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Impact of the Construction of Water Conservation Projects on Runoff from the Weigan River

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Abstract: In order to use water resources more efficiently, the construction of water conservation projects in dryland watersheds has changed the natural water cycle processes. This study used the SWAT (Soil and Water Assessment Tool) model coupled with the glacier module to simulate the hydrological processes in the upper reaches of the Weigan River estuary from 1965 to 1991, to restore and quantitatively evaluate the conditions of the estuarine runoff in the no-reservoir scenario, and to analyse the impact of the construction of water conservation projects on the estuarine runoff based on this model. The results show that the SWAT model has good applicability in the study area, with 41.45% and 58.55% of the increase in runoff due to increased precipitation and temperature, respectively, over the 52 years study period. The degree of influence of the construction of water conservation projects on runoff from the mountain in different seasons was spring > autumn > winter > summer, with 83.28% of the spring runoff being influenced by artificial regulation. The construction of water conservation projects has alleviated water shortage problems to a certain extent, and is an effective measure for achieving the efficient allocation of water resources in arid areas.

Keywords: human activities; water conservation construction; SWAT model; runoff configuration; glacial runoff simulation; Weigan River Basin

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1. Introduction

The study of the impact of human activities on the natural water cycle is a hot topic in current research [1–3]. Natural and anthropogenic factors are two major drivers of the water cycle in a basin. The natural factors are mainly reflected in changes in vertical water circulation due to climate change and changes in the spatial and temporal distribution of water resources in the horizontal direction. Anthropogenic factors mainly include changes in the basin substrate conditions due to human activities and the exploitation of water resources by humans [4]. In recent years, with the continuous social and economic progress and development, the demand for water resources for population growth, industrial, agricultural, and urban development has increased significantly [5,6]. The increasing human activities and exploitation of water resources have led to various forms of anthropogenic disturbances in the rivers, resulting in changes in the driving conditions and influencing factors of natural hydrological processes in the basin, which have a significant impact on water cycle processes [7].

This research area has received increasing attention from scholars around the world in recent years [8]. For example, Chawla et al. [9] used the VIC model to simulate the hydrological processes in the upper Ganges River Basin in India to analyse the effects of land use and climate change on runoff. Moldir Rakhimova et al. [10] assessed the impact of climate change and human activities on runoff from the Buktirma River Basin in Kazakhstan using various methods such as the climate elasticity method and circulation models. Lei Hou et al. [11] quantitatively assessed the impact of climate change and human activities on runoff changes in the upper reaches of the Yongding River Basin based on the Budyko hypothesis of the climate elasticity approach. Jinping Liu [12], Hongguang Chen [13], Jianyu Liu [14], and other scholars used hydrological models and other methods to analyse the contribution of climate change and human activities to runoff changes in different time periods; the results showed that the contribution of climate change and human activities to runoff varied greatly in different river sections and time periods, and the dominant factors affecting runoff changes were not the same. Lei Wang et al. [15] established a SWAT hydrological model of the Qingshui River Basin in Zhangjiakou and quantitatively analysed the impact of land use scenario changes on runoff in the study area. Cai Ren [16] and Zubaida Muyibul [17] used the SWAT model to simulate the runoff processes in the Yarkant River basin and Urumqi River basin, and quantitatively analysed the degree of influence of climate and subsurface changes on runoff; their studies concluded that the degree of influence of climate change on runoff was greater than that of subsurface changes (i.e., human activities). The research method to investigate the influence of basin water cycle drivers on runoff is more mature; the research conclusion can guide the actual production.

Most of the current studies on water cycle influences are limited to climate change and land use changes on the water cycle [18]. However, research on the impact of human exploitation of water resources in watersheds is less well documented, especially in arid zones. The construction of hydraulic projects, as the main component of human activities in water resource exploitation, refers to the human modification of the substratum structure in a strict sense [19], and also changes the distribution process of water resources in space and time, which, in turn, affects the water cycle processes in basins. As research progresses, scholars have found that the impact of water conservation construction on runoff has changed the original water cycle process in basins; however, how to quantify this impact needs further in-depth study.

In this study, we selected the upper reaches of the Weigan River outlet as the study area. A SWAT distributed hydrological model with a coupled glacier module was constructed to simulate the monthly runoff processes in the study area from 1965 to 1991 (27 years). The study area was investigated for the overall runoff evolution in the last 52 years, and the components of the runoff from the Weigan River were traced, while runoff from the study area from 1992 to 2016 (25 years) without the reservoir was predicted, and the impact of the construction of the Kizil Reservoir on the runoff from the Weigan River was subsequently analysed. This study can provide more comprehensive decision support for the sustainable development, use, and management of regional water resources.

2. Data Sources and Methods

2.1. Overview of the Study Area

The upstream area of the Weigan River outlet (Figure 1) is located in the Baicheng Basin in the Aksu region of Xinjiang, connected to the middle of the southern foothills of the Tianshan Mountains in the north and adjacent to the Queletage Mountains in the south, with a geographical location between 80°15′~83°02′ E and 41°31′~42°39′ N, covering an area of 16,792.56 km^2. The overall topography of the study area slopes from northwest to southeast, with elevations ranging from 1100 to 6778 m. The Weigan River is a typical dry inland glacial snowmelt recharge river. According to the Glacier Catalogue of China, 853 glaciers with a total area of 1783.86 km^2 are distributed in the upper headwater area of the Weigan River, and the river runoff exhibits clear seasonal changes due to the influence of glacial meltwater [20]. The five tributaries (Muzati River, Kapuslang River, Tylervichuk River, Karasu River, and Heizi River) in the area are distributed in the shape of a comb, and each tributary flows from north to south and from west to east, along the southern edge of the Baicheng Basin to the southeast corner of the basin near the Kizil Thousand Buddha Cave [21]. Here, it is called the Weigan River after gathering out of the mountains and passing southward through the southern edge of the basin in the Queletage Mountains [22], and finally flowing to the northern edge of the Tarim Basin through the Weigan River Canyon. Before the construction of the Kizil Reservoir, the hydrological station of the Kizil Reservoir was located 3 km above the dam site of the Kizil Reservoir. In 1985, construction officially started on the Kizil Reservoir; the hydrological station of Heizi Reservoir was moved down to 1 km below the cross-section of the dam site and named Heizi Reservoir (II) Station. In August 1991, the main project of the reservoir was completed and water storage operations began. The Kizil Reservoir de-risking and strengthening project started in 2009, and the highest reservoir storage level has gradually transitioned to the designed storage level of 1149.57 m after de-risking and strengthening [23], which has greatly reduced the flood control pressure in the downstream cities and counties of Kuche, Xinhe, and Shaya [24].

