Variation characteristics of hydrological response to water conservancy construction in the Qinhe River Basin of the Loess Plateau, China

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Abstract

Investigating the response characteristics of various hydrological factors to the construction of water conservancy projects and evaluating their impact on the ecological environment is crucial for ecological protection and restoration in the Loess Plateau, China with a complex environment. In this study, we employed a geomorphology-based hydrological model to simulate the hydrological elements of the Qinhe River Basin in the Loess Plateau. Additionally, we explored the response characteristics of the water cycle and hydrological processes to the construction of reservoirs in the basin. We also examined multiyear changes in peak flood volume and sediment discharge during flood seasons influenced by reservoirs. A thorough evaluation of the simulation results indicated their reliability. The sub-basins hosting reservoirs initially showed an increase in evaporation, followed by a decrease. During the change periods, both runoff and soil water decreased, but remained higher than the mean values for the basin during the same period. The Normalized Difference Vegetation Index of sub-basins associated with five reservoirs was significantly higher than the mean value for the basin during the same period. The peak flood volume and sediment discharge in the basin were characterized by decreasing trends, with the latter showing weak sustainability. The value of each index for a sub-basin associated with a reservoir was higher than the average value for the basin. The construction and operation of reservoirs had a positive impact on the ecology of the basin. Water and soil conservation measures, including sediment regulation and storage using reservoirs, significantly decreased water-related disasters and soil erosion in the basin. This study provides a scientific basis for the design of water conservancy projects and ecological governance in the basin.

Hydrological Processes

1. INTRODUCTION

Owing to the continuous growth of the human population, social productivity demands associated with development are rapidly increasing in many countries (Liu and Diamond, 2005). However, demands for the protection of water resources and ecological environments restrict development (Bian et al., 2022; Jiang et al., 2022). Water conservancy projects are essential for flood control, water storage, sediment retention, and enhancement of agricultural production. The interference of human activities on the ecological environments have been gradually amplified (Zeng et al., 2022; Zhu et al., 2017). Such projects enhance production and the standard of living in many regions. However, they also impact hydrological processes and damage nature in associated basins (Xu et al., 2022). For example, regardless of its benefits, flood control, directly or indirectly affects the natural water cycle and causes ecological changes in basins (Ding et al., 2020; Du et al., 2019).

Previous studies on water conservancy projects focused on the hydrological response to changes in runoff and impacts on the water ecological environment (Sun et al., 2019; Wu et al., 2019). For example, Assani et al. (2011) showed that changes associated with a water conservancy project on runoff in a basin differed from those caused by climate change. These obvious differences indicate that a water conservancy project represents an in–dependent factor that controls runoff changes in a basin. Based on several models, Callow and Smettem (2009) indicated that the construction of small water diversion embankments and collection infrastructures significantly impacted runoff changes in areas of major agricultural activities in Italy. Schreider et al. (2009) investigated 12 basins, including that of the Jamieson River in Mexico, and noted that the construction of dams in farming areas significantly affected runoff and its changes in basins. Flood forecasting and sediment transport in basins following water conservancy projects have been reported in many studies. Analyses of changes in water and sediment flow in response to varying driving factors have improved our understanding of the evolution of hydrological regimes associated with floods in basins and impacts on water and soil loss prevention (Roberta et al., 2022; Yuan et al., 2014). Considering the evolution of hydraulic engineering facilities and the paucity of records, a detailed characterization of the impacts of such facilities on runoff is challenging (Sarah et al., 2022). Therefore, hydraulic engineering modules have been incorporated into many simulators, and this has been exploited in many studies on hydrological modeling (Wu et al., 2020). Cao et al. (2019) incorporated water conservancy projects to explore trends in flooding based on basin hydrological models, and this significantly improved the accuracy of flood forecasting. Xiong et al. (2020) used a hydrological model and field data to explore changes in flooding and the ecological environment of a basin. GIS technology has been increasingly employed in the construction of distributed hydrological models for the characterization of ecological changes in basins (Lyu et al., 2019). Therefore, based on a distributed hydrological model, Guo et al. (2022) explored the impacts of the construction of check dams on ecological changes in the Loess Plateau. The increasing water conservancy projects are exacerbating the changes to the ecology in the plateau region; these changes elevate uncertainties in results from different studies (Wu et al., 2017). Comprehensive evaluation of the impact of water conservancy projects on the regional ecological environment is an important research topic.

The Loess Plateau is in the hinterland of Eurasia and is an important area of agricultural production in China. The ecology of the region is fragile because of the limited natural endowment of water resources and severe soil erosion. Therefore, as a prominent area in China that requires ecological protection, several water and soil conservation measures, including forest and grass measures and engineering measures, have been implemented in the region since the 1970s (Wu et al., 2017). Forest and grass measures can fundamentally prevent water and soil loss (Wang et al., 2016). However, the effects of the implementation of forest and grass measures on water and soil loss control cannot be immediately observed. Surveys indicate that afforestation to sediment reduction measures require 3–5 years to be effective. The benefits of engineering measures such as reservoirs in flood detention and sediment reduction are more obvious than those of forest and grass measures (Wu et al., 2018). Thus, construction of reservoirs can provide certain ecological benefits for the regional environment (Nilsson et al., 2005). These measures were intended to prevent deterioration of the regional environment, increase its ecological bearing capacity, and ensure a balance between development by humans and the conservation of nature. However, interference from human activities complicates the ecological environment and hydrological cycle in the region (Yang et al., 2004; Li et al., 2018; Guo et al., 2022). Therefore, evaluation of the extent and impacts of human activities on hydrological processes and the ecological environment, as well as shaping and preserving ecological stability in the basins under new water and sediment conditions associated with water conservancy projects, are gaining increasing attention in basin ecology and hydrology studies (Wen et al., 2022;Kang et al., 2021).

The Qinhe River Basin is part of the Shanxi Plate in the Loess Plateau. The upper and middle reaches of the basin are valley landforms, where flood disasters frequently aggravate water and soil loss. (Wang et al., 2006). The lower reaches are important areas for agricultural activities. According to Lyu (2006), cultivated land occupies approximately 26% of the drainage area but is under increasing pressure because of the increasing population and urbanization. Considering the safety of agricultural production and human life, many reservoirs have been constructed that have been implemented in the basin since the 1950s. The primary objectives of these measures were to mitigate ecological deterioration and water and soil loss (Wang et al., 2016). However, because of its complexity, the relationships between human activities and the ecology in the basin remain uncertain. The construction of reservoirs creates challenges in the assessment of trends in ecological and driving factors of changes in the basin (Zhang et al., 2011; Lv et al., 2018). Therefore, the achievement of coordinated sustainable development of the ecological environment and social component of the basin involving impacts of the construction of reservoirs is a major problem that requires urgent attention because of its significance for the development of semi–arid regions in the Loess Plateau (Wang et al., 2016). The findings of the present study are vital for assessing changes in the ecological environment in the region during the last 30 years of the 20th century (Lv et al., 2018). The findings also provide a reference for environmental governance and the prevention of soil erosion in the Qinhe River Basin (Montanari et al., 2013; Jerome, 2000).

2. Geographical setting and data sources

2.1 Study area

The Qinhe River Basin, situated in the central Loess Plateau (34.8°–37.1°N, 112°–113°E), encompasses an area of approximately 7339.98 km2 to the north of the Runcheng Gauge Station. The Qinhe River, a first-class tributary of the Yellow River, runs through this basin. The area is characterized by short and intense periods of rainfall, which often result in flood and landslide disasters. In the flood season (June-October), the basin receives approximately 411 mm of precipitation, accounting for [?] 70% of the total annual precipitation. Furthermore, the transport of sediments during this period constitutes [?] 80% of the annual total (Liu et al., 2022). The basin is mainly mountainous, with river gradients mostly exceeding 5%, resulting in abundant hydraulic resources. The lower reaches of the basin are crucial for agricultural activities. To ensure the safety of these activities, conserve water resources, and prevent water-related disasters and soil erosion during the flood season, several water conservancy projects have been implemented since the 1950s. However, the construction of reservoirs and the extraction of large volumes of water for agricultural and industrial purposes have considerably altered the hydrological processes in the basin. In this study, we selected five representative reservoirs associated with the main streams and tributaries of the Qinhe River, which were constructed after 1950, to evaluate their impacts on the hydrological characteristics of the basin. The distribution of weather stations and reservoirs in the basin is presented in Figure 1.

