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Scenario-based modeling of water yield under future climate conditions using the InVEST model (Jajrud watershed, Iran)

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Abstract

The increasing intensity of climate change and the accelerated urban expansion of cities in recent years have posed significant challenges to water resources in semi-arid regions such as the Jajroud Watershed, east of Tehran. This study applies a two-stage framework to assess the impact of future climate change on the basin's water yield. In the first stage, historical and future climate conditions were examined using observational data and the results of the CMIP6 General Circulation Models (GCMs). The LARS-WG model was used for downscaling and bias correction, and the MRI-ESM2-0 model was selected as the best-performing GCM based on statistical criteria. In the second phase, the Water Yield model from the InVEST suite was used to estimate the spatial distribution of water yield under present (2024) and future (2040) conditions, using climate projections under scenarios SSP2-4.5 and SSP5-8.5. Model inputs included precipitation, reference evapotranspiration (ET_0), root-limiting depth, plant-available water, land use/cover, and a GIS-based biophysical table. Results indicate that water yield increased from approximately 80 MCM in 2014 to about 110 MCM in 2024, mainly due to higher recent precipitation. However, future projections reveal a strong decline, with total water yield decreasing to about 60 MCM under SSP2-4.5 and further dropping to 44 MCM under SSP5-8.5 by 2040, representing nearly a 60% reduction compared with current conditions. Besides climatic drivers, land-use changes—especially expansion of built-up areas and reduction of vegetation cover—further intensify water loss by limiting infiltration and increasing evaporation. These findings align with results reported for other semi-arid regions and highlight the urgent need to integrate climate adaptation strategies into land-use planning and water resource management to sustain the basin's role in supplying water to Tehran.

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Introduction

In the last three decades, the extent of climate change has affected the Earth's hydrological cycle more than ever before: rising global temperatures, changing rainfall patterns, increasing drought and flood events, and decreasing groundwater reserves have all exacerbated the pressure on surface and subsurface water resources (Hou et al., 2025). Research shows that the intensity of the hydrological cycle is increasing, and these changes have led to greater complexity in water resource management, especially in arid and semi-arid regions (Acosta et al., 2022). In addition, the use of satellite data has shown that the Earth's water storage is decreasing significantly in some parts of Asia and Africa, and that droughts are becoming more severe than in the past (Park et al., 2023). Global studies also indicate that the combination of climate change with land use change has a complex and compound effect on runoff patterns, and the simultaneous assessment of both climate and human factors is essential for a more accurate understanding of the hydrological future (Rastgar et al., 2015; Wang et al., 2024). In studies using the InVEST-Water Yield model, advances in the analysis of combined climate and land use scenarios have clearly shown that climate is the dominant factor in runoff change and that the role of LULC is less significant (Wei et al., 2021). In addition, Bojer et al. (2025) found in a multi-basin study that for accurate runoff simulation, the integration of water scenario data and InVEST spatial modeling is essential, and the tool has the ability to integrate climate and LULC well (Bojer et al., 2025).

Sustainable management of water resources at the basin level requires a detailed understanding of hydrological processes, especially runoff generation, groundwater recharge, and river flow (Liu et al., 2025). Runoff, as a major component of the water cycle, is affected by multiple factors, including climate, topography, soil characteristics, vegetation, and land use, and any changes in these factors will alter the runoff pattern. Therefore, accurate modeling of runoff under different conditions, especially future climate scenarios, is of great importance (Hongxue et al., 2024). In response to this need, several models have been developed to simulate runoff. Among them, the SWAT model is one of the most well-known tools, but the need for abundant input data, complexity in calibration, and long-term implementation have led to the use of simpler and more flexible models in some areas. In the meantime, the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model and its Water Yield submodel, as a semi-empirical GIS-based model, have attracted special attention in recent years. This model uses data such as precipitation, potential evapotranspiration, land use and cover (LULC), root penetration depth, and soil moisture retention capacity to estimate annual runoff at a spatial scale and provide decision-support maps (Sharp et al., 2019; Wei et al., 2021).

Several global studies have examined the application of the InVEST–Water Yield model in analyzing the effects of climate change and land use change on runoff. For example, Wei et al. (2021) showed in the Shule Basin in China that more than 90% of runoff changes are attributed to climate change and only 10% to land use change. Also, in a multi-basin study, Guo et al. (2023) reported significant spatial differences in runoff patterns, which were caused by a combination of climate, vegetation, and soil factors, by comparative analysis of model results in different climates. Rafiei-Sardooi et al. (2022) also highlighted the effective role of climate scenarios in reducing surface water discharge by analyzing the long-term effect of climate and land use in the basins of central Iran in an article in Ecological Modelling. In Iran, some studies have investigated the effects of climate change and land use on runoff using the InVEST model. Balist et al. (2022) simulated the impact of two climate scenarios (RCP 2.6 and RCP 8.5) and two land use scenarios on runoff in a study in the Sirun Basin in Kurdistan Province and found that the reduction in runoff due to climate change is more than twice the effect of land use change. Daneshi et al. (2021) also showed in a study in northern Iran using the InVEST model that conservative land use policies can partially compensate for the reduction in runoff caused by climate change, but not completely. In another study, Emlaei et al. (2022) in the Haraz Basin, by integrating GCM data and the Water Yield model, emphasized the importance of spatial validation of results to reduce uncertainty.

