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Comparative analysis of the effects of climate change and land use on runoff and its prediction in a mountainous watershed in Northwestern Iran

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Abstract

Sustainable water resource management in semi-arid regions requires a precise understanding of the impacts of climate change and land use on hydrological processes. Climate change and land use are primary factors influencing the hydrological processes of mountainous watersheds in semi-arid areas. This study conducts a comparative analysis of their effects on runoff and water retention in the Zolachai watershed, located in northwestern Iran, using the InVEST model. Climate data based on the SSP5-8.5 scenario of the ACCESS-CM2 model, Sentinel-2 satellite imagery for 2016, 2020, and 2023, and hydrological soil group data (A, B, C) were used to generate runoff and water retention maps for 2016, 2023, and projections for 2030. Results revealed that residential areas, with Curve Numbers (CN) of 70–90, exhibit the lowest water retention and highest runoff (359.4–647 mm) due to impervious surfaces. Conversely, orchards and irrigated lands, with CN 36–80, demonstrate the highest water retention and lowest runoff (137.2–333.8 mm) owing to high soil permeability and vegetation cover. Projections for 2030 indicate an increase in orchards and irrigated lands from 221.11 to 528.18 km² and a decrease in Rangelands and bare soils, leading to increased water consumption and reduced surface flows. Climate change, particularly under the SSP5-8.5 scenario, intensifies rainfall, elevating flood risks. These findings highlight the need for integrated water resource management to mitigate environmental risks such as soil erosion and flooding.

Keywords: Watershed Management, Monitoring and Assessment, Climate Scenarios, Runoff Retention, InVEST Model
Article Type: Research Article

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1. Introduction

Climate change and land use change are recognized as key factors driving transformations in the hydrological processes of watersheds, particularly in mountainous regions. These factors, individually or interactively, influence the water cycle, soil water retention, infiltration, and the sustainability of surface and groundwater resources (IPCC, 2007). Climate change, primarily driven by human activities such as greenhouse gas emissions, is associated with altered precipitation patterns, rising temperatures, and intensified climatic phenomena such as droughts and floods (Trenberth, 2011). These changes can lead to reduced soil moisture, increased evapotranspiration, and decreased water infiltration (Bates et al., 2008). Conversely, land use change, particularly the conversion of forests and Rangelands to agricultural or residential areas, disrupts hydrological balance by reducing vegetation cover and increasing surface runoff, thereby heightening the risks of soil erosion and flooding (Foley et al., 2005). This study focuses on the Zolachai watershed in northern Iran, conducting a comparative analysis of the impacts of these two factors on water retention and infiltration, along with their prediction.

Climate change, due to its widespread effects on hydrological processes, has been the subject of numerous studies. According to IPCC reports (2007), rising global mean temperatures and shifting precipitation patterns are among the most significant consequences of climate change, altering surface and groundwater flows in watersheds. In mountainous regions, these changes can accelerate snowmelt and alter the timing of seasonal flows, significantly impacting water availability (Bates et al., 2008). For instance, rising temperatures may reduce snow storage in higher elevations, decreasing river flows during dry seasons and threatening water resources for agriculture and urban use (Trenberth, 2011). This is particularly critical in the Zolachai watershed, a primary water source for the region.

Land use change, as a local and human-induced factor, also has significant impacts on watershed hydrology. The conversion of forests and pastures to agricultural or residential lands reduces soil water retention capacity and increases surface runoff (Guzha et al., 2018). In mountainous watersheds like Zolachai, characterized by steep slopes and fragile soils, such changes can lead to soil erosion and increased sedimentation in rivers. Recent studies indicate that the expansion of agricultural activities and the reduction of forest cover in this region have increased runoff and decreased soil water infiltration (Shanani and Zarei, 2017). These changes not only affect natural ecosystems but also jeopardize the sustainability and quality of water resources.

The Zolachai watershed, due to its geographic location and critical role in supplying water for agricultural and urban needs in northern Iran, was selected as a sensitive study area. Located in a mountainous region, the Zolachai River serves as a key water source for various uses. Previous studies have shown that climate change and land use changes in this region have led to reduced surface and groundwater flows and increased environmental risks such as flooding and soil erosion (Ostadi et al., 2024). These changes make an accurate prediction of hydrological processes challenging due to the complex interactions between climatic and land use factors.

To analyze the impacts of climate change and land use change more precisely, the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model was employed as an effective tool. This model enables the assessment of ecosystem services such as water yield, water quality, and erosion control, and is widely used to simulate the effects of environmental changes in watersheds (Özgenç and Uzun, 2024). By integrating climate, land use, and soil data, InVEST can predict changes in water yield and infiltration under various climate and land use scenarios (Tang et al., 2023). Compared to other models, InVEST is particularly suitable for mountainous watersheds like Zolachai due to its ability to integrate remote sensing and GIS data and simultaneously evaluate multiple ecosystem services (Rahimi et al., 2020). The model has been used in recent studies to assess the impacts of climate change and land use change on water security in semi-arid regions like Iran, with results indicating reduced water yield and increased pressure on water resources due to environmental changes (Daneshi et al., 2021).

Several studies have investigated the impacts of climate change and land use change on runoff. Viviroli et al. (2011) examined the role of mountainous regions in providing freshwater and the impacts of climate change on their hydrology, noting that climate change can alter snowmelt and runoff patterns, affecting water retention and infiltration. Bai et al. (2019) used the InVEST model to study the effects of climate and land use changes on water yield ecosystem services in Kentucky, USA, from 1992 to 2011, finding that climate change had a greater impact on water yield at the state level. Li et al. (2021) analyzed the impacts of climate and land use changes on the hydrological performance of the Yellow River Basin, showing that land use changes improved water supply services. Wang et al. (2022) assessed water yield changes in response to urbanization in a Chinese urban area, finding a direct correlation between urbanization levels and hydrological performance, particularly water yield. Kusi et al. (2023) evaluated the effects of land use and climate change on water-related ecosystem services in a Moroccan watershed, concluding that climate change had a greater impact on hydrological performance than land use changes. Hou et al. (2024) used CA-Markov and FloodMap models to analyze land use changes and flood risk in Chongqing, predicting an increase in residential areas and flood-prone zones by 2030. Wang et al. (2024) used InVEST and remote sensing data to study spatiotemporal water yield changes in Henan Province from 1990 to 2020, noting initial increases followed by declines in water yield. Gao et al. (2025) analyzed water yield changes in the Yellow River Basin from 1982 to 2020 using InVEST, finding significant fluctuations driven by natural factors in upstream and midstream areas and land use changes in downstream areas, with projections for 2030 indicating a relative decline in water yield.