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Figure 1. Location of Station and Reservoirs in Qinhe River Basin

2.2 Study area

Based on hydrometeorological and underlying surface change data, a distributed hydrological model, the geomorphology-based hydrological model (GBHM) (Yang et al., 2001; Yang et al., 2002), was established.

The parameters employed in the creation of the model were calibrated and the effects of the simulation were evaluated. Based on the model, changes in hydro–logical characteristics and meteorological factors of the basin caused by the construction of reservoirs were explored and highlighted. Changes in the peak flood volume and sediment discharge that are related to the operation of reservoirs and other soil and water conservation measures in the basin were discussed. In addition, the impacts of the construction of reservoirs on the ecology of the basin were also examined. The research framework is shown in Figure 2.

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Figure 2. Research framework flowchart

2.2 Data

Daily meteorological data (e.g., precipitation, temperature) during the flood season from 1971 to 2000 recorded at 18 meteorological stations in the Qinhe River Basin were obtained from the Yellow River Hydrological Yearbook and China Meteorological Data Service Center (https://data.cma.cn/). Based on an inverse distance weighted approach, these daily data from different stations were spatially interpolated.

Land use / cover data and Normalized Difference Vegetation Index (NDVI) data for the Qinhe River Basin with a spatial resolution of 1 km for the period from 1982 to 2000 were retrieved from the geospatial data cloud (http://www.gscloud.cn). Digital elevation data with a spatial resolution of 30 m were collected and a topographic map that was vectorized through geometric correction, data splicing, and other processing techniques was used to create a digital elevation model (DEM). The hydrologic module in ArcGIS was used for analysis and underlying surface data, such as the DEM, sub–basins, river networks, and slope, with a resolution of 30 m that were obtained for the Qinhe River Basin, served as input data for the hydrological model.

3. Methods

3.1 Determination of a baseline period and trend analysis

Meteorological changes are an important driving factor of basin runoff changes. There are many methods to explore a trend-change in basin hydrological time series data but each method is based on a different principle. Due to uncertainty, a single method may cause unreliable results. The rationality of the results can be improved by analyzing the hydrological series of the basin in multiple ways. Lyu (2012) studied the hydrometeorological change trend of the Chabagou River Basin in China through Mann–Kendall (M–K) test and Spearman (Sp) method. This study uses the M-K test and Sp method to test the time series trend of hydrometeorology in the Qinhe River Basin.

Long-series hydrometeorological data are usually divided into multiple stages for comparative study. The division of stages is generally accomplished via two methods: 1) the "manual division method" based on special years or special events (Miao et al., 2011) and 2) the "breakpoint division method" based on different statistical methods (Tabari et al., 2014). The manual division method is simple but lacks specific division standards. The breakpoint division method is based on statistical methods to identify mutation years to divide different periods, which is more scientific. The traditional techniques for evaluating mutation points include the M-K test (Li et al., 2007), ordered clustering method (O-C) (Mohamed, 2017), and cumulative anomaly method (C-A) (Li and Song, 2020). In this study, the baseline period and change period were comprehensively divided using the above three methods.

3.2 Hydrological modeling using GBHM

The GBHM is a distributed hydrological model that was proposed in 1998 by Yang et al. (1998). In this model, the basin can be divided into several mountain slope units, and the regional runoff generation and concentration processes are expressed based on the "slope-river course" using physical equations (Lyu et al., 2019; Ma et al., 2010). The model can be described according to the following components: input, spatial database, calculation of hydrological processes, and output (Yang et al., 2002). Model input data include basic geographic information data (e.g., DEM, river network), daily meteorological data (e.g., precipitation, temperature), annual land use data, and annual NDVI data. To adequately characterize the hydrological response of the Qinhe River Basin to the construction of reservoirs, the principal parameters of the model were adjusted for the present study. The impacts of underlying changes at the surface and major soil and water conservation measures on temporal and spatial changes in runoff for the basin were also examined. A schematic illustration of the improved model is displayed in Figure 3.

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Figure 3. Schematic diagram of GBHM model

3.1 Determination of parameters and evaluation of the simulation

According to a time-related division, the daily-scale distributed hydrological model of the Qinhe River Basin was established, and the measured runoff from Runcheng Station was used to calibrate and test. Regarding the adjustment of parameters, a reasonable range was selected for each according to variations in hydrological processes during the flood season. Table 1 gives the results of GBHM simulation parameters.

A single index is inadequate for the evaluation of results from a hydrological simulation because it can be affected by the evaluation method. Consequently, in the present study, the NASH efficiency coefficient E_N, ratio of absolute error to daily runoff S, and correlation coefficient P were utilized as indexes to evaluate the results of the established hydrological model (Lyu et al., 2019). The established model simulation results and associated reliability checks are shown in Figure 4.

Table 1. GBHM modeling parameter values (Yang et al., 2002; Lyu et al., 2019)

Parameter	Value	Parameter	Value
Maximum surface water storage (mm)	11	Slope shape factor	0.21
Hydraulic conductivity of topsoil (mm/h)	1.2	Crop coefficient	0.8
Hydraulic conductivity of subsoil (mm/h)	1.6	Manning coefficient	5
Hydraulic conductivity of unsaturated soil (mm/h)	0.4	Channel roughness	0.06

Runoff data obtained from Runcheng Hydrological Station, which is at the outlet of the basin, were used for validation of the simulation results. Values that were obtained from the GBHM were evaluated using theE_N, S, and P and the results are presented in Table 1. The consistency between the simulated and measured values for a parameter increased as E_N and P increased and as Sdecreased. The E_N, S, and P for the model from 1971 to 1976 were 0.71, 0.05, and 0.86, respectively, and from 1977 to 1982, 0.55, 0.05, and 0.67, respectively. The evaluation revealed that runoff values obtained via the GBHM agreed well with measured values.

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Figure 4. Daily runoff simulation and inspection diagram of Qinhe River Basin during flood season

4. Results and Discussion

To understand the impacts of the construction of reservoirs on the changes in hydrological processes during the flood season in the Qinhe River Basin, five reservoirs associated with the main tributary of the Qinhe River that were built after 1950, were investigated. The runoff, actual evaporation, soil water, and NDVI data for the baseline period, change period I, and change period II for sub-basins hosting the five reservoirs were evaluated, and the differences in these parameters between the sub–basins and the Qinhe River Basin were analyzed.

4.1 Trend and mutation analysis of hydrometeorological elements

To reduce the uncertainty of the single mutation-point identification method, the hydrological and meteorological factor of the Qinhe River Basin in flood season were tested and analyzed using M-K, O-C, and C-A. Three abrupt change test results of hydrometeorological factors in the Qinhe River Basin were used as the basis for the division of hydrometeorological elements. The years 1982 and 1992 were selected as the two abrupt change years in the study area: 1971–1981 was the baseline period, 1982–1991 was the change period I, and 1992–2000 was the change period II. Table 2 gives the Stage division results of hydrometeorological factors.

Table 2. Stage division results of hydrometeorological factors.

Hydrometeorological factors	M-K	O-L	C-A	Period
Runoff	1977	1995	1982, 1992	Baseline period: 1971–1981
Precipitation	1984, 1989, 1995	1982	1987, 1993	Change period I: 1982–1991
Temperature	1990, 1992, 1994	1984	1985	Change period II: 1992–2000

Sp and M-K were used to analyze the trend change in runoff, temperature, and precipitation in the flood season. The results are presented in Table 3. The precipitation and runoff in the Qinhe River Basin showed an insignificant downward trend under the significance test at the 95% confidence level. The temperature showed an insignificant upward trend.

