4N + 0.4V + 0.2(1 - B)$$

In this equation, N denotes normalized NDVI, V is the sum of the temporal median probabilities for the trees, grass, and crops classes, and B is the temporal median probability of the built class at each pixel. To derive the vegetation component V, Dynamic World probability bands for membership in the trees, grass, and crops classes were used. First, the temporal median of each band over the selected 2024 imagery was calculated independently for each pixel.

In these expressions, the tilde denotes the temporal median of each class probability band, and the clip function restricts values to the specified range. The component weights were set to 0.4, 0.4, and 0.2, respectively. These weights are modeling choices made in this study, and no procedure to estimate or calibrate them was implemented in the supplied code. For area calculation, pixels with GII greater than 0.5 were designated as the area selected by the index.

Surface runoff generated by rainfall was simulated using the standard U.S. Soil Conservation Service Curve Number (SCS-CN) method. This method is commonly used in urban hydrology and accounts for the effects of land use, surface permeability, and hydrological conditions on runoff generation. The runoff curve number of each pixel was determined from the combination of land-cover class and hydrologic soil group. The hydrologic soil groups were extracted from the HSG layer of HiHydroSoil version 2.0, which has a spatial resolution of approximately 250 m. Within the study area, groups C and D covered approximately 63,052.75 and 14.21 hectares, respectively, of the area with valid soil data. CN values were assigned for each land-cover and soil-group combination (Table 2). The soil layer was transferred to the 10 m computational grid using nearest-neighbor resampling, which does not increase the resolution of the soil information. Average antecedent moisture conditions (AMC II) were used as the reference assumption. To characterize prior rainfall, total rainfall over the five days preceding the selected day, January 6–10, 2024, was calculated. Its areal mean within the study area was 15.75 mm. This value alone was not used to confirm uniform moisture conditions throughout the study area. Sensitivity to dry and wet

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conditions was examined by calculating AMC I and AMC III scenarios. In this test, antecedent moisture adjustments to CN were applied only to permeable classes, while CN for built-up surfaces and replacement surfaces in the conversion scenario was held at 98. Potential water retention after runoff begins was calculated using Equation 4.

Equation 4:

S=25400/CN-254

where S is the potential water retention in millimeters and CN is the runoff curve number. Runoff depth was then calculated using Equation 5.

Equation 5:

Q=((P-0.2S)^2)/(P+0.8S)

In this equation, Q is direct runoff depth and P is the rainfall depth used as input to the scenario, both in millimeters. P was extracted from the spatial maximum of the maximum daily rainfall raster for the study period and applied uniformly in the calculations. Annual total rainfall was not included in the equation. Runoff was calculated for a hypothetical rainfall input, and the resulting output should not be interpreted as annual runoff. Because the rainfall selected from this raster does not necessarily represent the spatial distribution of a concurrent event, the results are reported as the model response to the selected rainfall scenario.

In the main scenario, pixels belonging to the trees, grass, and shrub and scrub classes in the Dynamic World land-cover map were converted to impervious surfaces with a curve number of 98. In the extended scenario, crops were also converted to impervious surfaces with the same curve number. CN values for other valid land classes remained unchanged. Water bodies and flooded vegetation were excluded from the computational domain. Rainfall on the selected day, the computational grid, the valid analysis area, and the reference moisture assumption of AMC II were identical under existing conditions and in the conversion scenarios. Runoff was then calculated independently for each scenario using the SCS-CN equation, and the difference in runoff volume between the conversion scenario and existing conditions was estimated as the runoff avoided by retaining vegetation. These scenarios are hypothetical comparisons and do not predict actual urban development. A CN of 98 is also an explicit assumption for the replacement surface.

Table 2. Correspondence between land-use classes and CN values used in the SCS-CN model

Land-cover code	Land-cover class	Curve number assigned in the code
0	Water	100
1	Trees	45
2	Grass	61
3	Flooded vegetation	55
4	Crops	70
5	Shrub and scrub	65
6	Built-up land	90
7	Bare land	85
8	Snow and ice	100

The land-cover codes are solely identifiers for the Dynamic World classes and differ from curve number values. The CN values in the table were assigned as fixed values in the model and were not

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calibrated against observed runoff data. Areas outside the study boundary do not constitute a separate class for CN assignment. NoData values and areas outside the boundary are also excluded from the land-cover classes and have no defined curve number. Code zero in Dynamic World identifies the water class and should not be confused with NoData.

After runoff depth was calculated, runoff volume generated in each cell was computed using raster cell area. Runoff volume was obtained using Equation 6.