However, existing studies in Iran have not yet paid sufficient attention to up-to-date climate scenarios (such as SSPs), local calibration of biophysical parameters, and spatial sensitivity analysis of runoff. On the other hand, many critical basins in the country, including the Jajrud basin in eastern Tehran, have been less thoroughly studied with this model. The Jajrud basin, with an area of about 2700 km2, is one of the most important water supply basins for Tehran, which includes the two dams of Latyan and Mamlu. This basin has mountainous topography, cold semi-arid climate, predominantly winter precipitation, and severe land use changes in recent decades. Population growth, urbanization, and changes in vegetation in the basin have raised serious concerns about the sustainability of surface water discharge.

In this study, an attempt has been made to model the annual runoff of the basin in future time periods (2040) using prospective climate scenarios (SSP2–4.5 and SSP5–8.5), land use data, local biophysical parameters, and their combination in a GIS environment. The innovation of this study lies in several aspects: first, the simultaneous use of new IPCC climate scenarios and precise spatial data (IPCC., 2021); second, focusing on a strategic basin of national importance; and third, generating spatial outputs for decision-making in dam management, urban water management, and resource planning. The findings of this study can be used by the responsible agencies in the context of adaptive water resources management in Tehran, assessing the vulnerability of water supply structures, and designing climate-adapted scenarios. Also, from a scientific perspective, this study is an example of combining ecosystem services modeling with regional-scale scenario assessment that can be generalized to other arid regions of the world.

Despite numerous studies assessing runoff and water yield under climate or land-use changes, limited research in Iran has integrated up-to-date CMIP6 climate scenarios, locally calibrated biophysical parameters, and spatial ecosystem-service modeling to evaluate future water yield in strategically important basins. Moreover, the Jajroud Watershed—one of Tehran's main water supply sources—has not been comprehensively analyzed using scenario-based ecosystem service modeling approaches. The novelty of this study lies in (i) integrating bias-corrected CMIP6 climate projections with the InVEST Water Yield model, (ii) combining climate and land-use changes within a spatially explicit GIS framework, and (iii) producing quantitative and spatially distributed outputs to support basin-scale water management and climate adaptation planning. These contributions provide practical decision-support information that can be applied to similar semi-arid watersheds facing rapid environmental and urban pressures.

Materials & Methods

The Jajrud Watershed, whose upstream part includes the mountainous area above the Latyan Dam, is one of the important watersheds in the northeast of Tehran province. According to published studies, this watershed includes the mountainous areas of the central Alborz and the downstream plains around Pardis, Roudehen, Bumehen, and Lavasan, and plays a vital role in providing drinking water to the metropolitan city of Tehran (Najimi et al., 2023). The upstream watershed of the Latyan Dam has an area of about 670 square kilometers and its elevation varies from about 3960 meters touching the Tochal peak to about 1574 meters near the dam water level (Najimi et al., 2023). There are four different climatic zones in the area, including "humid-moderate", "dry-moderate", "dry-warm" and "humid-cold" climates, and there is a direct relationship between precipitation patterns and river flow (Najimi et al., 2023). In addition, analysis of long-term trends in temperature, precipitation and river flow in different climatic periods has shown that climate change can increase the intensity of seasonal precipitation, reduce the duration of snow cover and increase the risk of severe floods, along with a decrease in medium-term runoff (Najimi et al., 2023).

Studies of the water quality of the Jajrud basin and river also show that human activities, increasing urban population and migration pressure to marginal areas have had a significant negative impact on the quality of surface and groundwater resources; especially in areas close to water quality adaptive stations and the catchments below the Latyan Dam (Gholikandi et al., 2012; Givi et al., 2021). These cases indicate the importance of integrating climatic, hydrological, and environmental data for managing the basin's resilience to climate change and human development. Overall, the Jajrud basin, with its diverse topography, significant elevation differences, semi-arid mountainous climate, and dense population composition downstream, is a strategic case study for scenario analysis of runoff, land use changes, and designing adaptive water policies (Najimi et al., 2023).