Table 3. Trend of hydrometeorological factors.

Hydrometeorological factors	Sp	M-K	Result
Runoff in flood season	—	—+	—
Precipitation in flood season	—	—	—
Temperature in flood season	—	—+	—

Note: — and— denote upward or downward trend at 95% confidence level; + denotes significant; - denotes not-significant.

4.2 Variation characteristics of hydrometeorological elements

4.2.1 Runoff depth changes in the sub–basins

During the flood season in the Qinhe River Basin, runoff decreased continuously in all three periods, with a remarkable decline from 8.51 to 5.92 mm, which represents a decrease of more than 30%. This reduction occurred rapidly and can be attributed to various factors. Analysis of the sub-basins hosting the five studied reservoirs during the baseline period indicated that the runoff and R/P (Runoff/Precipitation) values were higher than the corresponding average values for the basin. In change period I, the average R/P value for the sub-basins that host the five reservoirs was 0.58, with the relatively low value observed in the sub-basin containing the No. 4 Reservoir attributed to low precipitation. In change period II, the average runoff and R/P for the five sub-basins hosting the studied reservoirs were 7.14 mm and 0.59, respectively. However, the total basin recorded 5.92 mm and 0.47 mm for runoff and R/P, respectively.

These findings indicate that, under the background of reduced precipitation, the basin's runoff has decreased to varying degrees. Nevertheless, the sub-basin where the reservoir is located has experienced a significantly lower decrease in runoff than the basin's average. Figure 5 illustrates the simulation of runoff for a typical sub-basin hosting a reservoir. In summary, the study reveals a continuous decline in runoff during the flood season in the Qinhe River Basin, with various factors contributing to the reduction. Furthermore, the sub-basins hosting the five studied reservoirs have experienced relatively lower decreases in runoff than the basin's average, suggesting that the construction of reservoirs has contributed to retaining water in these sub-basins during periods of reduced precipitation.

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Figure 5. Results of the runoff depth simulation for sub-basin in different periods

4.2.2 Soil water changes in the sub–basins

The simulation results of soil water in the Qinhe River Basin exhibited decreasing trends for the two change periods, which can be primarily attributed to the continuous decrease in precipitation. However, the ratio of soil water to precipitation has shown a continuous upward trend. Specifically, the S/P (Soil Water/Precipitation) of the entire basin increased from 0.22 to 0.24, and the S/P average of the sub-basins where the reservoir is located increased from 0.22 to 0.25. These findings indicate that the water conservation capacity of the entire basin has improved, and the water conservation capacity of the sub-basins where the reservoir is located is better.

Interestingly, in the last 30 years of the 20th century, despite the continuous reduction in precipitation, the change in soil water was relatively small, mainly due to the improved vegetation in the basin, which is associated with water and soil conservation measures. The utilization of soil water by plants promotes stability. However, this also demonstrates that the vegetation-carrying capacity of the basin reached a stable state in the 21st century.

Overall, these results reveal that the implementation of water and soil conservation measures, including water conservancy projects, in the Qinhe River Basin has positively impacted its ecology. The simulation results of soil water in a typical sub-basin hosting a reservoir are shown in Figure 6. The study highlights the importance of water and soil conservation measures in the Qinhe River Basin and their positive impact on its ecology. Specifically, the basin's water conservation capacity has improved, and its vegetation-carrying capacity has reached a stable state in the 21st century. These findings underscore the significance of sustainable water and soil management practices in maintaining the health of river basins.

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Figure 6. Results of soil water simulation of sub-basin in different periods

4.2.3 Actual Evaporation changes in the sub–basins

During the flood season, the detention of runoff due to the constructed reservoirs resulted in an increase in evaporation in the basin, particularly during change period I. This increase in evaporation was attributed to the larger surface area covered by water in the basin, the abundance of water sources, and the growth of vegetation resulting from improved water and soil conservation measures. Furthermore, the rates of evaporation in the middle and lower reservoirs were higher than those in the upper reservoirs, which is consistent with the temperature changes in the basin. The temperature increased faster in the lower reaches of the basin than in the upper reaches. During change period II, although the overall evaporation in the basin decreased compared to the baseline period, the conversion ratio of precipitation to evaporation increased from 0.37 to 0.44. Upon comparison, the evaporation rates in the entire basin and the sub-basin where the reservoir was located were found to be similar. However, the average E/P (E/P=Evaporation/Precipitation) of the sub-basin where the reservoir was located was higher than that of the entire basin. The evaporation associated with the No. 5 Reservoir was lower than the average value for the basin due to human activities, such as the conversion of cultivated land and grassland to construction land in the lower reaches of the basin. The limited forest land cover in the area further explains the lower evaporation rate.

A comparison of the five sub-basins containing reservoirs revealed that the upstream area had higher evaporation rates than the downstream area, despite the opposite trend in temperature and precipitation. This finding suggests that the water and soil conservation measures were more effective in the upstream area, and the transpiration capacity of vegetation played a significant role in enhancing the changes in evaporation. Moreover, the evaporation in the sub-basins where the reservoirs were located was better than that of the entire basin. Figure 7 depicts the simulation results of evaporation for a reservoir-controlled sub-basin.The detention of runoff due to the constructed reservoirs resulted in an increase in evaporation rates in the basin, particularly during change period I. Although the overall evaporation decreased during change period II, the conversion ratio of precipitation to evaporation increased. The sub-basin where the reservoir was located had higher average E/P than the entire basin, and the evaporation rates were higher in the upstream area than in the downstream area. The water and soil conservation measures played a crucial role in enhancing the changes in evaporation.

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Figure 7. Results of evaporation simulation of sub-basins in different periods.

4.2.4 Changes in NDVI in sub-basins

Starting from the 1970s, the Qinhe River Basin has implemented large-scale water and soil conservation measures, with a focus on afforestation of hillsides, creating forests for water and soil conservation, and transforming residual forests. In this study, the NDVI data of the Qinhe River Basin during change periods I and II were analyzed. The average NDVI of the basin increased by 5.36%, from 0.56 to 0.59. However, the average increase rate of the sub-basin where the reservoir is located was 6.77%. The NDVI growth rate of the upstream No. 1 reservoir was lower than the average value of the basin, as it is located upstream and is more affected by natural factors. Due to the good initial vegetation coverage, the growth potential in this sub-basin is low. On the other hand, the NDVI growth rate of the downstream No. 5 Reservoir was the same as the average value of the whole basin. The NDVI growth rates of the No. 2, No. 3, and No. 4 Reservoirs were 6.78%, 10.53%, and 9.62%, respectively. The sub-basin where the downstream No. 5 Reservoir is located is severely disturbed by human activities, and the land types are frequently transformed. This explains the lack of evident NDVI growth in this area.

Field investigations have revealed that to maintain the flood detention capacity of the reservoir and protect the safety of the dam site, the local government has paid more attention to vegetation restoration and water and soil conservation measures in the upstream area of the reservoir. This has partly contributed to the higher NDVI growth of the sub-basins containing reservoirs than the average value of the basin during the same period. Figure 8 illustrates the NDVI changes in the sub-basins containing reservoirs.

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Figure 8. Characteristics of NDVI changes in the sub–basin for different periods

4.3 Variation of Flood and Sediment Discharge in the River Basin

The upper and middle reaches of the Qinhe River Basin are geographically characterized by steep gradients, predominantly due to the presence of valleys and mountains. As a result of the low vegetation coverage and intense but brief precipitation, flood-related incidents frequently occur in the downstream urban regions. Rainstorms and floods represent primary driving forces for the transportation of sediments within the basin. Over the years, various water and soil conservation measures have been implemented within the basin, with a focus on water conservancy projects aimed at constructing reservoirs to regulate floods and reduce water and soil loss. In light of these developments, the current study aims to investigate the time-series of flood and sediment discharge and their link to human activities within the basin during the flood season between 1971 and 2000. Furthermore, the study aims to explore the benefits of water and soil loss control, flood control, and disaster prevention within the basin in response to forest and grassland conservation measures, as well as engineering measures.