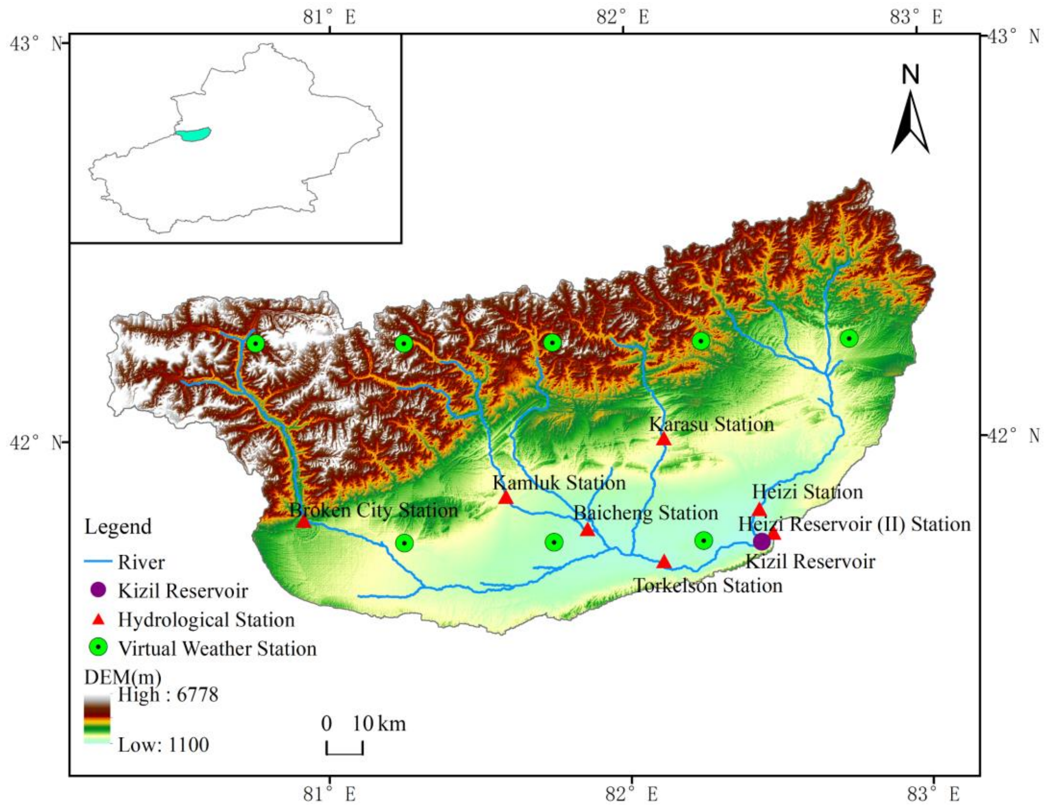

Figure 1. Overview of the area upstream of the Weigan River outlet.

2.2. Data Sources

The basic data used in this study included digital elevation model (DEM) data, glacier cataloguing data, soil data, land use data, and meteorological data. Among them, the DEM data were obtained from the Geospatial Data Cloud, and original SRTMDEM elevation data with a resolution of 90 m were used. The glacier cataloguing data were obtained from the National Cryosphere Desert Data Center, including the first glacier cataloguing data produced from aerial topographic maps from 1987 to 2004 [25] and the second glacier cataloguing data extracted from Landsat TM/ETM+ and ASTER remote sensing images from 2006 to 2013 [26]. In this study, the initial glacier inventory data were applied to the model calibration period (1965–1978) and validation period (1979–1991), and the secondary glacier inventory data were applied to the model prediction period (1992–2016). Soil data were obtained from the 1:1 million soil data provided by the Second National Land Survey of Institute of Soil Science, Chinese Academy of Sciences. The land use data were obtained from the national land use datasets of 1980 and 2000 with a resolution of 30 m provided by the Geospatial Data Cloud. The glacial snow land use types in the 1980 and 2000 land use datasets and the glacial soil types in the soil data were replaced with the glacial distribution in the first and second glacial cataloguing data, respectively. The hydrometeorological data were obtained from the China Meteorological Data Service Centre using the 0.5° × 0.5° grid point dataset (V2.0) of daily values of surface air temperature and precipitation in China. In this study, the time series of daily maximum temperature and daily minimum temperature with daily precipitation data from 1961 to 2016 were selected to drive the SWAT model simulation to restore the hydrological processes in the study area.

2.3. Research Methodology

2.3.1. Glacier Module Algorithm

The glacier module consists of three main modules: a glacier ablation algorithm, glacier area change, and the glacier accumulation rate [27]. Among them, the glacier ablation algorithm is mainly based on the modified temperature index method to simulate the glacier melting process [28,29], which corrects spatial heterogeneity with the influence of solar radiation factor and topography factor, and then uses the linear relationship between the ablation factor and temperature to finally find the amount of glacier melting. The calculation formulae are as follows:

$$M = \begin{cases} \left(F_M + R_{ice} I_{pot}\right) \times (T - T_{mlt,ice}), & T > T_{mlt,ice} \\ 0, & T \leq T_{mlt,ice} \end{cases} \quad (1)$$

where M is the daily-scale glacier ablation (mm), F_M is the glacier temperature ablation factor, R_{ice} is the glacier radiation ablation factor, I_{pot} is the potential direct solar radiation (W·m^{-2}), T is the daily-scale mean temperature (°C), and $T_{mlt,ice}$ is the temperature threshold reached at glacier ablation (°C).

$$V = cS^{\gamma} \quad (2)$$

where V is the glacier volume (m^3), S is the glacier surface area (m^2), c is a constant, and γ is a dimensionless scale factor.

$$F = W_s \times \beta_o \left\{1 + \sin\left[\frac{2\pi}{365}(t - 81)\right]\right\} \quad (3)$$

where F is the glacial material accumulation, W_s is the snow water equivalent, β_o is the base accumulation factor, and t is the ordinal number of a given day.

2.3.2. Hydrological Process Simulation and Evaluation of Results

(1) SWAT-based hydrological process simulation

The SWAT model is a distributed watershed hydrological model that uses the daily scale as the unit running step, and is based on the GIS platform to simulate and construct the hydrological cycle process under the changes in different influencing factors [30]. In the 1990s, the United States Department of Agriculture (USDA) Institute of Agriculture developed the SWAT model. Its predecessor is the SWRRB model, which is based on the integration of the features of CREAMS, EPIC, and GLEAMS [31], and has been continuously modified and developed to form the most representative distributed hydrological model [32,33] which can be used as a tool for large-scale watershed runoff simulation [34]. This study took the upper area of the Weigan River outlet as an example, and constructed a SWAT model to restore the hydrological processes in the study area before the reservoir had been built. The modelling process is mainly divided into the following steps.

