

Article

Response of Runoff Change to Soil and Water Conservation Measures in the Jing River Catchment of China

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Abstract: Soil and water conservation measures (SWCMs) are vital in reducing runoff and ultimately affect water security and regional development. However, previous studies have mainly focused on the impact of a single SWCM, neglecting to distinguish between the effects of different SWCMs on runoff reduction. A Soil and Water Assessment Tool (SWAT) model was established in the Jing River catchment to identify the responses to runoff changes resulting from climate change and human activities. The model was used to quantitatively analyse the impact of different SWCMs on runoff reduction. The results indicated that human activities contributed significantly more to runoff reduction than climate change. The reduction benefits of different unit area changes for each SWCM on discharge, surface runoff and water yield at the outlet were ranked as follows: changing cultivated land to forest land > changing cultivated land to grassland > building terraces on a 5–15° slope > building terraces on a 5–25° slope > building terraces on a 15–25° slope. Regional authorities should comprehensively consider the effects of various SWCMs on water reduction, and optimise the layout of vegetation and terracing measures, to support the efficient utilization of water resources in the Jing River catchment.

Keywords: SWAT model; climate change; human activities; runoff reduction; Jing River catchment



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1. Introduction

Runoff is an important water resource, reflecting the hydrological evolution of watersheds [1]. In the context of global warming and increasingly intense human activities, the temporal pattern of runoff has changed significantly [2,3]. In some arid and semi-arid regions with severe soil erosion and fragile ecological environments, continuous soil and water conservation measures (SWCMs) have reduced water and soil losses [4], but increased local ecological water consumption, resulting in a significant reduction in runoff [5]. In the long run, this has brought about water shortage problems, affecting economic and social development [6]. It is important to clarify the contribution of different SWCMs to runoff reduction for watershed management and the sustainable development of water resources.

To clarify the driving factors of runoff reduction, the attribution of runoff change has become a common scientific problem at different spatial scales [7–9]. In recent years, several studies have used attribution analyses to distinguish the contributions of climate and human activities to runoff changes [9,10]. Based on different methods and time scales [11,12], most indicated that climate change might lead to an increase or decrease in runoff, and human activities were the prime influencing factor of runoff reduction [8,13,14]. As a form of human activity, SWCMs have greatly influenced the spatial and temporal patterns of runoff and have become the main reason for runoff reduction in some regions [4,15–18]. Many studies have analysed the relationship between SWCMs and runoff change. Terracing measures serve

as a common SWCM, capable of reducing the production of water and sediment, while intercepting sediment inflow on the upper slope. They also have a substantial impact on the water-sediment process at both slope and watershed scales [19]. Previous studies in various regions have demonstrated their effectiveness in reducing runoff [20,21]. Vegetation measures are also very important types of SWCMs; these measures mainly include planting trees and grasses to prevent soil erosion and conserve water sources, which can effectively convert precipitation into soil moisture and evapotranspiration, thus reducing runoff. Previous studies have compared the differences in soil and water conservation functions between different forest land types and land-use types [22,23].

At present, studies on the response of runoff to SWCMs remain a hot topic in the fields of watershed management and ecological restoration. The research method has also been developed from the traditional statistical analysis to the hydrological model method [24]. The hydrological model method can simulate hydrological processes in large- or medium-scale basins. With fewer parameters, the conceptual hydrological model has certain advantages in rainfall and runoff simulations; however, it is usually a lumped model that ignores the spatial distribution difference of the underlying surface of the basin. Freeze et al. [25] proposed a physically based hydrological response model, which was the first distributed hydrological model, to address the shortcomings of conceptual models. The distributed hydrological model accounts for the uneven spatial distribution within a watershed, offering spatiotemporal resolution [26,27]. Consequently, it simulates hydrological processes more accurately, reflecting real-world conditions. The SWAT distributed hydrological model can simulate runoff changes throughout a basin under various SWCMs. SWAT is a crucial tool that academics use both locally and internationally to simulate runoff change and soil and water loss at the watershed scale [28–30]. Previous studies have simulated the effect of building terraces on runoff by adjusting parameters [31–33], which is a very user friendly method for research lacking relevant measured data, and have simulated and analysed the water reduction benefits of changing cultivated land to forest land or grassland by setting different land-use scenarios in the SWAT distributed hydrological model [34,35]. The integration of the SWAT model with the runoff reduction method has been employed to attribute changes in runoff. This approach offers a more accurate representation of climatic and surface conditions, minimizing errors associated with individual meteorological elements representing climate change.

However, prior investigations into the runoff change response to SWCMs in the basin have primarily concentrated on individual SWCMs [18,21], with limited efforts made to differentiate the impact of the unit area changes from the various SWCMs. Therefore, we conducted a study on the influence of different SWCMs on runoff reduction in the Jing River catchment. The Jing River catchment is typical of the Loess Plateau, China [36], with severe soil erosion (approximately 3×10^8 t of sediment load per year) [37] and strong human management activities. To reduce soil erosion, a series of SWCMs have been adopted in recent decades [38]. In response to Chinese government policies, projects such as terraces, dams, afforestation, and grass planting have been conducted since the 1970s. These measures have had a significant impact on regional hydrological processes, and the average annual runoff coefficient of the Loess Plateau has decreased by 74% after treatment [39]. At the beginning of the 21st century, a large-scale project was implemented to return farmlands to forests and grasslands [40]. The woodland and grassland areas in the basin have since increased significantly, whereas the sloping farmland area has decreased significantly. From 2000 to 2015, the average annual water yield was 1.11×10^9 m³, which is 36.2% lower than the average level in the previous 50 years [41]. Large-scale SWCMs have effectively controlled soil and water losses, but have also resulted in a substantial reduction in runoff [23]. Separating the contributions of climate change and human activity to runoff change and analysing the impact of different SWCMs on runoff reduction are important issues in the management of the Jing River catchment and the Loess Plateau. It is important to strengthen the positive influence of human activities on hydrological change

and regulate hydrological processes under ever-changing socio-economic and complex natural environmental conditions [42–44].

Therefore, the main objectives of this study were to (1) quantify the influence of climate change and human activities on runoff changes through an attribution analysis; (2) implement scenarios to simulate different SWCMs at the basin scale, and quantitatively analyse the effects of their changes in unit area on runoff reduction. This study provides scientific support for integrating management techniques, optimising the layout of SWCMs, and utilising water resources more effectively in the Jing River catchment as well as in the Loess Plateau, China.

2. Materials and Methods

2.1. Study Area

The Jing River is a second-tier tributary of the Yellow River and originates at the eastern foot of Liupan Mountain in Jingyuan County, Ningxia Hui Autonomous Region, China. The river flows through the Ningxia, Gansu, and Shaanxi provinces before flowing into the Wei River in the Chenjiatan, Xi'an, Shaanxi Province, with a total length of 455.1 km. The Jing River catchment ($34^{\circ}46' \sim 37^{\circ}19' \text{ N}$, $106^{\circ}14' \sim 108^{\circ}42' \text{ E}$) is situated on the Loess Plateau, which is known for severe soil erosion and a delicate ecological environment. The catchment has a watershed area of 43,265 km^2 and an elevation of 384–2924 m (Figure 1). The average annual precipitation, from 1960 to 2020 is 499.5 mm, of which 54.9 mm is in the form of sleet and snowstorms, with a peak of 754.3 mm and a minimum of 337.2 mm. Most rainfall occurs between July and October. The average temperature is 9.6°C , fluctuating between 8.1°C and 10.9°C , and the average annual wind speed is $2.2 \text{ m}\cdot\text{s}^{-1}$. The average annual relative humidity is 62%, and the average annual total solar radiation is $5659.4 \text{ MJ}\cdot\text{m}^{-2}$. The basin experiences a temperate continental climate, with the northern and central areas being arid and the southern part being semi-arid and sub-humid. The basin is encircled by mountains on three sides and comprises predominantly hills and terraces. It is less influenced by external water systems, and the river system is relatively well developed.

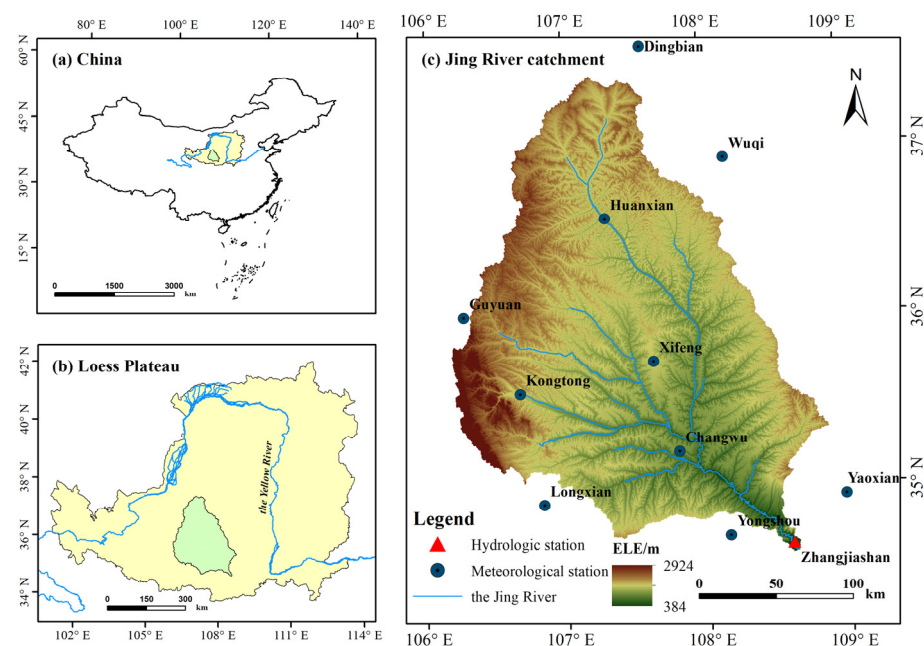


Figure 1. Geographical location and distribution of hydrological and meteorological stations in the Jing River catchment.

