Quantifying the impact of climate variability and human activities on the streamflow of the Qingzhang River

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Abstract: Environmental change is the main factor leading to the disturbance of hydrological processes in the basin, the evaluation of which is of great importance to the formulation of water resources planning and management strategies. Non-parametric Mann-Kendall test and Pettitt test were used to diagnose the variation trend and abrupt change of runoff time series of Kuangmenkou station. Based on hydrological and meteorological data, the VIC model was setup to simulate runoff processes. The influence of environmental change on annual runoff was quantified during different human activity period. The results showed that the runoff of the Shizhandao station presented a decreasing trend, and the abrupt change year appeared in 1978. Based on the abrupt change year the study period was divided into runoff base period from 1959 to 1978 and change period from 1979 to 2015. The model has a high applicability to the research area, and the Nash-sutcliffe efficiency coefficient and relative error both meet the requirements of the model of more than 0.80 and less than 10%. During 1979-2015, the impact of climate change and human activities on runoff reduction are 79.8%, and 20.2%, respectively. Human activities are the main driving force of runoff change of Kuangmenkou station.

1. Introduction
The Qingzhang River Basin is one of the most frequent conflicts in China's water disputes, and it is also one of the most vulnerable to environmental changes [1]. The Kuangmenkou Station is an extremely important runoff observation station for the Qingzhang River. Since the 1960s, runoff has shown a significant reduction trend, which has brought great challenges to water resources management in the basin. Effective water resources management is essential for the healthy development of regional social economy. In the future, regional water resources planning needs to fully understand the impact of environmental changes on runoff processes [2]. Attribution analysis of runoff change and quantitative determination of the dominant factors of runoff change have become one of the prerequisites for formulating effective water resources management in the future.

At present, climate change and human activities are the main environmental factors affecting runoff change. The elastic coefficient method and the hydrological simulation method are the two main methods used to quantitatively assess the impact of environmental changes on runoff. The elasticity coefficient method has lower requirements on the original data, and can individually evaluate the impact value of each influencing factor [3]. For example, Peng Dingzhi and others used the double cumulative curve method and elastic coefficient method to study the Taihu Lake Basin, and the results show that runoff changes are mainly affected by human activities [4]. However, the elastic coefficient method can only quantitatively analyze the impact of environmental changes on an annual scale [5]. The hydrological simulation method is based on a physically distributed hydrological model and can...
be applied on a variety of scales, such as monthly or daily scales \[6\]. The model simulation results have higher accuracy, can more reasonably simulate the rainfall runoff process, and can be coupled and used with multiple models \[7\]. Zeng Sidong and others used the SIMHYD model to study the runoff at different time scales in the Zhanghe River Basin. The results show that the effects of climate change and human activities on monthly runoff changes are different in different months \[8\]. Huang Ya and others nested the CMIP5 and VIC models and analyzed the future runoff changes in the upper watershed of the Hongshui River \[9\].

This study takes the Kuangmenkou Hydrological Station as the research object, and uses the VIC hydrological model to quantitatively evaluate the impact of environmental changes on the annual runoff of the Kuangmenkou Hydrological Station based on hydrometeorological data, with a view to providing relevant basis for flood forecasting at Kuangmenkou Station and water resources planning in the Qingzhang River Basin.

2. Study area and data
The Qingzhang River is a tributary of the upper Zhanghe River in the Zhangwei River system of the Haihe River Basin, divided into east and west sources. The Qingzhang River Basin covers an area of 5339 km\(^2\), the main stream is 38.7 km long, and the average annual rainfall is about 560 mm. Kuangmenkou Station is an important hydrological station on the main stream of the Qingzhang River. The control area of Kuangmenkou Station is located between 113°0′~114°0′ E, 36°15′~36°45′ N, and has an area of 5060 km\(^2\), which is the control station for the entire river basin.

