



Evaluating the Hydrologic Control of Check Dam Systems under Combined Climate and Land-Use Change Scenarios in a Semi-arid Watershed, Iran

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ABSTRACT

Aims: This study aims to evaluate the hydrological impacts of check dam systems under climate and land-use change scenarios in an arid watershed, and to assess their role in enhancing water balance and resilience.

Materials & Methods: The Soil and Water Assessment Tool (SWAT) was calibrated and validated with observed streamflow data from the Gharah Kahriz Watershed, Markazi Province, Iran. Four simulation scenarios were designed: (1) climate change without check dams, (2) climate change with check dams, (3) land-use change without check dams, and (4) land-use change with check dams. Future climate scenarios under RCP 2.6, 4.5, and 8.5 pathways were generated using the LARS-WG stochastic weather generator. The model was calibrated with observed daily data from 2005–2021 as the baseline period, and monthly change factors derived from bias-corrected GCM outputs were applied to simulate daily weather data for 2021–2098. Simulations were conducted for near (2021–2040), mid (2041–2070), and far (2071–2098) future periods, and the results were aggregated to assess long-term climatic trends. Land-use maps for 1990, 2000, 2010, and 2020 were generated from multi-temporal Landsat imagery. Supervised classification techniques were applied to distinguish major land-use categories, supported by ground truth data and accuracy assessment. The resulting maps provided a consistent spatial framework for analysing land-use dynamics and their impacts over the study period.

Findings: In this study, the SWAT model was executed under two conditions—before and after the construction of check dams — using baseline period data, including the 2020 land-use map and existing climatic records. The results indicate that annual mean runoff increased by 17%, 24%, and 25% under RCP 2.6, RCP 4.5, and RCP 8.5 scenarios, respectively, compared to the baseline period. The mean monthly runoff in 2000 and 2010 was higher than in 1990 and 2020. The inclusion of check dams reduced annual runoff by 53.8 mm (43%), while increasing evapotranspiration by 35.4 mm (27%) and groundwater recharge by 18.4 mm (40%).

Conclusion: Check dams substantially mitigate surface runoff while enhancing subsurface recharge and evapotranspiration, thereby improving watershed resilience under changing climatic and land-use conditions. These results highlight the importance of integrating check dam systems into watershed management strategies, especially for: optimizing water-harvesting and recharge programs in arid and semi-arid basins; designing adaptive land and water management policies that account for future climate uncertainty; and guiding investment priorities for nature-based solutions to sustain water resource management.

Keywords: Arid Environment; Check Dams; Climate Change; Land-Use Change; Runoff; SWAT Model.

CITATION LINKS

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Introduction

Climate and land-use changes have profoundly influenced the distribution and availability of water resources ^[1,2]. Climate change arises from both anthropogenic activities and natural processes ^[3], while land-use and land-cover change (LUCC), driven by human development, can adversely affect watershed hydrology by altering surface runoff, infiltration, and evapotranspiration. These impacts are particularly significant in arid and semi-arid regions, where the frequency and intensity of floods and droughts have increased. Understanding rainfall-runoff processes is therefore essential for effective water resource management, as climate change and LUCC are key drivers of hydrological cycle variability ^[4]. Global warming, one of the most critical environmental challenges, intensifies extreme rainfall events and modifies hydrological processes worldwide ^[5,6].

To mitigate these effects, various structural interventions have been implemented to reduce water-induced erosion on sloped lands ^[7, 8, 9]. Among these, check dams are widely used to slow down surface runoff, enhance water retention, and control gully erosion ^[10, 11, 12, 13]. They also play a vital role in reducing sediment transport, improving water quality, and modifying streamflow regimes within catchments ^[14, 15, 16, 17, 18]. Specifically, check dams are designed to reduce peak discharge, extend the time of concentration, retain floodwaters, and trap sediment, thereby stabilizing watershed hydrology ^[19, 20, 21].

Remote sensing (RS) and hydrological modelling are powerful tools for assessing environmental changes and their impacts on water systems. Advances in GIS and RS technologies have facilitated the development of spatially distributed models capable of simulating watershed-scale hydrological behaviour ^[22]. Among these

models, the Soil and Water Assessment Tool (SWAT) has proven particularly effective for simulating the impacts of LUCC, climate change, and structural interventions on watershed processes using hydrological response units (HRUs) ^[23,24]. Previous research has demonstrated the utility of SWAT for evaluating the hydrological effects of check dams, land-use, and climate variability. For instance, Sun et al. (2020), using the SWAT model in the Nam Rom River basin, reported that structural interventions significantly reduced streamflow ^[22], while Shahid et al. (2021) in the Gilgit watershed found that increased precipitation under changing land-use conditions led to higher runoff ^[25]. Similarly, Yuan et al. (2022) in Wangmaogou (WMG) catchment concluded that check dams effectively reduced peak flows and prolonged flood durations, thereby enhancing watershed flood regulation capacity ^[26].

A review of the available literature indicates that no such study has been conducted in this region to date. While some research has examined the role of check dams, their influence on the hydrological behaviour of watersheds in Iran has received limited attention. Moreover, existing studies rarely integrate multiple drivers of hydrological change. In particular, the combined impacts of climate change, land-use dynamics, and watershed management practices on runoff generation remain largely unexplored. Addressing this gap is crucial for developing more effective water resource management strategies under changing environmental conditions. To support sustainable watershed management, it is essential to evaluate the effects of LUCC and climate change on water resources at the regional scale ^[27,28].