2.2. Data

Digital elevation model (DEM) data were obtained from the geospatial data cloud (<http://www.gscloud.cn>, accessed on 16 August 2022), which was used to extract the topography and generate river network water systems, basin outlets and sub-basins. The daily data of 10 national meteorological stations (Figure 1) from 1970 to 2019 were derived from the daily value dataset of surface climatological data in China, the basic data categories selected for input into the model included daily precipitation, temperature, solar radiation, wind speed, and relative humidity. The Zhangjiashan Hydrology Station is situated at the outlet of the Jing River catchment, and the daily measured runoff data from this station from 1970 to 2019 were derived from the *Yellow River Basin Hydrological Data* and National Earth System Science Data Center (<http://www.geodata.cn>, accessed on 25 October 2022). The data were used to perform runoff abrupt change tests and model parameter calibration. Land-use data for 1980, which comprised the basic data required for modelling, were obtained at a 1 km resolution from the Resource Environmental Science and Data Center (<https://www.resdc.cn/>, accessed on 20 September 2022). Soil data with a resolution of 1 km were derived from the Harmonised World Soil Database (HWSD) developed by the United Nations Food and Agriculture Organization (FAO) and the International Institute for Applied Systems in Vienna (IIASA). The data representing the soil conditions of the Chinese region, another important basic data component required for modelling, comprised the soil data of the second National Land Survey in 1995, provided by the Nanjing Soil Institute.

2.3. Methods

2.3.1. Cumulative Anomaly Method

The cumulative anomaly method is a test method based on the mean value and is used to reflect the changing trends in the data [45]. If there is an evident increasing and decreasing trend around a certain time value of the curve, this point can be regarded as an abrupt point of the changing trend. For sequence X , the cumulative anomaly at time t is expressed by Equation (1):

$$X_t = \sum_{i=1}^t (x_i - \bar{x}), \quad t = 1, 2, \dots, n \quad (1)$$

where $\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$.

2.3.2. Runoff Reduction Method

The attribution analysis method is mainly used to determine the degree of contribution of climate change and human activity to runoff change, and is quantitatively assessed using the SWAT model [46], thereby providing a meaningful guarantee for further research on SWCMs. First, the cumulative anomaly mutation analysis method was used to identify the mutation point so that the hydrological sequence of the basin could be divided into natural and changing periods. The natural period is solely influenced by climate change, free from human activity interference, while the changing period is impacted by both. The hydrometeorological data in the natural period were used to calibrate the parameters in the hydrological model. The model could reflect the runoff in the natural period approximately combined with the calibrated parameters and the meteorological data of that period. When maintaining the same input parameters for the model, the hydrological model receives meteorological data from the changing period, simulating natural runoff only under climate change conditions. Thus, we can calculate the runoff change (ΔR_c) caused by climate change and the runoff change (ΔR_w) caused by human activities, and then calculate the contribution rates of both by combining them with the total runoff change (ΔR) before and after the abrupt change. The formulas (Equations (2)–(6)) are as follows:

$$\Delta R = R_{post} - R_{pre} \quad (2)$$

$$\Delta R_c = R_{sim} - R_{pre} \quad (3)$$

$$\Delta R_\omega = R_{post} - R_{sim} \quad (4)$$

$$\eta_c = \frac{\Delta R_c}{|\Delta R_c| + |\Delta R_\omega|} \quad (5)$$

$$\eta_\omega = \frac{\Delta R_\omega}{|\Delta R_c| + |\Delta R_\omega|} \quad (6)$$

where R_{post} is the measured annual average runoff during the changing period (1997–2019), R_{pre} is the measured annual average runoff during the natural period (1972–1996), R_{sim} is the annual average runoff simulated in the model by using the meteorological data of the changing period (1997–2019), and η_c and η_ω represent the rates at which climate change and human activities contribute to runoff changes, respectively.

2.3.3. SWAT Model

The Soil and Water Assessment Tool (SWAT) is a physics-based distributed hydrological model that can predict the effect of land management practices on basin-scale runoff [47].

Application of SWAT Model

The same projection coordinate system must be used for all input spatial data. The WGS_1984_UTM_Zone_48N projection was used to transform all the spatial data to meet the modelling requirements. Using the input DEM data, the model used ArcSWAT2012 to extract the river network and divide the 27 sub-basins in the Jing River catchment (Figure 2). The sub-basins were then divided into 471 hydrological response units (HRUs) by inputting reclassified grid maps of land use and soil type into the model.

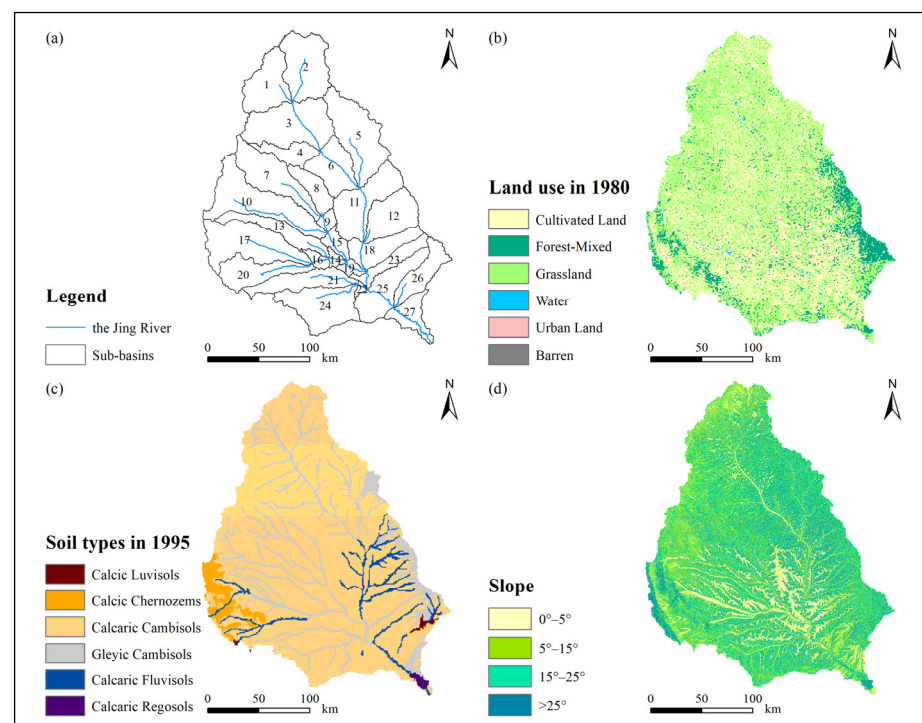


Figure 2. Classification of (a) sub-basins, (b) land use, (c) soil types, (d) slope in the Jing River catchment.

Before the 1980s, SWCMs were not implemented on a large scale within the basin; the basin was less affected by human activities than currently and had a consistent underlying surface. Therefore, land-use data from 1980 and meteorological data from 1970 to 1985 were used as benchmark data to simulate runoff production in the Jing River catchment.

Model Applicability Evaluation

Based on the measured data, the average monthly discharge at the Zhangjiashan Hydrology Station from 1970 to 1985 was selected for model calibration and verification. This study set 1970–1971 as the warm-up period, and selected data from 1972 to 1979 for model calibration and 1980 to 1985 for model verification. The coefficient of determination (R^2), Nash–Sutcliffe efficiency coefficient (NSE) and percentage bias (PBIAS) were employed to assess the accuracy of the calibration and verification results, and the model's applicability in the Jing River catchment [48]. R^2 represents the consistency of the change trend between the observed and simulated values. NSE was used to quantify the prediction accuracy of the model simulation. The PBIAS represents the bias between the total observed value and the total simulated value. $PBIAS > 0$ indicates a relatively high simulated value, $PBIAS = 0$ indicates a simulated value equal to the observed value and $PBIAS < 0$ indicates a relatively small, simulated value. The formulae for the three indices (Equations (7)–(9)) are as follows:

$$NSE = 1 - \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (7)$$

$$R^2 = \frac{[\sum_{i=1}^n (O_i - \bar{O})(S_i - \bar{S})]^2}{\sum_{i=1}^n (O_i - \bar{O})^2 \sum_{i=1}^n (S_i - \bar{S})^2} \quad (8)$$

$$PBIAS = \left[\frac{\sum_{i=1}^n (O_i - S_i) * 100}{\sum_{i=1}^n (O_i)} \right] \quad (9)$$

where O_i is the observed value, S_i is the simulated value, $\bar{O}$ is the average observed value, $\bar{S}$ is the average simulated value, and n is the number of observed values. Based on the R^2 , NSE, and PBIAS values, the reliability of SWAT model simulation results can be divided into four levels: very good, good, normal and unsatisfactory (Table 1). When $NSE > 0.5$, $R^2 > 0.5$ and $PBIAS < \pm 25\%$, the accuracy of the model meets the requirements.