Meteorological data include (1) there are 23 precipitation observation stations in the study area including Kuangmenkou, Luijiazhuang, Piancheng, Xijing, Caijiazhuang, Zuoquan, and Shexian. The time period is from 1959 to 2015. (2) There are 9 national meteorological stations around Xingtai, Yangcheng, Jiexiu, Pingding, Taiyuan, Anze, Xiangyuan, Changzhi, and Yushe in the study area, with the average temperature, maximum temperature, and minimum temperature from 1953 to 2015 and daily data on average wind speed, data source "China Meteorological Data Sharing Service Network". The daily average runoff data on Kuangmenkou Station are from Hydrological Yearbook, and the period is from 1959 to 2015. Other data, such as the DEM data source geospatial data cloud, the vegetation data uses the global 1 km land cover data developed by the University of Maryland, and the soil data uses the Harmonized World Soil Database.

3. Methodology
3.1 Mann-Kendall trend test
In this study, the linear regression method is used to analyze the overall trend of hydrological time series firstly. The sequential version of Mann–Kendall test is used to detect the significance of the changing trends in the hydrological time series, which is widely used to test significant trends in hydrological time series, for it has an advantage without assuming any distributional form for the data.

3.2 Mann-Kendall abrupt change test
In this paper, the abrupt change point which indicates strong human activities effects on runoff is detected firstly before the separation of the effects of climate change and human activities. Before the abrupt change point, the effects of human activities on runoff are not significant, runoff is mainly controlled by natural condition, while after the abrupt change point, and both human activities and climate change have important effects on runoff changes. Nonparametric Mann-Kendall mutation test and Pettitt test were used to diagnose the abrupt change point of runoff at the Kuangmenkou Station on the Qingzhang River.

3.3 Construction of attribution analysis model of runoff change based on VIC model
According to the annual runoff sequence at Kuangmenkou Station, the trend and mutation analysis are performed to divide the runoff sequence into a reference period and a change period. Based on the
hydrological and meteorological data on the base period, a VIC runoff simulation model was constructed, and the parameters of the model were calibrated and tested. Based on the meteorological data in the changing period, the monthly runoff process of the Kuangmenkou Station in the changing period was simulated, and the contribution rate of environmental changes to the change in runoff was quantitatively evaluated according to the following formula [10],

\[
\Delta W_r = W_{hr} - W_b
\]

\[
\Delta W_H = W_{HR} - W_{HN}
\]

\[
\Delta W_C = W_{HR} - W_{HN}
\]

\[
\eta_H = \Delta W_H / \Delta W_T
\]

\[
\eta_C = \Delta W_C / \Delta W_T
\]

Where \( \Delta W_r \) is the change of runoff at the Kuangmenkou station; \( W_{hr} \) is the average runoff at the Kuangmenkou station during the change period; \( \Delta W_H \) is the average runoff at the base period of the Kuangmenkou station; \( W_{HN} \) is the contribution of human activities to runoff; \( \Delta W_C \) is the Kuangmenkou The multi-year average runoff simulated by the hydrological model during the station change period; \( \eta_H \) is the contribution of climate change to runoff; \( \eta_C \) is the contribution of human activities to runoff; \( d \) is the contribution of climate change to runoff.

4. Results and analysis

4.1 Runoff Trend Analysis

Based on the continuous measured runoff data from Kuangmenkou Station from 1959 to 2015, regardless of the analysis of the annual runoff process or the 5-year moving average annual runoff process, the runoff process at the Kuangmenkou Station showed a decreasing trend, with an annual average decreasing rate of \( 790 \times 10^4 \) m\(^3\)/a. In order to further verify the changing trend of Kuangmenkou runoff, the trend test was performed using Mann-Kendall. The calculated statistic was -3.85 and \( Z < 0 \), the annual runoff series showed a decreasing trend, when \( |Z| > 1.96 \), the annual runoff series change trend passed the 5% significant level test.

Therefore, the runoff sequence of Kuangmenkou Station from 1959 to 2015 has an average annual decreasing rate of \( 790 \times 10^4 \) m\(^3\)/a, and the decreasing trend is significant.

4.2 Division of runoff reference period

Based on the continuous measured runoff data from Kuangmenkou Station from 1959 to 2015, Mann-Kendall and Pettitt methods were used to perform mutation tests, and the results as shown in Figures 1 and 2.