First, the DEM data were imported, and the Heizi Reservoir (II) station was set as the basin outlet. By drawing up different discretization schemes with different catchment area thresholds, it was finally determined that the best runoff simulation was achieved when the catchment threshold was 300 km^2. The input DEM data were then subjected to operations such as water system extraction, watershed boundary depiction, sub-basin delineation, and parameter calculation to discretize the study watershed into 33 sub-basins. Second, the database of soil types, the land use database, and slope types of the Weigan River Basin established in advance were entered in turn. Notably, the period of 1965–1978 was selected as the model calibration period and the period of 1979–1991 was the validation period in this study. Among them, the first glacial inventory dataset and 1980 land use data were used in the calibration period intra model, and the second glacial inventory dataset and 2000 land use data were used in the validation period. Meanwhile, the glacial snow land use types in the land use data and the glacial soil types in the soil data were replaced with the glacial distribution in the first and second glacier cataloguing data, respectively. To reflect the differences in the hydrologic responses of different soil types, land uses, and slope combinations in the model, the SWAT model with 419 hydrologic response units (Hrus) was divided. Finally, the meteorological data required for the model operation and the prepared weather generator were imputed, and the model warm-up period was set to 1961–1964 to minimize the influence of the initial model conditions on the simulation results. Through the parameter sensitivity analysis, the more sensitive parameters (Table 1) were automatically or manually adjusted if necessary, until the model evaluation results met the simulation criteria to determine the model parameter, and complete model calibration and validation work.

Table 1. Results of parameter determination.

Parameter Module	Parameters	Definition	Scope	Optimum Value
Runoff	CN2	Initial SCS runoff curve number for moisture condition II	−0.2~0.2	0.0650
	SOL_AWC	Available water capacity of the first soil layer (mm·mm^{-1})	0~1	0.8250
	ESCO	Soil evaporation compensation factor	0~1	0.4450
	CH_K2	Effective hydraulic conductivity in the main channel alluvium (mm·h^{-1})	−0.01~500	13.8742
	ALPHA_BF	Baseflow alpha factor (days)	0~1	0.0167
	REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur (mm H_2O)	0~1000	79.5000
	GW_DELAY	Groundwater delay (days)	0~500	417.5000
	GWQMIN	Threshold depth of water in the shallow aquifer for return flow to occur (mm H_2O)	0~5000	103.0000
	GW_REVAP	Groundwater "revap" coefficient	0.02~0.2	0.0659
Snow	SFTMP	Snowfall temperature (°C)	−5~5	4.1150
	SMTMP	Snow melt base temperature (°C)	−5~5	4.5700
	SMFMX	Maximum melt rate for snow during the year (mm H_2O·°C^{-1}·day^{-1})	0~10	7.2500
	SMFMN	Minimum melt rate for snow during the year (mm H_2O·°C^{-1}·day^{-1})	0~10	1.4050
	TIMP	Snow pack temperature lag factor	0~1	0.0225
	TLAPS	Temperature lapse rate (°C·km^{-1})	−50~50	−8.7500
Glacier	B_{melt6}	Maximum melt rate for the glacier during the year (mm H_2O·°C^{-1}·day^{-1})	1.4~16	1.9000
	B_{melt12}	Minimum melt rate for the glacier during the year (mm H_2O·°C^{-1}·day^{-1})	1.4~16	2.8000
	gmlt_tmp	Glacier ablation threshold temperature (°C)	−5~5	1.0000

(2) Evaluation of simulation results

To verify the reliability of the model, the Nash–Sutcliffe efficiency coefficient (*NSE*), the ratio of the root mean square error to the standard deviation of the measured values (*RSR*), the percent bias (*PBIAS*), and the coefficient of determination (R^2) were selected to evaluate the model fitting effect in this study; the formulae are shown below:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{oi} - Q_{si})^2}{\sum_{i=1}^{n}(Q_{oi} - \overline{Q}_o)^2} \quad (4)$$

$$RSR = \frac{RMSE}{STDEV_o} = \frac{\sqrt{\sum_{i=1}^{n}(Q_{oi} - Q_{si})^2}}{\sqrt{\sum_{i=1}^{n}(Q_{oi} - \overline{Q}_o)^2}} \quad (5)$$

$$PBIAS = \sum_{i=1}^{n} \frac{Q_{si} - Q_{oi}}{Q_{oi}} \times 100 \quad (6)$$

$$R^2 = \frac{\left(\sum_{i=1}^{n}(Q_{oi} - \overline{Q}_o)(Q_{si} - \overline{Q}_s)\right)^2}{\sum_{i=1}^{n}\left(Q_{oi} - \overline{Q}_o\right)^2 \sum_{i=1}^{n}\left(Q_{si} - \overline{Q}_s\right)^2} \tag{7}$$

where Q_{si} denotes the model simulated runoff, m^3, and Q_{oi} denotes the actual observed runoff, m^3.

The *NSE* indicates the degree of fit between the simulated and measured values, with a range from $-\infty$ to 1. The closer to 1, the better the simulation. *RSR* standardizes the standard deviation of the measured values, and the closer to 0, the better the simulation. *PBIAS* reflects the cumulative deviation between simulated and measured values. A *PBIAS* value greater than 0 indicates that the model underestimates the deviation of measured values, a value less than 0 indicates that the model overestimates the deviation of measured values, and a *PBIAS* value equal to 0 is the optimal value, indicating that the model simulation is accurate. R^2 indicates the degree of linear correlation between simulated and measured values, and the closer it is to 1, the better the simulation effect is, but the response to the overall deviation of high or low simulated values is not very obvious. The model simulation results are generally accepted when $NSE > 0.5$, $RSR \leq 0.7$, and $PBIAS < \pm 25\%$, and the model simulation results are excellent when $NSE > 0.75$, $RSR \leq 0.5$, and $PBIAS < \pm 10\%$.

2.3.3. The Process of Predicting Natural Mountain Runoff and its Response to the Construction of Water Conservation Projects

Since the Kizil Reservoir started to lower its gates for storage in August 1991, it has caused the flow measured at the Heizi Reservoir (II) station, which is not far downstream, to change from natural flow to artificial regulated flow. Therefore, 1992 was taken as the dividing point between natural flow and artificial regulated flow in this study. In this study, we selected 1992–2016 as the model prediction period, based on the constructed and validated reliable SWAT model with the required input data, to predict the natural outflow runoff in the reduced study area without human activities, and to explore the response of the Weigan River outflow runoff to human activities from seasonal-scale and monthly scale comparisons. In recent years, the area of arable land within the study region (Baicheng County) has grown rapidly (Figure 2), with a 29.0% increase during the 30 years period from 1990 to 2020 (1348 km^2 in 2020); arable water use in Baicheng County increased from 6.89×10^8 m^3 to 8.86×10^8 m^3 from 2000 to 2020. However, the actual measured runoff into the Kizil Reservoir did not decrease (Table 2): the multi-year (1961–2000) average runoff (27.37×10^8 m^3) of the five tributaries in the area was basically consistent with the multi-year average runoff into the Kizil Reservoir of 27.10×10^8 m^3 in this study, indicating the existence of a more complex and special water cycle relationship in Baicheng County. Therefore, this study only considered the impact of human activities on runoff from the Weigan River outflow from the perspective of the construction of water conservation projects. The overall research process approach is shown in Figure 3.