Table 1. SWAT model performance parameter level table.

Model Evaluation Indexes	R^2	NSE	PBIAS/%
very good	$0.8 < R^2 \leq 1$	$0.75 < NSE \leq 1$	$ PBIAS \leq 10$
good	$0.7 < R^2 \leq 0.8$	$0.65 < NSE \leq 0.75$	$10 < PBIAS \leq 15$
normal	$0.5 < R^2 \leq 0.7$	$0.5 < NSE \leq 0.65$	$15 < PBIAS \leq 25$
unsatisfactory	$R^2 \leq 0.5$	$NSE \leq 0.5$	$ PBIAS > 25$

Scenario Simulation

To quantitatively analyse the effects of different SWCMs on runoff reduction in the Jing River catchment, this study incorporated different scenarios based on the SWAT model by analysing the influences of different horizontal slope terraces, changing cultivated land to forest land, and changing cultivated land to grassland on outlet discharge, surface runoff, and water yield values. The following six scenarios were simulated (Table 2): (1) S0, no measures. (2) S1, building terraces on a 5–15° slope. (3) S2, building terraces on a 15–25° slope. (4) S3, building terraces on a 5–25° slopes. (5) S4, changing cultivated land to forest land. (6) S5, changing cultivated land to grassland. The slope is defined as the angle between the slope and the horizontal plane. S0 is the reference group, which reflects the runoff from 1972 to 1985 under actual underlying surface conditions. Compared with S0, scenarios S1, S2, and S3 evaluated the outcomes of building terraces on the discharge, surface runoff, and water yield at the watershed outlet, whereas scenarios S4 and S5 evaluated the effect of vegetation change on these same variables.

Table 2. Scenarios of different soil and water conservation measures.

Scenario	Measures	Description
S0	No measures	
S1	Building terraces on a 5–15° slope	Reducing the CN2 value by 6 from the existing value on the slope of 5–15°
S2	Building terraces on a 15–25° slope	Reducing the CN2 value by 6 from the existing value on the slope of 15–25°
S3	Building terraces on a 5–25° slope	Reducing the CN2 value by 6 from the existing value on the slope of 5–25°
S4	Changing cultivated land to forest land	Changing all cultivated land in 1980 to forest land by reclassification
S5	Changing cultivated land to grassland	Changing all cultivated land in 1980 to grassland by reclassification

To overcome the lack of measured terrace data, this study simulated the effect of horizontal terraces on runoff by adjusting the parameters related to terraces in the model. The initial SCS runoff curve number (CN2) is an important parameter used to characterize the influence of horizontal terraces on runoff in the HRU. Hence, the hydrological effect of the horizontal terraces was simulated by decreasing the CN2 value by six from its current value [31]. The adjusted CN2 values closely matched those recommended by Neitsch et al. [49] for terraces with varying soil types [50]. For changing cultivated land to forest land and grassland, an extreme scenario simulation method was adopted to simulate the impacts on the discharge, surface runoff, and water yield.

3. Results

3.1. Model Applicability Evaluation

This study performed numerous iterations of 28 parameters associated with runoff simulation [51] from 1972 to 1985 in the study area to ascertain their sensitivity to runoff simulation using a global sensitivity analysis (Table S1), identifying 18 sensitive parameters. These parameters (Table 3) were automatically calibrated and verified using the SWAT-CUP tool. The optimal parameter values were obtained after several iterations.

Table 3. Sensitive parameters and calibration results.

Parameter Code	Description	Initial Range	Optimal Value
r__SOL_AWC().sol	Available water capacity of the soil layer	−0.5~0.5	0.4889
v__SLSUBBSN.hru	Average slope length	10~150	25.8329
r__CN2.mgt	Initial SCS runoff curve number for moisture condition II	−0.5~0.5	0.1461
v__HRU_SLP.hru	Average slope steepness	0~0.6	0.2161
v__RCHRG_DP.gw	Deep aquifer percolation fraction	0~1	0.2821
v__ALPHA_BF.gw	Baseflow alpha factor	0~1	0.0748
r__SOL_BD().sol	Moist bulk density	−0.5~0.5	0.2533
v__REVAPMN.gw	Threshold depth of water in the shallow aquifer for “revap” to occur	0~500	175.6100
v__CANMX.hru	Maximum canopy storage	0~100	7.2444
v__SURLAG.bsn	Surface runoff lag time	1~24	3.3209
v__TLAPS.sub	Temperature lapse rate	0~50	46.7875
v__SFTMP.bsn	Snowfall temperature	−5~5	−2.7349
v__EPCO.hru	Plant uptake compensation factor	0.01~1	0.5588
r__BIOMIX.mgt	Biological mixing efficiency	−0.5~0.5	−0.3762
r__SOL_Z().sol	Depth from soil surface to bottom of layer	−0.5~0.5	0.4978
r__SOL_K().sol	Saturated hydraulic conductivity	−0.8~0.8	−0.2278
v__GW_REVAP.gw	Groundwater “revap” coefficient	0.02~0.2	0.0637
v__ESCO.hru	Soil evaporation compensation factor	0.01~1	0.1647

Notes: v__ and r__ represent the substitution of the given value for the current parameter value and the multiplication of the current parameter value by (1 + a given value).

The parameters that had a substantial influence on the runoff of the Zhangjiashan Hydrology Station were SOL_AWC, SLSUBBSN, CN2, HRU_SLP, RCHRG_DP, ALPHA_BF and SOL_BD, and their definitions are described in Table 2. The SOL_AWC parameter, related to soil properties, had the most significant effect on runoff. The larger the value, the more water the soil layer can hold, the stronger the water-holding capacity, and the smaller the runoff. The SLSUBBSN is a topographic parameter. CN2 changed with the changes in land cover and soil type. The overall runoff from the watershed and the impermeability of the underlying surface increased with increasing CN2. HRU_SLP is a topographic parameter that mainly affects the lateral flow. The change in the slope was positively correlated with the change in the discharge. RCHRG_DP is related to subsurface runoff. ALPHA_BF showed that the baseflow in the Jing River catchment was responsive to recharge, consistent with the findings obtained by Liu et al. [52] using the DREAM algorithm. SOL_BD is also related to soil properties. Greater values correspond to earlier runoff production times and higher runoff coefficients, indicating a greater conversion of rainfall into runoff.

According to the comparison curve (Figure 3) and correlation relationship (Figure 4) between the simulated and observed monthly average discharge of the Zhangjiashan Hydrology Station during the calibration period (1972–1979) and the verification period (1980–1985), the simulated monthly discharge in these two periods was in close accordance with the observed discharge.

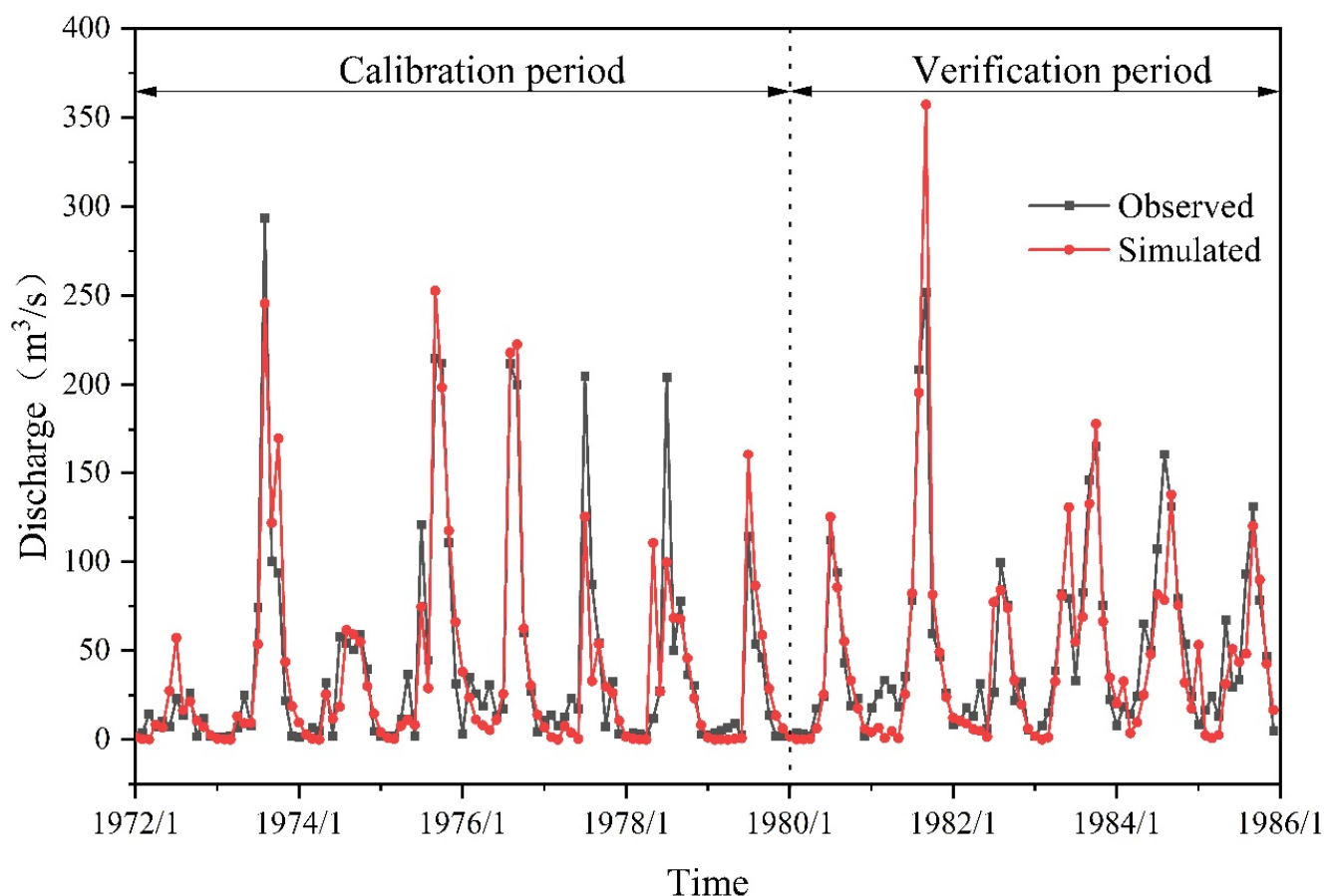


Figure 3. Comparison between the simulated and observed monthly average discharge during the calibration and verification periods.