![Figure 1. Mann-Kendall mutation test.](image)

![Figure 2. Pettitt test.](image)

It can be seen from Figure 1 that the intersection of the UF and UB curves in the Mann-Kendall test results is from 1977 to 1978, and the abrupt point of annual runoff at the Kuangmenkou Hydrological Station are around 1978. As can be seen from Figure 2, the minimum value of the Pettitt test occurred
in 1978 and \( P = 0.0467 \). Therefore, the mutation point of the annual runoff at the Kuangmenkou Hydrological Station was 1978, and the mutation passed the 5% significance level test, and the mutation was significant.

According to the results of Mann-Kendall and Pettitt method, 1978 was selected as the abrupt change point of annual runoff sequence from 1959 to 2015. The abrupt point divides the annual runoff time series into a runoff reference period (1959-1978) and a change period (1979-2015).

4.3 Attribution analysis of runoff changes based on VIC model
The annual runoff sequence of the base period is selected to construct a VIC model of the runoff simulation of the Kuangmenkou Station during the base period and adjust the parameters of the VIC model. In the VIC model parameter calibration process, considering the effect of the model's state variables on the simulation values, 1959 was set as the model's warm-up period, 1960-1969 was set as the model's calibration period, and 1970-1978 was the validation period of model parameters.

The simulated and measured values of the model are compared, and the NSC coefficient is used as the objective function of the calibration and verification parameters, and the relative error \( R_e \) is calculated. If the NSC coefficient is higher, it means that the analog value is more consistent with the measured value. Table 1 shows the comparison results between the measured values of the monthly runoff and the model simulation values of Kuangmenkou Station from 1960 to 1979.

| station    | Monthly runoff | Annual average runoff |
|------------|----------------|-----------------------|
|            | 1960-1969      | 1960-1969             | 1970-1978            | 1970-1978            |
|            | Nsc \( \ ) Re (\%) | Nsc \( \ ) Re (\%) | Nsc \( \ ) Re (\%) | Nsc \( \ ) Re (\%) |
| Kuangmenkou| 0.92 -2.62     | 0.86 0.59            | 0.91 1.08           | 0.82 6.03           |

It can be known from table 1 that the objective function and relative error of the VIC model both reached above 0.80 and below 10% required by the model. Therefore, the VIC model is more reasonable to restore the runoff process during the changing period of Kuangmenkou Station. The model has high applicability and credibility in the research area.

According to the VIC model constructed in the reference period, combined with relevant data, the monthly runoff data on the Kuangmenkou Station in the changing period were simulated. Evaluate the response value of the runoff from the Kuangmenkou station to environmental changes during the changing period, and the specific calculation results as shown in table 2.

| Period        | 1959-1978 | 1979-2015 |
|---------------|-----------|-----------|
| Measured runoff average (mm) | 108.32 | 51.99 |
| Simulated runoff average (mm) | 96.95 | |
| Total added value of runoff (mm) | -56.33 | |
| Contribution of climate change(mm) | -11.37 | |
| Contribution of human activities(mm) | -44.96 | |
| Contribution rate of climate change (%) | 20.2 | |
| Contribution rate of human activities (%) | 79.8 | |

It can be known from table 2 that the amount of change in runoff is negative during the change period, which indicates that changes in the underlying surface caused by human activities have reduced the productivity of the river basin. The contribution rate of human activities to the reduction of interval runoff from 1979 to 2015 was 79.8%, and the contribution rate of climate change to the reduction of interval runoff during this period was 20.2%. During 1979-2015, the impact of human activities on runoff was dominant.

5. Conclusions
(1) The annual runoff at Kuangmenkou Station shows a significant downward trend. According to the Mann-Kendall mutation test, the runoff mutation point is from 1977 to 1978, and the Pettitt test
mutation point is 1978. Based on comprehensive judgment analysis, the mutation year is determined to be 1978. 1959-1978 was used as the reference period for the Kuangmenkou runoff time series.

(2) During the base period, the objective function is controlled above 0.80, and the absolute value of relative error is controlled within 10%. Therefore, the VIC model is more reasonable to restore the runoff process during the changing period of Kuangmenkou Station. The model has high applicability and credibility in the research area.

(3) Quantitatively analyze the impact of human activities and climate change on runoff based on the VIC model to simulate the runoff process during the changing period. From 1979 to 2015, the runoff change at the Kuangmenkou Station on the Qingzhang River was greatly affected by human activities. The impact of human activities on runoff reduction was 79.8%.

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