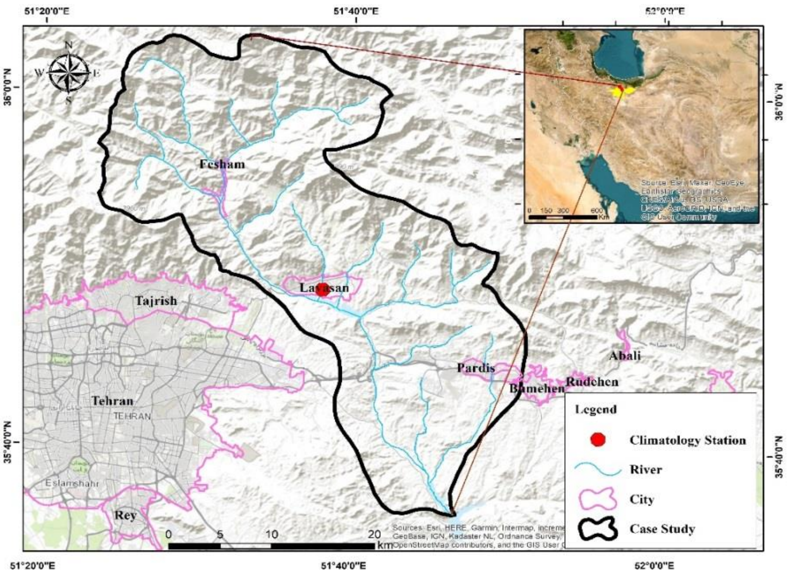


Figure 1- The study area

In this study, the "Water Yield" model of InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) toolkit was used to analyze the impact of climate change on runoff in the Jajrood Watershed. This model is based on a simple water balance equation and estimates the annual water yield at the watershed level under different climatic and land use conditions using spatial, quantitative, and biophysical data (Sharp et al., 2019).

First, climate data including annual precipitation (P) and annual actual evapotranspiration (AET) were prepared. These data were generated for the observation period and future scenarios based on the output of climate modeling conducted in the researcher's previous research. Climate scenarios based on SSP2-4.5 and SSP5-8.5 were extracted from the CMIP6 model suite and then bias-corrected using statistical methods (Rahman and pekkat., 2024). All these data were processed in a GIS environment (ArcGIS) and converted into annual raster layers (Zhou et al., 2023).