The specific objectives of this study are to (1) evaluate the impacts of climate and land-use changes on runoff generation in an arid watershed using the SWAT model,

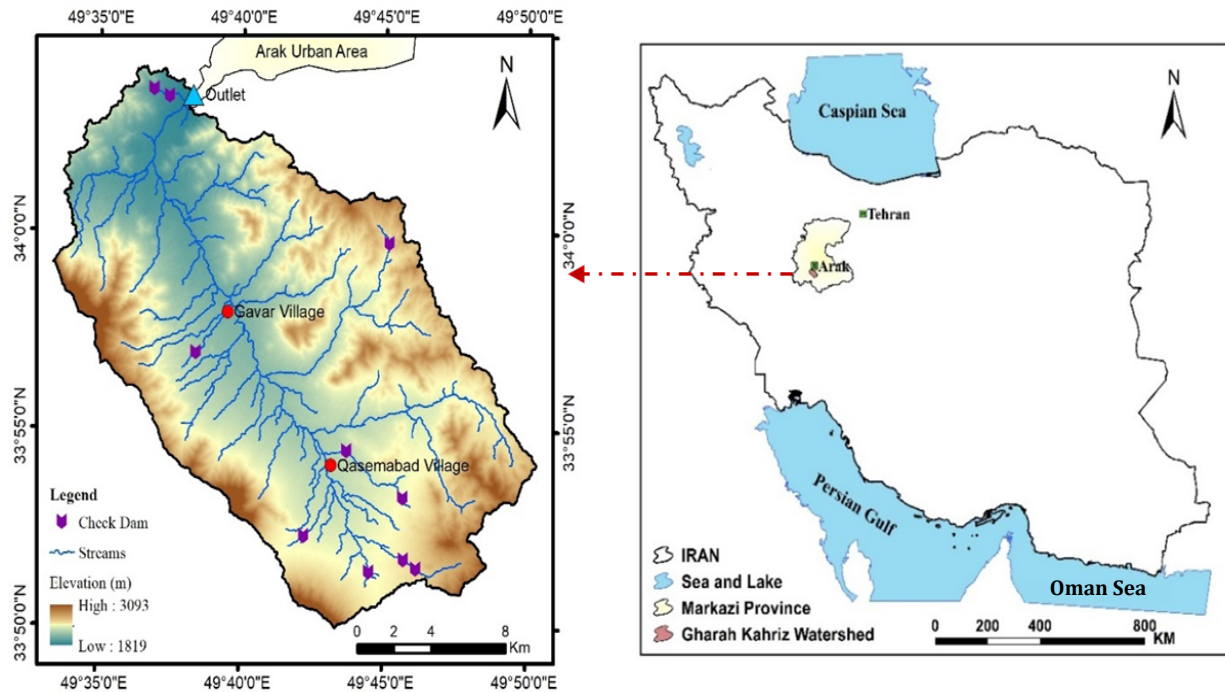


Figure 1) Location of the Gharah Kahriz Watershed in Markazi Province and Iran.

(2) quantify the influence of check dam infrastructure on the water budget, and (3) analyse the role of check dams in water redistribution under future LUCC and climate scenarios. In this study, we used Representative Concentration Pathways (RCPs) because they remain widely used in hydrological and watershed studies, facilitating comparisons with previous research.

Material & methods

Study Area

The Gharah Kahriz Watershed ($33^{\circ}49' - 34^{\circ}04' \text{ N}$, $49^{\circ}33' - 49^{\circ}50' \text{ E}$) is located south of Arak city in Markazi Province, Iran (Figure 1). The watershed spans approximately 38240 hectares, with elevations ranging from 1790 to 3093 meters above mean sea level and a mean slope of 23%. The mean annual rainfall is about 341 mm, with nearly 70% occurring between November and April. The mean annual temperature in the region is 11.55°C , which classifies the region as semi-arid according to the

Martonne aridity index.

This study evaluated the hydrologic performance of check dams using the SWAT model. The model was first calibrated and validated under current land-use and climate conditions. Subsequently, hydrologic simulations were performed under four distinct scenarios, including (1) climate change without check dams, (2) climate change with check dams, (3) land-use change without check dams, and (4) land-use change with check dams. The overall methodological framework is illustrated in Figure 2.

Data Collection

The required data included daily rainfall and temperature data, land-use maps, and topographic and soil data. A 12.5-meter resolution Digital Elevation Model (DEM) was used. Land-use maps for the years 1990, 2000, 2010, and 2020 were developed using Landsat imagery classification. Future climate scenarios under RCP 2.6, 4.5, and 8.5 pathways were generated using the LARS-WG stochastic weather generator. The model was calibrated with observed

daily data from 2005–2021 as the baseline period, and monthly change factors derived from bias-corrected GCM outputs were applied to simulate daily weather data for 2021–2098. Simulations were conducted for near (2021–2040), mid (2041–2070), and far (2071–2098) future periods, and the results were aggregated to assess long-term climatic trends. The accuracy of the land-use maps was evaluated using an error matrix approach based on reference data derived from high-resolution Google Earth imagery and field observations. A stratified random sampling method was applied to select validation points for each land-use class. For each map, a confusion matrix was constructed to compare the classified pixels with reference data, from which overall accuracy, producer's accuracy, user's accuracy, and the Kappa coefficient were calculated. The overall classification accuracy exceeded 85%, and the Kappa coefficient was greater than 0.80, indicating strong agreement between the classified maps and reference data. These results confirm that the classification outputs were sufficiently accurate for subsequent hydrological modeling and change analysis. To assess precision, the classification procedure was repeated with different training samples, and the resulting accuracies varied by less than 3%, indicating consistent and reliable classification performance. Soil data were extracted from the FAO soil map. Daily climate and streamflow data (2005–2021) were obtained from Arak, Gavar, and Karahroud meteorological and hydrological stations within the study area. The investigations revealed 10 large check dams within the watershed (Figure 2). The impacts of these structures were simulated during the modeling process using reservoir characteristics. Their characteristics are presented in Table 1.

Table 1) Characteristics of check dams in the Gharah Kahriz Watershed.