Table 2. Major river conditions in the study area.

River	Hydrological Station	Measured Annual Runoff (10^8 m^3)
Muzati River	Broken City Station	14.66
Kapuslang River	Kamluk Station	6.65
Tylervichuk River	Baicheng Station	0.80
Karasu River	Karasu Station	2.19
Heizi River	Heizi Station	3.08
Total		27.37

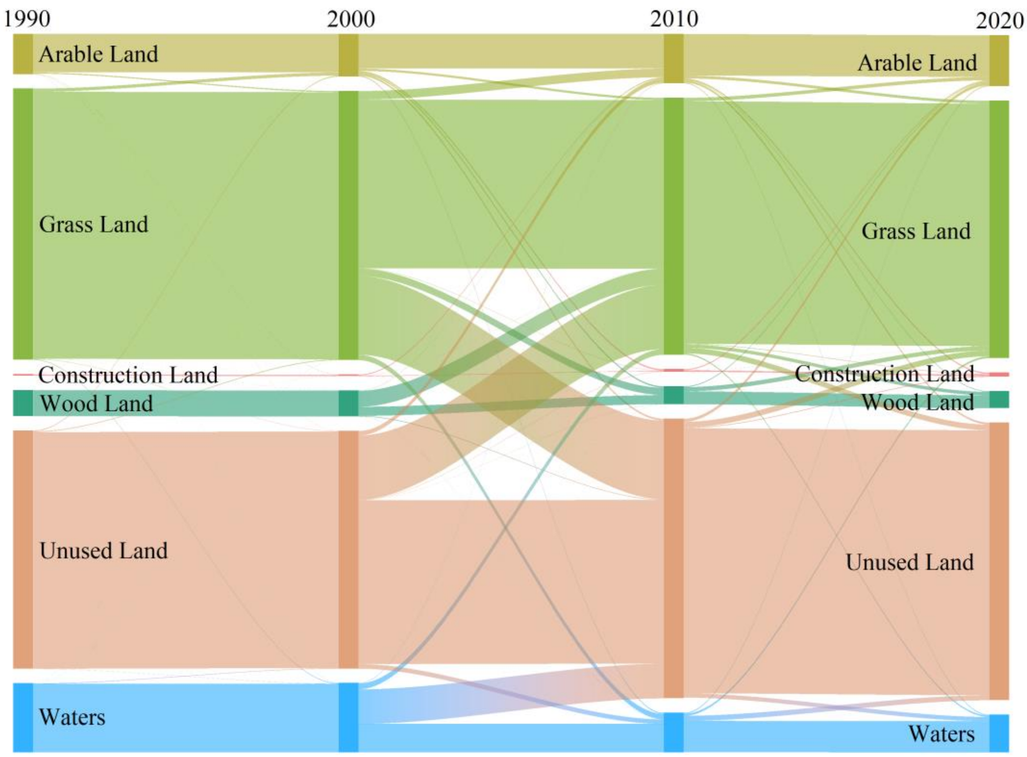

Figure 2. Land use status and interannual transfer changes in the upper reaches of the mountain pass of Weigan River from 1990 to 2020 based on remote sensing.

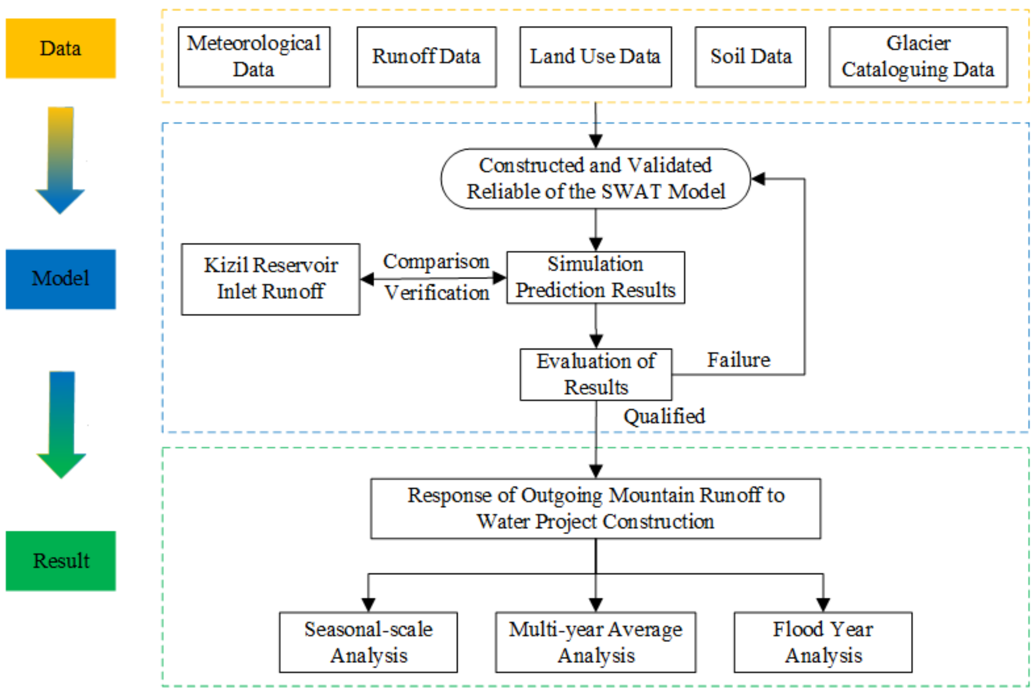

Figure 3. Flow chart of the study on the prediction of natural mountain runoff and its response to the construction of water conservation projects.

3. Results and Analysis

3.1. Simulation Prediction Results and Evaluation Analysis

First, monthly runoff data from 1965 to 1991 at the Heizi Reservoir hydrological station were selected to calibrate and validate the SWAT model for the upstream area of the Weigan

River outlet. The simulation results of the model calibration period and validation period are shown in Figure 4a; the simulation results with the glacier module added were better than those without the glacier module, so the glacier module was included in the simulation when reverting the prediction of the runoff from the Weigan River outlet without human activities. The simulated values with the glacier module are in good agreement with the measured values at the Heizi Reservoir hydrological station during the flat and dry periods of 1965–1991. Except for 1971, 1979, 1983, and 1986, when the simulated values of the glacier module were lower than the measured values in the same period, and 1973, 1974, 1977, 1980, and 1981, when the simulated values of the glacier module were higher than the measured values in the same period, the overall fit was good in the other years. The simulation results of the calibration period and validation period were evaluated, and the simulation results were evaluated with reference to the model evaluation criteria (Table 3). The evaluation of the simulation results of the Heizi reservoir hydrological station in the calibration period and the validation period were excellent, and the simulation effect was good, which showed that the model could accurately reflect the runoff process of the Weigan River from the mountain.