4.3.1 Flood Peak and Three-day Flood Volume Changes

In this section, flood peak and three-day flood volume data recorded at the Runcheng Station in the Qinhe River Basin during the flood season from 1971 to 2006 were analyzed to investigate their characteristics during different periods. As shown in Figure 9, peak flow during the flood season demonstrated an increasing trend in the baseline period, followed by a decreasing trend in change periods I and II. Additionally, the three-day flood volume exhibited a significant decrease during the baseline period, which could be attributed to the construction of small and medium-sized reservoirs and a decrease in precipitation in the basin during the 1970s (Yang et al., 2004).

Despite continued construction of reservoirs in the basin, their flood detention capacity remains limited. Therefore, peak flow remains high following heavy rainfall. However, water and soil conservation measures implemented during change period I in the Qinhe River Basin have yielded positive results. The completed reservoir has effectively reduced peak flood volume, resulting in a decreasing trend in flood peak and three-day flood volume data. In change period II, the water and soil conservation measures, including water conservancy projects, in the basin impacted flood detention and peak cutting. Furthermore, precipitation in the basin decreased during the same period, leading to a further decrease in the three-day flood volume and peak flow. These results demonstrate that the construction of reservoirs has significantly enhanced the prevention of water-related disasters in the basin.

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Figure 9. Variation characteristics of three–day flood volume and peak in Qinhe River basin during flood season

4.3.2 Annual Variation Characteristics in Sediment Discharge during the Flood Season

This section evaluates the changes in sediment discharge during the flood season in the Qinhe River Basin for different periods. Data recorded at the Runcheng Station from 1971 to 2000 were used, and the significance of changes and future trends were assessed using the M-K trend and Hurst index tests. The results from the M-K trend test showed a highly decreasing trend in sediment transportation in the Qinhe River Basin during the flood season, with a Z-value of -2.72 at the 95% confidence level. Furthermore, the discharge of sediments during the flood season was found to be weakly persistent, with an H-value of 0.69 from the Hurst index test.

Figure 10 illustrates that the average sediment discharge during the flood season decreased by more than 79% since the implementation of major water and soil conservation measures in the Qinhe River Basin in the 1970s. The baseline, change I, and change II periods recorded an average sediment discharge of 4.711 × 106, 2.659 × 106, and 0.943 × 106 tons, respectively. Over the same period, the land use in the basin significantly changed. Specifically, the area occupied by grassland decreased in change period I, while areas covered by forest and cultivated lands increased. In change period II, forest and cultivated lands also increased. These changes led to increased vegetation cover, which improved soil and water conservation in the basin. Vegetation stabilizes soil and sand, reduces erosion associated with runoff, and effectively prevents water and soil loss. Moreover, water and soil conservation measures such as the construction of terraced fields and others significantly weakened the ability of runoff to transport soil on slopes in the basin. The NDVI index for the basin increased from 0.56 in change period I to 0.59 in change period II, confirming the increased vegetation cover in the basin.

The construction of water conservancy projects, which began in the 1950s and 1970s, regulated and stored water in the basin, reducing the amount of water and sediment transported to the river channel during the operation of reservoirs. Sediments were predominantly deposited in areas containing reservoirs during the flood season, and this reduced water and soil loss, positively impacting the ecological environment of the basin.

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Figure 10. Variation characteristics of sediment discharge in Qinhe River Basin during flood season

5. CONCLUSIONS

This study has established a distributed GBHM based on years of hydrological and meteorological data, as well as underlying surface data of the Qinhe River Basin. It aimed to explore the response characteristics of hydrological and meteorological factors in the basin under the influence of reservoir construction over the last 30 years of the 20th century. Additionally, based on abundant flood and sediment discharge data, the prevention of water-related disasters and soil erosion in the basin because of reservoir construction and other soil and water conservation measures was explored.

The Qinhe River Basin possesses a unique climate and geographical environment, and the water and soil conservation measures employed in the basin, mainly based on reservoir construction, have influenced the hydrological cycle system of the basin. The simulation results indicate that the runoff, soil water, and evaporation of the sub-basin where the reservoir is located exceed the average value of the basin. Furthermore, the NDVI growth of the sub-basin where the reservoir is situated is also higher than the average of the basin. Under the influence of the reservoir, flood and sediment discharge in the basin have been effectively controlled. In the context of climate change and rapid urbanization, the ecological environment of the basin is undergoing a positive transformation. These findings enhance our understanding of the changes in the water cycle and hydrological response characteristics of the basin that are linked to the construction of reservoirs and other soil and water conservation measures. They can be used as a reference for studying other basins in the Loess Plateau. To achieve sustainable development, water resource planning and basin management measures that minimize the contribution of human activities to the deterioration of the ecological environment in the Loess Plateau must be formulated.

Considering the increasing human activity and rapid urbanization in the Qinhe River Basin, the evolutionary mechanism of the hydrological process will become more complicated, and the uncertainty of hydrological simulations will increase. Therefore, it is necessary to study the impact mechanism of typical human activities on basin hydrological factors and optimize the model's structure accordingly to improve the simulation accuracy of the model in subsequent research.

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REFERENCES

Assani, A.A., Landry, R., Daigle, J., et al., 2011. Reservoirs Effects on the Interannual Variability of Winter and Spring Streamflow in the St–Maurice River Watershed (Quebec, Canada). Water Resour. Manag. 25, 3661–3675. https://doi.org/10.1007/s11269–011–9875–1

Bian, D.H., Yang, X.H., Lu, Y., et al., 2022. Analysis of the spatiotemporal patterns and decoupling effects of China's water resource spatial equilibrium. Environ. Res. 216, PP. 114719. https://doi.org/10.1016/j.envres.2022.114719

Callow, J.N., Smettem, K.R., 2009. The effect of farm dams and constructed banks on hyologic connectivity and runoff estimation in agricultural landscapes. Environ Model Softw. 24, 959–968. https://doi.org/10.1016/j.envsoft.2009.02.003

Cao, R., Shen, J.J., Cheng, C.T., et al., 2019. Multi–objective optimal control of cascaded reservoirs during drawdown period before flood season. Proc CSEE. 39, 3465–3475. https://doi.org/10.13334/j.0258–8013.pcsee.180939

Ding, X.K., Guo, X.Y., Zhang, C., et al., 2020. Water conservancy project on the Yellow River modifies the seasonal variation of Chlorophyll–a in the Bohai Sea. Chemosphere. 254, PP. 126846. https://doi.org/10.1016/j.chemosphere.2020.126846

Du, L.J., Xu, L., Li, Y.P., et al., 2019. China's Agricultural Irrigation and Water Conservancy Projects: A Policy Synthesis and Discussion of Emerging Issues. Sustainability. 11, PP. 7027. https://doi.org/10.3390/su11247027

Guo, P., Lyu, J.Q., Yuan, W.N., et al. 2022. Detecting the Quantitative Hydrological Response to Changes in Climate and Human Activities at Temporal and Spatial Scales in a Typical Gully Region of the Loess Plateau, China. Water. 14, pp. 257. https://doi.org/10.3390/W14020257

Jerome, D.P., 2000. Water and civilization: Using history to reframe water policy debates and to build a new ecological realism. Water Policy. 1, 623–636. https://doi.org/10.1016/S1366–7017(99)00019–7

Jiang, Q.T., Li, Z.B., Qu, S., et al., 2022. High–resolution map of China's sustainability. Resour. Conserv. Recycl. 178, PP. 106092. https://doi.org/10.1016/j.resconrec.2021.106092

Kang, J.F., Zhang, Y.N., Biswas, A., 2021. Land Degradation and Development Processes and Their Response to Climate Change and Human Activity in China from 1982 to 2015. Remote Sens. 13, PP. 3516. https://doi.org/10.3390/RS13173516

Li, H., Song, W., 2020. Characteristics of Climate Change in the Lancang–Mekong Sub–Region. Climate. 8, 115–132. https://doi.org/10.3390/cli8100115