The objective of this study is to conduct a comparative analysis of the effects of climate change and land use change on water retention and infiltration in the Zolachai watershed using the InVEST model. By simulating various climate and land use scenarios, this research aims to provide management strategies to mitigate environmental risks and protect the region's water resources. In the mountainous region of the Zolachai watershed, the interaction between climate change and land use changes exerts complex effects on hydrological processes. For instance, increased precipitation intensity driven by climate change, particularly in agricultural lands or residential areas with reduced vegetation cover and compacted soils, significantly enhances surface runoff, thereby exacerbating the risks of flooding and soil erosion (Viviroli et al., 2011). These interactions, by reducing water infiltration and increasing sedimentation, pose a threat to the sustainability of water resources and downstream ecosystems (Foley et al., 2005). The results can serve as a model for the sustainable management of other mountainous watersheds in Iran and similar regions.

2. Materials and Methods

2.1. Study Area

The Zolachai watershed is located in the northwestern part of Lake Urmia in West Azerbaijan Province, Iran, and is a sub-basin of the Lake Urmia watershed. Its geographical extent lies between 44°13' and 45°29' East longitude and 37°52' and 37°24' North latitude, covering an area of 2,258 km^2. The Zolachai River originates from the Sari Dash mountains and highlands, flows through the middle of Lakestan and Zola villages, and ultimately drains into Lake Urmia, one of the watersheds contributing to the lake (Nazar Neghad et al., 2020). Figure 1 illustrates the location of the study watershed within the province and the country.

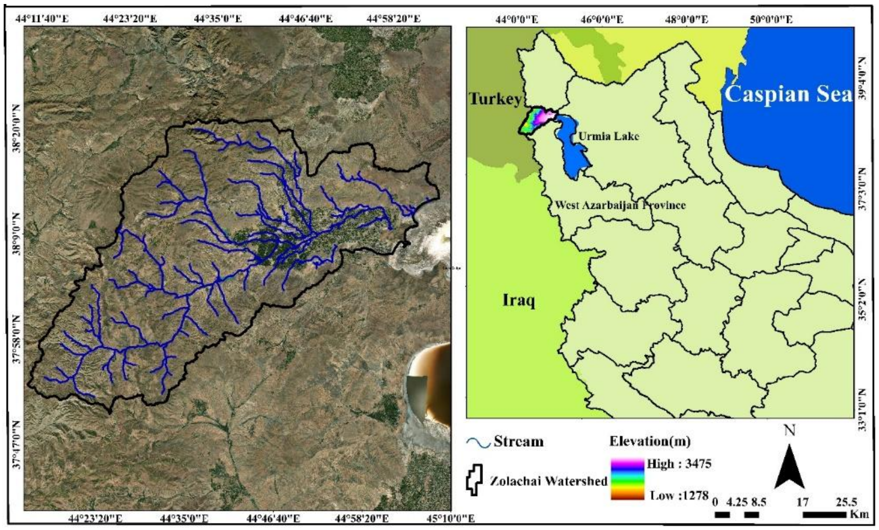

Figure 1- Geographical Location of the Zolachai Watershed-Lake Urmia

2.2 Climate Model and Precipitation Forecasting Scenarios

Precipitation has been forecasted using climate scenarios. The data from rain gauge stations. Located within the Zolachai watershed, utilized for the period from 1968 to 2021, are presented in Table 1.

Table 1: Specifications of rain gauge stations in the Zolachai watershed

Rain gauge station	Longitude	Latitude	Elevation	Year of Establishment
Chehriqe Olya	464363	4214549	1611	1968
Salmas	479861	4227656	1379	1978
Yalquz Aghaj	494605	4231612	1293	1976

The Coupled Model Intercomparison Project (CMIP) is utilized through collaboration among various institutions to standardize the structure of distributed simulated models and general circulation models of the atmosphere (Taylor et al., 2012). In this study, the CMIP6 climate model, ACCESS-CM2, has been utilized based on the SSP5-8.5 scenario. The data related to this model were extracted from the Climate4impact database. For precipitation modeling, data from the mentioned rain gauge stations (those with over 30 years of precipitation records) were used. The data from these stations, spanning from 1966 to 2021, were applied to estimate precipitation in accordance with the characteristics outlined in Table 2 under the climate scenarios. The precipitation for the study area for the years 2023 and 2030 was estimated based on precipitation statistics from 1968 to 2021, using the SSP2-4.5 and SSP5-8.5 scenarios.

Table 2- Characteristics of the Access-CM2 Model

Model name	Resolution	Institution	Period of historical/future simulation	Simulated scenarios
ACCESS-CM2	192*145	CSIRO-ARCCSS; Commonwealth Scientific and Industrial Research Organization, and Bureau of Meteorology (Australia)	1985-2014&2014-2100	SSP2-4.5 SSP5-8.5

2.3. Soil Hydrology Group

Soil hydrological groups at the watershed scale represent the soil's water regime and hydrological behavior during rainfall events. In the fields of irrigation, agriculture, soil science, and hydrology, soil texture information is of critical importance (Rawls et al., 1993). Therefore, soil texture data were utilized to prepare maps of soil hydrological groups. To develop the soil texture map for the plain areas of West Azerbaijan Province, field sampling data and soil maps produced by the Soil and Water Research Institute were employed. In mountainous regions and rangelands, where field data were unavailable, data on clay, silt, and sand percentages provided by the global SoilGrids.org database were used. Subsequently, using SAGA GIS software (version 2.1.1), the clay, silt, and sand layers were integrated, and a soil texture map was generated based on the USDA soil texture triangle. The resulting layers from various sources were then integrated into the ArcGIS environment. Finally, based on the classification proposed by Mahdavi (2013), soil hydrological groups (HSGs), including groups A, B, and C, were derived. However, the use of global SoilGrids.org data in mountainous regions has limitations. These limitations include the data's coarse resolution (1 km), low accuracy in representing small-scale soil variations, lack of complete alignment with local conditions, and the impact of complex topography on data accuracy.