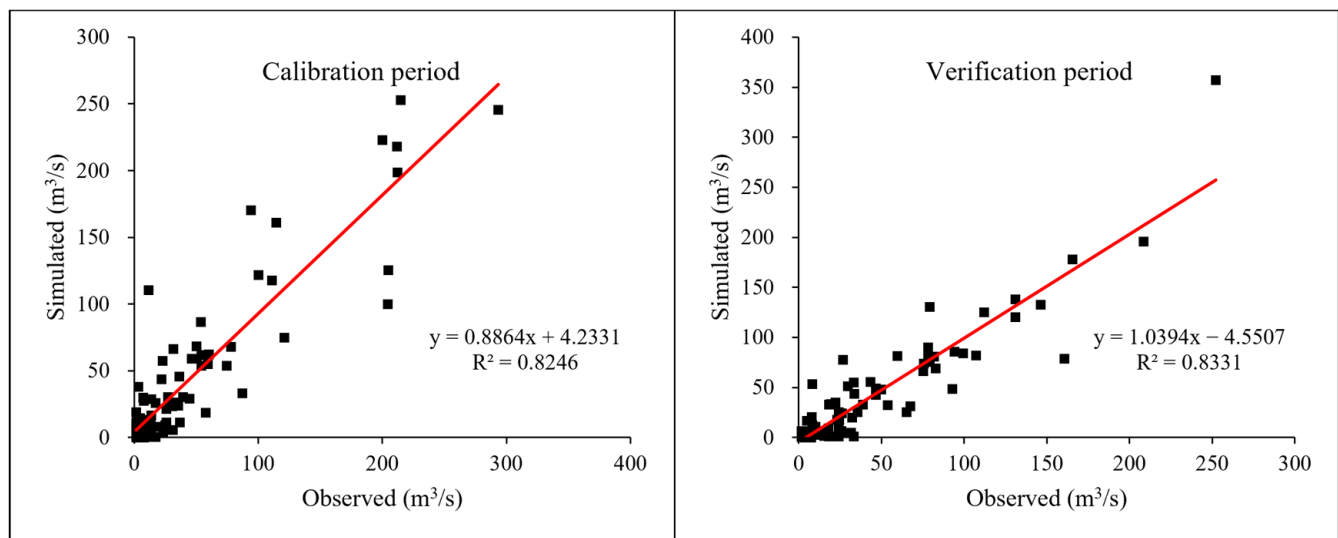


Figure 4. Correlation relationship between the simulated and observed monthly average discharge during the calibration and verification periods.

During the calibration period, the NSE, R^2 , and PBIAS values of the simulated and observed monthly average flow were 0.82, 0.82, and 0.40%, respectively, reaching the standard of “very good”. During the verification period, these values for the simulated and observed monthly average flow were 0.78, 0.83, and 5.30%, respectively, reaching the standard of “very good” as well (Table 4). Overall, the monthly runoff simulation at the Zhangjiashan Hydrology Station met the accuracy requirements, indicating the applicability of the SWAT model for runoff simulations in the Jing River catchment.

Table 4. Applicability evaluation of model simulation results.

Period	Time	NSE	R^2	PBIAS/%
Calibration period	1972–1979	0.82	0.82	0.40
Verification period	1980–1985	0.78	0.83	5.30

3.2. Attribution Analysis of Runoff Change in the Jing River Catchment

According to the abrupt change analysis, runoff in Zhangjiashan changed abruptly in 1996 (Figure 5). Thus, the monthly runoff series was divided into a natural period (1972–1996) and a changing period (1997–2019). The calibrated model parameters reflect the flow production process in the natural period. Therefore, with the model parameters unchanged, meteorological data from 1997 to 2019 was input into the model to calculate the runoff, which was the simulated runoff under the original underlying surface conditions.

The average measured annual runoff from 1972 to 1996 was $13.72 \times 10^8 \text{ m}^3$, while from 1997 to 2019, it averaged $7.44 \times 10^8 \text{ m}^3$. The total reduction in runoff attributed to human activities and climate change was $6.28 \times 10^8 \text{ m}^3$. The average simulated annual runoff from 1997 to 2019 was $14.84 \times 10^8 \text{ m}^3$. Compared with the average measured annual runoff from 1997 to 2019, human activities reduced the runoff volume by $7.40 \times 10^8 \text{ m}^3$, with a contribution rate of 86.85%. Thus, climate change increased the runoff volume by $1.12 \times 10^8 \text{ m}^3$, with a contribution rate of 13.15% (Table 5). In summary, human activities constitute the primary reason for runoff reduction. Thus, it was essential to analyse the effects of human activities, such as varying SWCMs, on runoff reduction.

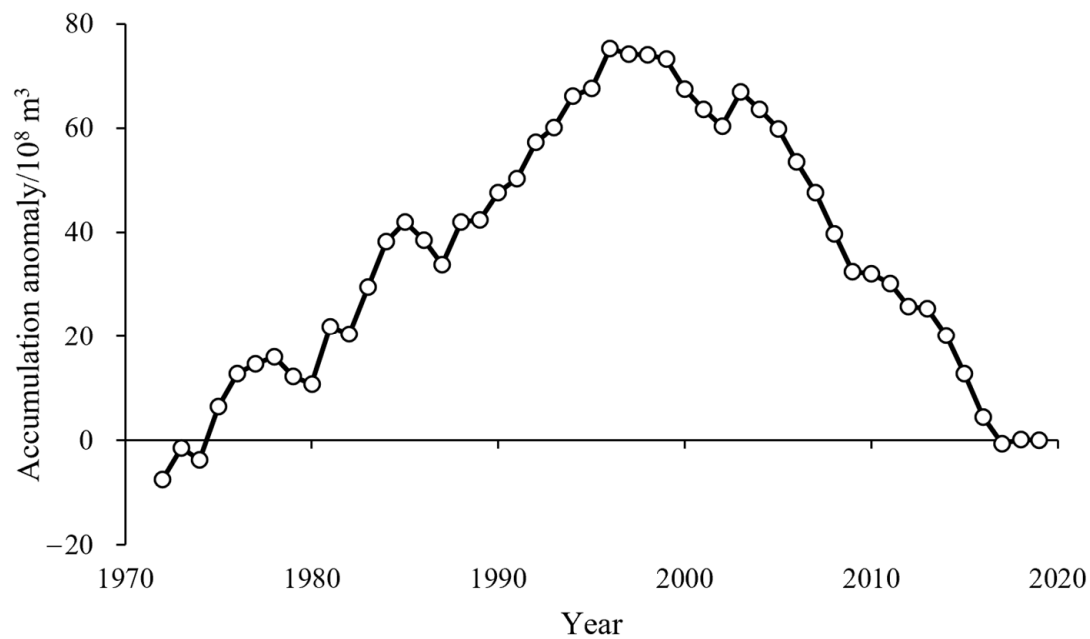


Figure 5. Mutation test of runoff at Zhangjiashan Station.

Table 5. Contribution of climate change and human activities to runoff change in the Jing River catchment.

Period	Mean Value of Runoff/ 10^8 m^3			Runoff Change/ 10^8 m^3			Contribution Rate/%	
	R_{pre}	R_{sim}	R_{post}	ΔR	ΔR_c	ΔR_w	η_c	η_w
1997–2019	13.72	14.84	7.44	−6.28	1.12	−7.40	13.15	−86.85

Notes: “−” in ΔR and ΔR_w denotes the reduction in runoff, and “−” in η_w denotes the contribution to runoff reduction.