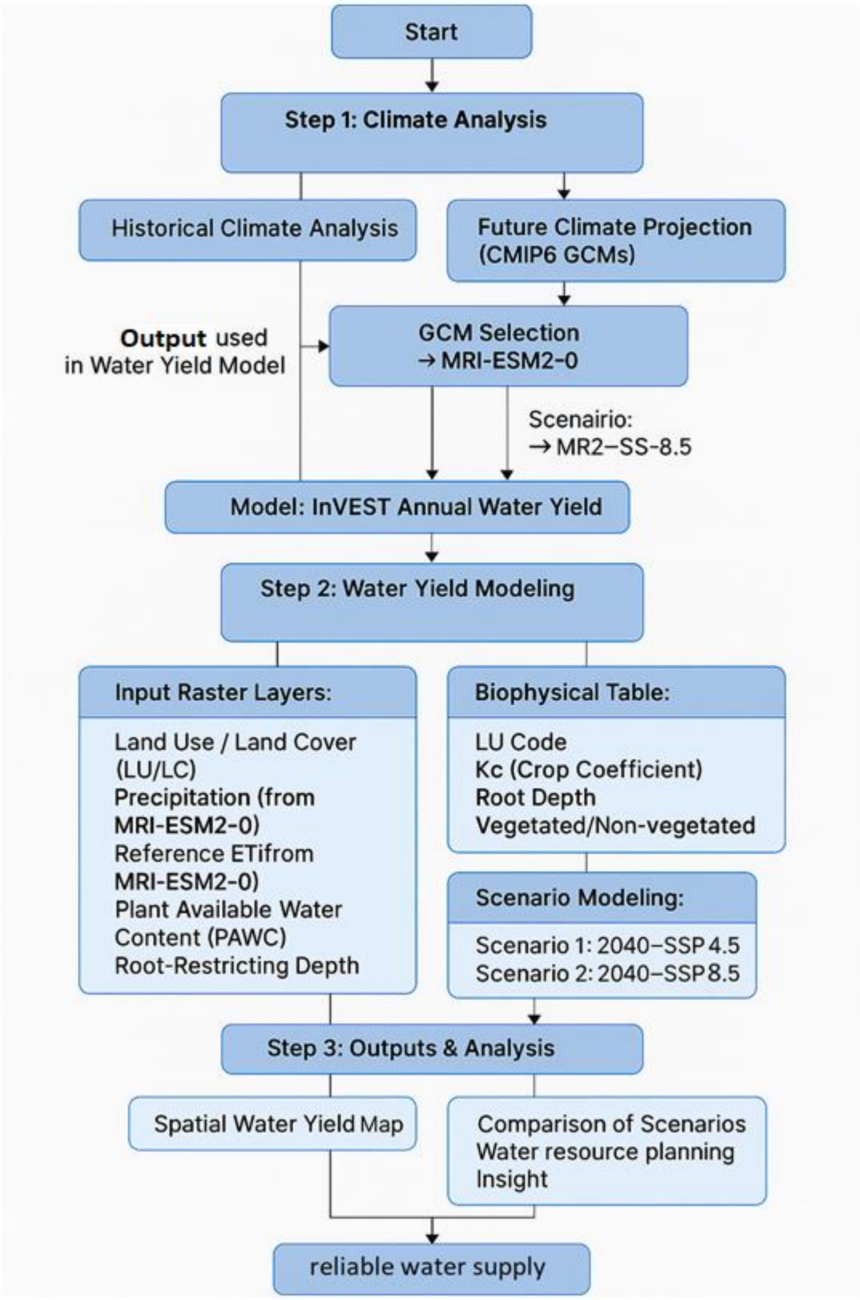


Figure 2. Research flowchart

All spatial input layers were standardized to a 30 m spatial resolution consistent with Landsat-based land-use data. Climate data for the 1993–2014 period were used to evaluate CMIP6 models, and future projections for 2040 under SSP2-4.5 and SSP5-8.5 were generated using LARS-WG bias correction and downscaling. Land-use maps were derived from Landsat imagery for 2014 and 2024 obtained from USGS. Model reliability was assessed by comparing GCM precipitation outputs with observed data using R^2 statistics, and simulated runoff trends were found to be consistent with historical observations and previous regional studies.

In order to examine the trends in land use changes and related phenomena in the Jajrood watershed, ENVI 5.6 software was used to process and interpret satellite images. The required images were extracted from the US Geological Survey website. To examine the trends in changes in the study area, reference land images from the Landsat satellite, associated with the OLI sensor, for the years 2014 and 2024 were used.

The water yield was modeled in the InVEST 3.13.0 software. The model was used to evaluate water yield in different studies around the world (Balist et al., 2022a). The model is based on the Budyko curve (Budyko 1974) and annual precipitation. Also, it is a practical approach for estimating ecosystem services like water at various scales. In this model, first, the average annual water yield per pixel (Y (x)) of the region is calculated according to Equation 1 (Sharp et al 2019).

$$Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right).P(x) \quad (1)$$

where AET (x) is the average annual actual evapotranspiration of cell x, and P (x) is the average annual precipitation of the same cell.

In the InVEST water yield model, the land-use layer is divided into two classes with vegetation and no vegetation, and the ratio $\frac{AET(x)}{P(x)}$ of each class is calculated separately. For the covered class, this ratio is calculated based on the Budyko curves proposed by Fu (1981) and Zhang (2004) (Equation 2)

$$.\frac{AET(x)}{P(x)} = 1 + \frac{PET(x)}{P(x)} - \left[1 + \left(\frac{PET(x)}{P(x)}\right)^{w}\right]^{\frac{1}{w}} \quad (2)$$

PET (x) is the potential annual evapotranspiration of cell x and w (x) is a non-physical parameter that depends on the natural climatic-soil characteristics of the cell. Potential evapotranspiration, PET (x), is defined according to Equation 3

$$PET(x) = K_c(L_x).ET_0(x) \quad (3)$$

where ET0 (x) is a parameter reflecting the climatic conditions of the region based on the evapotranspiration of a reference plant in the region and Kc (Lx) is mainly determined by the vegetation characteristics of the cell soil (Allen et al 1998).

W (x) is an experimental parameter that can be measured by a linear equation $\frac{AWC*N}{P}$, where N is the number of precipitation events per year and AWC is plant available water content (mm). This linear equation is like Equation 4 (Donohue et al 2012):

$$w(x) = Z\frac{AWC(x)}{P(x)} + 1.25 \quad (4)$$

where AWC (x) is plant available water content (mm) in cell x, depending on the soil texture and the adequate root depth. AWC (x), which specifies the amount of water that the soil retains for plant use, is obtained by multiplying the plant available water content capacity (PAWC) at the root restricting depth or plant root depth given in Equation 5 (Yang et al 2019):

$$AWC(x) = Min(Rest.layer.depth, root.depth).PAWC \quad (5)$$

Root-restricting layer depth refers to the depth beyond which roots cannot penetrate due to the soil's physicochemical properties. In contrast, plant root depth is typically defined as the depth containing 95% of the total root biomass. Plant-available water capacity (PAWC) is calculated as the difference between soil water holding capacity and the permanent wilting point (Yang et al., 2019).

The hydrological parameter Z is an empirical constant ranging from 1 to 30, which reflects local precipitation patterns, rainfall intensity, seasonal climatic variations, and basin topography. Following Donohue et al. (2012), Z is calculated using the equation Z = N × 0.2, where N represents the number of rainy days per year.

For the classes without vegetation of the land use layer (like urban areas and wetlands), the actual evapotranspiration of AET (x) is obtained directly from the evapotranspiration of the reference ET0 (x) according to Equation 6:

$$AET(x) = Min\left(K_c(L_x).ET_0(x), P(x)\right) \quad (6)$$

where ET0 (x) is the reference evapotranspiration and Kc (Lx) the specific land use evaporation factor (Table 4).

Table 1. Biophysical table

Row	Land use	Lu-code	k_c	Root depth (mm)	Vegetation
1	Bare land	1	0.5	0	0
2	Forest	2	0.85	1500	1
3	Water	3	1	0	0
4	Built-up	4	0	0	0
5	Rangeland	5	0.8	300	1

Results and Discussion

Comparison of model results in different climate scenarios was carried out spatially and statistically. Its aim was to spatially analyze runoff changes and identify areas vulnerable to a decrease or increase in annual runoff under the influence of climate change.