2.4. Land Use

In this study, to prepare land use/land cover maps using Sentinel-2 satellite imagery for the years 2016, 2020, and 2023, images with a 10-meter spatial resolution and diverse spectral bands were obtained from the Copernicus database. The selected images, captured during the plant growing season (late June), exhibited acceptable cloud cover quality. Data preprocessing, including cropping and mosaicking, was performed in the ArcGIS environment. Subsequently, multi-resolution segmentation was conducted in eCognition Developer 10.3 software using bands 2, 3, 4, 8, and 11, with optimal values for scale (56), shape (0.3), and compactness (0.7). The segmentation performance was assessed using two types of observational data: Google Earth imagery and ground-based data. High-resolution Google Earth imagery (sub-meter resolution) was employed for qualitative evaluation, enabling visual comparison of the generated object boundaries with real-world features such as agricultural fields and vegetation cover. This facilitated the assessment of boundary accuracy, intra-object homogeneity, and inter-object separability. Ground-based data, comprising GPS points, land use maps, and field observations, were utilized for quantitative evaluation. A confusion matrix was applied to compute metrics, including overall accuracy, Kappa coefficient, producer's accuracy, and user's accuracy, thereby validating the classification and segmentation accuracy. The evaluation results demonstrated that the generated objects, produced with the specified parameters, closely aligned with real-world features in terms of size, shape, and spectral characteristics. Comparisons with Google Earth imagery and ground-based data confirmed high accuracy in both boundary delineation and classification. Information regarding the images used in this study is presented in Table 3.

Table 3-Specifics of remotely sensed data used for the study

Year of Study	Satellite	Acquisition Date	Spatial Resolution
2016	Sentinel2	2016.06.23	10,20,60m
2020	Sentinel2	2020.06.19	10,20,60m
2023	Sentinel2	2023.06.25	10,20,60m

The images were classified using object-based analysis and the SVM algorithm. Land use maps for the three periods were derived through object-based analysis. The areas of classified land uses were calculated. Subsequently, land use change predictions were conducted using the Markov and CA-Markov methods.

2.5. Predicting the trend of land use changes using the Markov chain model

Based on the capabilities of the hybrid Markov chain and cellular automata algorithm, this model is employed for modeling land surface cover and estimating future land uses. This approach generates a transition probability matrix, a transition area matrix, and a set of conditional probability images by analyzing two land use maps through the Markov chain. Depending on the number of land use classes, the transition probability matrix illustrates the likelihood of each land use transitioning to another (Mirakhorlo and Rahimzadegan, 2018). The model predicts future land use by constructing a transition probability matrix for changes between the first and second years. The estimation of land use changes is calculated using Equation (1).

$$S = \left(T_0 + T_1\right) = Pij * S\left(t\right) \quad (1)$$

S(t) represents the land use status in the initial year (T0), while T1 indicates the land use status in the subsequent year, and Pij denotes the transition probability matrix (Hamad et al., 2018). The foundation for generating the transition probability matrix relies on utilizing prior land use conditions for prediction, which was accomplished using Equation 2.

$$Pij = \begin{vmatrix} p_{11} & p_{12} \cdots p_{1n} \\ p_{1n} & p_{2n} \cdots p_{nn} \end{vmatrix} \left(0 \le Pij \ge 1\right) \quad (2)$$

Where the coefficient Pij represents the probability of land use transitions from the initial year (i) to the subsequent year (j) (Mirakhorlo and Rahimzadegan, 2018). For accuracy validation of the land use maps, the 2016 land use classification map was selected as the reference image, and a five-year interval was defined as the model input. Consequently, the 2023 land use prediction map was generated. After producing the land use maps and performing accuracy assessment and validation, Markov and CA–Markov models were employed to predict land use changes.

2.6. Curve number

The method employed by the United States Soil Conservation Service (SCS), known as the Curve Number (CN) approach, estimates runoff from rainfall across various watershed regions by considering soil characteristics, land use, land cover, and antecedent soil moisture conditions (Mahdavi, 2013; Hoseinzadeh et al., 2018). Specifically, CN values were determined using the CN Calculator software, which integrates data on soil hydrological groups (derived from soil texture maps as per Mahdavi, 2013) and land use classifications (obtained from the classification of Sentinel-2 imagery). CN values for each land use category (e.g., irrigated agriculture and orchards, rangelands, residential areas) and soil hydrological groups (A to D) were calculated based on the USDA SCS approach, as described in Mahdavi (2013) and Hoseinzadeh et al. (2018). To validate these CN values, a comparison was made with values reported in similar studies. Ultimately, using these input data (Precipitation, Curve Number, Land Use, and Soil Hydrologic Group), the InVEST model was executed, and runoff and infiltration maps were generated for the years 2016, 2023, and 2030.

3. Results and Discussion

3.1. Precipitation

Precipitation is a key parameter required for the InVEST model, calculated for the Zolachai watershed using climate scenarios. Rainfall for this watershed for the years 2023 and 2030 was projected based on precipitation data from 1966 to 2021, utilizing the SSP5-8.5 scenarios. Given that the objective of this study is to predict maximum runoff, the results of the SSP5-8.5 scenario (the pessimistic scenario) were adopted, and the findings are presented in Figure 2.