3.3. Runoff Simulation under Different Soil and Water Conservation Measures

The effects of different SWCMs on the discharge, surface runoff, and water yield at the watershed outlet were quantitatively analysed through the simulations of S0, S1, S2, S3, S4, and S5 (Figure 6). Compared with the S0 scenario, the five SWCMs all reduced the discharge, surface runoff, and water yield. Among them, the reduction efficacy of building terraces on the 5–15° slope was slightly greater than that of building terraces on the 15–25° slope. The reduction efficacy of changing cultivated land to forest land was stronger than that of changing cultivated land to grassland. In general, the reduction intensity of the terracing measures on runoff was lower than that of the vegetation measures. Changing cultivated land to forest land had the most significant influence on overall hydrological processes. Moreover, they all reduced the flood peak. The degree of reduction in flood peaks by each measure was ordered as follows: returning farmland to forest > returning farmland to grass > building terraces on a 5–25° slope > building terraces on a 5–15° slope > building terraces on a 15–25° slope.

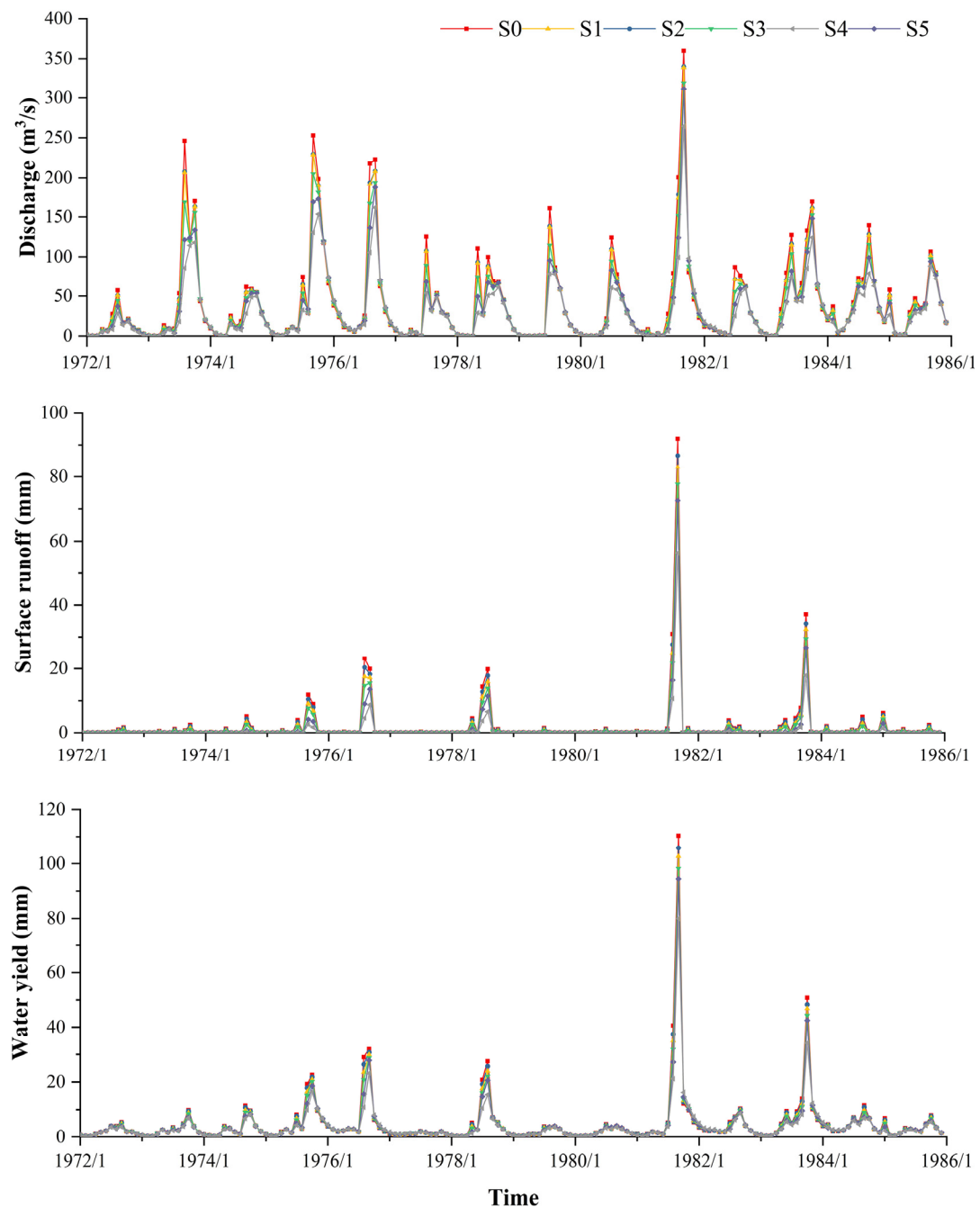


Figure 6. Simulation of monthly average discharge, surface runoff and water yield under different soil and water conservation measures (SWCM).

3.4. Influence of Different Soil and Water Conservation Measures on Runoff Change

This study quantified the effects of different SWCMs on the discharge (Figure 7). Compared with the average annual discharge in the basin with no measures, building terraces on the 5–15°, 15–25°, and 5–25° slopes, changing cultivated land to forest land, and changing cultivated land to grassland reduced the discharge by 6.42, 5.93, 12.35, 28.40, and 18.53%, respectively (Figure 7a). Due to the various area settings of the five SWCM scenarios, it was not possible to directly compare their water reduction benefits on this basis. Therefore, it was necessary to generate statistics on the area changes of the SWCMs in the S1–S5 scenarios and analyse the impact of their unit area changes on runoff. According to the statistics of the area changes from the SWCMs in the S1–S5 scenarios (Figure 8), the area used for building terraces on the slope of 5–15° was 12,772.86 km^2 , or 29.52%

of the whole basin area, the area for the 15–25° slope was 12,228.86 km², or 28.26% of the whole basin area, and that for the slope of 5–25° was 255,001.72 km², or 57.78% of the whole basin area; and the area used for cultivated land changed into forest land was 18,380.67 km², or 42.48% of the whole basin area, and that for cultivated land changed into grassland was 18,380.67 km², or 42.48% of the whole basin area. From the analysis of the influence of unit area changes of different SWCMs on the average annual discharge at the watershed outlet, building terraces could potentially reduce the discharge by approximately 2.07×10^{-4} , 2.00×10^{-4} , and 2.03×10^{-4} m³/s/km² for the 5–15°, 15–25° and 5–25° slopes, respectively; changing cultivated land to forest land could potentially reduce the discharge by approximately 6.35×10^{-4} m³/s/km², and changing cultivated land to grassland could reduce the discharge approximately 4.15×10^{-4} m³/s/km² (Figure 7b). The reduction benefits of the five measures on the average annual discharge were ranked as follows: changing cultivated land to forest land > changing cultivated land to grassland > building terraces on a 5–15° slope > building terraces on a 5–25° slope > building terraces on a 15–25° slope.

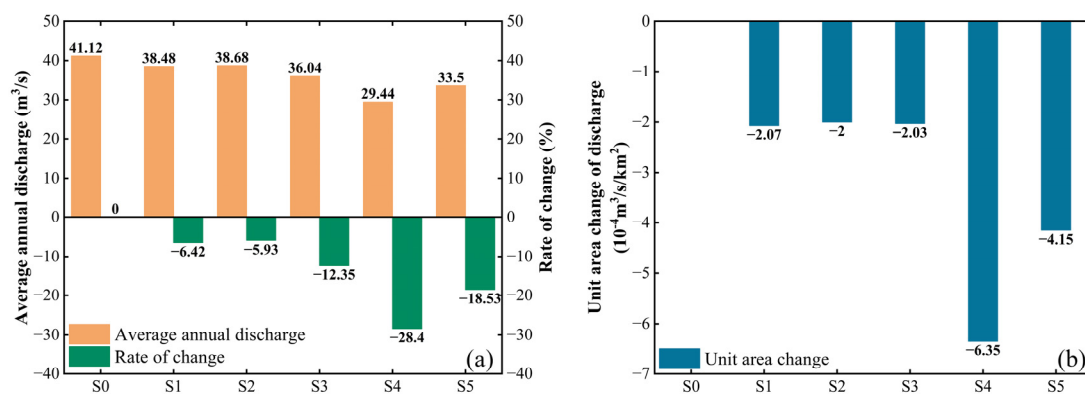


Figure 7. Analysis of the influence of SWCMs on the average annual discharge in the S1–S5 scenarios: (a) change rate of the average annual discharge, (b) unit area change of the average annual discharge.