According to the table provided, the R^2 value for different models varies between 0.41 and 0.68. The MRI model with a coefficient of determination of 0.68 has the best performance in reproducing the precipitation observational data in the study basin, followed by the BCC_CSM2-MR (0.67) and INM_CM5_0 (0.63) models. These models probably have a higher ability to simulate regional precipitation patterns.

In contrast, models such as MPI and GLDF with R^2 of 0.41 and 0.43, respectively, showed the lowest accuracy and are not suitable for predicting the future climate of the region. This difference in performance indicates the importance of choosing the right GCM model in local climate studies, as well as the advantage of using machine learning algorithms such as XGBoost to more accurately assess the agreement between forecast and actual data.

Therefore, the MRI model was selected as the most appropriate model for future climate scenarios in the region and was used in subsequent modeling steps such as the InVEST model.

Table 2. GCM models

Raw	GCM	R^2	Raw	GCM	R^2	Raw	GCM	R^2
1	BCC_CSM2-MR	0.67	6	GISS_E2_2_G_	0.55	11	ACCESS	0.47
2	INM_CM5_0	0.63	7	TaiESM1	0.53	12	CNRM	0.45
3	CESM2	0.6	8	UKESM1_0	0.52	13	GLDF	0.43
4	MIROC6	0.59	9	CanESM5	0.5	14	MPI	0.41
5	CC_CSM2	0.57	10	Hadjem	0.48	15	MRI	0.68

The 2024 precipitation map of the Jajrud River Basin (Fihure 3-a) shows a spatial pattern of precipitation with significant variations across the basin. The precipitation amounts in this map range from a minimum of 192.5 mm in the lower reaches of the basin (southeast and areas adjacent to Mamlu Dam and the cities of Pardis and Bumehan) to a maximum of 617.5 mm in the highlands of the northwestern basin (areas around Fasham and the northern highlands). This sharp difference in precipitation is mainly due to the difference in altitude and the effect of topographic factors on the distribution of moisture and sudden air ascent in mountainous areas.

Also, this pattern shows that the upstream parts, which play a key role in feeding the rivers and water resources of the basin, have higher precipitation, while the downstream areas, which include urban and built-up areas, face a shortage of precipitation. Such a distribution plays an important role in designing water resource management scenarios; Because the inflow rate to Mamlu Dam and Tehran's drinking water supply must be considered. This difference in rainfall can also affect runoff patterns, soil erosion, and recharge of local aquifers, and plays a vital role in assessing the effects of climate change on regional water supply.

Figure 3-b presents the different land use/land cover classes of the Jajrud Watershed in 2024 based on raster data with a cell size of 30 m × 30 m. These classes include barren land uses, orchards, water resources, built-up areas, and pastures. The largest land use area is allocated to pastures, which covers about 506 km2 (equivalent to 50% of the total area of the basin). This is followed by barren land use with 322 km2 and built-up areas with about 110 km2. Orchards cover only about 48 km2 and water resources cover only 2 km2 of the basin surface. This land use mix indicates the dominance of natural lands (pasture and barren) in this mountainous and semi-arid basin, while the share of urban and garden spaces is significant but limited, especially in downstream areas such as Pardis, Bumehen, and Lavasan. The total area of the basin is estimated to be about 988 square kilometers based on this analysis.

