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Applicability of the HBV model to a human-influenced catchment in northern China

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ABSTRACT

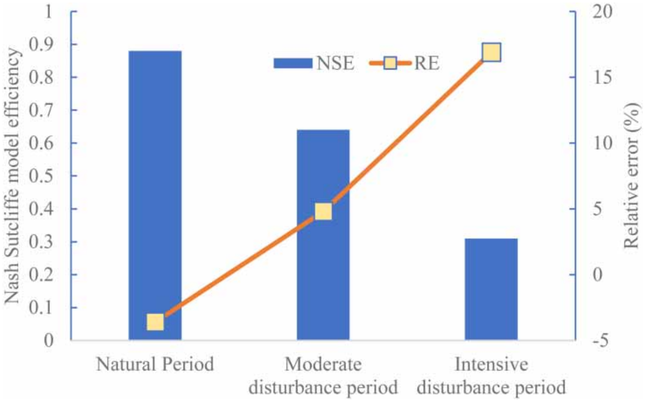
The Hydrologiska Byrans Vattenbalansavdelning (HBV) model is a catchment hydrological model that has been widely applied to hundreds of catchments worldwide. Taking the Nanjuma River Basin which is located in a semi-arid climate zone and has been highly regulated by human activities, as a case, the applicability of the HBV model to the basin was investigated. Results show that (1) due to environmental change, recorded stream flow of the Nanjuma River presented a significant decreasing trend, and the relationship between runoff and precipitation was changed as well, with the correlation coefficient decreasing from 0.58 in the natural period of 1961–1979 to 0.01 in a highly regulated period of 2000–2018. (2) The HBV model performs well on daily and monthly discharge simulation for the natural period with the Nash–Sutcliffe efficiency (NSE) coefficients in calibration and validation periods of 0.63 and 0.81 for daily discharge simulation. (3) The HBV model's applicability would like to decrease when the Nanjuma River Basin was moderately and intensively regulated by human activities. The daily-scale NSEs in moderate-disturbance and intensive-disturbance phases are 0.42 and −0.3, which means the HBV model almost lost its capacity in capturing hydrological features for a highly regulated catchment.

Key words: applicability, environmental change, HBV model, hydrological modeling, Nanjuma River catchment

HIGHLIGHTS

- Data series was divided into three segment phases: natural, moderate human disturbance, and intensive human-disturbance phases based on hydrological features.
- The HBV model can well simulate hydrological processes in the natural phase. Applicability of the HBV model tends to decrease when the catchment has been highly regulated by human activities.

GRAPHICAL ABSTRACT



INTRODUCTION

With rapid socioeconomic development, domestic water demands have largely increased since the 1980s, particularly in arid areas (Liu *et al.* 2019). As a result, the observed stream flow has declined significantly in most rivers in dry climate regions (Wang *et al.* 2020). Meanwhile, both land use change induced by intensive human activities, and climate change in the context of global warming, have complicated runoff yield mechanisms and altered the hydrological cycle (Zhang *et al.* 2014; Sohoulande Djebou 2015). Environmental changes are challenging hydrological modeling and forecasting, as well as water resources management efforts (Guan *et al.* 2019; Liu *et al.* 2021a, 2021b). The mechanism of climate change and water use altering ephemeral rivers in (semi-)arid regions is, therefore, treated as one of the 23 Unsolved Problems in Hydrology (UPH) identified by the IAHS (International Association of Hydrology Sciences) community (Blöschl *et al.* 2019). Mathematical models can help to understand the impact mechanism of environmental change on the hydrological process under different land use scenarios (Bao *et al.* 2019; Song *et al.* 2020). However, previous studies indicated that hydrological models have a certain regional suitability due to differences in model structure, and runoff yield mechanisms (Rosero *et al.* 2009; Guan *et al.* 2019). It is, therefore, important to test a model's performance for a specific region before its application to support efforts such as flood control, water allocation, and drought relief.