Equation 6:
$$V=(Q/1000)\times A$$

where V is runoff volume in cubic meters, Q is runoff depth in millimeters, and A is cell area in square meters. The runoff regulation ecosystem service was defined as the difference in runoff volume between conditions without green infrastructure and current conditions. This value represents the volume of water prevented from becoming additional runoff by the presence of urban green infrastructure.

To estimate the monetary equivalent of the runoff regulation service, a replacement cost coefficient was transferred from a reference study. The InVEST Urban Stormwater Retention model user guide, citing Simpson and McPherson (2007), reports a value of USD 1.59 per cubic meter for the San Francisco Bay Area (Simpson & McPherson, 2007). In this study, the coefficient served as the basis for a conditional transfer estimate, and the monetary equivalent of the service was calculated using Equation 7.

Equation 7:
$$E=V\times A$$

In this equation, E is the monetary equivalent of the service in US dollars, V is the reduction in runoff volume between the two scenarios in cubic meters, and A is the replacement cost coefficient of USD 1.59 per cubic meter. This coefficient was applied without adjustment for inflation or regional cost differences. Economic values were mapped in dollars per hectare to allow spatial comparison of ecosystem service value across different parts of the city.

Data were processed in Google Earth Engine and Python. In Google Earth Engine, data were accessed through the JavaScript programming interface and restricted to the study area. Land-cover data were obtained from GOOGLE/DYNAMICWORLD/V1, and Sentinel-2 surface reflectance imagery was obtained from COPERNICUS/S2_SR_HARMONIZED. Processing involved applying temporal and spatial filters, generating a temporal median composite, extracting the required layers, calculating spectral indices and the Green Infrastructure Index, and exporting the raster layers. Details of the Green Infrastructure Index equations and parameters are provided in the relevant section. The output layers from this stage were exported as GeoTIFFs with a 10 m output pixel size for subsequent processing. The land-cover, Green Infrastructure Index, and rainfall layers were imported into Python for hydrological and economic calculations. The main steps comprised raster preparation, assignment of curve numbers to land-cover classes, calculation of retention capacity and runoff depth using the SCS-CN method, calculation of runoff for the reference scenario, estimation of the runoff difference between the two scenarios, conversion of runoff depth to volume, and economic valuation. Scenario definitions, curve numbers, and valuation assumptions are reported in the corresponding sections.

4.Results

The results showed substantial ecological and hydrological heterogeneity across the Tehran urban area and an uneven distribution of environmental indices across the city. As shown in Table 3, the

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mean Green Infrastructure Index was 0.271, indicating a moderate level of green infrastructure performance at the citywide scale. The index ranged from 0.094 to 0.898, indicating substantial spatial differences among urban areas and a concentration of ecological capacity in some parts of the city. A standard deviation of 0.103 also indicates considerable spatial variation in green infrastructure distribution, with its pattern shaped by the urban structure and natural conditions.

Table 3. Summary statistics of the spatial layers used in the study

Spatial layer	Mean	Minimum	Maximum	Standard deviation
GII	0.271	0.094	0.898	0.103
NDVI	0.142	−0.419	0.835	0.145
NDBI	0.059	−0.521	0.703	0.097
Maximum daily rainfall (mm)	40.069	19.381	107.018	17.655
Annual rainfall (mm)	456.045	210.703	991.479	209.840
Runoff (mm)	35.239	0	107.018	38.640
Vegetation probability	0.124	0.068	0.775	0.082

The vegetation and urban development indices also revealed substantial spatial differences in Tehran's urban structure. Mean NDVI was 0.142, indicating limited to moderate vegetation cover across much of the urban area. However, the NDVI range from negative values to 0.835 indicates dense vegetation in some areas and little substantial vegetation in others (Figure 3). Mean NDBI was 0.059, indicating the widespread presence of built-up surfaces in the urban area (Figure 4). High NDBI values in some areas reflect concentrated urban development, more impervious surfaces, and consequently greater potential for surface runoff generation.