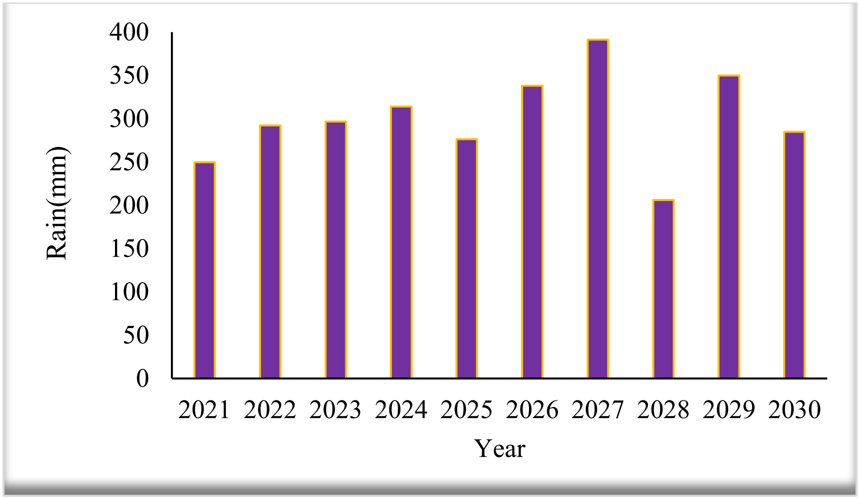

Figure 2- Maximum predicted precipitation for the Zolachai watershed

3.2. Land-Use Change Detection Analysis

Using the SVM method, the images were classified into seven categories: water bodies, bare soil, irrigated agriculture and orchards, rainfed agriculture, salt flats around Lake Urmia, rangelands, and residential areas. Accordingly, land use maps for the years 2016, 2020, and 2023 were generated, and the area of each land use category was calculated. The results indicate that in 2016, the areas of water bodies, bare soil (areas with less than 5% cover), irrigated agriculture and orchards, rainfed agriculture, salt flats, rangelands, and residential areas were 7.22, 773.27, 221.11, 389.57, 0.03, 857.95, and 9.08 km², respectively. In 2023, the areas of water bodies, bare soil, irrigated agriculture and orchards, rainfed agriculture, salt flats, rangelands, and residential areas were 2.97, 644.56, 409.66, 458.36, 0.2, 724.52, and 18.06 km², respectively. To assess the accuracy of the 2023 classification map, it was compared with the predicted map for the same year. The accuracy indices, including Kno, Klocation, Klocationstrata, and standard Kappa (Kstandard), were calculated as 0.87, 0.93, 0.93, and 0.84, respectively. Given the high accuracy of the model in predicting land use change maps for 2023, a land use change map for 2030 was also derived. The 2016 land use classification map was selected as the base image, and five-year intervals were defined as model inputs. Subsequently, the predicted land use map for 2023 was generated. After producing the land use maps and validating their accuracy, Markov and CA-Markov models were employed to predict land use changes. In evaluating the prediction accuracy of the CA-Markov model, the Kappa coefficient was calculated as a measure of model accuracy. This coefficient, ranging from 0 to 1, reached a value of 0.84 in this study. Values close to 1 indicate high model accuracy. The results of this study align with those of Yirsaw et al. (2017) in the Su-Xi-Chang coastal region of China, where a Kappa coefficient of 0.91 was reported, confirming the high accuracy of the CA-Markov model in predicting future land use changes. To calculate the transition area matrix, classified images from 2016 and 2023 were used in the Markov model to generate the transition area matrix. This matrix served as input to the CA-Markov model for predicting land use in 2030. The time interval between the images was set at 7 years, and the prediction interval for 2030 was also set at 7 years. The predicted land use map for 2030 was generated using the CA-Markov model with a Kappa coefficient of 0.84, as presented in Figure 3.

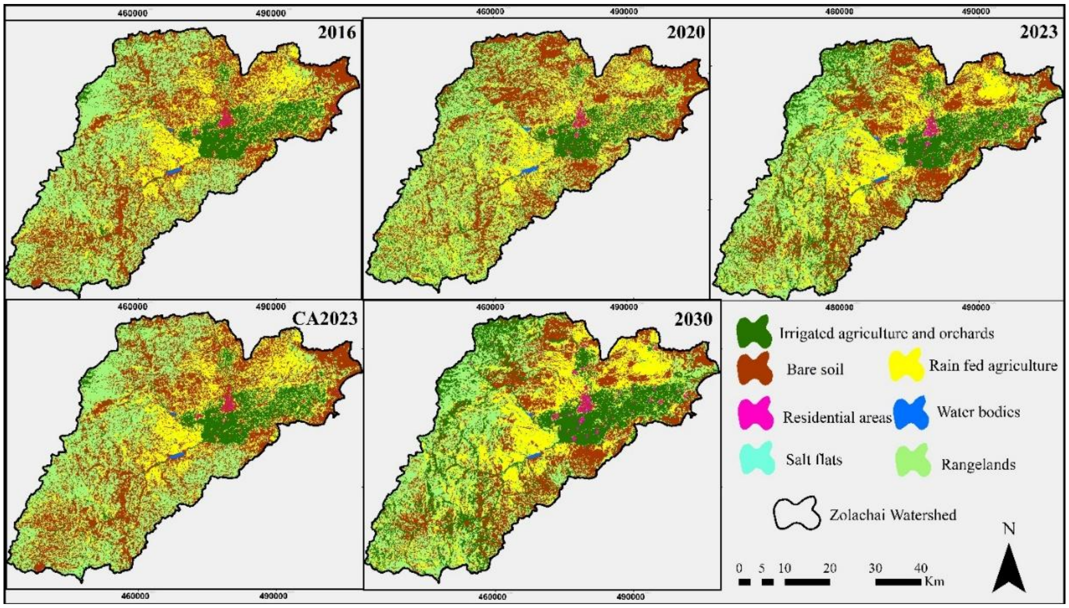

Figure 3- Land Use Maps for the Years Under Review in the Zolachai Watershed - Lake Urmia

To investigate regional changes, the areas of land use classes for the years 2016, 2020, 2023, and 2030, expressed in km^2, are presented in Table 4. Based on the data presented in Table 4, the most significant changes in the area are associated with irrigated agriculture and orchards. The area of this land use class increased from 221.11 km² in 2016 to 528.18 km² in 2023. Specifically, the areas of bare soil, water bodies, and rangelands decreased, while the areas of residential areas, irrigated agriculture and orchards, and salt flats increased. Projections indicate that by 2030, the areas of bare soil, water bodies, and rangelands will continue to decline, whereas residential, irrigated agriculture and orchards, and salt flats will further expand.

Table 4: Land Use Area of the Zolachai Watershed in Km^2

Year land use	2016	2020	2023	2030
Irrigated agriculture and orchards	221.11	273.16	409.66	528.18
Residential areas	9.08	12.39	18.06	24.36
Rangelands	857.95	809.19	724.52	670.63
Rain-fed agriculture	389.57	416.45	458.36	484.63
Water bodies	7.22	4.31	2.97	2.90
Salt flats	0.03	0.05	0.20	0.001
Bare soil	773.27	742.67	644.56	547.52

Specifically, the areas of irrigated agriculture and orchards, residential areas, and salt flats, which accounted for 9.79%, 0.4%, and 0.001% of the total area in 2016, respectively, are projected to reach 23.39%, 1.08%, and 0.002% of the total area by 2030. These results align with the findings of Fatollahi et al. (2018), who investigated land use changes in Neka County using a land change model. They demonstrated, using Landsat satellite imagery, that between 1988 and 2016, forest areas decreased by 2,297 hectares, with the most significant change being the conversion of forest lands to agricultural lands. Their modeling also predicted that by 2030, forest areas would decrease further, while agricultural and urban areas would increase.