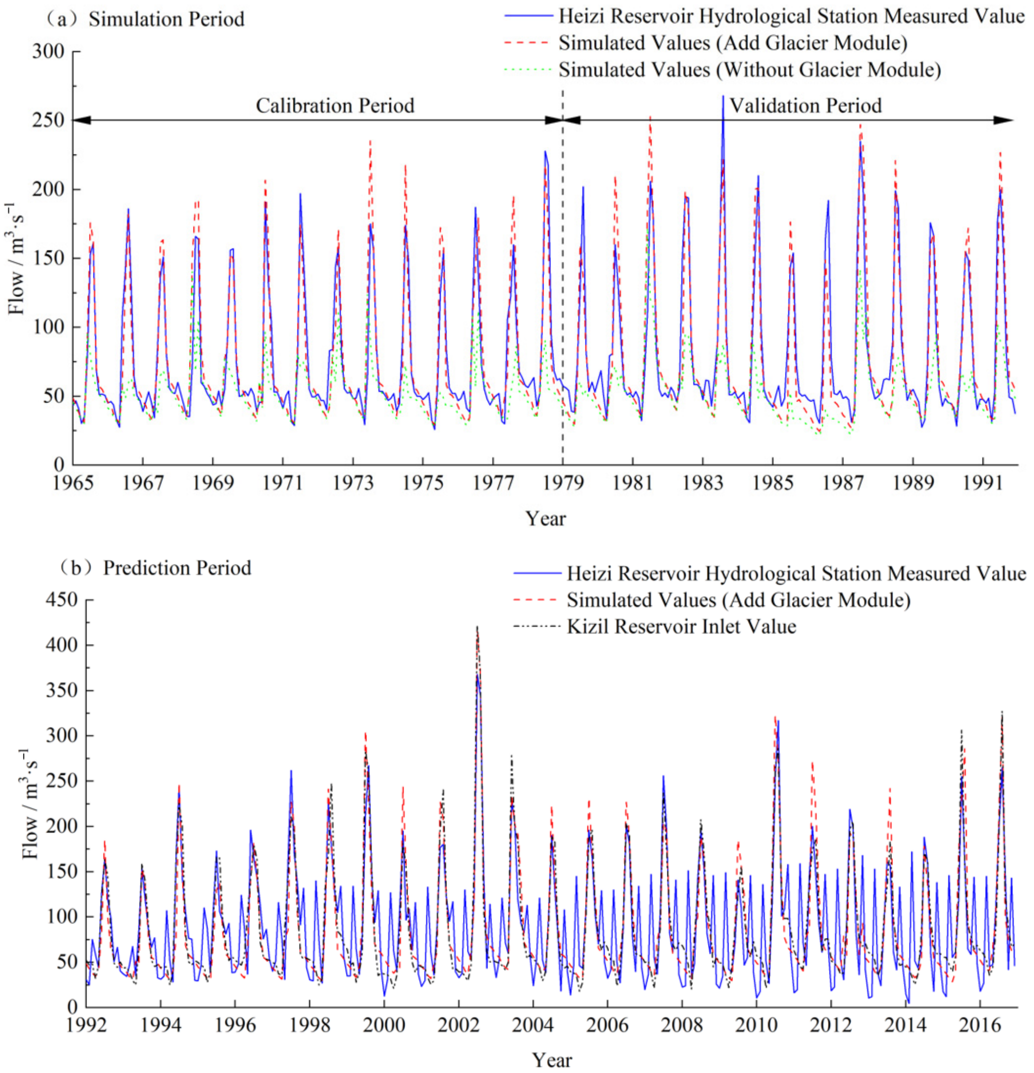

Figure 4. Simulation (**a**) and prediction (**b**) results of monthly average flow of SWAT model, 1965–2016.

Table 3. Evaluation of monthly scale runoff simulation results in the upstream area of the Weigan River outlet.

Station Name	Time Period	Scenario	NSE	RSR	PBIAS (%)	R^2	Simulation Results
Heizi Reservoir Hydrological Station	Calibration Period (1 January 1965–31 December 1978)	No Glacier Module	0.08	0.96	29.54	0.35	Unqualified
		Glacier Module	0.84	0.40	−0.16	0.86	Excellent
	Validation Period (1 January 1979–31 December 1991)	No Glacier Module	0.09	0.96	34.02	0.39	Unqualified
		Glacier Module	0.82	0.42	2.90	0.85	Excellent
	Prediction Period (1 January 1992–31 December 2016)	Glacier Module	0.88	0.34	1.11	0.89	Excellent

Based on the SWAT model that was constructed and verified to be reliable, combined with the input data from 1992 to 2016, the natural mountain runoff in the study area from 1992 to 2016 under no human activity conditions was obtained. The measured flow at Heizi Reservoir (II) station has been influenced by the artificially regulated storage and release of water from the reservoir since 1992; therefore, the predicted runoff from the mountain without human activities from 1992 to 2016 was compared with the runoff into the Kizil Reservoir during the same period (Figure 4b). The results show that the relative errors between the two are small, except for the floods in 2000, 2011, and 2013, when the model simulation results were larger than the incoming flow of Kizil reservoir in the same period. At the same time, in 2002, 2010, and 2016, when floods in the study area broke out and the incoming water from the upper reaches increased compared with the other years, the flow predicted by the model simulation for the same period was also closer to the actual situation. The simulation results of the model in the prediction period are presented in Table 3, in which R^2 reached 0.89 and NSE was 0.88, the model simulation prediction results are excellent, and the simulation effect is good. The model had considerable reliability in predicting the hydrological process in the mountain area before the reservoir was built in the restored study area, and could more realistically reflect the runoff from the mountain when there was no human activity in the study area.

3.2. Portrayal and Analysis of the Weigan River Outflow Runoff Group Structure

From the actual measured runoff at the Heizi reservoir hydrological station (Figure 5a), it can be seen that the multi-year average runoff from the Weigan River from 1965 to 2016 was 26.63×10^8 m^3, of which the multi-year average glacial runoff was 8.17×10^8 m^3, accounting for 32.40% of the total runoff from the mountain. The actual measured month-by-month runoff from the Heizi reservoir hydrological station from 1965 to 2016 showed an overall increasing trend, increasing from 21.41×10^8 m^3 in 1965 to 32.47×10^8 m^3 in 2016, at a rate of approximately 2.1×10^8 m^3/10a, an increase of 51.66% compared to 1965. This indicated that the water inflow from the outlet of the Weigan River showed a significant increasing trend in the last 52 years, which has, to a certain extent, relieved the water stress in the middle and lower reaches of the Weigan River and the irrigation area. Separating the simulation results of the outflow from the mountains showed that glacier runoff increased from 6.15×10^8 m^3 in 1965 to 8.77×10^8 m^3 in 2016, an increase of 2.62×10^8 m^3 or 42.60% over 1965, with an increase rate of about 0.5×10^8 m^3/10a, and the contribution of glacier runoff fluctuated from 27.09% in 1965 to 28.49% in 2016, which was as high as 44.84% in 2008.