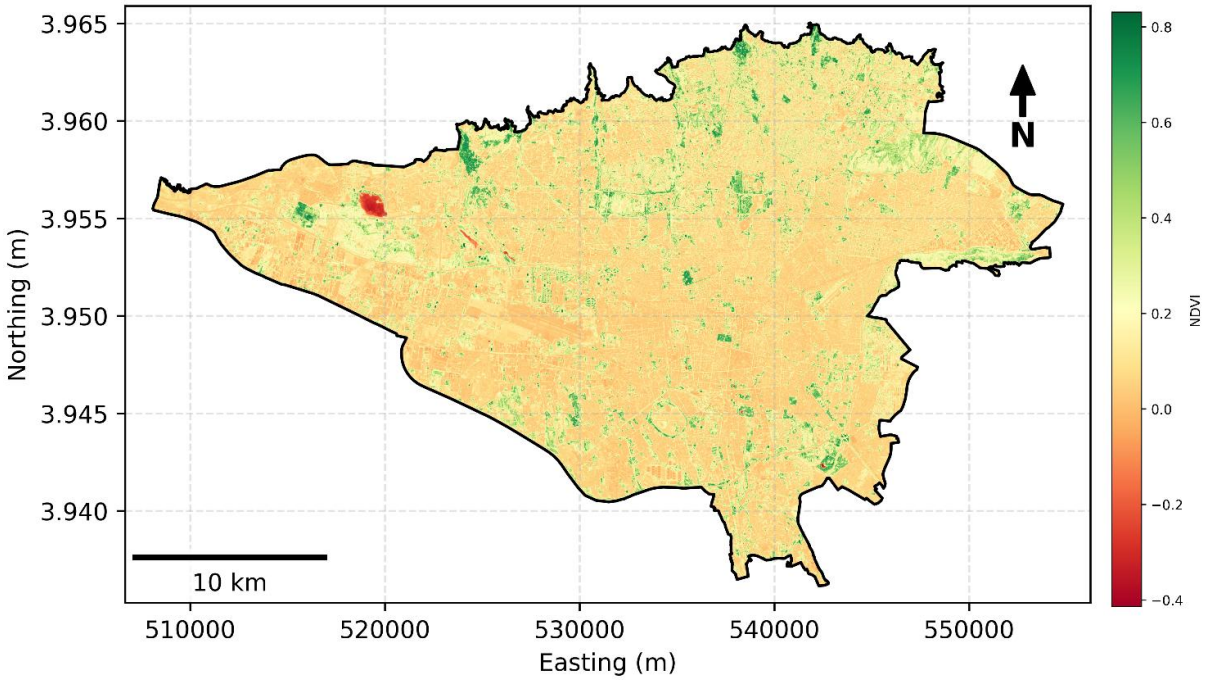


Figure 3. Map of the spatial distribution of NDVI; spatial distribution of environmental indices including NDVI