Check Dam	Height (m)	Reservoir Volume (m ³)
1	16	514054
2	12	260914
3	11	388958
4	14	226187
5	14	485576
6	12	116748
7	12	405792
8	12	74328
9	11	58146
10	12	99768

SWAT Model Description

The Soil and Water Assessment Tool (SWAT) is a semi-distributed, process-based model widely used to simulate runoff and watershed hydrology on both small and large spatial scales [29]. It operates on a daily time step and evaluates the impacts of land-use, management practices, and structural interventions on sediment, water, and nutrient dynamics over long periods. The basic modelling unit in SWAT is the Hydrological Response Unit (HRU). The SWAT model simulates watershed hydrology based on several key assumptions includes 1) hydrological processes: The model assumes that precipitation, runoff, infiltration, evapotranspiration, and baseflow are the primary processes governing water movement in the watershed; 2) spatial discretization: The watershed is divided into sub-basins and further into hydrologic response units (HRUs), which are assumed to be homogeneous in terms of land-use, soil type, and slope; 3) temporal scale: Hydrological processes are simulated on a daily time step, assuming that this resolution is sufficient to capture rainfall-runoff dynamics in the study area; 4) land-use and soil properties: land-use characteristics and soil properties are considered static within each simulation period, except when explicitly modified to reflect changes over

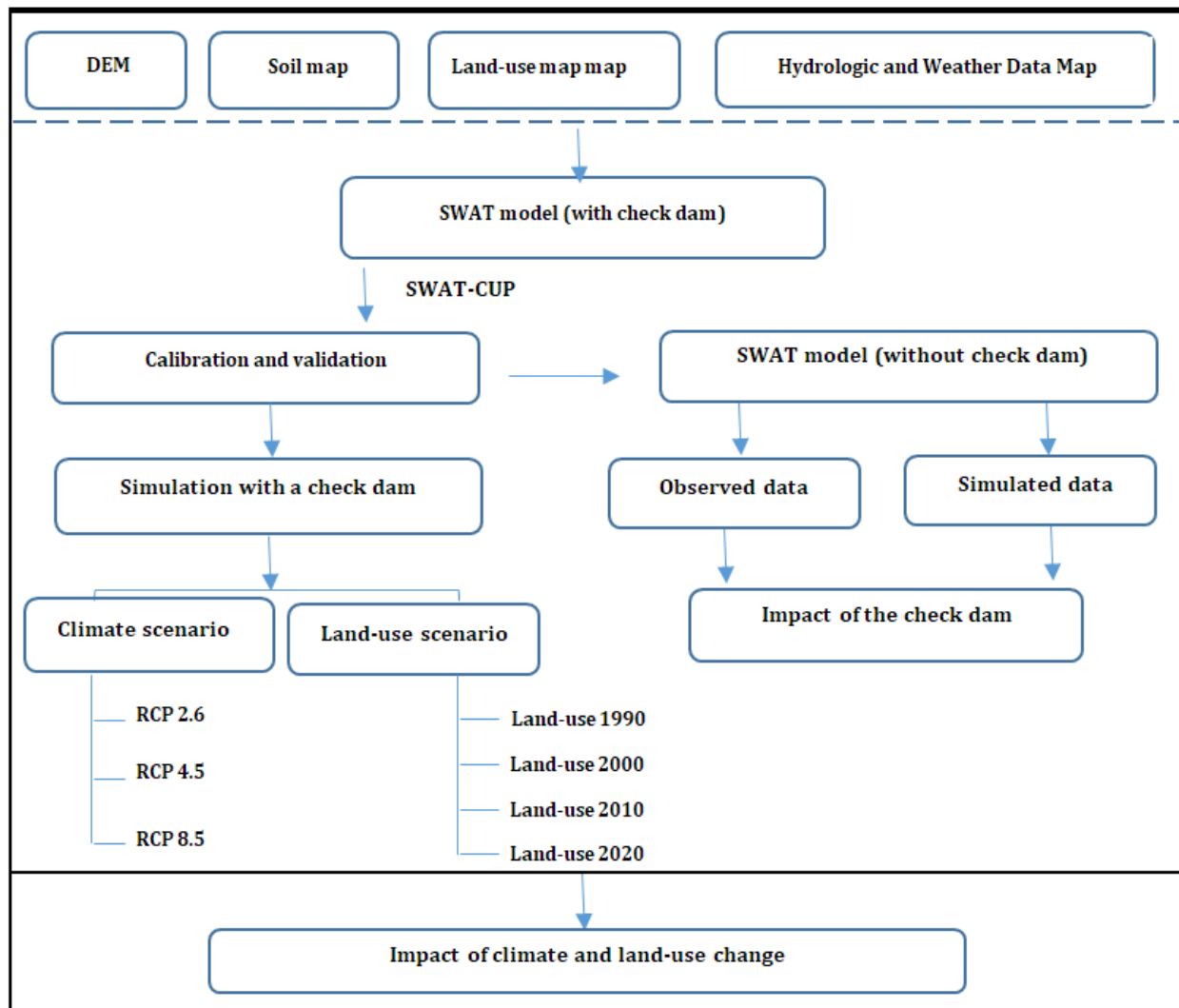


Figure 2) Conceptual framework of the study design.

time; 5) surface runoff generation: The model uses the Curve Number (CN) method to estimate surface runoff, assuming that runoff is primarily a function of land-use, soil type, and antecedent moisture; 6) groundwater processes: Baseflow is modelled using a shallow aquifer concept, with the assumption that groundwater contribution to streamflow can be approximated by linear reservoir equations [29, 30]. These assumptions allow SWAT to simulate the integrated effects of climate, land-use, and management practices on watershed hydrology while recognizing that model simplifications may limit its ability to capture very short-term, localized, or extreme events.

In this study, the watershed, covering approximately 38,000 ha, was divided into 167 Hydrologic Response Units (HRUs) generated from unique combinations of land-use, soil type, and slope class. To minimize spatial overlap and maintain hydrological realism, HRUs were defined using a 10% threshold [30, 31].

The hydrological component of the SWAT model is based on the following water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^t (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})_i \quad \text{Eq. (1)}$$

where SW_t is the final soil water content (mm), SW_0 is the initial soil water content (mm), R_{day} is daily

precipitation (mm), is daily surface runoff (mm), is daily evapotranspiration (mm), is percolation from the soil profile to the vadose zone (mm), and is groundwater return flow (mm) [32].

Model Calibration and Validation

The SWAT model was calibrated for the 2007–2008 period and validated for 2005–2006 using daily observed streamflow data. These calibration (2007–2008) and validation (2005–2006) periods were selected based on the availability and continuity of reliable daily observed streamflow data for the watershed. Check dams constructed in the watershed during the reference period were incorporated into the model setup. Calibration, sensitivity analysis, and uncertainty assessment were performed using the Sequential Uncertainty Fitting (SUFI-2) algorithm implemented in SWAT-CUP [33].