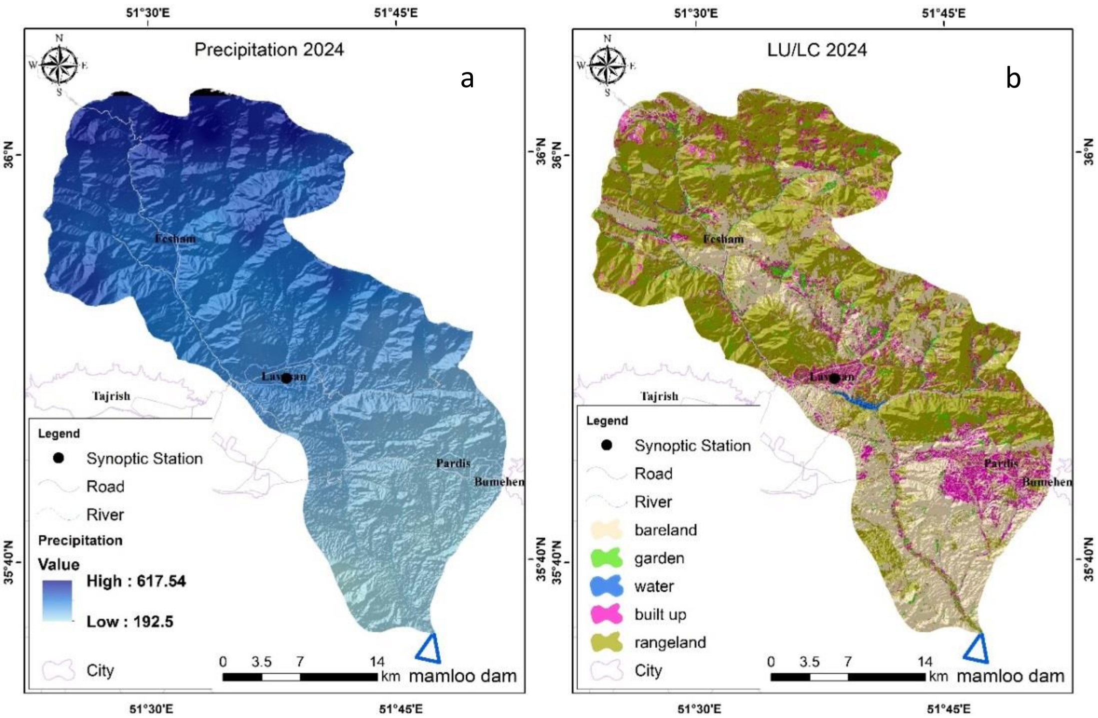


Figure 3- a, LU/LC and b, Precipitation

The map of plant-available water in the Jajrud Watershed shows the amount of moisture that remains in the soil and can be absorbed by plant roots. This value is a function of soil characteristics such as texture, structure, and rooting depth. In this map, PAWC values range from zero to about 0.13. Areas in blue and green (such as parts of the center and southeast of the watershed) have a higher capacity to hold water in the soil and provide more favorable conditions for plant growth. In contrast, large parts of the north and center of the watershed, shown in red and orange, have lower PAWC values and indicate soils with a low capacity to hold water. The Root-Restricting Layer Depth map for the Jajrud Watershed illustrates the depth below which root growth is inhibited by physical or chemical constraints, such as soil compaction or the presence of a hardpan. Across the watershed, this layer ranges from 0 m (indicating complete restriction at the surface) to a maximum depth of approximately 1.9 m. Darker areas, particularly in parts of the south, east, and central regions, denote zones of severe root limitation, often associated with shallow, rocky soils or physical barriers. In contrast, lighter areas—especially in the central and northern portions of the basin—indicate deeper soils with greater root penetration nd higher water storage capacity.