The expansion of agricultural land use, particularly irrigated agriculture and orchards, in the Zolachai watershed will lead to increased water resource consumption. This finding is consistent with the results of Roushangar et al. (2022), who examined the impact of land use changes on agricultural water consumption in the Lake Urmia basin over the next 20 years. Using Landsat satellite imagery from 2000 to 2020 and classifying the images with the SVM algorithm, they calculated data related to changes in cropping patterns and water inflows to Lake Urmia. Simulations of land use changes for 2030 and 2040 were conducted using the LCM and CA-Markov methods. The results showed that the areas of irrigated agriculture and orchards would increase from 1,450 km^2 and 2,395 km^2 in 2000 to over 3,600 km^2 and 1,650 km^2, respectively, by 2040. These changes will result in an increase in agricultural water demand from 1,500 million m^3 in 2000 to over 4,100 million m^3 in 2040. The local population's inclination toward establishing orchards and generating income from horticulture is the primary driver of the potential increase in irrigated agriculture and orchards. According to the CA-Markov model predictions, the area of irrigated agriculture and orchards will increase near water sources and existing agricultural lands, which can be attributed to the development of irrigated agriculture and the adoption of modern irrigation techniques, such as drip irrigation. Additionally, the interest in owning private orchards and the income generated from orchard products are further reasons for the expansion of orchard areas.

The results of this study are consistent with the findings of Aburas et al. (2018), who stated that over the next 10 years, agricultural areas will be influenced by the expansion of urban areas, driven by economic development. Furthermore, these results align with the study by Rasouli et al. (2021), who investigated land use and land cover (LU/LC) changes using Sentinel-2 satellite imagery for 2016 and 2021, employing advanced object-based techniques. They used the Markov chain and cellular automata (CA) model to predict that forest and rangeland areas would decrease, while barren and abandoned lands would significantly increase. The trend of land use changes is presented in Figure 4.

Based on the findings of this study, the most significant land use changes are associated with the conversion of rangelands and bare soil to irrigated agriculture, orchards, rainfed agriculture, and residential areas. These results are consistent with the study by Birhanu et al. (2019), which demonstrated that over 29 years in the Gomara watershed in Ethiopia, the area of rangelands decreased, while the area of agricultural lands increased. These changes have led to a reduction in the volume of surface water flow in the watershed.

3.3. Hydrological Soil Groups

The estimation of soil hydrological groups revealed that the Zolachai watershed comprises three hydrological groups: A, B, and C. The central parts of the watershed were classified into groups A and B, while the northwestern, southern, and western parts belong to group C Figure 5.

3.4. Curve Number

In the Zolachai watershed, our analysis revealed Curve Number (CN) values ranging from 36 to 93 for various land use categories and soil hydrological groups, as detailed in Table 5. For instance, Haghdadi et al. (2018) reported CN values between 60 and 85 for agricultural and rangeland areas in the Delichay watershed in Iran, which aligns with the estimated CN values ranging from 65 to 80 for similar land use types in the Zolachai watershed. Additionally, Birhanu et al. (2019) reported CN values between 70 and 90 for agricultural and urban areas in the Gomara watershed in Ethiopia, further corroborating our findings. These comparisons confirm the reliability of our CN estimates for the study area.