From the annual runoff simulation results (Figure 5a), it can be seen that the overall trends in the simulated and measured values were generally the same during the simulation period, except for 1985 and 1986, when the simulated values were lower than the measured values at the Heizi reservoir hydrological station. In the prediction, although the simulated values without human activities were consistent with the overall runoff trend in the measured values, the model simulated runoff from 1994 to 2001 was lower than the measured runoff by 4.91×10^8 m^3 per year. If the simulated runoff without human activities was compared with the incoming runoff from the Kizil Reservoir, the average annual deviation between the two was only 1.21×10^8 m^3, and the relative error did not exceed 5%. This indicates that the runoff from the mountain without human activities predicted in this study had a high degree of confidence. Meanwhile, comparing the runoff from the Weigan River before and after the presence of human activities, the annual average increase in incoming water from 1992 to 2016 compared with 1965 to 1991 was 2.99 × 10^8 m^3, and the quantitative separation showed that the increase in runoff caused by precipitation was 1.24 × 10^8 m^3, accounting for 41.45% of the increase in incoming water; the increase in runoff due to glacial melt caused by temperature rise was 1.75 × 10^8 m^3, accounting for 58.55%. This shows that under global climate change conditions, the increase in runoff due to temperature rise was predominant in the study area.

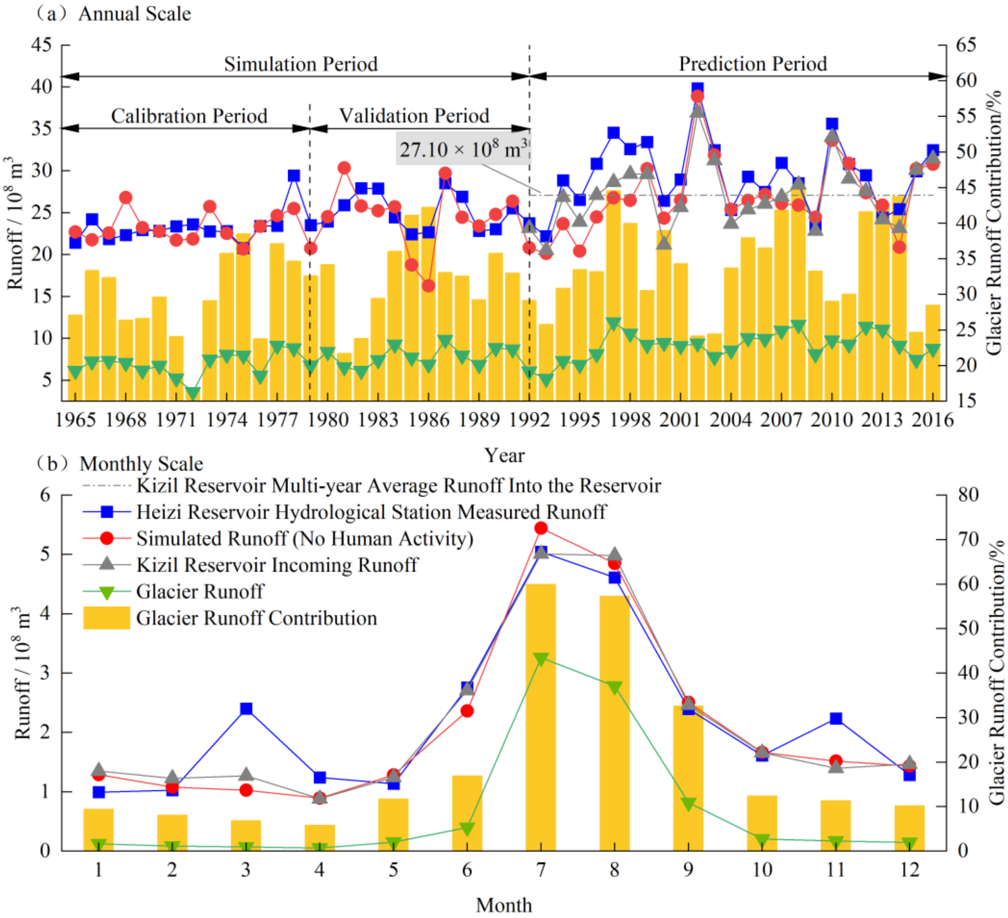

Figure 5. Annual scale (**a**) and monthly scale (**b**) simulation predictions of mountain runoff and glacier runoff contributions.

From the monthly scale analysis (Figure 5b), the hydrological processes in the study area mainly occurred in June, July, August, and September. According to the actual measured values at the hydrological station of the Heizi Reservoir, the flow production in June to September accounted for 55.39% of the annual flow production. The glacier flow production mainly occurred in July, August, and September, accounting for 82.98% of the annual glacier runoff. Comparing the simulated results of runoff from the mountain without human activity with the inlet runoff of the Kizil Reservoir, the simulated values were closer to the natural runoff values in the remaining months except for February, March, and June, when the simulated runoff was slightly lower than the inlet runoff of the Kizil Reservoir, and July and November, when the simulated runoff was slightly higher than the inlet runoff of Kizil Reservoir; the overall trends in the two curves were basically the same.

3.3. Impacts of the Construction of Water Projects on Runoff from the Mountains

The measured data from the Heizi reservoir hydrological station showed an increasing trend in runoff from the upper reaches of the Weigan River from 1965 to 2016 in spring, summer, and autumn, and a decreasing trend in winter. The Weigan River outflow runoff was mainly concentrated in summer, and according to the simulation results of the natural outflow runoff, incoming water in the summer accounted for 51.06% of the annual accumulation of water. The response of the runoff from the Weigan River to the artificial regulation of reservoir storage was analysed by comparing the measured and model simulated predictions from 1992 to 2016 at the Heizi Reservoir (II) station (Figure 6). The cut-off year between natural runoff and runoff influenced by artificial regulation was 1992, and the simulated natural runoff in summer and spring was greater than the measured runoff influenced by artificial regulation after the reservoir began storing water. The analysis shows that, under the influence of artificial regulation, the multi-year average runoff values in summer and winter were 0.15×10^8 m^3 and 0.41×10^8 m^3 greater than the simulated natural runoff, accounting for 3.33% and 7.08% of the natural runoff in summer and winter, respectively. However, comparing the simulated natural runoff in spring and autumn with the measured runoff affected by the artificial adjustment, we found that the simulated natural runoff in spring and autumn was lower than the measured runoff affected by the artificial adjustment, and the natural outflow in spring and autumn was increased by an additional 0.92×10^8 m^3 and 0.49×10^8 m^3, respectively, after the artificial adjustment, which accounted for 83.28% and 24.36% of the natural outflow in spring and autumn, respectively. This shows that the degree of impact of the construction of the water conservation project on natural runoff in spring and autumn was greater than its impact on natural runoff in summer and winter.