The model's uncertainty was quantified using the 95% Prediction Uncertainty (95PPU) band. Model performance was evaluated using the P-factor (percentage of observed data within the 95PPU band) and the R-factor (band thickness relative to the standard deviation of observations).

Additionally, Objective Functions Coefficient of Determination (R^2), Nash–Sutcliffe efficiency (NSE), and Percent Bias (PBIAS) metrics were used to assess model accuracy (Eq. 2-4):

$$R^2 = \frac{\left[\sum_{i=1}^n (O_i - \bar{O})(S_i - \bar{S}) \right]^2}{\sum_{i=1}^n (O_i - \bar{O})^2 \sum_{i=1}^n (S_i - \bar{S})^2} \quad \text{Eq. (2)}$$

$$E_{NS} = 1 - \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad \text{Eq. (3)}$$

$$PBIAS = \frac{\sum_{i=1}^n (O_i - S_i)}{\sum_{i=1}^n O_i} \times 100 \quad \text{Eq. (4)}$$

where O_i is observed data, S_i is simulated data, $\bar{O}$ is the mean observed data, $\bar{S}$ is the mean simulated data, and n is the number of data.

Simulation Scenarios

In this study, four main scenarios were evaluated:

S0 (Baseline): Model calibration and validation using observed data (2005–2021) and 2020 land-use considering check dams.

S1 (Climate Change): SWAT simulations using climate projections under RCP 2.6, 4.5, and 8.5, keeping land-use fixed at 2020, considering check dams.

S2 (land-use Change): Simulations with historical land-use maps (1990, 2000, 2010, and 2020) and constant climate conditions considering check dams.

S3 (Check Dam Impacts): Comparing hydrological outputs with and without check dams under the same climate and land-use conditions.

In this study, the impacts of ten large check dams within the watershed were examined. These structures were incorporated into the model based on their reservoir storage characteristics, primarily by representing them as reservoirs with specified storage volumes and surface areas within the model framework. The dams were not explicitly modelled as physical structures within individual HRUs, nor were channel parameters such as roughness or conductivity modified to simulate their presence. The effects of dam height and number were not the focus of this study and were therefore not analysed separately.

Findings

Climate and Land-Use Change

Future climate scenarios under the RCP 2.6, RCP 4.5, and RCP 8.5 pathways were generated using the LARS-WG stochastic weather generator. The results indicate that both minimum and maximum temperatures are projected to increase across all three

scenarios, with the most significant increase under RCP 8.5. According to the simulations, annual rainfall is expected to decrease in all near-, mid-, and far-term periods under RCP 8.5. In contrast, rainfall is projected to increase across all three time periods under RCP 2.6. Under RCP 4.5, precipitation is expected to decrease during the near- and mid-term periods but increase in the far-term period. Analysis of mean annual runoff in the watershed under different land-use conditions for 1990, 2000, 2010, and 2020 revealed considerable temporal variation. In 1990, approximately 72.58 mm of the total annual precipitation was converted into surface runoff. In contrast, the corresponding runoff depths for 2000, 2010, and 2020 were 124.03, 122.34, and 69.87 mm, respectively. The assessment of surface runoff variations across different land-use types indicated that the mean annual runoff in the Gharah Kahriz Watershed in 2000 was higher than in 1990. During this period, agricultural lands declined while residential areas expanded, resulting in reduced infiltration capacity and increased runoff. In 2010, the areas of agricultural land and range land increased by 3.36% and 1.73%, respectively, compared to 2000, leading to a decrease in surface runoff. In 2020, the expansion of rainfed farming, range land, and irrigated agricultural areas, along with the reduction of barren lands, further decreased the mean annual runoff compared to 2010 and 1990.

Model Calibration and Validation

Sensitivity analysis using SUFI-2 in SWAT-CUP identified the most influential parameters for model calibration (Table 2). The sensitivity analysis (Table 2) shows that the most sensitive parameters for streamflow simulation were CN2 (Curve Number), SOL_K (Saturated Hydraulic Conductivity), and ALPHA_BF (Baseflow Alpha Factor). These parameters strongly influence surface runoff, infiltration, and

baseflow generation, which are the dominant hydrological processes in the watershed. On the other hand, parameters such as GW_DELAY (Groundwater Delay), EPCO (Plant Uptake Compensation Factor), and SMFMN (Minimum Melt Factor for Snowmelt) were among the least sensitive. This can be explained by the hydroclimatic conditions of the study area: snow processes are limited, reducing the importance of SMFMN. At the same time, EPCO and GW_DELAY represent slower or less variable processes that have only minor effects on short-term fluctuations in daily streamflow.

Table 2) Parameters used in sensitivity analysis, their ranges, methods of adjustment, and the final best-fit values for calibrating the SWAT model.

Parameter	Method	Parameters Ranges		Best Adjustment Value
		Minimum	Maximum	
SMFMN	V	9.13	9.19	9.16
GW_REVAP	V	0.194	0.2	0.199
GW_DELAY	V	309	313.1	313.01
CH_K1	V	189	190.7	189.8
REVAPMN	V	240.95	241.6	241.17
SOL_K	R	0.67	0.68	0.673
CN2	R	0.06	0.072	0.071
ALPHA_BF	V	0.191	0.1917	0.1911
CH_K2	V	74.4	76.07	75.83
SOL_Z	R	1.342	1.346	1.343
SOL_AWC	R	0.424	0.441	0.429
EPCO	V	0.0062	0.0064	0.0063
GWQMN	V	465.4	465.73	465.41
SOL_ALB	R	0.3125	0.315	0.3127
SOL_BD	R	2.6	2.65	2.61

Daily simulations were conducted from 2005 to 2021, and model performance was evaluated using statistical indices. During the calibration period (2007–2008), R^2 and NSE values were 0.57, with a PBIAS of 6.7%. In the validation period (2005–2006), R^2 was 0.67, NSE was 0.58, and PBIAS was 6.9% (Table 3). According to the results, the evaluation indicators (R^2 and NSE) performed slightly better during the validation period compared to the calibration period. Several factors can explain this result. First, the hydrological conditions during the validation years

(2005–2006) may have been more stable and less influenced by extreme events, which often increases model performance. Second, the calibration period (2007–2008) included greater streamflow variability and more extreme events, which generally make calibration more challenging and can slightly reduce indicator values. Third, the model performed well in validation, even better than in calibration, indicating that it was not overfit and was robust and transferable. Similar outcomes have been reported in previous SWAT applications, where validation statistics occasionally exceeded calibration results due to differences in hydrological variability between periods. These results indicate an acceptable agreement between observed and simulated streamflow values.