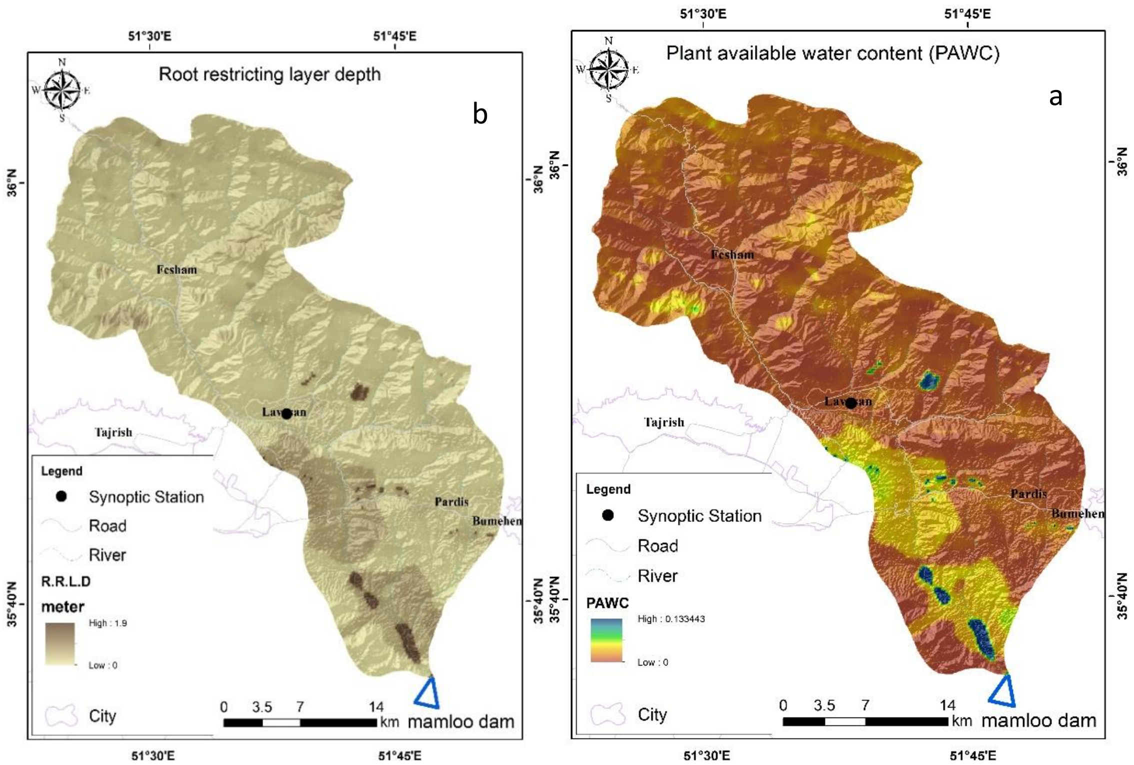


Figure 4-a, Root restricting layer, and b, plant available water content

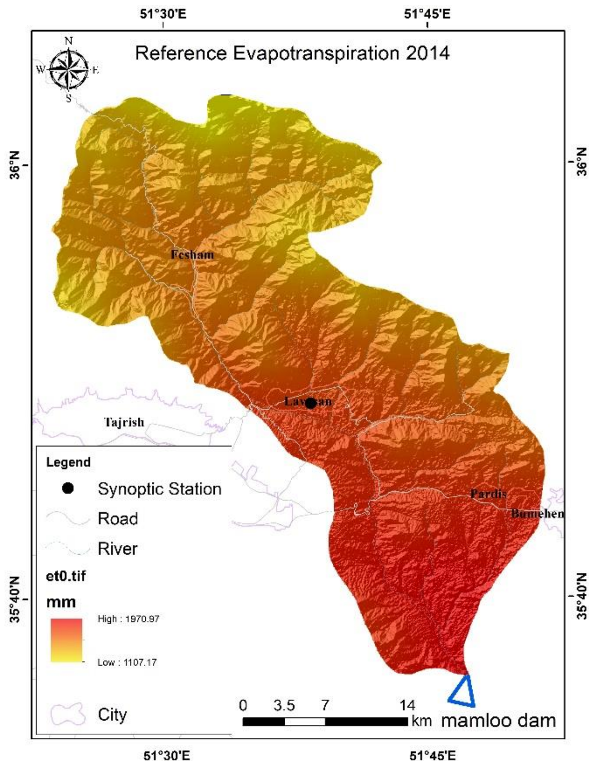


Figure 5- Evapotranspiration

The 2024 reference evapotranspiration (ET_0) map for the Jajrud Watershed (figure 5) shows a different spatial distribution of evapotranspiration demand across the region. According to this map, ET□ ranges from about 1107 mm in the northern highlands of the basin (such as Fesham) to nearly 1971 mm in the southern and downstream areas of the basin (near Bumehen, Pardis, and Mamlu Dam). This pattern reflects differences in topography, temperature, and solar radiation in the region; southern areas with lower elevations and higher temperatures have higher evapotranspiration. In contrast, northern areas with higher elevations and more vegetation experience lower ET_0.

This table presents the final results of the runoff yield modeling for the Jajrud watershed in four different time periods including the past (2014), the present (2024), and two future scenarios (2040-1 and 2040-2).

In 2014, an average rainfall of 288.7 mm, relatively high potential evapotranspiration (1088.8 mm), and a runoff volume of 80 million cubic meters were recorded. This value indicates an acceptable performance for runoff production in the past conditions with moderate rainfall and significant evaporation.

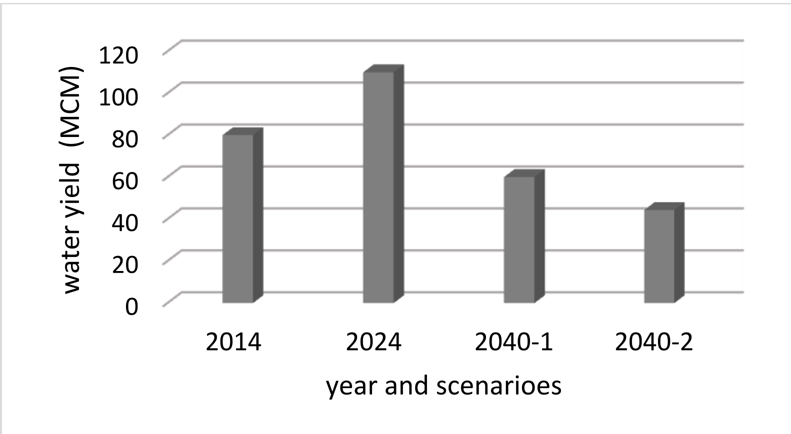
In 2024, rainfall has increased significantly and reached 383.2 mm, while evapotranspiration has not changed much and has remained around 1090.3 mm. As a result, actual evapotranspiration and runoff have also increased, and the runoff volume has reached 110 million cubic meters, which is the highest value among the scenarios. This shows that the increase in precipitation has already had a direct effect on the increase in runoff.

In the 2040-1 scenario, precipitation decreases to 268.3 mm, and potential evapotranspiration reaches 1199.4 mm. As a result, actual evapotranspiration and runoff decrease sharply. The runoff volume has decreased to 60 million cubic meters, which is about 45% less than in 2024. This decline is alarming.

This scenario is the most pessimistic. Precipitation reaches 229.9 mm and runoff reaches 44.3 million cubic meters. While PET increases to 1308.4 mm, indicating a sharp increase in the temperature of the region and higher evaporation. As a result, more critical conditions are predicted for surface water resources in the future.