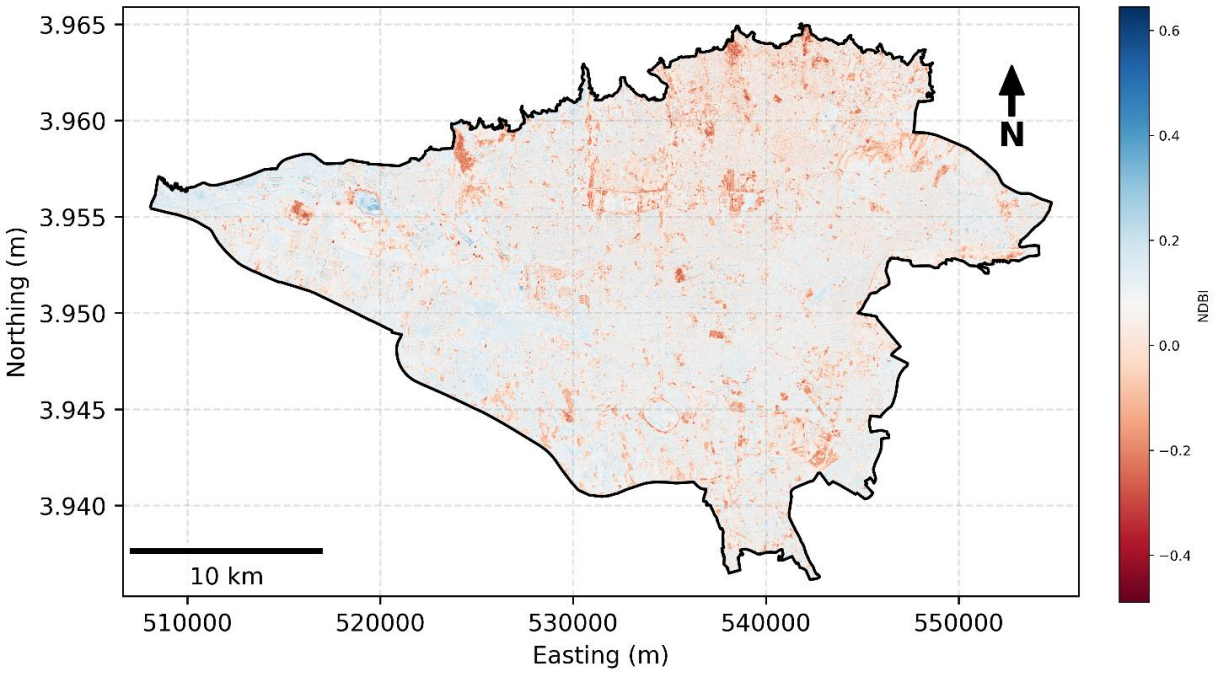


Figure 4. Map of the spatial distribution of NDBI within Tehran

Statistics for the annual rainfall and maximum daily rainfall rasters were reported to describe rainfall conditions (Table 3). The mean annual rainfall across valid pixels was approximately 456 mm. The spatial mean of the maximum daily rainfall raster was approximately 40 mm, with a maximum of approximately 107 mm. These descriptive statistics should be distinguished from the model rainfall input: runoff calculations were based on the rainfall scenario defined in the methodology, rather than on annual total rainfall.

Runoff modeling showed that existing green infrastructure in Tehran has considerable capacity to reduce surface flow and provide runoff regulation services. The area covered by valid Green Infrastructure Index data was 63024.96 hectares, and the area classified as green infrastructure was calculated at 273562 hectares. Runoff generated under existing conditions was estimated at 2.65903×10^7 cubic meters, indicating a substantial volume of surface flow in a dense urban environment. Green infrastructure, in turn, regulated 1.471229×10^6 cubic meters of the runoff generated. These values are calculated under the stated rainfall, curve number assignment, and scenario assumptions and do not represent measured runoff.

Table 4. Quantitative results for green infrastructure performance in urban runoff regulation

Value	Indicator	No.
63,168.18	Area covered by valid Green Infrastructure Index data (hectares)	1
2,735.62	Green infrastructure area based on the GII > 0.5 threshold (hectares)	2
4.33	Share of green infrastructure in the valid map area based on the GII > 0.5 threshold (%)	3
0.271	Mean Green Infrastructure Index (GII)	4
0.142	Mean vegetation index (NDVI)	5
0.059	Mean built-up index (NDBI)	6
107	Spatial maximum of the maximum daily rainfall raster (mm)	7
71.086	Maximum estimated runoff depth (mm)	8
26,590,034	Estimated current runoff volume (cubic meters)	9
1,471,229	Estimated runoff regulation service volume (cubic meters)	10

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Spatial analysis of the model outputs showed that the distribution of runoff regulation services was uneven across Tehran, with areas of higher green infrastructure capacity providing the greatest reductions in runoff. Comparing the GII map with the runoff regulation service map showed that areas with higher GII values had greater runoff control capacity. Areas with higher NDVI and lower NDBI were also identified as locations with better ecological performance. Densely developed urban areas with more impervious surfaces generated higher amounts of surface runoff. This spatial pattern is shown in Figures 5 and 6.