Li, L.J., Zhang, L., Wang, H., et al., 2007. Assessing the impact of climate variability and human activities on streamflow from the Wuding River basin in China. Hydrol Process. 10, 3485–3491. https://doi.org/10.1002/hyp.6485

Li, Y., Piao, S., Li, L.Z.X., et al., 2018. Divergent hydrological response to large–scale afforestation and vegetation greening in China. Sci. Adv. 4, eaar4182. https://doi.org/10.1126/sciadv.aar4182

Liu, J.G., Diamond, J. 2005. China's environment in a globalizing world. Nature. 439, PP. 1179–1186. https://doi.org/10.1038/4351179a

Liu, Y.Q., Huang, S.Z., Guo, Y., et al., 2022. Propagation threshold of meteorological drought to different levels of hydrological drought. A case study of Qinhe. J. Hydraul. Eng. 41, 9–19. https://doi.org/10.11660/slfdxb.20220202

Lv, M., Ma, Z., Lv, M., 2018. Effects of climate/land surface changes on streamflow with consideration of precipitation intensity and catchment characteristics in the Yellow River basin. J Geophys Res–Atmos. 123, 1942–1958. https://doi.org/10.1002/2017JD027625

Lyu, J.Q. The Hydrological Response to Climate Change and Human Activity in Typical Regions, Northwest China. Doctoral Thesis, Xi'an University of Technology, Xi'an, China, 2012.

Lyu, J.Q., Mo, S.H., Luo, P.P., et al., 2019. A quantitative assessment of hydrological responses to climate change and human activities at spatiotemporal within a typical catchment on the Loess Plateau, China. Quat. Int. 527, 1–11. https://doi.org/10.1016/j.quaint.2019.03.027

Ma, H., Yang, D.W., Tan, S.K., et al., 2010. Impact of climate variability and human activity on streamflow decrease in the Miyun Reservoir catchment. J. Hydrol. 389, 3317–324. https://doi.org/10.1016/j.jhydrol.2010.06.010

Miao, C.Y., Ni, J.R., Borthwick, A.G.L., et al., 2011. A preliminary estimate of human and natural contributions to the changes in water discharge and sediment load in the Yellow River. Glob. Planet. Chang. 76, 196–205. https://doi.org/10.1016/j.gloplacha.2011.01.008

Mohamed, A.B., 2017. A unicriterion analysis based on the PROMETHEE principles for multicriteria ordered clustering. Omega. 69, 126–140. https://doi.org/10.1016/j.omega.2016.08.007

Montanari, A., Yang, G., Savenije, H.H.G., et al., 2013. "Panta Rhei–everything flows": change in hydrology and society—the IAHS scientific decade 2013–2022. Hydrol Sci J. 58, 1256–1275. https://doi.org/10.1080/02626667.2013.809088

Nilsson, C., Catherine, A., Reldy, M, et al., 2005. Fragmentation and flow regulation of the world's large river systems. Science. 308, 405–408. https://doi.org/10.1126/science.1107887

Roberta, P., Marco, G., Edward, G., et al., 2022. Assessing Coastal Flood Risk in a Changing Climate for Dublin, Ireland. J. Mar. Sci. Eng. 10, PP. 1715. https://doi.org/10.3390/JMSE10111715

Sarah, J., Juliance, Q., Marta, Z., et al., 2022. Advancing reservoir operations modelling in SWAT to reduce socio–ecological tradeoffs. Environ Model Softw. 157, PP. 105527. https://doi.org/10.1016/J.ENVSOFT.2022.105527

Schreider, S.Y., Jakman, A.J., Letcher, R.A., et al., 2022. Detecting changes in streamflow response to changes in non–climatic catchment conditions: farm dam development in the Murray–Darling basin, Australina. J. Hydrol. 262, 84–98. https://doi.org/10.1016/S0022–1694(02)00023–9

Sun, X.P., He, S.M., Guo, Y., et al., 2019. Comprehensive Evaluation of The Impact of the Water Conservancy Project in on the Ecosystem of the Yangtze River Basin. J Coast Res. 94, 758–762. https://doi.org/10.2112/SI94–150.1

Tabari, H., Talaee, P.H., Nadoushani, S.S.M., et al., 2014. A survey of temperature and precipitation based aridity indices in Iran. Quaternary Int. 345, 158–166. https://doi.org/10.1016/j.quaint.2014.03.061

Wang, H.J., Yang, Z.S., Saito, Y., et al., 2006. Interannual and seasonal variation of the Huanghe (Yellow River) water discharge over the past 50 years: connections to impacts from ENSO events and dams. Glob Planet Change. 50, 212–225. https://doi.org/10.1016/j.gloplacha.2006.01.005

Wang, S., Fu, B.J., Piao, S.L., et al., 2016. Reduced sediment transport in the Yellow River due to anthropogenic changes. Nat Geosci, 9, 38–41. https://doi.org/10.1038/ngeo2602

Wen, Y., Guo, B., Zang, W.Q., et al., 2022. Quantitative discrimination of the influences of climate change and human activity on rocky desertification based on a novel feature space model. Open Geosci. 14, 367–381. https://doi.org/10.1515/GEO–2022–0365

Wu, J.W., Miao, C.Y., Zhang, X.M., et al., 2017. Detecting the quantitative hydrological response to changes in climate and human activities. Sci. Total Environ. 586, 328–337. https://doi.org/10.1016/j.scitotenv.2017.02.010

Wu, J.W., Haw, Y., Jeffrey, G., et al., 2020. Development of reservoir operation functions in SWAT+ for national environmental assessments. J. Hydrol. 583, PP. 124556. https://doi.org/10.1016/j.jhydrol.2020.124556

Wu, P., Liang, S., Wang, X., et al., 2018. Climate–induced hydrologic change in the source region of the Yellow River: a new assessment including varying permafrost. Hydrol Earth Syst Sci. PP. 1–35. https://doi.org/10.5194/hess–2017–744

Wu, Y., Guo, L.D., Xia, Z.Q., et al., 2019. Reviewing the Poyang Lake Hydraulic Project Based on Humans' Changing Cognition of Water Conservancy Projects. Sustainability. 11, PP. 2605. https://doi.org/10.3390/su11092605.

Xiong, J.H., Tang, C.Y., Jiang, L.L., et al. 2020. Flood dispatching and forecasting model for cascade reservoirs in Wujiang River Basin. Yangtze River. 51, 87–91. https://doi.org/10.16232/j.cnki.1001–4179

Xu, A.N., Yang, L.E., Yang, W.B., 2020. Water conservancy projects enhanced local resilience to floods and droughts over the past 300 years at the Erhai Lake basin, Southwest China. Environ. Res. Lett. 15, PP. 125009. https://doi.org/10.1088/1748–9326/abc588.

Yang, D.W., Herath, S., Musiake, K. Development of a geomorphology–based hydrological model for large catchments. Proceedings of Hydraulic Engineering. 1998, 42, 169–174. https://doi.org/10.2208/prohe.42.169

Yang, D.W., Herath, S., Musiake, K., 2001. Spatial resolution sensitivity of catchment geomorphologic properties and the effect on hydrological simulation. Hydrological Processes. 15, 2085–2099. https://doi.org/10.1080/02626660209492907

Yang, D.W., Herath, S., Musiake, K., 2002. A hillslope–based hydrological model using catchment area and width functions. Hydrol Sci J. 47, 49–65. https://doi.org/10.1080/02626660209492907