Table 3) Model performances for daily runoff simulation during calibration and validation periods.

Period	R ²	NSE	P-Factor	R-Factor	PBIAS
Calibration (2007–2008)	0.57	0.57	0.27	0.08	6.7
Validation (2005–2006)	0.67	0.58	0.12	0.05	6.9

Figure 3 shows the visual comparison of observed and simulated flows, along with the 95PPU bands. The SWAT model demonstrated satisfactory performance in reproducing low to moderate flows and capturing the general trend of baseflow conditions, with the majority of observed values falling within the 95PPU band. However, peak discharges were simulated with lower accuracy, with several flood events either underestimated or shifted in

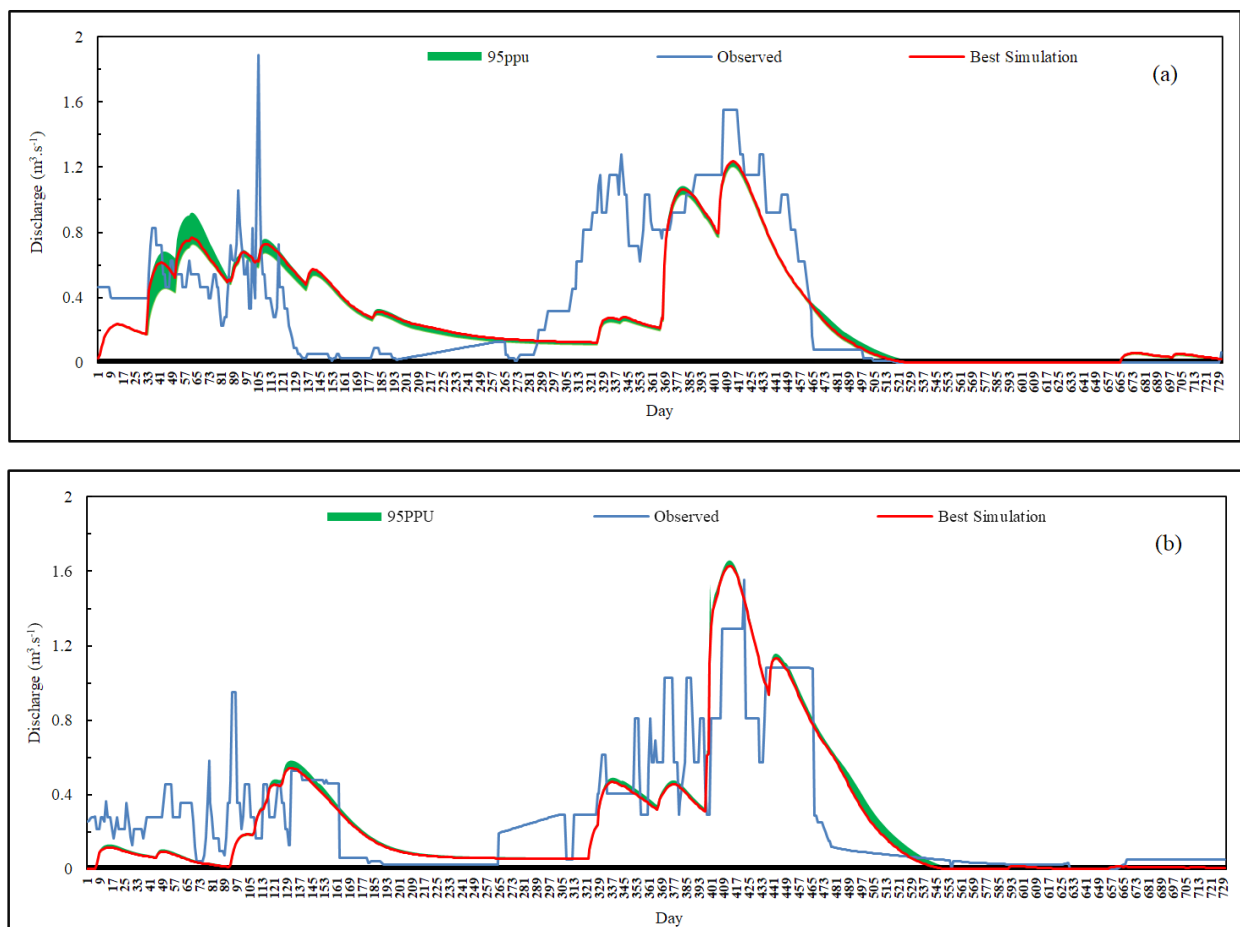


Figure 3) Comparison of observed and simulated daily streamflow with 95% prediction uncertainty for calibration (a) and validation (b).

timing. This limitation is commonly reported in SWAT applications, particularly in arid and semi-arid catchments, where the model tends to underperform in representing short-duration, high-intensity runoff events.

Climate Change Scenario (S1)

Daily streamflow was simulated under RCP 2.6, RCP 4.5, and RCP 8.5 scenarios for the period 2021–2098. The data were simulated for the near, mid, and far future periods, and the results were subsequently aggregated. These were compared with observed streamflow for the baseline period (2005–2021). In all future scenarios, simulated streamflow was higher than in the baseline period (Figure 4).