Table 3. Water yield in 4 time periods

	precip_mm/pixel	PET_ mm/pixel	AET_ mm/pixel	wyield_vol (MCM)
2014	288.6761993	1088.829654	207.6696852	80.04169
2024	383.2426634	1090.326981	271.8797377	110.0353
2040-1	268.2698623	1199.35969	207.5027189	60.04113
2040-2	229.9456061	1308.392398	185.0730454	44.33561



The results of runoff modeling in the Jajrood watershed indicate that the region is entering a period of severe water stress resulting from the simultaneous occurrence of climate change, land use changes, and soil physical conditions. Climate data for 2014, 2024, and two future scenarios for 2040 show a worrying trend of decreasing runoff and changing water levels in the basin. The increase in rainfall in 2024 compared to 2014 increased the generated runoff from about 80 million cubic meters to more than 110 million cubic meters, indicating the direct sensitivity of runoff to rainfall changes in the study area. However, in the future scenarios of 2040, even assuming the use of the best identified GCM model (MRI-ESM2-0 with R^2 equal to 0.68), the significant decrease in precipitation and the increase in reference evapotranspiration have caused a sharp decrease in runoff to about 60 and 44 million cubic meters in the two scenarios SSP1-2.6 and SSP5-8.5.

Analysis of the 2024 precipitation map shows that the highest precipitation occurs in the northwest of the basin, in the highlands of Feshm, and the lowest amount in the southeast near the Mamlu Dam. This spatial distribution of precipitation is consistent with the topography and natural slope of the region. In contrast, the 2014 reference evapotranspiration map shows the highest amount in the southeast (downstream of the basin), where temperatures are higher and vegetation is less. This spatial disparity between precipitation and evaporation creates unbalanced conditions for runoff production and groundwater recharge, leading to the emergence of critical areas downstream of the basin.

The study of soil parameters also indicates significant limitations in the ability of the soil in the region to retain water. The root-limiting layer depth map shows that in many areas, this depth is less than 1 meter, which limits the growth and performance of vegetation. The plant usable water holding capacity (PAWC) map also shows that most areas have very low values of this index (below 0.05), except in certain areas in the southeast of the basin that have higher values. These findings indicate that even in the event of precipitation, a large part of the water cannot be stored in the soil and as a result, it either evaporates or quickly turns into surface runoff and becomes unavailable.

In addition to climatic and soil factors, the role of land use is also very prominent. According to the biophysical table of the region, the largest area belongs to pastures and barren lands, which have significant differences in terms of vegetation cover, root depth, and evapotranspiration coefficient. Pastures with roots of 300 mm and Kc of 0.8 play an effective role in storing and maintaining water, while barren lands and built-up areas lack this feature and contribute to accelerating surface runoff and reducing natural recharge. The gradual change in land use from vegetation to built-up areas, especially in the eastern and southern areas of the region (near Bumehen and Pardis), has increased surface resistance, reduced soil permeability, and consequently reduced useful runoff.

Compared to international studies, the trends observed in this study are consistent with similar findings in semi-arid regions of the world, such as the research of Li et al. (2023) in China, Jajrud (Najimi et al., 2023) and Devkota et al. (2015) in the Nile Basin. These studies have also identified reduced precipitation, increased temperature, and land use change as the main factors reducing runoff and increasing drought risk. At the national level, studies in basins such as Karkheh and Zayandehroud using the InVEST or SWAT model have shown a similar trend of reduced runoff in extreme climate scenarios (SSP5-8.5). Overall, the results of this study are a clear warning for water resource managers and regional planners. The Jajroud basin, which plays a key role in supplying water to Tehran through the Letian and Mamlu dams, will experience a serious reduction in surface water resources if the current trend continues. This requires urgent management interventions such as enhancing vegetation cover, controlling runoff, improving land use, and developing climate adaptation mechanisms. Also, expanding modeling studies with higher accuracy, reviewing urban development policies downstream of the basin, and designing localized scenarios can help maintain the sustainability of water resources in this critical region.

Conclusion

The findings of this study clearly indicate that the Jajrood watershed—a critical water supply source for the Tehran metropolitan area—is facing a substantial decline in runoff and increasing water stress under the combined pressures of climate change, soil constraints, and land use changes. Future climate projections, particularly under the extreme warming scenario (SSP5-8.5), suggest that reduced rainfall and heightened evapotranspiration could decrease annual runoff to nearly half of current levels. This trend is further exacerbated by soil physical properties—such as restricted root depth and low water retention capacity—alongside diminishing vegetation cover and the expansion of impervious surfaces resulting from urban development.

These results align with findings from similar studies conducted in semi-arid regions worldwide (Nasiri and Yamani, 2009; Madadi et al., 2026) and underscore that, in the absence of effective management interventions, the sustainable supply of water from this basin will face serious challenges in the coming decades. Consequently, the adoption of adaptive strategies is imperative. These include enhancing vegetation cover, implementing comprehensive land use planning, developing runoff control and storage systems, and reassessing urban growth patterns. Moreover, the integration of more precise hydrological modeling and continuous monitoring of climatic and hydrological conditions will be essential for informed decision-making to ensure the long-term sustainability of water resources in this vital basin.

Collectively, these findings highlight the urgent need for policy measures aimed at protecting upstream vegetation, regulating urban expansion, and promoting watershed-scale water conservation practices. Incorporating climate-adaptive land use planning and runoff management into regional water policies will be crucial to securing a reliable water future for the Tehran metropolitan area.

Conflict of Interest

The authors declare no conflict of interests regarding the publication of this manuscript.

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