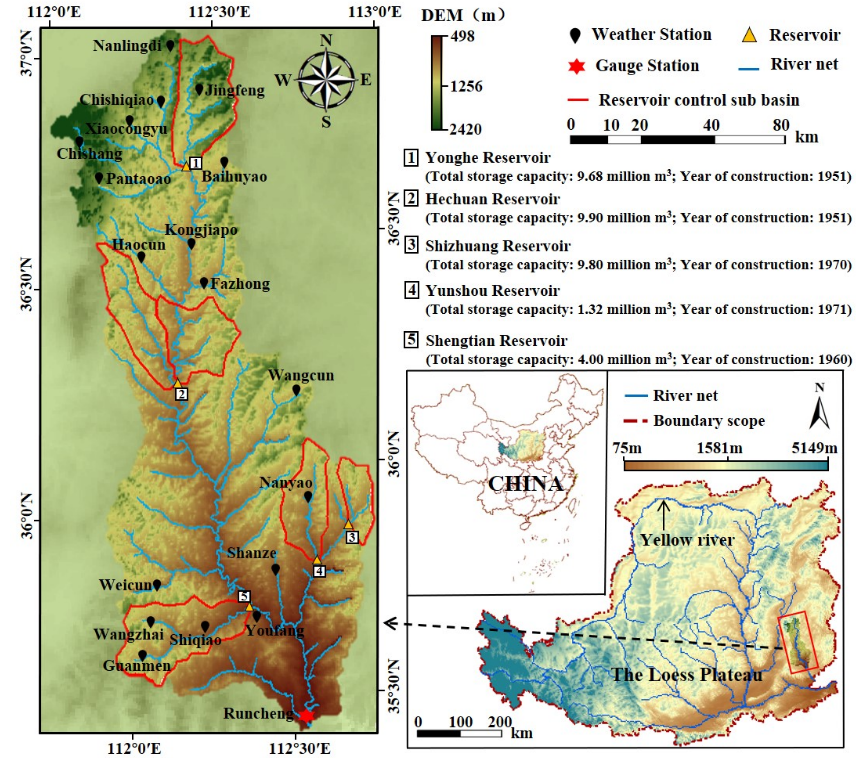
Yang, D.W., Li, C., Hu, H., et al., 2004. Analysis of water resources variability in the Yellow River of China during the last half century using historical data. Water Resour. Res. 40, W06502.1–W06502.12. https://doi.org/10.1029/2003WR002763

Yuan, J.X., Wu, L., 2014. Carrying Capacity of Resources and Problems of Sustainable Development in Dongting Lake's Flood Detention Basin. Adv Mat Res. 3246, PP. 1961–1964. https://doi.org/10.4028/www.scientific.net/AMR.962–965.1961

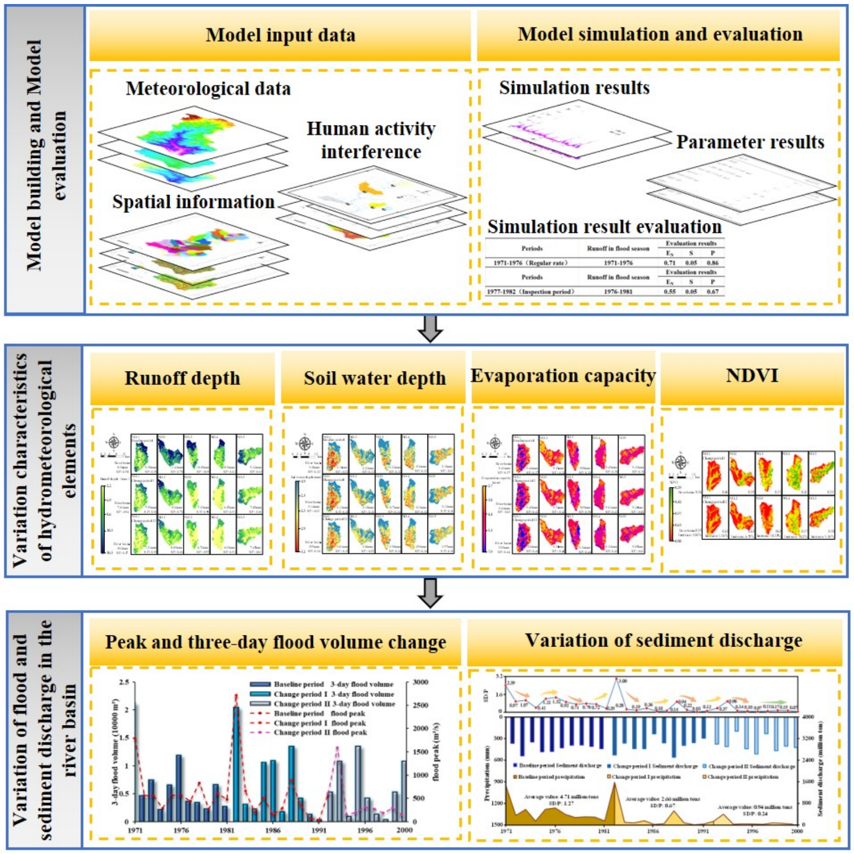
Zeng, C.F., Qi, W.Y., Mao, Y.Q., et al., 2022. Water Conservation Ecological Service Function and Its Value Response Mechanism in a Nested Water Conservancy Project Area. Front. Environ. Sci. https://doi.org/10.3389/FENVS.2022.887040

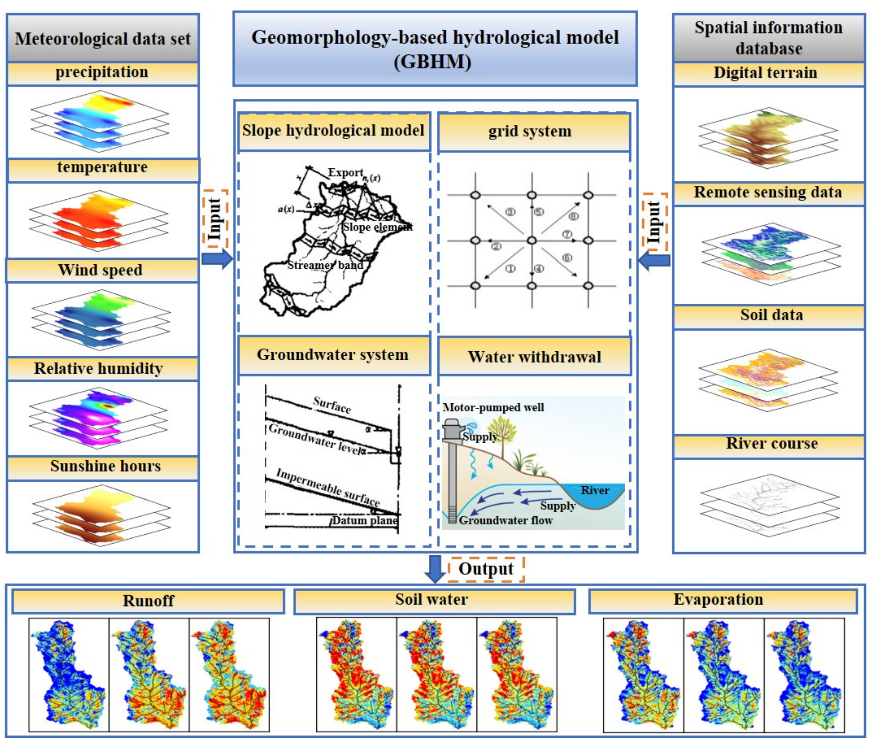
Zhang, Z.X., Chen, X., Xu, C.Y., et al., 2011. Evaluating the nonstationary relationship between precipitation and streamflow in nine major basins of China during the past 50 years. J. Hydrol. 409, 81–93. https://doi.org/10.1016/j.jhydrol.2011.07.041

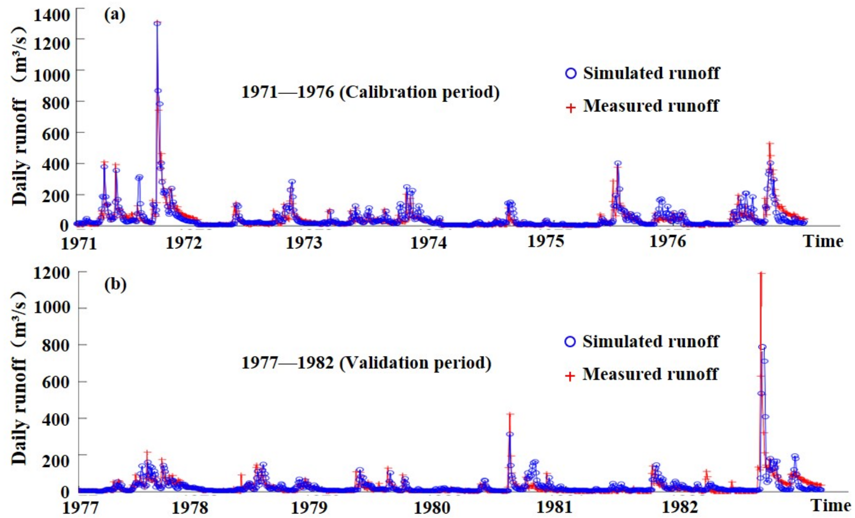
Zhu, Z.X., Zhao, K.K., Lin, Q.W., et al., 2017. Systematic Environmental Impact Assessment for Non–natural Reserve Areas: A Case Study of the Chaishitan Water Conservancy Project on Land Use and Plant Diversity in Yunnan, China. Front. Ecol. Evol. 5, 1–14. https://doi.org/10.3389/fevo.2017.00060.