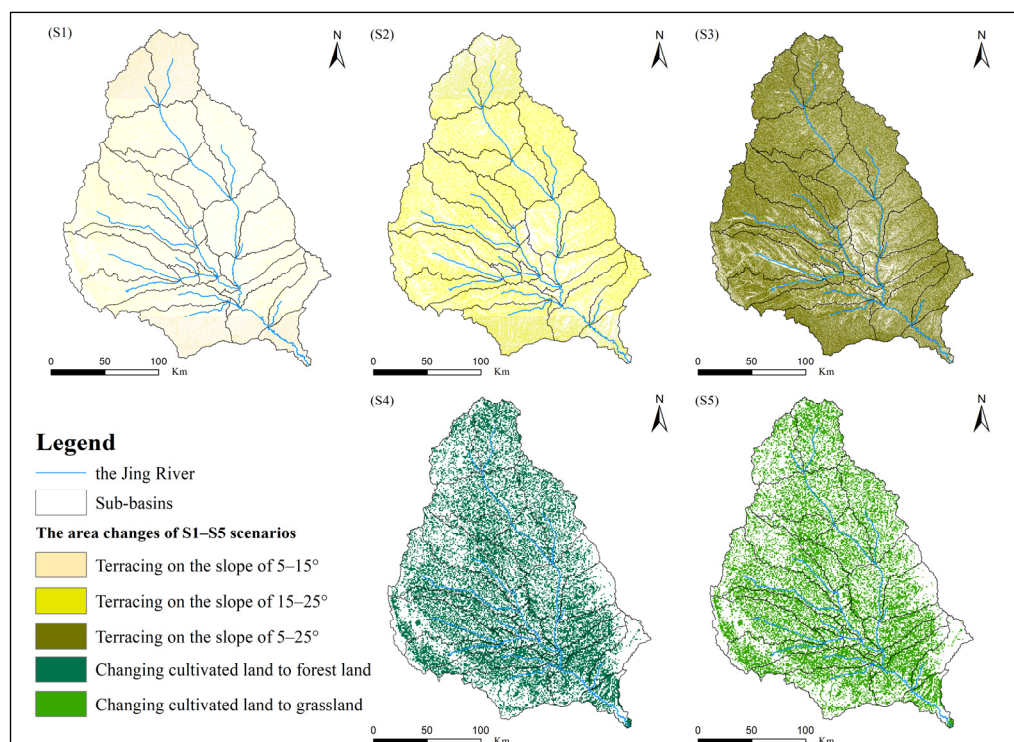


Figure 8. Areal changes of SWCMs in the (S1–S5) scenarios.

The effects of the various SWCMs on surface runoff were quantitatively analysed (Figure 9). Compared with the average annual surface runoff with no measures, the surface runoff was reduced by 20.42, 9.84, 30.22, 65.13, and 48.33%, respectively, by building terraces on 5–15°, 15–25°, and 5–25° slopes, as well as changing cultivated land to forest land and grassland, respectively (Figure 9a). The impact of the unit area changes from the different SWCMs on the average annual surface runoff at the watershed outlet was analysed based on the above statistics on the areal changes of the SWCMs in scenarios S1–S5. Surface runoff could potentially be reduced by approximately 3.88×10^{-4} , 1.95×10^{-4} , and 2.94×10^{-4} mm/km² when building terraces on a 5–15°, 15–25°, and 5–25° slope, respectively, and approximately 8.61×10^{-4} and 6.39×10^{-4} mm/km² when changing cultivated land to forest land and grassland, respectively (Figure 9b). The reduction benefits of SWCMs on surface runoff were ranked as follows: changing cultivated land to forest land > changing cultivated land to grassland > building terraces on a 5–15° slope > building terraces on a 5–25° slope > building terraces on a 15–25° slope.

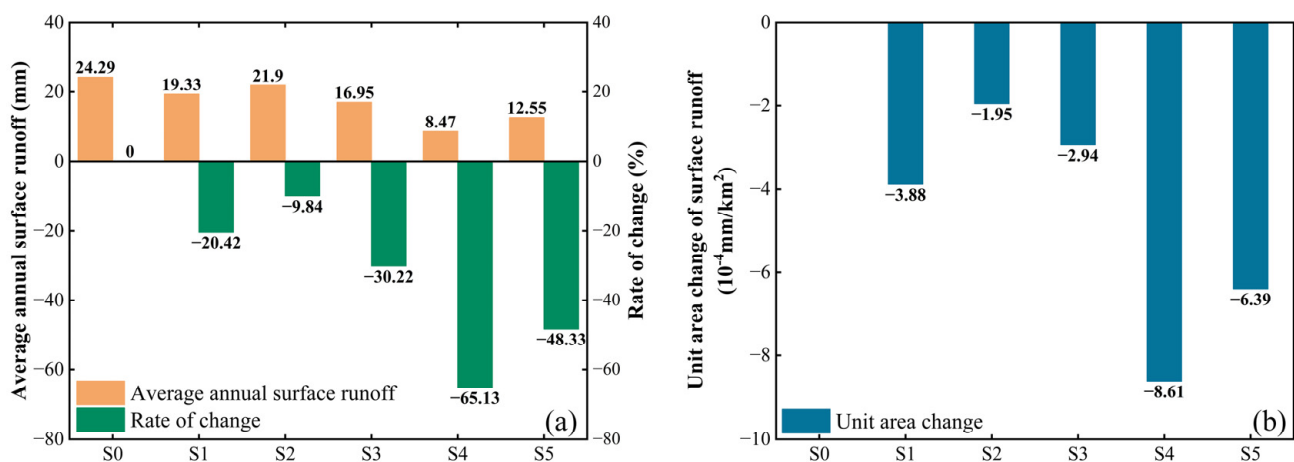


Figure 9. Analysis of the influence of SWCMs on the average annual surface runoff in the S1–S5 scenarios: (a) change rate of the average annual surface runoff, (b) unit area change of the average annual surface runoff.

This study quantified the effect of different SWCMs on water yield (Figure 10). Compared with the average annual water yield with no measures, the water yield decreased by 6.28, 2.95, 9.23, 22.07, and 13.95%, when building terraces on the slope of 5–15°, 15–25°, and 5–25°, as well as changing cultivated land to forest land or grassland, respectively (Figure 10a). The influence of the unit area changes of the different measures on the average annual water yield was analysed. We calculated that the water yield could potentially be reduced by approximately 2.92×10^{-4} , 1.43×10^{-4} , and 2.19×10^{-4} mm/km² when building terraces on 5–15°, 15–25°, and 5–25° slopes, respectively. Changing cultivated land to forest land and grassland could potentially reduce the water yield by approximately 7.13×10^{-4} and 4.50×10^{-4} mm/km², respectively (Figure 10b). The reduction benefits of SWCMs on water yield were ranked as follows: changing cultivated land to forest land > changing cultivated land to grassland > building terraces on a 5–15° slope > building terraces on a 5–25° slope > building terraces on a 15–25° slope.

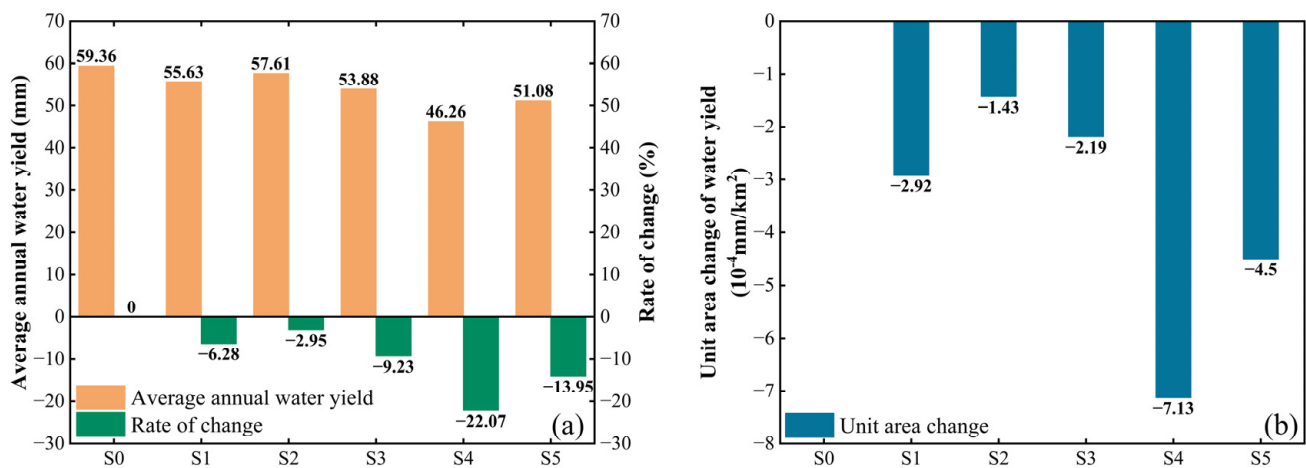


Figure 10. Analysis of the influence of SWCMs on the average annual water yield in the S1–S5 scenarios: (a) change rate of the average annual water yield, (b) unit area change of the average annual water yield.

4. Discussion

4.1. Attribution Analysis

Researchers worldwide have mostly studied runoff changes from two perspectives: climate change and human activity [53,54]. In most areas of China, climate change leads to an increase in runoff, whereas human activity leads to a decrease in runoff [55]. Precipitation, the main source of runoff, is the most direct climatic factor affecting changes in runoff. Climate change has had an increasing effect on runoff in the Jing River catchment and is mainly related to an increase in precipitation in this area. From the analysis of the relationship between annual precipitation and annual runoff in the basin from 1972 to 2019 (Figure 11), the annual runoff generally presents a downward trend. Before 1996, runoff increased with increasing precipitation; however, after 1996, it showed a downward trend. In summary, an increase in rainfall did not lead to an increase in runoff after 1996. The significant decrease in runoff in the basin was not caused by a change in precipitation but by human activities, which weaken the influence of precipitation on runoff and become the main factor in runoff reduction. On the one hand, the level of urbanization in the study area has improved, the population has increased, and the water consumption for industry, agriculture, and domestic use has increased in the catchment [56]. On the other hand, since the 1970s, large-scale SWCMs have been adopted in the Jing River catchment, such as building terraces, returning farmland to forest and grasslands, resulting in reduced runoff [41,57,58]. This conclusion is consistent with the research conclusion obtained by Dong et al. [59], based on the SWAT hydrological model combined with sequential cluster and separation methods to quantify and distinguish the impact of human activities and climate change on runoff.