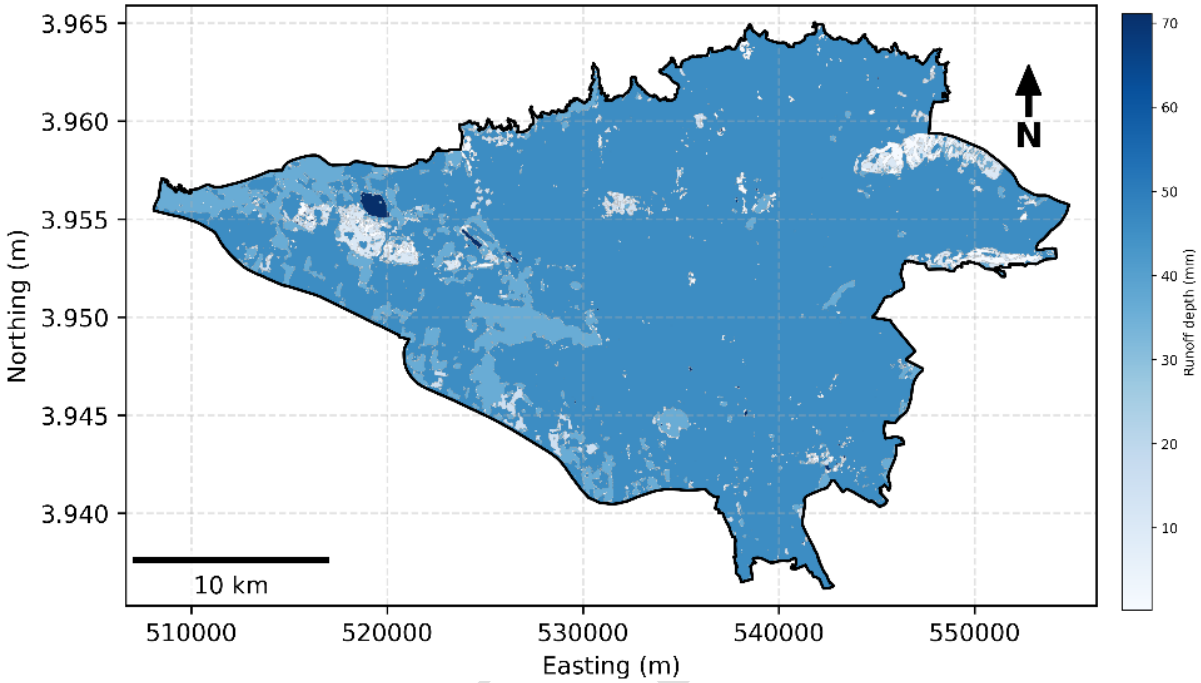


Figure 5. Spatial distribution of surface runoff depth in Tehran

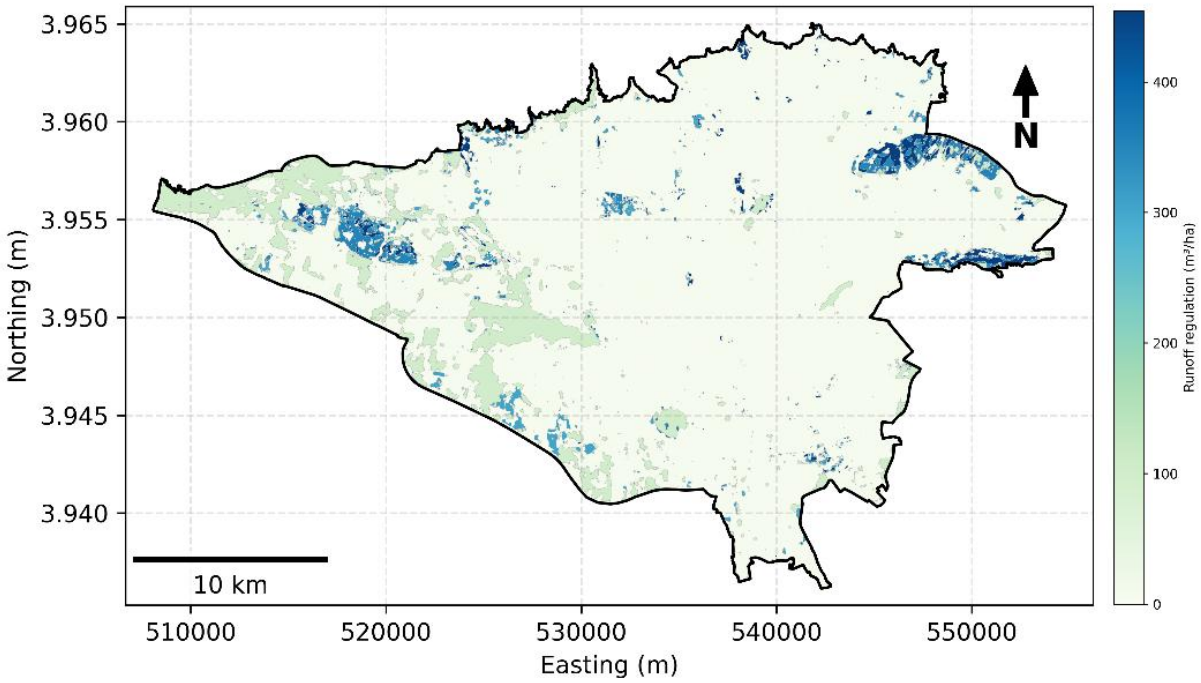


Figure 6. Spatial distribution of the runoff regulation service provided by urban green infrastructure.

Applying the transferred replacement cost coefficient of USD 1.59 per cubic meter to the runoff regulation service volume yielded a scenario-specific monetary equivalent of USD 2,339,254, or approximately USD 2.34 million. This estimate depends on the modeled volume and selected

economic coefficient and does not represent observed financial savings or the actual cost of runoff management in Tehran. It is a transfer estimate for the rainfall scenario examined and should not be interpreted as an annual value or as avoided flood damage. This amount indicates that urban green infrastructure, in addition to its environmental benefits, has considerable economic value in reducing urban runoff management costs. The results emphasize that developing and protecting green infrastructure can serve as an economic and ecological strategy for sustainable surface water management. The spatial distribution of the economic value of the runoff regulation service is shown in Figure 7.