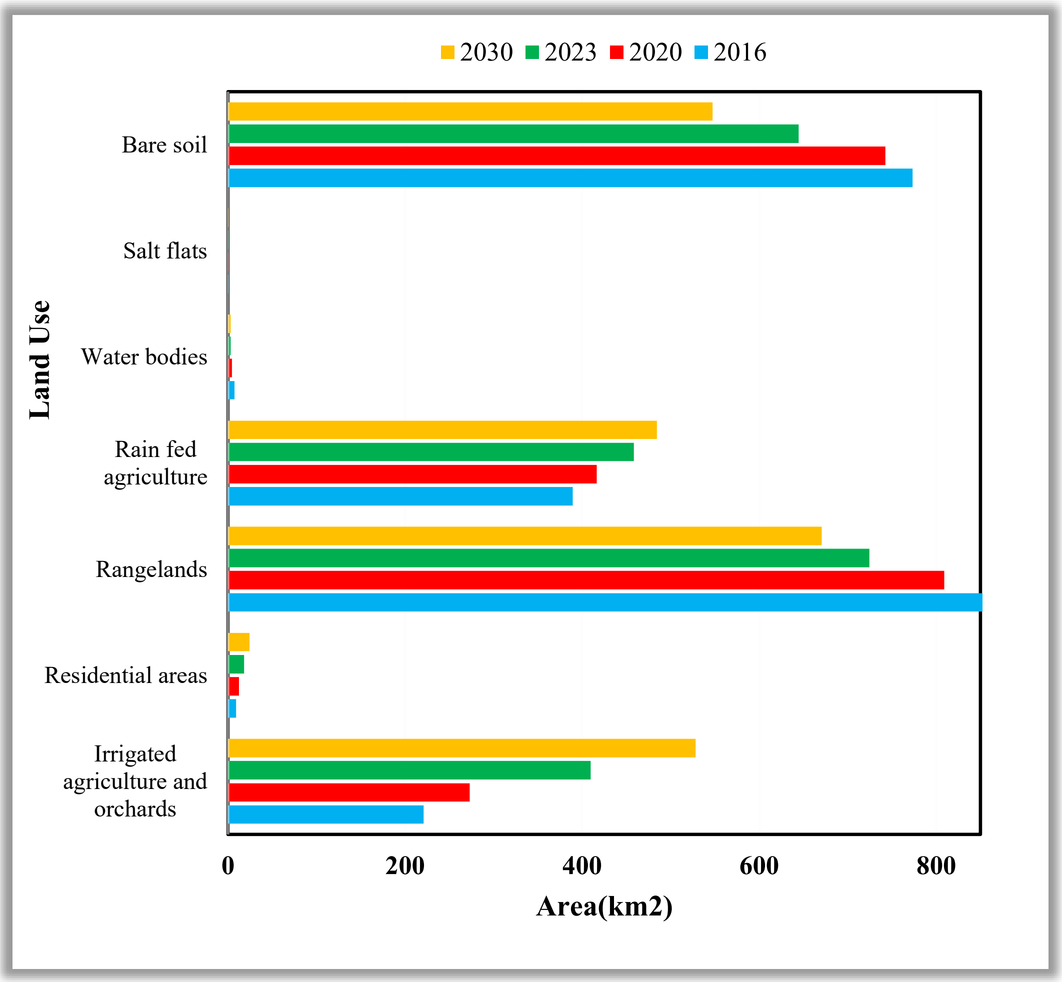

Figure 4- Land Use Change Trends Using Object-Oriented Methodology

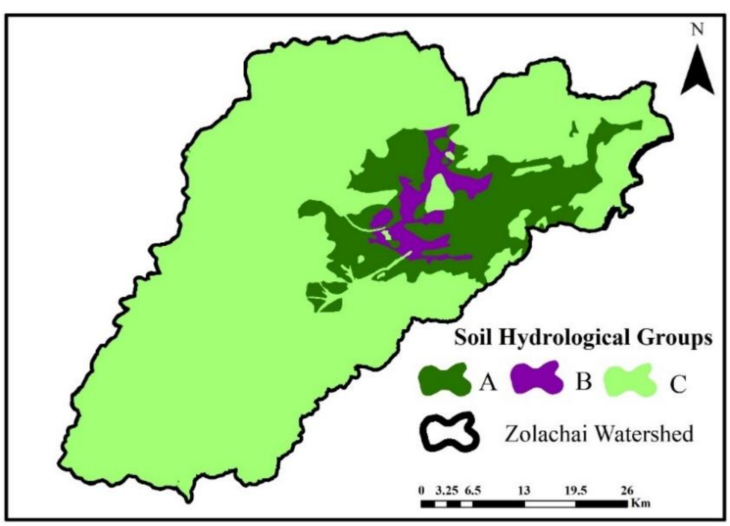

Figure 5- Hydrological Soil Group Map of the Zolachai Watershed

Table 5- CN Values for Land Use Categories and Soil Hydrological Groups

Land Use	CN-A	CN-B	CN-C
Rain-fed agriculture	72	81	88
Irrigated agriculture and orchards	36	64	73
Salt flats	77	86	91
Rangelands	39	61	74
Residential areas	81	88	89

3.5. Runoff Volume

To estimate runoff in the Zolachai watershed, the InVEST model was utilized. This model is capable of estimating water quantities across different locations and illustrates the impact of land use and land cover (LULC) changes on water production and performance in various regions. InVEST is a suite of open-source tools designed for mapping and evaluating ecosystem services in watersheds. The software employs layered data, including land use, land management information, and environmental conditions, to provide spatially explicit predictions.

The InVEST water yield model has been widely applied in numerous studies due to its simplicity and high efficiency, including research by Bai et al. (2013), Redhead et al. (2016), Bastola et al. (2019), Wang et al. (2022), and Reheman et al. (2023). In Iran, several studies have also utilized the InVEST model to simulate water yield services, such as Haghdadi et al. (2018) in the Delichai watershed, Huang et al. (2023) in the Gharesou watershed, and Karimi et al. (2019) in the Karaj River basin.

The results of runoff estimation in the Zolachai watershed using the InVEST model indicate that the minimum and maximum runoff values for the years 2016, 2023, and 2030 were 137.2, 179.5, and 333.8 mm, and 359.4, 418.8, and 647 mm, respectively. Based on the analysis of runoff volume in relation to land use, it was determined that irrigated agriculture and orchards exhibited the lowest runoff, while residential areas showed the highest runoff during the studied years.

Based on Table 6, the runoff volume across various land uses during the years 2016, 2023, and 2030 exhibits a consistent declining trend across all categories. In 2016, the highest runoff was observed in irrigated agriculture and orchards, reaching 588.1 mm, while the lowest was recorded in bare land at 355.5 mm. By 2023, runoff decreased across all land uses; notably, rainfed agriculture experienced a reduction of approximately 59% compared to 2016, and irrigated agriculture and orchards showed a decline of over 34%. The projected data for 2030 continues this downward trend, with runoff in rainfed agriculture dropping to 167 mm (a 74% decrease from 2016) and in irrigated agriculture and orchards falling to 308 mm (a roughly 47% reduction). Overall, the highest runoff volumes are consistently associated with irrigated agriculture and orchards, while the lowest are observed in bare land and salt flats. Additionally, the spatial variability of runoff is notably higher in land uses such as rainfed agriculture and bare land compared to others. This declining trend reflects the combined effects of climatic changes (reduced precipitation and increased evaporation) and land use alterations on surface runoff.

3.6. Water Retention

Based on Table 7 and Figure 7, the highest average runoff volume for the year 2023 was 61.91 m^3, while the lowest was projected for 2030 at 53.59 m^3. According to Figure 7, the northeastern part of the Zolachai watershed exhibits low runoff potential.

In contrast, the central and southern parts of the watershed show moderate to high runoff potential for the years 2016, 2023, and 2030. Based on the predictions for 2030, the runoff potential across most sections of the Zolachai watershed is expected to be low to moderate. This reduction in runoff in 2030 can be attributed to several factors: the expansion of irrigated agricultural lands and water withdrawal for irrigation, changes in the pattern and intensity of annual precipitation, increased vegetation cover and soil permeability, and water and soil conservation management practices. Collectively, these factors have led to a decrease in the volume of surface runoff.