The conclusions on the driving factors of runoff change in the present study can be mainly divided into two aspects: climate change and intervention by human activities, without quantifying the contribution of specific climate change factors such as temperature, precipitation and evapotranspiration, and specific human activities such as land-use change and human water use to runoff change, which can be further explored in future research. In addition, the parameters of the SWAT hydrological model could not be obtained directly owing to their overabundance. In this study, the parameters were calibrated automatically. However, automatic calibration mostly uses an optimisation algorithm for iterative trial calculation, and no strict parametric solution equation is established; therefore, it was difficult to obtain unique numerical solutions for parameter calibration, resulting in uncertainty in the runoff simulation results.

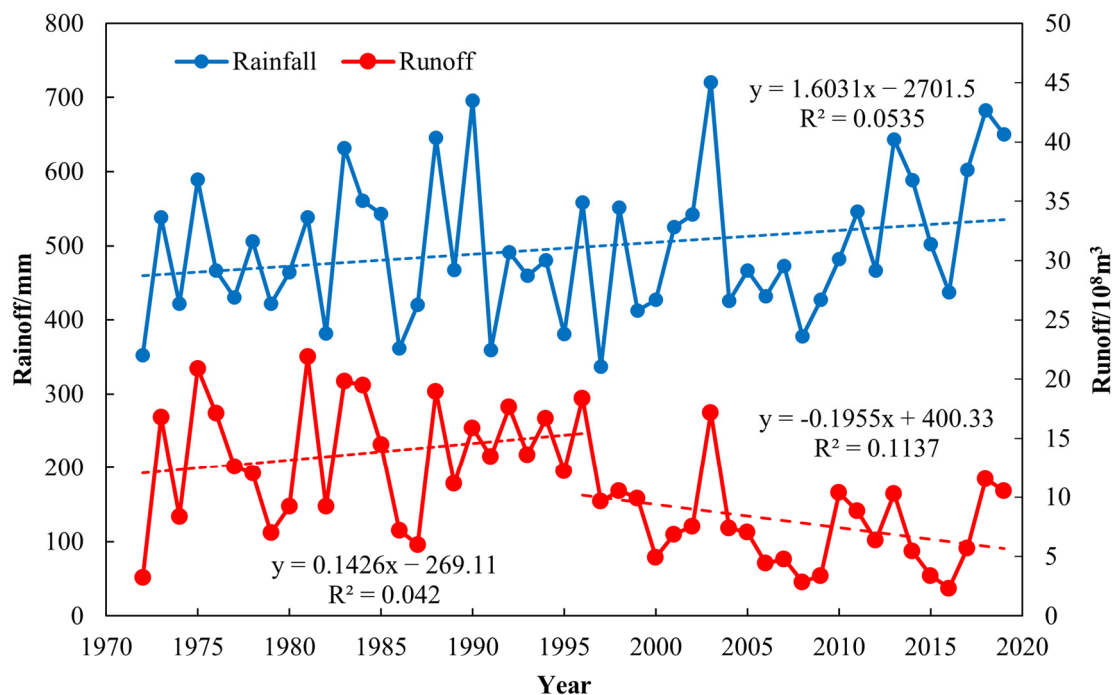


Figure 11. Average annual rainfall and runoff in the Jing River catchment from 1972 to 2019.

4.2. Analysis of the Influence of Different Soil and Water Conservation Measures on Runoff Change

The monthly average discharge at the outlet of the basin had several flood peaks during the period 1972–1985, and the most prominent was in September 1981, when the simulated discharge under the S0 scenario reached $359.6 \text{ m}^3/\text{s}$. The observed discharge reached $252.1 \text{ m}^3/\text{s}$ in September 1981, which was lower than the simulated value, but constituted the flood peak (Figure 6). On analyses of the relationship between monthly rainfall and discharge in the basin from 1972 to 1985 (Figure 12), the precipitation level in September 1981 was found to be relatively large, reaching 213.3 mm. Hence, we attributed the occurrence of the monthly runoff peaks to an increase in rainfall. Furthermore, the peaks in runoff and precipitation mainly occurred from July to September, and runoff increased with an increase in precipitation. This is because heavy rainfall can cause surface sealing in the soil, resulting in high runoff [60]. The five SWCMs in scenarios S1–S5 all obviously reduced the flood peaks. The implementation of the SWCMs weakened the influence of precipitation on runoff.

Based on the analysis of the influence of unit area changes of different SWCMs on average annual runoff, the reduction benefits of each measure on discharge, surface runoff, and water yield under the same meteorological conditions were ordered as follows: changing cultivated land to forest land > changing cultivated land to grassland > building terraces on a $5\text{--}15^\circ$ slope > building terraces on a $5\text{--}25^\circ$ slope > building terraces on a $15\text{--}25^\circ$ slope. For vegetation measures, vegetation change has a long-term impact on the hydrological process in the soil erosion area, and changing cultivated land to forest and grasslands reduces runoff significantly; however, their regulation mechanisms for runoff are completely different [61]. On the one hand, forest land intercepts rainfall in the canopy to reduce rainfall [62]; on the other hand, roots improve soil and water conservation capacity and increase rainwater penetration [63], thus reducing runoff and soil erosion. However, owing to the shallow roots of grasslands, runoff reduction is mainly achieved through rainfall interception. Furthermore, the vegetation coverage of forest land is often larger than that of grassland, and the interception and evapotranspiration capacity of forest land are stronger than those of grassland [64]. The runoff from grassland was greater than that of forest land but smaller than that of cultivated land [65]. Therefore, the effect of changing cultivated land to forest land on runoff reduction was greater than that of changing cultivated land to

grassland. A study of temperate forest areas in Russia [66] showed that soil erosion area increases with an increase in cultivated land area, indicating that returning the forest to farmland will have a negative impact on soil and water conservation.

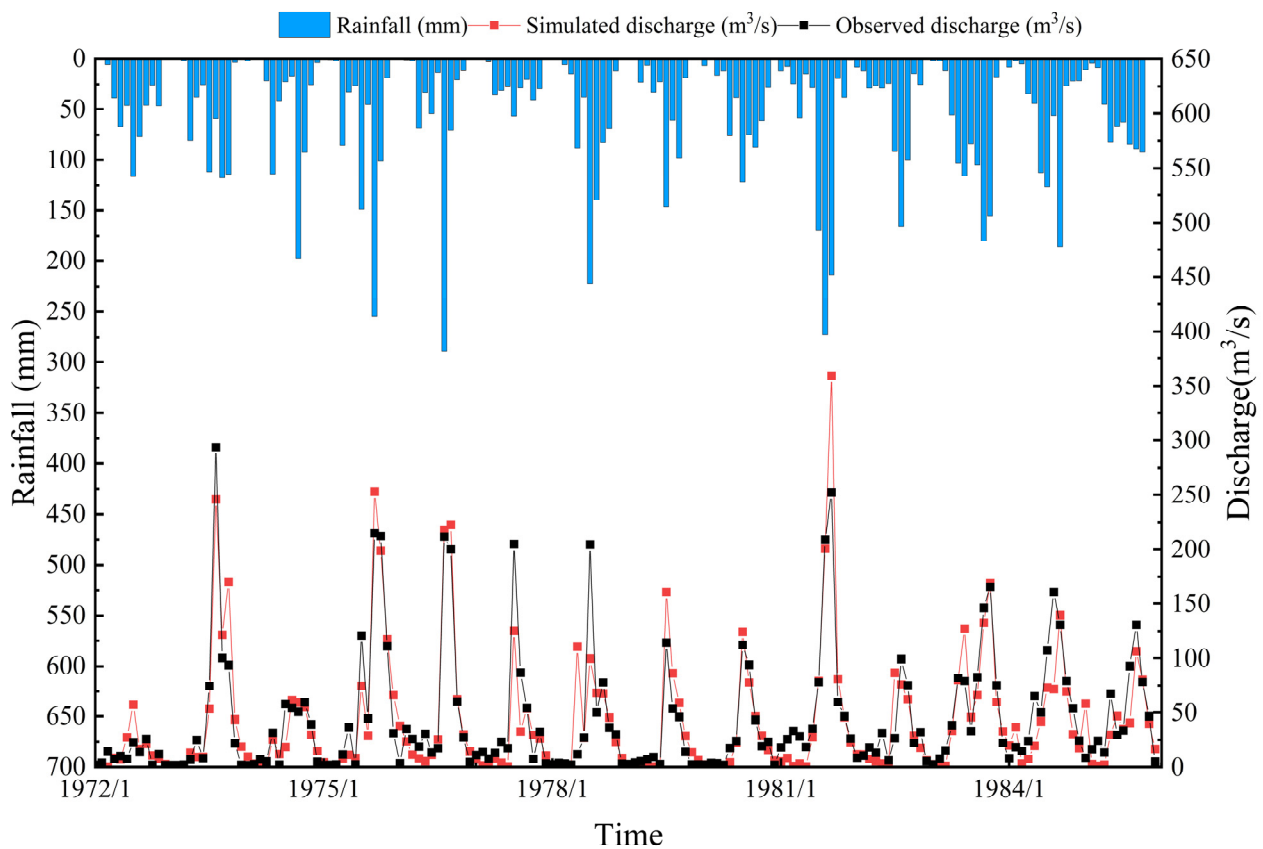


Figure 12. Monthly average rainfall and discharge in the Jing River catchment from 1972 to 1985.