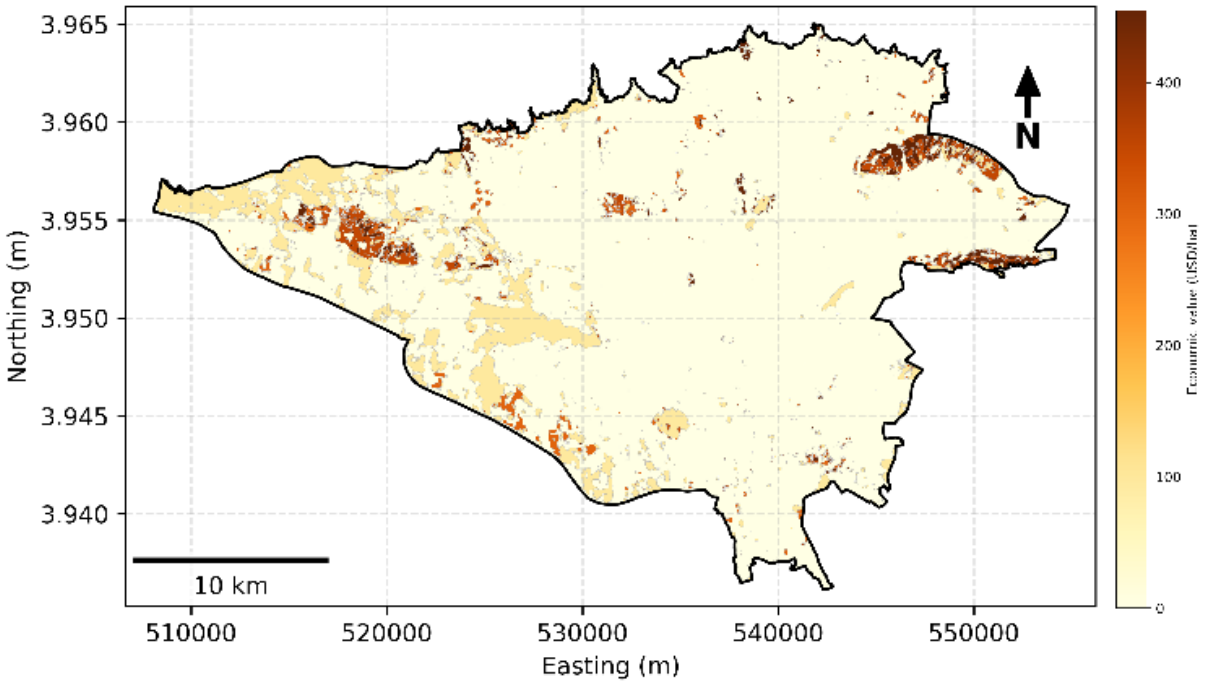


Figure 7. Spatial distribution of the economic value of the runoff regulation service in Tehran

5.Discussion and Interpretation of Results

The results showed that existing green infrastructure in Tehran is spatially heterogeneous and that the capacity to provide ecosystem services varies across the city. The mean Green Infrastructure Index was 0.271, indicating moderate green infrastructure capacity at the citywide scale. However, its range of 0.094 to 0.898 indicates considerable differences in ecological capacity among urban areas. This finding agrees with previous studies emphasizing the importance of the spatial distribution and connectivity of green elements for the actual performance of green infrastructure (Benedict & McMahon, 2006; Tian et al., 2021). The presence of green space alone cannot guarantee hydrological performance. Characteristics such as connectivity, location, land-cover type, and the relationship to areas with high runoff generation determine the extent of services provided.

The remote sensing indices also confirmed this pattern. Mean NDVI of 0.142 indicated that dense vegetation was concentrated in a limited part of the city, while mean NDBI of 0.059 indicated the relative predominance of built-up surfaces in Tehran's urban fabric. This inverse relationship between vegetation cover and physical development has been reported in many urban studies, with higher building density typically associated with reduced surface permeability, less vegetation cover, and a greater runoff risk (Dietz, 2007; Donofrio et al., 2009; Saeedi and Darabi, 2019). The results therefore suggest that Tehran's pattern of urban development has created areas with lower capacity for natural water regulation. From an urban planning perspective, this finding underscores the importance of moving beyond increasing green space area toward performance-based planning

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of green infrastructure. In many cities, small and scattered green spaces may account for a substantial area but have limited effects on hydrological processes because of unsuitable placement or a lack of functional connectivity (Dvornikov et al., 2025; Saeedi, 2025). The composite GII used in this study made it possible to identify areas with green cover and a greater capacity to provide regulating services. This approach can help prioritize future interventions such as developing linear parks, increasing permeable surfaces, and creating urban green networks.