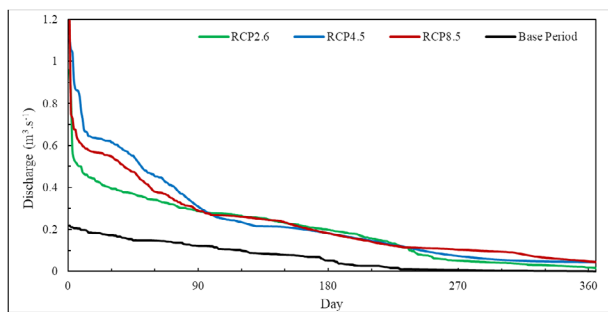


Figure 4) Comparison of observed daily discharge (2005–2021) with simulated daily discharge (2021–2098) under RCP 2.6, RCP 4.5, and RCP 8.5 scenarios.

The most significant increases in monthly runoff occurred in January, February, and December, with the highest values under RCP 2.6. In contrast, monthly runoff in April was consistently lower than in the baseline period across all scenarios (Figure 5).

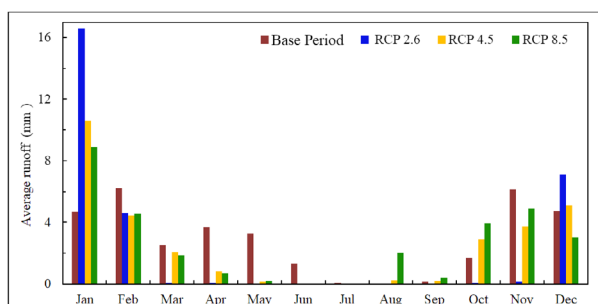


Figure 5) Comparison of observed monthly runoff (2005–2021) with simulated monthly runoff (2021–2098) under RCP 2.6, RCP 4.5, and RCP 8.5 scenarios.

Water Balance Components Under RCP Scenarios

Table 4 presents the key components of the water balance for each RCP scenario. RCP 2.6 resulted in the highest annual precipitation (310.57 mm), but also the most significant evapotranspiration losses (248.69 mm). Groundwater recharge was lowest under RCP 2.6 (33.31 mm) and highest under RCP 4.5 (59.09 mm). Surface runoff increased by 17%, 24%, and 25% under RCP 2.6, RCP 4.5, and RCP 8.5, respectively, relative to the base period. While land-use change from bare land to range land typically leads to increased infiltration and reduced runoff, the observed increase in runoff in this scenario is likely influenced by changes in rainfall intensity associated with climate change. The increased rainfall under this scenario may have outweighed the infiltration benefits of land-cover change, leading to higher runoff volumes despite the shift to range land. These findings suggest that climate change will intensify runoff generation, particularly under more severe emission scenarios.

Table 4) Water balance components under RCP scenarios.

Components (mm)	RCP 2.6	RCP 4.5	RCP 8.5
Rainfall	310.57	302.4	291.2
Evapotranspiration	248.69	213	208.3
Recharge	33.31	59.09	52.35
Surface Runoff	28.57	30.31	30.55

Land-Use Change Scenario (S2)

Land-use maps for 1990, 2000, 2010, and 2020 were classified into five categories: agricultural/garden lands, dry farming, bare land, range land, and residential areas (Figure 6). Following the classification of the land-use map, the accuracy and validity of the classified images were assessed (Table 5).