For terracing measures, the change of slope land to a horizontal terrace will ensure that the original slope runoff is transformed into “water surface” under the condition of stagnant water; therefore, the slope runoff can be stored in different degrees, thus increasing the infiltration process of intercepting flow and filling depression, supplementing soil water and groundwater, and increasing the water retention of soil and the regulation role of the “soil reservoir” in the hydrological cycle. Ultimately, this modification changes the water cycle in the basin and reduces river runoff [67]. Furthermore, the rate of soil infiltration is the main index for measuring terrace infiltration. The rate of soil infiltration is not only related to soil properties, but also to slope, and soil infiltration decreases with an increase in slope [68]. This study designated the S1–S3 scenarios as building terraces on different slopes and evaluated the influence of their changes on runoff. The soil infiltration caused by building terraces on the 5–15° slope was greater than that on the 15–25° slope. Therefore, the runoff reduction caused by building terraces on the 5–15° slope was greater than that on the 15–25° slope. Since the measure in the S3 scenario is the sum of the measures in the S1 and S2 scenarios, the total amount of runoff reduction caused by building terraces on the 5–25° slope is the sum of runoff reduction caused by building terraces on the 5–15° slope and the 15–25° slope. However, for the unit area change of terracing measures, excluding the influence of different areas, the reduction benefits in runoff by building terraces on the 5–25° slope was at the middle level. This is because, from the perspective of slope size, a 5–15° slope < 5–25° slope < 15–25° slope, which in turn confirms that the soil infiltration decreases with the increase in slope. Similarly, a study in the tropical humid Ethiopian Highlands [17] showed that runoff increased significantly when the slope of cultivated land increased from 5 to 15%.

The reduction efficacies of the different SWCMs on runoff were evaluated by changing the water cycle process in the watershed. Based on the water balance formula of the basin, evapotranspiration and runoff are the main forms of rainfall transformation that reach a dynamic balance in the basin. Therefore, when evapotranspiration increases, runoff decreases [69]. The water trapped by terracing measures is used less for evapotranspiration; instead, it is mainly utilized for increasing infiltration and replenishing groundwater to change the water cycle process in the basin, thus reducing river runoff. In addition to increasing infiltration and replenishing soil water, water trapped by vegetation measures can lead to a significant increase in evapotranspiration, thereby reducing river runoff [70]. This study also quantified the effects of different SWCMs on evapotranspiration (Figure 13). Compared with the average annual evapotranspiration in the basin with no measures, the evapotranspiration increased by 0.42, 0.18, 0.59, 1.48 and 0.76%, respectively, when building terraces on the slopes of 5–15°, 15–25°, and 5–25°, as well as changing cultivated land to forest land and grassland (Figure 13a). The influence of the unit area changes of the five measures on average annual evapotranspiration was analysed based on the statistics of the areal changes of the SWCMs in the S1–S5 scenarios. Based on our calculation, building terraces on a 5–15°, 15–25°, and 5–25° slope could potentially increase evapotranspiration by approximately 1.66×10^{-4} , 0.73×10^{-4} and 1.20×10^{-4} mm/km², respectively, while evapotranspiration could potentially be increased by approximately 4.09×10^{-4} and 2.12×10^{-4} mm/km² when changing cultivated land to forest land and grassland, respectively (Figure 13b). The increasing benefits of the five measures on evapotranspiration were ranked as follows: changing cultivated land to forest land > changing cultivated land to grassland > building terraces on a 5–15° slope > building terraces on a 5–25° slope > building terraces on a 15–25° slope. These results were positively correlated with the reduction benefits of the five measures on discharge, surface runoff, and water yield. Therefore, vegetation measures have far greater water reduction efficacy than terrace-engineering measures.

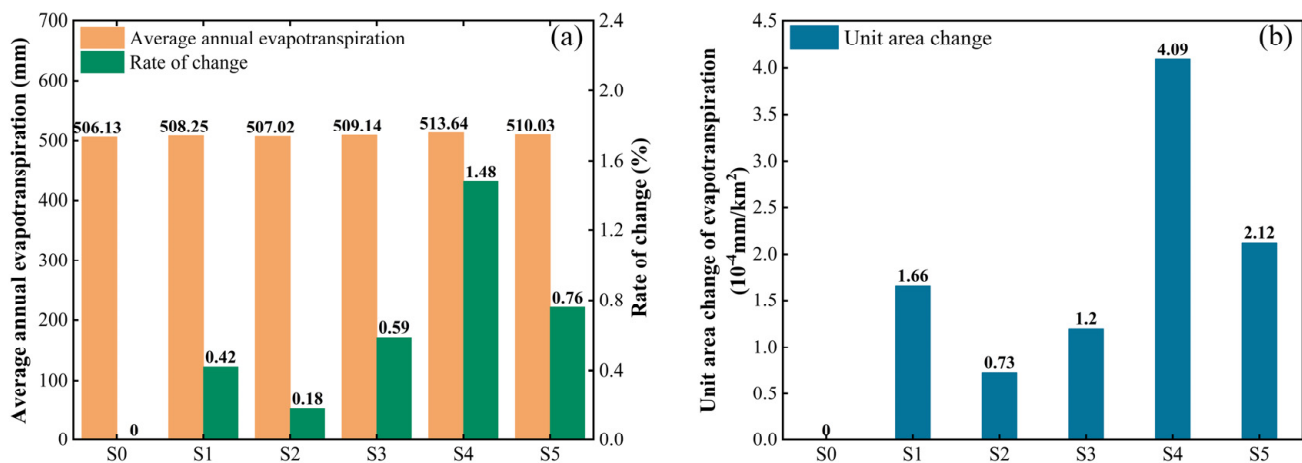


Figure 13. Analysis of the influence of SWCMs on the average annual evapotranspiration in the S1–S5 scenarios: (a) change rate of the average annual evapotranspiration, (b) unit area change of the average annual evapotranspiration.

Furthermore, to mitigate the water shortage caused by large-scale SWCMs, the Jing River catchment should comprehensively consider the water reduction efficacies of various SWCMs and optimise the adoption of measures such as building terraces and changing cultivated land to forest land or grassland. Thinning experiments can be conducted to appropriately reduce the degree of change from cultivated land to forest land and increase the benefits of changing cultivated land to grassland. Terraces can be constructed on gentle slopes to store and conserve water and reduce pressure on the water supply in downstream areas. Soil and water conservation management must also shift from small-

basin management to basin-wide coordination [4] to maintain the balance of water resources in the Jing River catchment as well as the sustainability of water resources in the Loess Plateau and Yellow River Basin as a whole.

5. Conclusions

This study established a SWAT model to quantitatively investigate the impact of climate change and human activities on runoff change, and to analyse the effects of different SWCMs on runoff reduction in the Jing River catchment. The main conclusions are as follows:

Runoff at the Zhangjiashan Hydrology Station changed abruptly in 1996. The monthly runoff series can be divided into a natural period (1972–1996) and a changing period (1997–2019). The contribution of runoff change was quantitatively analysed using the simulation method of the SWAT model. The results indicated that climate change contributed to 13.15% of the runoff increase, and human activities contributed to 86.85% of the runoff decline. Therefore, human activities were the primary reasons for runoff reduction.

The effects of different SWCMs on the outlet discharge, surface runoff, and water yield were analysed by simulating six scenarios. The unit area changes for building terraces on 5–15°, 15–25°, and 5–25° slopes, as well as changing cultivated land to forest land and grassland, reduced the average annual discharge by approximately 2.07×10^{-4} , 2.00×10^{-4} , 2.03×10^{-4} , 6.35×10^{-4} and 4.15×10^{-4} m³/s/km², respectively. The average annual surface runoff was reduced by approximately 3.88×10^{-4} , 1.95×10^{-4} , 2.94×10^{-4} , 8.61×10^{-4} and 6.39×10^{-4} mm/km², respectively. The average annual water yield was reduced by approximately 2.92×10^{-4} , 1.43×10^{-4} , 2.19×10^{-4} , 7.13×10^{-4} and 4.50×10^{-4} mm/km², respectively. The reduction benefits of the SWCMs on the discharge, surface runoff and water yield were ranked as follows: changing cultivated land to forest land > changing cultivated land to grassland > building terraces on a 5–15° slope > building terraces on a 5–25° slope > building terraces on a 15–25° slope.

This study discusses the degree of runoff reduction from each SWCM from the perspective of the watershed water cycle. In summary, the Jing River catchment should comprehensively consider the water reduction effects of different SWCMs and optimise the adoption of measures such as building terraces and changing cultivated land to forest land or grassland to mitigate the water shortage caused by large-scale SWCMs.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/land13040442/s1>, Table S1: Sensitivity analysis of parameters.

Author Contributions: Conceptualization, R.M.; methodology, X.L.; software, X.L.; formal analysis, X.L. and W.X.; investigation, J.S. resources, R.M.; data curation, J.S.; writing—original draft preparation, X.L.; writing—review and editing, R.M., J.G., A.S. and H.S.; supervision, J.S.; project administration, J.S.; funding acquisition, J.S. All authors have read and agreed to the published version of the manuscript.

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