One of the most important findings was the quantification of the role of Tehran's existing green infrastructure in reducing urban runoff. Modeling showed that under the rainfall conditions examined, runoff generated in Tehran was approximately 26.59 million cubic meters, of which existing green infrastructure was able to regulate approximately 1.47 million cubic meters. This amount indicates that existing green infrastructure has measurable hydrological performance even without further expansion. Similar studies have shown that urban green elements can effectively reduce runoff by increasing temporary water storage and infiltration and reducing flow velocity (Donofrio et al., 2009; Pour et al., 2020; dos Santos, Barbassa and Vasconcelos, 2021). Tehran's particular climatic conditions make this finding especially relevant. Tehran is located in a region with limited mean annual rainfall but short, intense rainfall events. The rapid response of the urban catchment to intense rainfall is therefore a key problem alongside the annual amount of rainfall. Under these conditions, green infrastructure can act as a natural regulating system and increase the time of concentration of runoff. This agrees with recent studies on nature-based solutions in arid and semi-arid cities that emphasize the role of these systems in increasing water resilience (Lizárraga-Mendiola et al., 2017; Saeedi & Goodarzi, 2020; Van Mechelen et al., 2015). Spatial comparison of the runoff and runoff regulation service maps also showed that the greatest runoff reduction capacity occurred in areas with a suitable combination of vegetation, permeable surfaces, and higher GII values. Areas with high building density and higher NDBI generated the most runoff. This confirms the importance of spatial analysis in urban runoff management, because a uniform strategy for all areas of a city cannot perform adequately. In other words, green infrastructure planning should reflect the hydrological needs and ecological capacity of each area.

An important aspect of this study was expressing the hydrological performance of green infrastructure as an economic indicator that urban decision-makers can interpret. The results showed that the runoff regulation service provided by Tehran's existing green infrastructure had an economic value of approximately USD 1.47 million. This amount indicates that urban green spaces provide direct economic benefits alongside their environmental and social values. Recent studies of ecosystem service valuation have also emphasized that accounting for the economic value of urban nature can shift the perspective of urban management from the cost of maintaining green space toward investment in natural infrastructure (Kuller et al., 2017; Sarkar et al., 2018). The economic value obtained in this study represents only part of the actual benefits of green infrastructure, because the study evaluated only runoff regulation. Urban green infrastructure also provides other services, including lower land surface temperature, improved air quality, greater biodiversity, and enhanced mental health for residents. The actual value of Tehran's green infrastructure is therefore likely to exceed the amount calculated in this study. This underscores the importance of future studies that can evaluate the full range of urban ecosystem services.

The reduction in runoff volume in this study relative to the reference scenario without green infrastructure was estimated at approximately 5.24%. For comparison, a 2024 study in Wuhan, China, reported runoff volume reductions of 24.85%, 5.23%, and 5.50% for events with return periods of 1, 5, and 10 years, respectively (Lin et al., 2024). The estimate from this study is numerically close to those of the last two scenarios, but this similarity does not imply identical

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performance or validate the model, because the rainfall, study scale, intervention types, and definition of the reference scenario differ. At the scale of residential parcels in Los Angeles, Xiao et al. (2007) also reported a 12% runoff reduction when lawns were converted to retention basins and a 97% reduction for the full set of measures (Xiao et al., 2007). The difference in spatial scale and the annual basis of the latter assessment limit direct comparison with the rainfall scenario examined here.

The framework introduced in this study can also be applied to other cities with similar conditions because it requires data that are available in many cities through remote sensing and geographic information systems. The results also indicate that decisions about developing green infrastructure should emphasize optimal siting and the ecological performance of these elements in addition to increasing the number or area of green spaces. Composite indices such as GII can support evidence-based urban planning in this context.

The study maps can be used for preliminary screening of locations requiring further investigation. To identify opportunities for green infrastructure development, areas with higher modeled runoff, lower GII values, and a predominance of built-up surfaces should be examined together. Areas with higher GII values and higher modeled runoff regulation service are candidates for assessing how to protect existing cover and prevent its conversion. These criteria are proposed for subsequent spatial assessments and were not combined into an integrated prioritization map in this study.