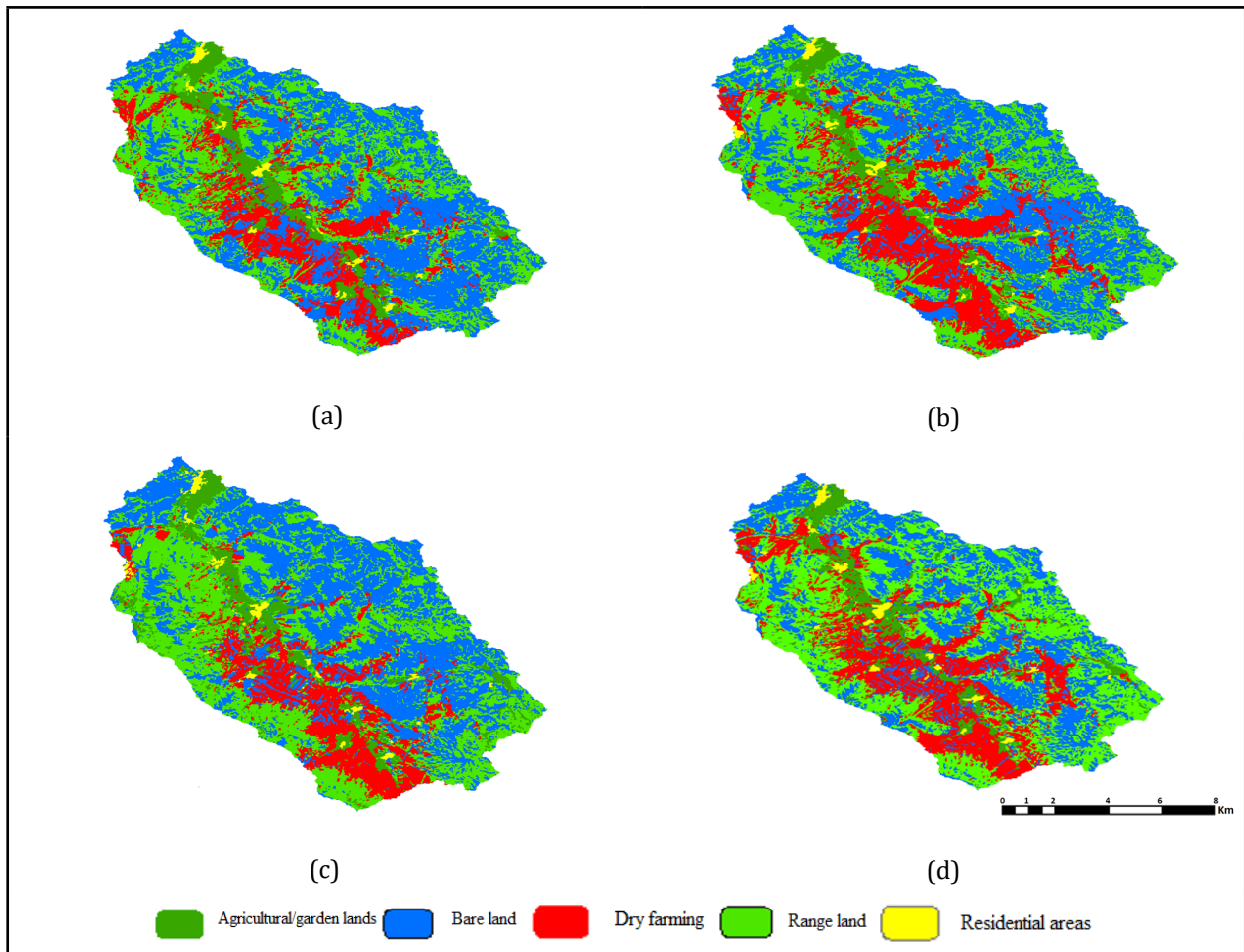


Figure 6) land-use maps of the Gharah Kahriz Watershed for 1990 (a), 2000 (b), 2010 (c), and 2020 (d).

Table 5) Accuracy coefficient of classification of land-use map.

Accuracy Coefficients	1990	2000	2010	2020
OA	92.1	92.3	99.2	97.6
Kappa	0.9	0.89	0.99	0.97

Over time, the area of bare land declined, while range lands and dry-farming areas expanded. Simulations showed a difference in mean daily discharge between 1990 and 2000 ($3.25 \text{ m}^3 \cdot \text{s}^{-1}$), while a decrease in discharge was observed from 2010 to 2020 (Figure 7). Monthly runoff was highest in April and lowest during the dry summer months (June–September), as shown in Figure 8.

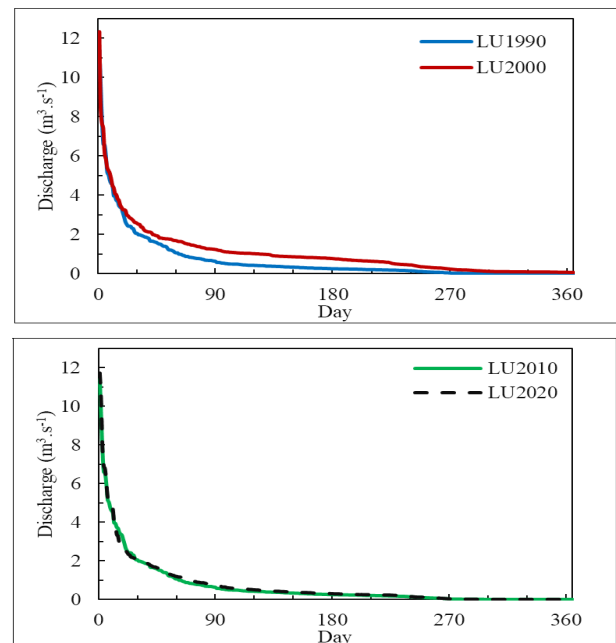


Figure 7) Simulated mean daily discharge of the Gharah Kahriz Watershed based on land-use conditions in 1990, 2000, 2010, and 2020.

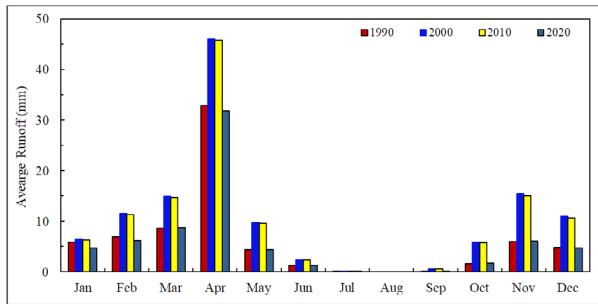


Figure 8) Simulated monthly runoff response to land-use changes in the Gharah Kahriz Watershed.

As presented in Table 6, land-use changes influenced the water balance. From 1990 to 2020, evapotranspiration increased by 27 mm, and groundwater recharge rose from 58.8 mm to 65.6 mm. Surface runoff showed an overall decreasing trend, from 76.9 mm in 1990 to 73.1 mm in 2020, despite slight increases in 2000 (124.11 mm) and 2010 (122.37 mm). This reduction is attributed to increased vegetative cover and improved land management practices over time. These findings underscore the critical role of land-use planning in shaping watershed hydrology and regulating runoff dynamics.

Table 6) Water balance components under different land-use conditions.

(mm) Components	Land-Use Maps			
	1990	2000	2010	2020
Evapotranspiration	165	133.3	138.37	162
Recharge	58.8	43.29	39.96	65.6
Surface Runoff	76.9	124.11	122.37	73.1

* Rainfall in all scenarios was considered constant at 300.7 mm

Check Dam Scenario (S3)

The impact of check dams was evaluated by comparing model outputs with and without the structures, under identical climate and land-use conditions (2020). Figure 9 shows that the mean daily discharge decreased for flows below $4 \text{ m}^3 \cdot \text{s}^{-1}$ in the presence of check dams, whereas higher flows were less affected. As shown in Figure 9, check dams were effective in reducing low to moderate flows ($<4 \text{ m}^3 \cdot \text{s}^{-1}$), but their impact on higher

flows was limited. This reflects structural limitations, as check dams have relatively small storage capacity and can be quickly exceeded during high-intensity rainfall events. Once the dams reach capacity, their ability to mitigate peak flows diminishes significantly. This highlights the need for integrated watershed management strategies that combine check dams with other structural and non-structural flood control measures to address extreme flood events effectively.

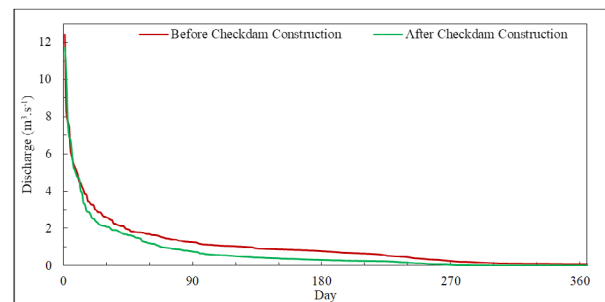


Figure 9) The mean daily discharge before and after the check dam construction.