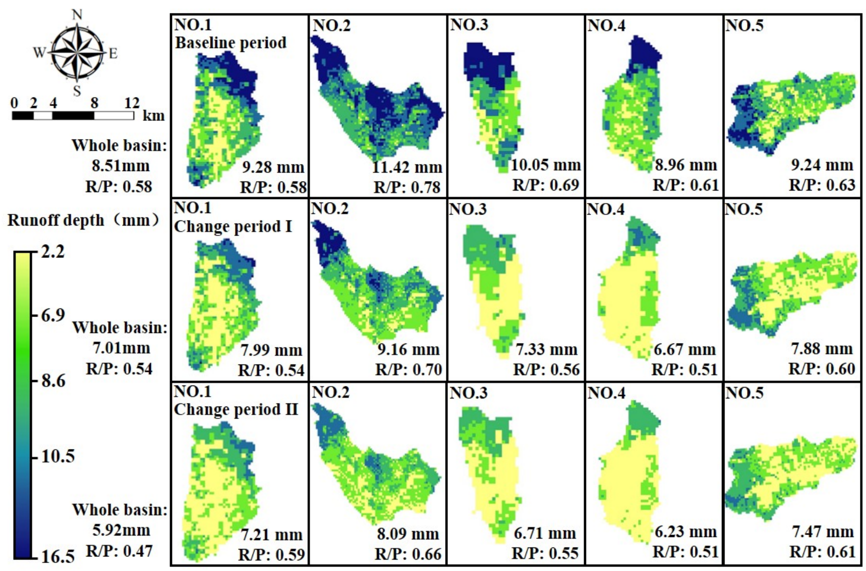


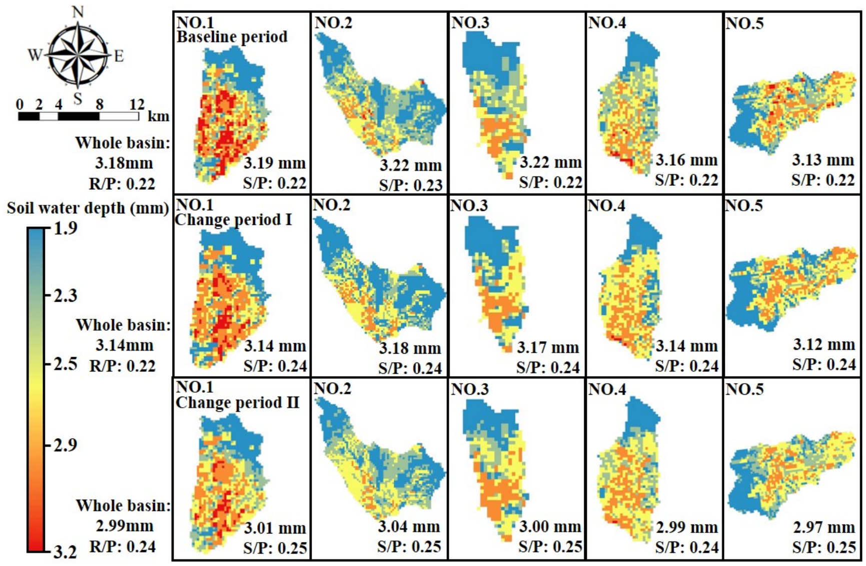
DEM（m）
498
1256
2420
Weather Station
Reservoir
Gauge Station
River net
Reservoir control sub basin
0 10 20 40 80 km
1 Yonghe Reservoir
(Total storage capacity: 9.68 million m³; Year of construction: 1951)
2 Hechuan Reservoir
(Total storage capacity: 9.90 million m³; Year of construction: 1951)
3 Shizhuang Reservoir
(Total storage capacity: 9.80 million m³; Year of construction: 1970)
4 Yunshou Reservoir
(Total storage capacity: 1.32 million m³; Year of construction: 1971)
5 Shengtian Reservoir
(Total storage capacity: 4.00 million m³; Year of construction: 1960)
Nanlingdi
Jingfeng
Chishiqiao
Xiaocongyu
Chishang
Pantaoao
Baihuyao
Kongjiapo
Haocun
Fazhong
Wangcun
Nanyao
Shanze
Weicun
Wangzhai
Shiqiao
Youfang
Guanmen
Runcheng
112°0′E
112°30′E
113°0′E
37°0′N
36°30′N
36°0′N
35°30′N
N
S
W
E
River net
Boundary scope
75m
1581m
5149m
CHINA
Yellow river
The Loess Plateau
0 100 200 km


Model building and Model evaluation
Model input data
Model simulation and evaluation
Meteorological data
Human activity interference
Spatial information
Simulation results
Parameter results
Simulation result evaluation
Variation characteristics of hydrometeorological elements
Runoff depth
Soil water depth
Evaporation capacity
NDVI
Variation of flood and sediment discharge in the river basin
Peak and three-day flood volume change
Variation of sediment discharge

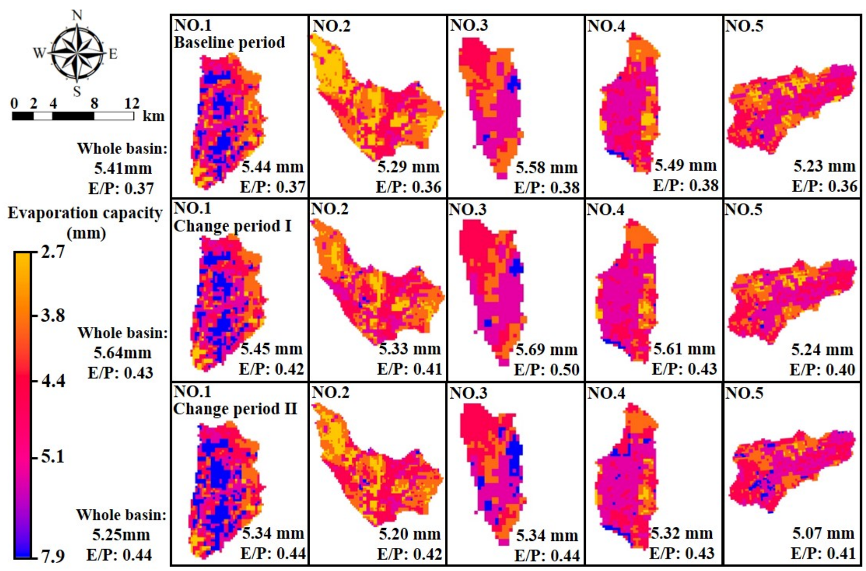

Meteorological data set
precipitation
temperature
Wind speed
Relative humidity
Sunshine hours
Geomorphology-based hydrological model (GBHM)
Slope hydrological model
grid system
Groundwater system
Water withdrawal
Spatial information database
Digital terrain
Remote sensing data
Soil data
River course
Input
Input
Output
Runoff
Soil water
Evaporation


(a)
Daily runoff（m³/s）
1971—1976 (Calibration period)
Simulated runoff
Measured runoff
Time
(b)
Daily runoff（m³/s）
1977—1982 (Validation period)
Simulated runoff
Measured runoff
Time