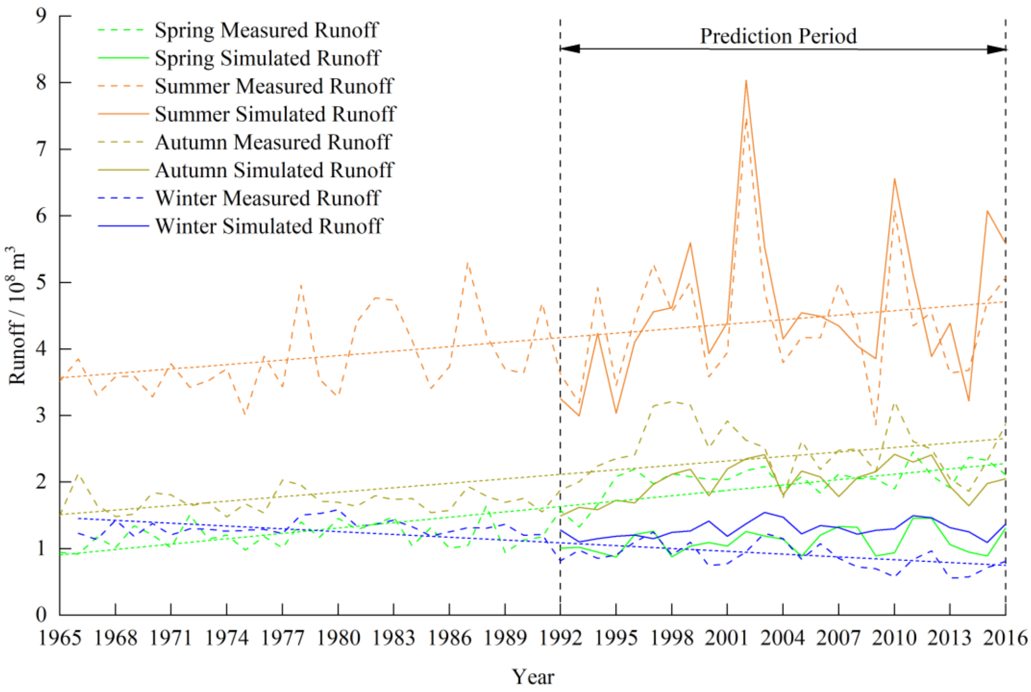

Figure 6. Seasonal-scale comparison of measured and simulated runoff at the outlet of the Weigan River.

To further analyse the impact of the construction of water projects on the intra-annual distribution of runoff, the simulated runoff was compared to the measured runoff at Heizi Reservoir (II) station (Figure 7a). It can be seen that the simulated values in March and November were significantly lower than the measured runoff values, while the simulated runoff in the rest of the months exhibited less deviation from the measured runoff, and the overall trend was basically the same. The reason for this is that in August 1991, the Kizil Reservoir started to store water, and the artificial storage of the reservoir, such as storage at the end of the flood and replenishment during the dry period, made the actual measured runoff in March and November at the Heizi Reservoir (II) station higher than the incoming runoff from the Kizil Reservoir. The flood season of water coming from the outlet of the Weigan River also increased from July and August to March, July, August, and November, solving the problem of insufficient spring irrigation in March and pressurized saltwater resources for winter irrigation in November for the irrigation areas downstream of the Weigan River. At the same time, an average of 2.74 × 10^8 m^3 more water was impounded annually, and 5.28 × 10^8 m^3 more water was regulated across seasons through storage than before the reservoir was built. Since the reservoir was built and started storing water, the Kizil Reservoir has held the equivalent of a 10-year flood 13 times, the equivalent of a 40-year flood once ("1 August 2016" flood peak flow 3420 $m^3 \cdot s^{-1}$ [35]), and the equivalent of a 100-year flood twice ("23 July 2002" flood peak flow 3677 $m^3 \cdot s^{-1}$ [21] and "29 July 2010" flood peak flow 3360 $m^3 \cdot s^{-1}$ [36]). After the construction of the reservoir, the actual measured runoff from the Heizi Reservoir (II) station, compared with the simulated runoff values without human activities (Figure 7b–d), the temporal distribution of water resources increased by an additional 0.92 × 10^8 m^3, 2.04 × 10^8 m^3, and 1.62 × 10^8 m^3 of water in 2002, 2010, and 2016, respectively, which strongly alleviated the problem of the uneven temporal distribution of water resources.

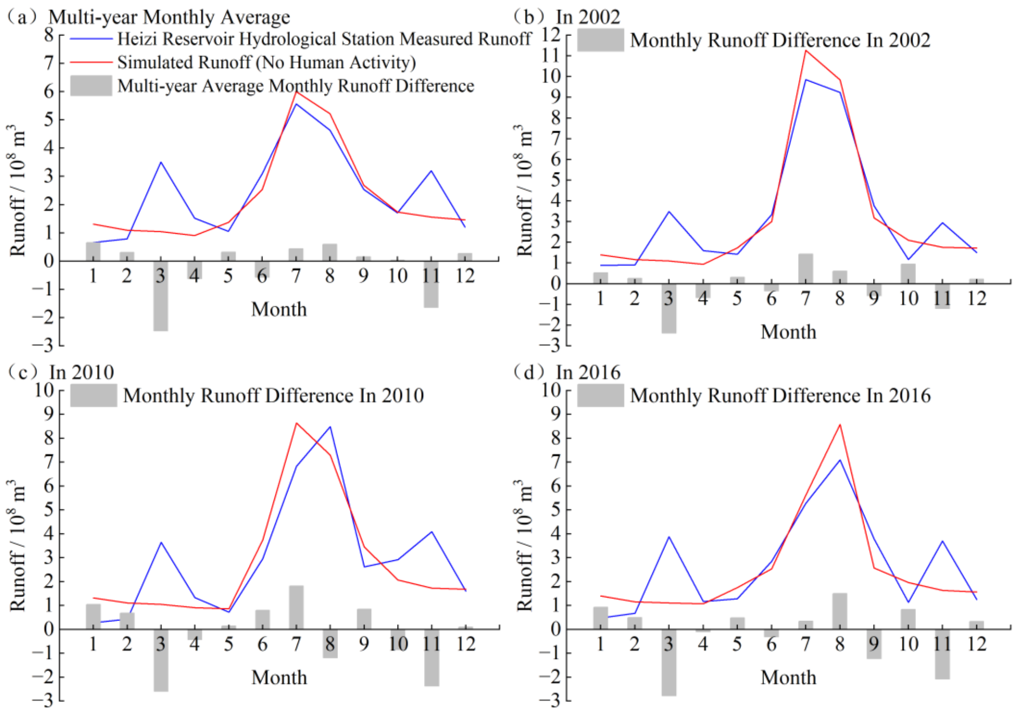

Figure 7. Comparison of monthly measured and simulated runoff for multi-year average (**a**), 2002 (**b**), 2010 (**c**), and 2016 (**d**).