At the implementation stage, the choice of site and intervention type should be informed by slope, soil permeability, groundwater depth, flow paths, drainage networks, inundation history, ownership, and underground utilities. Along streets and in parking lots with sufficient space, the feasibility of rain gardens and vegetated strips should be examined. In public open spaces and parks, opportunities for temporary retention and controlled discharge of runoff should be assessed. In densely developed parcels, the potential for rooftop water collection and green roof installation should be assessed through structural review. The choice of infiltration-based measures should also depend on verification of soil conditions and consideration of contamination.

The results are affected by uncertainty in the input data, model structure, and economic assumptions. In the inputs, errors in land-cover classification and temporal changes in vegetation can affect the Green Infrastructure Index and curve number assignment. In addition, the temporal composite for the land-cover map used the median of nominal class codes, which produced non-integer values in the output file. This layer therefore has a specific processing limitation, and class assignments and associated parameters require review. The coarse spatial resolution of CHIRPS rainfall and the use of uniform rainfall in the Python calculations also fail to represent intra-urban rainfall heterogeneity. A smaller output pixel size does not resolve this information limitation. Differences in the spatial extent of valid pixels among layers also affect the direct comparability of areas and statistics.

Hydrological results depend on the curve numbers, the initial abstraction assumption, and the definition of the reference scenario. In the Python implementation examined, fixed curve numbers were assigned to land-cover classes, and spatial differentiation by hydrologic soil group and adjustments for antecedent moisture conditions were not applied. Flow routing, drainage network performance, and runoff entering from outside the study boundary were also excluded. The outputs therefore represent runoff generation within the computational domain and are insufficient to determine the location, depth, or damage associated with inundation. Weights and thresholds for the Green Infrastructure Index and the criteria for selecting scenario pixels also affect the results. In the absence of validation against observations and a comprehensive uncertainty analysis, the reported volumes should be treated as conditional model estimates.

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For the economic analysis, transferring a replacement cost coefficient of USD 1.59 per cubic meter from an external study without temporal or spatial adjustment introduces further uncertainty. Differences in construction costs, operating costs, and runoff management requirements between the reference area and Tehran limit direct transfer of this coefficient. Applying the coefficient to the volume from this study's rainfall scenario is also a scenario-specific approximation. The resulting amount is linearly related to the cost coefficient, so for a fixed volume, any percentage change in the coefficient produces the same percentage change in the estimated amount. The economic result does not represent realized financial savings or a verified current cost in Tehran.

6.Conclusion

This study aimed to quantify the role of existing green infrastructure in regulating urban runoff in Tehran and to estimate the economic value of this ecosystem service. To achieve this goal, an integrated framework was developed using remote sensing data, GIS spatial analysis, a composite Green Infrastructure Index, the SCS-CN hydrological model, and economic valuation. The results showed that Tehran's urban green infrastructure is unevenly distributed and that the capacity to provide ecosystem services differs substantially across areas of the city. Mean GII of 0.271 showed that although Tehran has a network of urban green elements, their distribution and performance are uneven across the city. Remote sensing indices indicated that areas with more vegetation cover and higher NDVI generally have greater capacity to regulate hydrological processes, while areas with higher NDBI and more densely built surfaces have greater potential to generate runoff. This finding indicates that urban development without attention to preserving natural elements and permeable surfaces reduces the city's hydrological self-regulation capacity.

Runoff modeling showed that approximately 26.59 million cubic meters of runoff were generated under existing conditions in Tehran. Existing green infrastructure was able to regulate approximately 1.47 million cubic meters of this volume. This amount indicates that urban green elements play a substantial role in reducing pressure on urban drainage systems and supporting sustainable surface water management. Economic valuation also showed that this ecosystem service has measurable monetary value, with the economic value of runoff regulation by existing green infrastructure estimated at approximately USD 2.34 million.

Based on the findings, future planning in Tehran should move from a sole focus on expanding green spaces toward designing functional networks of green infrastructure. Prioritizing areas based on a combination of ecological indices, runoff generation potential, and ecosystem service value can increase the effectiveness of urban investment. The results also indicate that green infrastructure should be treated as urban natural capital alongside gray infrastructure for water management. Finally, the framework presented here can serve as a decision-support tool for assessing green infrastructure performance in other metropolitan areas with similar climatic conditions. Future studies can provide a more comprehensive picture of the contribution of green infrastructure to urban resilience by developing climate change scenarios, evaluating multiple ecosystem services, and using dynamic hydrological models.

Author's Contributions

The sole author was responsible for all aspects of the study and approved the final manuscript.

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Conflict of Interest

This article has no conflict of interest.

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