The 27% increase in evapotranspiration (ET) observed in Table 6 is primarily attributed to two factors: (i) enhanced soil moisture availability due to the water retention effect of check dams, which promotes vegetation growth and increases transpiration, and (ii) direct evaporation from the surface of the impounded water behind the check dams. Both mechanisms contribute to the overall rise in ET. Monthly discharge also declined when check dams were included in the simulation. The most significant reductions occurred in April (31%) and November (61%) (Figure 10). Figure 10 shows a substantial decrease in monthly runoff following the construction of check dams, with the most pronounced reductions occurring in April (31%) and November (61%). This indicates their effectiveness in moderating seasonal flood peaks. In addition, low-flow conditions during dry months became more stable, suggesting enhanced baseflow resulting from increased

infiltration and groundwater recharge. These findings demonstrate that check dams not only attenuate runoff extremes but also enhance water storage and regulation within the hydrological cycle. Overall, the figure highlights the dual role of check dams in flood mitigation and in strengthening hydrological resilience in the Gharah Kahriz Watershed.

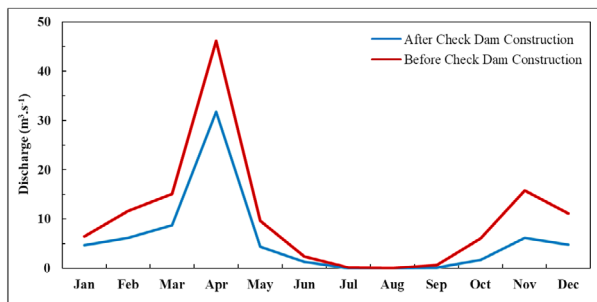


Figure 10) Mean monthly runoff before and after the construction of check dams.

Table 7 presents the water balance components before and after check dam construction. Annual runoff decreased by 53.8 mm (43%), evapotranspiration increased by 35.4 mm (27%), and groundwater recharge improved by 18.4 mm (40%).

Table 7) Water balance components under watershed operations

Components (mm)	Before Check Dams Construction	After the Check Dams Construction
Evapotranspiration	129.7	165.13
Recharge	45.88	64.27
Surface Runoff	125.12	71.3

These results suggest that check dams substantially modify watershed hydrology by slowing runoff, enhancing infiltration, and increasing water storage. Such modifications contribute to sustainable water management in arid regions. These findings align with previous research [34, 35, 36,37,38,39,40], which emphasized the importance of check dams in increasing soil moisture and promoting local groundwater recharge.

Discussion

Climate change can substantially alter hydro-meteorological parameters, leading to shifts in rainfall intensity, frequency, and distribution that directly affect watershed hydrology^[39]. In this study, simulations under RCP 2.6, 4.5, and 8.5 scenarios indicated increases of 17%, 24%, and 25% in annual mean runoff, respectively, compared with the baseline period, confirming that intensified precipitation under climate forcing enhances surface runoff generation, as also reported by Shahid et al. (2021) in the Gilgit Watershed^[25]. Concurrently, land-use changes over the past three decades, particularly the expansion of agricultural areas and the reduction of rangelands, have modified infiltration and runoff dynamics. The model results showed higher runoff during 2000 and 2010, when bare and degraded lands were more extensive, highlighting the sensitivity of hydrological processes to land-cover conversion. When check dams were introduced into the system, surface runoff was reduced by approximately 43%, while evapotranspiration and groundwater recharge increased by 27% and 40%, respectively, demonstrating their efficiency in mitigating runoff peaks and enhancing water retention. These outcomes align with studies by Sun et al. (2020) and Zahedikhah et al. (2024), who reported that check dams effectively reduce streamflow and sediment yield^[37, 41], and with Xu et al. (2013), who found improved subsurface storage following dam construction^[35]. In combined climate and land-use change scenarios, check dams notably dampened amplified runoff responses, reducing hydrological extremes and promoting system resilience. Comparatively, the influence of climate change on runoff generation was found to be more pronounced than that of land-use change; however, their combined effects were synergistic, underscoring the need

for integrated watershed management that combines adaptive land-use planning with structural measures such as check dams to sustain water resources under future climate variability.

Conclusion

This study applied the SWAT model to evaluate the hydrological impacts of check dam systems under various climate and land-use change scenarios in an arid watershed. The key findings can be summarized as follows:

- *Climate change impacts*: Surface runoff is expected to increase under both RCP 4.5 and RCP 8.5 scenarios, highlighting the potential for more frequent or intense flood events.
- *Land-use change effects*: Alterations in land-cover influence the water balance by modifying evapotranspiration, surface runoff, and groundwater recharge.
- *Check dam effectiveness*: The construction of check dams substantially reduces runoff peaks, stabilizes low flows, and enhances groundwater recharge, demonstrating their dual role in flood mitigation and water storage. This study highlights how climate and land-use changes jointly impact watershed hydrology, increasing water stress in arid regions. Check dams effectively reduce runoff extremes and enhance baseflow, making them vital for climate resilience. Sustainable water management requires integrating climate adaptation, land-use planning, and structural measures like check dams. Stakeholders should prioritize strategic check dam placement, community engagement, and complementary conservation practices. Applying these recommendations can improve water sustainability and resilience in arid catchments facing environmental change. Research Suggestions and Study Limitations: This study provides valuable insights into the hydrologic impacts of check dams but is limited by data availability, particularly for long-term,

high-resolution climatic and hydrological records. Additionally, the effects of dam height and number were not separately analysed, which could influence localized hydrological responses. Future research should focus on incorporating finer-scale temporal and spatial data, evaluating the cumulative impacts of multiple structural and non-structural measures, and assessing the socio-economic benefits of check dams. Moreover, exploring climate change scenarios with a broader range of models and downscaling techniques would strengthen predictions of watershed responses under future conditions.

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Ethical Permission

The authors ensure that they have written entirely original works and that the previous studies were appropriately cited.

Author's Contribution

All authors contributed equally to the development, analysis, and writing of the manuscript.

Conflict of Interest

The authors have no conflict of interest.

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