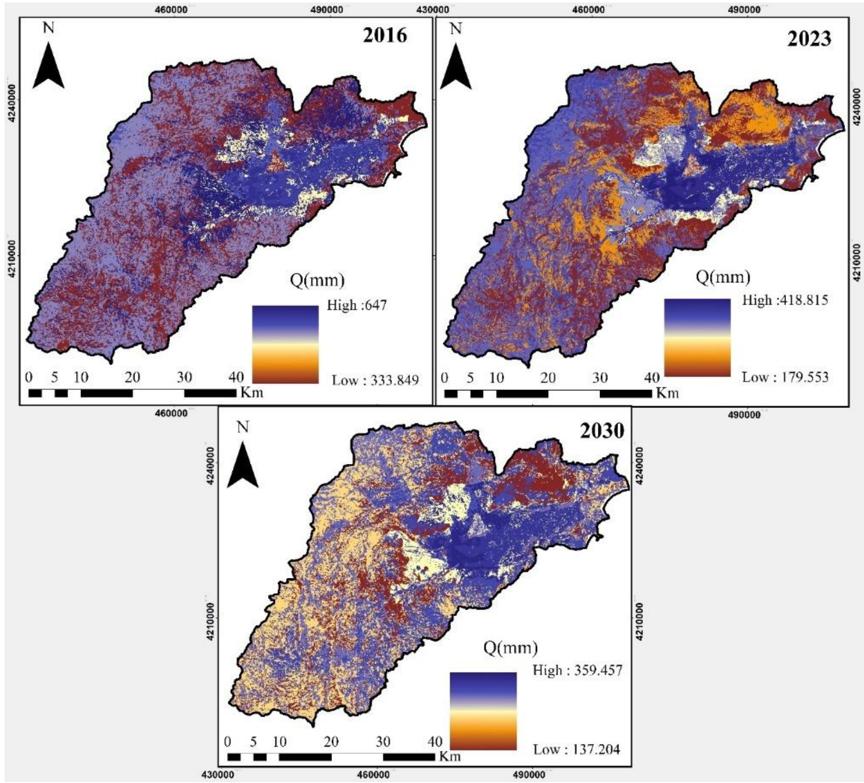

Figure 6- Spatial Changes in Runoff Volume in the Zolachai Watershed

Table 6- Runoff volume values for various land uses in the studied years

Year	land use	Minimum	Maximum	Mean	Standard Deviation
2016	Rainfed agriculture	541.9	647.0	644.5	13.5
	Rangelands	541.9	603.6	544.5	10.6
	Residential areas	502.4	584.6	526.5	32.5
	Salt flats	462.9	580.6	479.7	34.6
	Bare soil	333.8	551.0	355.5	55.5
	Irrigated agriculture and orchards	564.1	614.3	588.1	18.9
	Water bodies	541.9	584.6	559.2	21.0
2023	Rainfed agriculture	239.3	379.0	265.7	45.6
	Rangelands	350.9	408.4	354.2	11.4
	Residential areas	315.7	397.7	344.1	33.4
	Salt flats	315.7	390.4	323.6	19.4
	Bare soil	179.6	359.2	194.2	41.1
	Irrigated agriculture and orchards	371.2	418.8	385.1	17.7
	Water bodies	350.9	408.4	365.5	19.1
2030	Rainfed agriculture	137.2	301.5	167.0	51.3
	Rangelands	137.2	328.0	233.7	17.7
	Residential areas	260.3	331.6	284.8	28.8
	Salt flats	309.3	309.3	309.3	0.0
	Bare soil	313.1	359.5	316.3	9.5
	Irrigated agriculture and orchards	137.2	349.3	308.2	20.7
	Water bodies	228.9	349.3	253.8	31.9

Table 7- Statistical Changes in Water Retention in the Zolachai Watershed

Year	Maximum	Minimum	Mean	Standard Deviation
2016	125.26	0	58.08	46.32
2023	108.57	12.87	61.91	32.72
2030	101.67	12.77	53.59	25.81

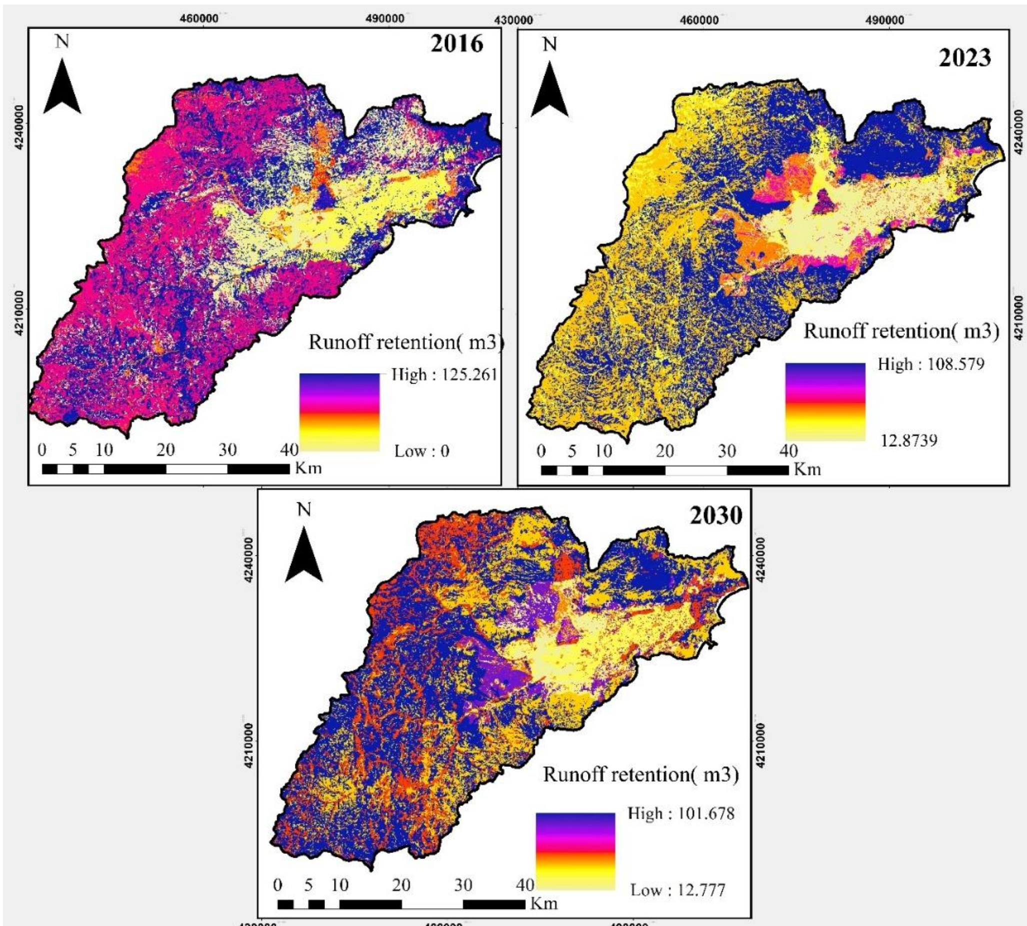

Figure 7- Spatial Changes in Water Retention in the Zolachai Watershed

Based on Table 8, an analysis of water retention values across various land uses during the years 2016, 2023, and 2030 reveals significant changes. In 2016, the highest water retention was recorded in bare land at 116.6 m³, while the lowest was observed in rainfed agriculture at 1.0 m³. By 2023, water retention in bare land decreased to 102.7 m³, whereas rainfed agriculture exhibited a substantial increase, rising from 1.0 m³ to 74.1 m³. In 2030, the highest water retention is projected for rainfed agriculture at 89.8 m³, with the lowest occurring in bare land at 30.1 m³. Overall, the trend indicates a gradual reduction in water retention in bare land and salt flats, contrasted by a noticeable increase in rainfed agriculture and water bodies. Other land uses, such as rangelands and irrigated agriculture, have experienced more moderate changes. These findings suggest the combined influence of climatic variations, soil management, vegetation cover, and land use changes on water retention capacity.