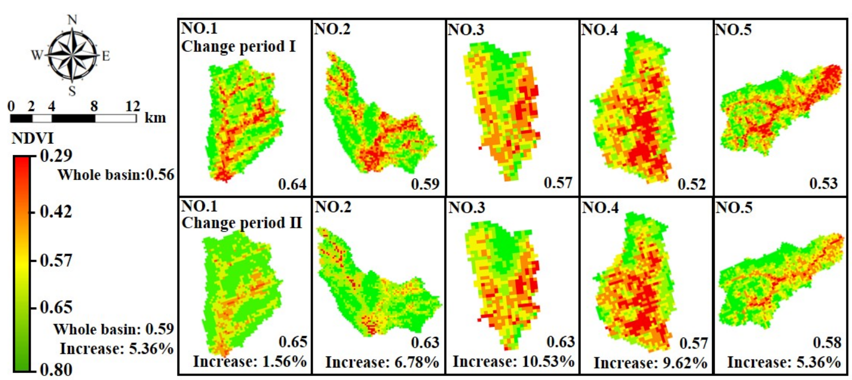

N
W
E
S
0 2 4 8 12 km
Whole basin: 8.51mm R/P: 0.58
Runoff depth（mm）
2.2
6.9
8.6
10.5
16.5
Whole basin: 7.01mm R/P: 0.54
Whole basin: 5.92mm R/P: 0.47
NO.1 Baseline period 9.28 mm R/P: 0.58
NO.2 11.42 mm R/P: 0.78
NO.3 10.05 mm R/P: 0.69
NO.4 8.96 mm R/P: 0.61
NO.5 9.24 mm R/P: 0.63
NO.1 Change period I 7.99 mm R/P: 0.54
NO.2 9.16 mm R/P: 0.70
NO.3 7.33 mm R/P: 0.56
NO.4 6.67 mm R/P: 0.51
NO.5 7.88 mm R/P: 0.60
NO.1 Change period II 7.21 mm R/P: 0.59
NO.2 8.09 mm R/P: 0.66
NO.3 6.71 mm R/P: 0.55
NO.4 6.23 mm R/P: 0.51
NO.5 7.47 mm R/P: 0.61



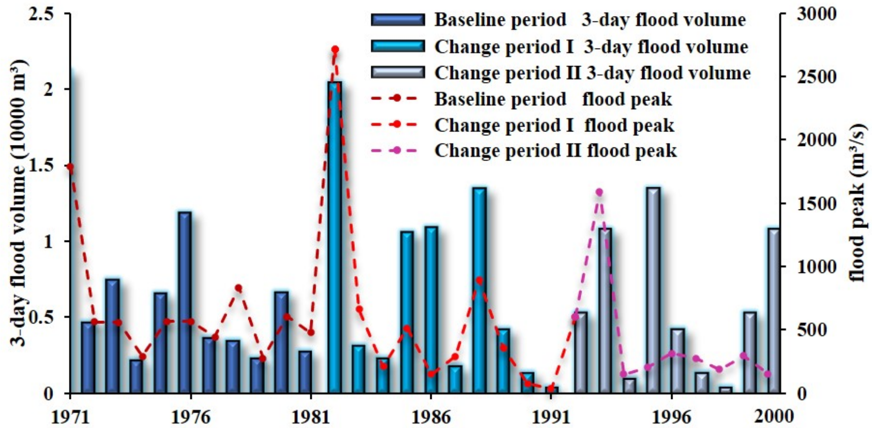
N
W
E
S
0 2 4 8 12 km
Whole basin: 3.18mm R/P: 0.22
Soil water depth (mm)
1.9
2.3
2.5
2.9
3.2
Whole basin: 3.14mm R/P: 0.22
Whole basin: 2.99mm R/P: 0.24
NO.1 Baseline period
3.19 mm S/P: 0.22
NO.2
3.22 mm S/P: 0.23
NO.3
3.22 mm S/P: 0.22
NO.4
3.16 mm S/P: 0.22
NO.5
3.13 mm S/P: 0.22
NO.1 Change period I
3.14 mm S/P: 0.24
NO.2
3.18 mm S/P: 0.24
NO.3
3.17 mm S/P: 0.24
NO.4
3.14 mm S/P: 0.24
NO.5
3.12 mm S/P: 0.24
NO.1 Change period II
3.01 mm S/P: 0.25
NO.2
3.04 mm S/P: 0.25
NO.3
3.00 mm S/P: 0.25
NO.4
2.99 mm S/P: 0.24
NO.5
2.97 mm S/P: 0.25

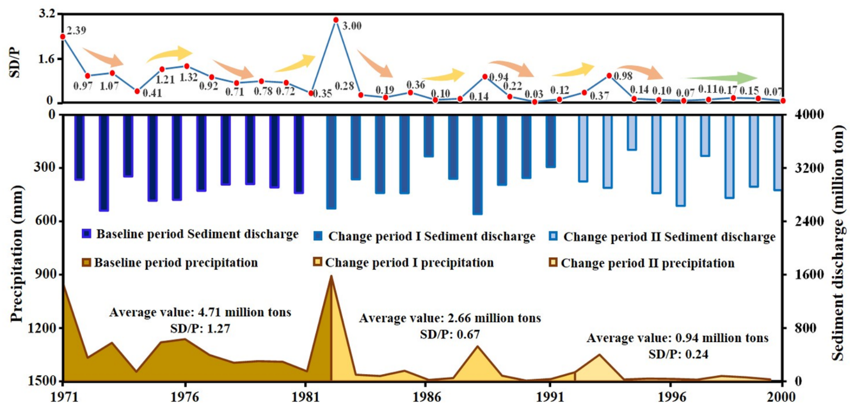


N
W
E
S
0 2 4 8 12 km
Whole basin: 5.41mm E/P: 0.37
Evaporation capacity (mm)
2.7
3.8
4.4
5.1
7.9
Whole basin: 5.64mm E/P: 0.43
Whole basin: 5.25mm E/P: 0.44
NO.1 Baseline period
5.44 mm E/P: 0.37
NO.2
5.29 mm E/P: 0.36
NO.3
5.58 mm E/P: 0.38
NO.4
5.49 mm E/P: 0.38
NO.5
5.23 mm E/P: 0.36
NO.1 Change period I
5.45 mm E/P: 0.42
NO.2
5.33 mm E/P: 0.41
NO.3
5.69 mm E/P: 0.50
NO.4
5.61 mm E/P: 0.43
NO.5
5.24 mm E/P: 0.40
NO.1 Change period II
5.34 mm E/P: 0.44
NO.2
5.20 mm E/P: 0.42
NO.3
5.34 mm E/P: 0.44
NO.4
5.32 mm E/P: 0.43
NO.5
5.07 mm E/P: 0.41



N
W
E
S
0 2 4 8 12 km
NDVI
0.29
0.42
0.57
0.65
0.80
Whole basin:0.56
Whole basin: 0.59 Increase: 5.36%
NO.1 Change period I
0.64
NO.2
0.59
NO.3
0.57
NO.4
0.52
NO.5
0.53
NO.1 Change period II
0.65 Increase: 1.56%
NO.2
0.63 Increase: 6.78%
NO.3
0.63 Increase: 10.53%
NO.4
0.57 Increase: 9.62%
NO.5
0.58 Increase: 5.36%


Baseline period 3-day flood volume
Change period I 3-day flood volume
Change period II 3-day flood volume
Baseline period flood peak
Change period I flood peak
Change period II flood peak
3-day flood volume (10000 m³)
flood peak (m³/s)


SD/P
Precipitation (mm)
Sediment discharge (million ton)
Baseline period Sediment discharge
Change period I Sediment discharge
Change period II Sediment discharge
Baseline period precipitation
Change period I precipitation
Change period II precipitation
Average value: 4.71 million tons
SD/P: 1.27
Average value: 2.66 million tons
SD/P: 0.67
Average value: 0.94 million tons
SD/P: 0.24