4. Discussion

4.1. Model Applicability and Simulation Results

In this study, the SWAT model with a coupled glacier module was used to simulate the mountain runoff in the Weigan River Basin from 1965 to 1978 (calibration period) and from 1979 to 1991 (validation period). NSE coefficients of 0.84 and 0.82 were achieved in the simulation evaluation results; the simulated values fit the measured runoff curves relatively well, and the relative error was small. Therefore, the model can not only simulate the restoration of the outflow runoff process in the study area without reservoir construction more accurately, but also predict the restoration of the natural outflow runoff in the study area without human activities from 1992 to 2016 based on the model. This study compared the model prediction results with the NSE coefficient of 0.88 for the prediction period using the runoff from the Kizil Reservoir in the same period instead of the runoff measured at the Heizi Reservoir (II) station without the influence of artificial regulation. This shows that the SWAT model has good applicability in the area upstream of the Weigan River outlet and can be further used for the study of related problems.

The multi-year average runoff of the Weigan River outflow from 1965 to 2016 was 26.63×10^8 m^3, with an overall upward trend. Its increase rate was approximately 2.1×10^8 m^3/10a, which is closer to the increase in runoff from the Weigan River Basin from 1960 to 2013 (1.8×10^8 m^3/10a) calculated by Peng Qin [37]. During the 52 years, the glacial runoff of the upper Weigan River Basin showed a fluctuating yet stable upward trend, with an average multi-year glacier runoff of 8.17×10^8 m^3, accounting for 32.40% of the total runoff from the mountain, similar to the results of Minxia Ni (30.8%) [38]. The result of 51.06% of the annual incoming water in summer in this study is more consistent with the range of 50~70% evident in the statistics of Jianjun Duan [39] and others, and the calculation results of Peng Qin [37] and others (56%). The simulated reduced runoff in this paper better reflects the actual runoff process in the study area, and also showed that the model has some reliability.

4.2. Analysis of the Response of Outgoing Mountain Runoff to the Construction of Water Conservation Projects

In a related study of the Kizil Reservoir, Mingwang Zhang [40] analysed the effects of precipitation and human activities on factors such as runoff from the perspective of water and sedimentary sequences, using methods such as double accumulation curves. However, this study was an analysis of the relationship between the response of runoff from the Kizil Reservoir to the construction of the water project from the perspective of artificial storage in the Kizil Reservoir. The construction of the Kizil Reservoir has expanded the flood season of water coming from upstream of the study area from July and August to March, July, August, and November. During the runoff discharge process, 2.74×10^8 m^3 more water was stored each year, and 5.28×10^8 m^3 more water was released in the time distribution of water resources than before the reservoir was built. Notably, there are many irrigation areas around the Kizil Reservoir, and the irrigation return water produced by watering the irrigation areas will be delayed, which makes the measured runoff of the Heizi Reservoir (II) station larger than the simulated natural runoff. At the same time, the degree of impact of the construction of water conservation projects on runoff from the mountain varied from season to season (in descending order, spring > autumn > winter > summer), where the proportion of natural runoff affected by artificial regulation in spring was as high as 83.28%. The construction of water conservation projects has, to a certain extent, regulated the distribution of runoff from the mountain over time, alleviating the problem of insufficient water resources for downstream irrigation areas and ecological inter-seasonal diversion, spring irrigation salt washing, and autumn irrigation overwintering.

4.3. Shortcomings of this Study

The response of outgoing mountain runoff to human activities in this study was explored and analysed based on the SWAT distributed hydrological model. However, the existing hydrological model is only a general description of the water cycle process [41], which cannot fully and objectively restore the real hydrological situation. This conclusion was also reached by Zhenliang Yin et al. [42] in their discussion of the progress of hydrological simulation studies in the mountainous region of the main stream of the Heihe River in the Qilian Mountains. At the same time, because the outgoing runoff at the Heizi Reservoir (II) station before the reservoir was constructed could not actually be measured, the incoming runoff from the Kizil Reservoir during the same period was used for the evaluation of the simulation results of the outgoing runoff under no human activity conditions during the prediction period. Although the distance between the Heizi Reservoir (II) station and Kizil Reservoir is not far, it cannot be denied that the errors between the two caused by seepage losses in the runoff process, as well as reservoir seepage and surface evaporation, still exist. This aspect should be studied in more depth in future simulations to provide a reference for watershed water resource management.

5. Conclusions

In order to make more efficient use of water resources, water conservation projects are constructed in arid watersheds. This study considered the impact of human activities on the runoff from the Weigan River from the perspective of water conservation construction, and thus explored the extent to which water conservation projects affect natural water cycle processes. In this study, the SWAT model was used to simulate and predict runoff for the 1965–2016 scenario without a reservoir in the upstream area of the Weigan River outlet, and then analysed the component composition of runoff from the study area, and compared and explored the degree of influence of the presence or absence of human activities on the runoff from the study area to obtain the following conclusions:

(1) The SWAT model with the coupled glacier module was used to simulate the outflow runoff from 1965 to 1991 in the Weigan River Basin, and to predict natural runoff in the study area without human activities from 1992 to 2016 based on the constructed SWAT model predictions; its NSE coefficients all reached above 0.8. This shows that the SWAT model with a coupled glacier module has good applicability in the upper Weigan River Basin and can be further used for studies of glacial-runoff-related problems in arid zones.

(2) During the 52 years from 1965 to 2016, the overall runoff volume from the Weigan River showed an increasing trend, among which glacial runoff exhibited a stable increasing trend, and runoff due to precipitation also exhibited a fluctuating increasing trend. The average value of the increase in incoming water from 1992 to 2016 compared with 1965 to 1991 was 2.99×10^8 m^3, with 41.45% and 58.55% of the increase in incoming water was caused by the increases in precipitation and temperature, respectively.

(3) The runoff from the Weigan River is mainly concentrated in summer, with 51.06% of the annual water intake in summer. The construction of hydraulic projects has translated to human activities having a very different impact on the runoff from the mountain in different seasons (in descending order spring > autumn > winter > summer), with 83.28% of the natural runoff in spring being influenced by artificial regulation.

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