Table 8- Water Retention values for various land uses in the studied years

Year	land use	Minimum	Maximum	Mean	Standard Deviation
2016	Rainfed agriculture	0.0	42.0	1.0	5.4
	Rangelands	17.4	42.0	41.0	4.2
	Residential areas	25.0	57.9	48.2	13.0
	Salt flats	26.6	73.6	66.9	13.8
	Bare soil	38.4	125.3	116.6	22.2
	Irrigated agriculture and orchards	13.1	33.2	23.6	7.6
	Water bodies	25.0	42.0	35.1	8.4
2023	Rainfed agriculture	28.8	84.7	74.1	18.2
	Rangelands	17.0	40.0	38.7	4.5
	Residential areas	21.3	54.1	42.7	13.3
	Salt flats	24.3	54.1	51.0	7.8
	Bare soil	36.7	108.6	102.7	16.4
	Irrigated agriculture and orchards	12.9	31.9	26.4	7.1
	Water bodies	17.0	40.0	34.2	7.6
2030	Rainfed agriculture	36.0	101.7	89.8	20.5
	Rangelands	25.4	101.7	63.1	7.1
	Residential areas	23.9	52.4	42.6	11.5
	Salt flats	32.9	32.9	32.9	0.0
	Bare soil	12.8	31.3	30.1	3.8
	Irrigated agriculture and orchards	16.9	101.7	33.3	8.3
	Water bodies	16.9	65.0	55.0	12.8

The assessment of water retention capacity revealed that residential areas exhibit the lowest water retention capacity, while irrigated agricultural lands and orchards demonstrate the highest retention capabilities. Lands with human-induced uses showed lower water retention abilities compared to areas with natural uses, such as orchards, irrigated agricultural lands, and rangelands, which exhibited greater water retention. In this study, maps predicting runoff volume and water retention for the year 2030 were developed using land use data, precipitation records, runoff curve number (CN), and soil maps. These maps indicate that residential areas, Bare soils, rangelands, and hydrological soil group C have a high potential for runoff generation, whereas irrigated agricultural lands and orchards have lower runoff production potential.

These findings are consistent with the results of Reheman et al. (2023), who investigated changes in water yield in the northern slopes of the Tian Shan Mountains using the InVEST and PLUS models. Additionally, these results align with studies conducted in Iran, including those by Emlaei et al. (2021) and Azizi et al. (2022). Consequently, the combined effects of climate change and land use in the Zolachai watershed show that increased precipitation in residential areas intensifies runoff due to low permeability. In contrast, in gardens and irrigated lands, a significant portion of the rainfall is stored, and less runoff is generated, owing to greater soil infiltration and vegetation cover.

4. Conclusions

Rapid population growth and improper land exploitation have intensified pressure on rangelands, particularly through agriculture on steep slopes. This has led to forest degradation, soil erosion, reduced agricultural productivity, and diminished drinking water quality due to increased runoff. In this study, the ecosystem service of water retention in the Zolachai Watershed was assessed using the InVEST software. Runoff simulation with the InVEST model incorporated variables such as precipitation, which was simulated using the LARS-WG software and the CMIP6 climate model (ACCESS-CM2) under the SSP5-8.5 scenario. Precipitation in the Zolachai basin for the years 2023 and 2030 was forecasted using precipitation data from 1966 to 2021 and the SSP5-8.5 scenario. Given the study's objective to estimate maximum runoff, the results of the pessimistic SSP5-8.5 scenario were adopted. This scenario indicated an increase in days with heavy precipitation in the near future (2030). Data pertaining to land use, soil hydrological groups, curve numbers, and precipitation were inputted into the software. Using the InVEST software, predictive maps of runoff volume and water retention for the Zolachai watershed were generated, leveraging land use data, precipitation, curve numbers, and the 2030 soil map. Based on the distribution of land uses, soil hydrological groups, and precipitation, the highest runoff production in 2030 will be observed in areas with residential land use, rangelands, and soil hydrological groups C and D, whereas irrigated agricultural lands and orchards will exhibit the lowest runoff production. The results of this study highlight differences in water production across various land uses. Given the importance of water supply for the region's residents, water resource management is crucial. Since water production is higher in the upstream sections of the basin compared to downstream areas, management and decision-making should ensure that water needs are met in each section. The assessment and modeling of ecosystem services, along with the examination of factors influencing them, are essential for future research. This tool can be utilized to formulate strategies aimed at benefiting from ecosystem functions in meeting needs, improving human livelihoods, and preserving biodiversity. Over the past three decades, the concept of ecosystem services has garnered significant attention in research; however, some prior studies have addressed only a limited number of ecosystem services, and the regulation and production of runoff as an ecosystem service have not been fully examined. Considering the global and particularly Iranian importance of runoff, identifying influencing factors, controlling, and protecting areas with runoff production potential are regarded as key national responsibilities. Therefore, conducting comprehensive studies and developing methods for quantitative assessment and prediction of ecosystem services based on runoff regulation can play a vital role in prioritizing runoff production areas and formulating effective management and conservation strategies. The practical findings of the research indicate significant differences in runoff production among various land uses in the Zolachai Watershed, which can serve as a basis for sustainable water resource management. Given the higher runoff production in upstream sections compared to downstream areas, water resource management should be designed to meet the water needs of each section. Limitations of the study include the InVEST model's dependence on the quality and accuracy of input data, particularly precipitation and land use data. Additionally, the failure to account for short-term climatic changes and local human activities may impact the accuracy of predictions. For sustainable water resource management in the Zolachai watershed, it is recommended to implement watershed management schemes and erosion control measures, manage land use and agriculture on steep slopes, enhance irrigation efficiency in agricultural lands and orchards, and protect and restore rangelands. Furthermore, the study's results can be applied in water resource planning and the evaluation of land use and climate change scenarios using the InVEST model, with long-term monitoring of runoff and water-related ecosystem services conducted.

Author Contributions:
Tayebeh Irani: Contributed to the conceptualization and design of the study, performed data analysis, visualized the data, interpreted the results, drafted the initial manuscript, and prepared the materials.
Hirad Abghari: Contributed to the conceptualization and design of the study and supervised the project.
Ali AkbarRasouli: Conducted statistical analysis and performed the final editing.
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