As a conceptual hydrological model, the HBV (Hydrologiska Byrans VattenbalansavdeIning) model has been applied to hundreds of catchments all over the world (Bergström 1992; Engeland & Hisdal 2009; Dakhlaoui *et al.* 2012; Wu *et al.* 2017; Huang *et al.* 2019; Osuch *et al.* 2019), including the Huai River Basin in eastern China. The basin's runoff yield is mainly based on the mechanism of saturation excess (Li *et al.* 2012; Xu 2021). Zhao *et al.* (2007) applied the HBV model to the Guanzhai River, a tributary of the Huai River, and found that it simulated rainfall–runoff process well with the Nash–Sutcliffe model efficiency (NSE) coefficient over 0.75. Based on the discharge–stage relationship, the HBV model was used to determine the critical rainfall threshold of flash floods for the upper reaches of the Huai River (Lu & Tian 2015). Rainfall and snowfall are two types of precipitation in cold areas of northeastern China. The mechanism of runoff yield in cold regions is more complex than that in southern China because it needs to consider runoff generation from rainfall and snowmelt (Stewart 2010). Zhang *et al.* (2007) and Wu *et al.* (2017) tested the performance of the HBV model for discharge simulation of the Naoli River and the Mudan River in northeastern China, where communities are frequently threatened by both ice floods in the spring and storm floods in the summer and autumn. They found that the HBV model was effective in simulating discharge on both daily and monthly scales for these two river basins, with NSEs over 0.8 in most cases. China's coastal areas in the southeast are subject to high-intensity rainfall and frequent floods. The HBV model has also proved to be applicable to these areas according to the work by Hu *et al.* (2008) and Wang *et al.* (2014) .

Numerous studies indicate that the HBV model is applicable to catchments in different climatic zones (Zhao *et al.* 2007; Hu *et al.* 2008; Yang *et al.* 2010; Dakhlaoui *et al.* 2012; Wu *et al.* 2017). However, most case studies of the HBV model application employed a very consistent data series that was only slightly influenced by human activities (Vormoor *et al.* 2018; Jin *et al.* 2019). Due to the effects of intensive human activities, hydrological processes in arid or semi-arid regions have changed significantly (Sun *et al.* 2019; Yan *et al.* 2020; Guan *et al.* 2022). It is critical to evaluate the performance of the HBV model for widening its application. We took the Nanjuma River, located in a semi-arid region of China, as a case study to investigate hydrological changes of the river basin under a changing environment, and to evaluate the performance of the HBV model in different human-disturbance scenarios. The findings will provide strong support to improve capacity building of early warning, forecasting, rehearsing, and pre-scheming in flood control.

DATA SOURCES AND METHODOLOGY

The study river basin

The Nanjuma River originates from Tiesuoya Mountain, flows through Yi County and Dingxing County and joins the Baigou River in Baigou Town, Gaobeidian, Hebei Province, forming the Daqing River, one of the major tributaries of the Hai River. The Nanjuma River Basin covers a drainage area of 2,157 km^2, bordered by the Cao River and Pu River in the south and the Beijuma River in the north. Influenced by the temperate continental monsoon, the climate of the basin is characterized by hot and rainy summers and autumns, and cold and dry winters and springs.

The Nanjuma River catchment is a highly developed agricultural area, where several large-scale irrigation regions exist, namely the Juyue irrigation region, Fanglaizhuo irrigation region, Caijiajing irrigation region, etc., with a total irrigation area of approximately 12,330 km^2. The irrigated area in the river basin reached its peak in the 1990s. As of 2021, 20 reservoirs have been constructed on the river and its tributaries for water supply and irrigation since the 1960s, including large and medium-sized reservoirs such as the Angezhuang Reservoir, Wanglong Reservoir, and Matou Reservoir, with a total capacity of 0.33 billion m^3. Most of the reservoirs were reinforced and put into regular operation after the 1970s.

The Beihedian station is an outlet hydrometric station of the Nanjuma River. The river basin above the station is segmented into 12 sub-basins for dealing with spatial heterogeneity in climate, soil, and underlying surface. Daily meteorological data, including air temperature and precipitation, from 1961 to 2017 gauged at five stations, i.e., Laiyuan, Xiayunling, Fangshan, Yi County, and Zhuozhou, were collected from the China Meteorological Administration, and interpolated into the 12 sub-basins using the Kriging method (Wang *et al.* 2007). River systems of the Nanjuma River and locations of hydro-meteorological stations are shown in Figure 1.

According to the observations of hydro-meteorological variables, the average annual temperature is approximately 8.7 °C. The average annual precipitation is less than 500 mm, with 75% of the falls in the flood season from June to September. Meanwhile, the annual precipitation shows high inter-annual variability, with a ratio of the maximum value to the minimum value exceeding 3.0.

Description of the HBV model

The HBV model, developed by the Swedish Meteorological and Hydrological Institute (SMHI), is often used in discharge simulation, flood forecasting, and assessment of environmental change (Deckers *et al.* 2010; Chen *et al.* 2012; Tian *et al.* 2013). The model can simulate stream flow for a small-scale catchment as a lumped hydrological model. It also can be applied to distributed hydrological simulation for a large-scale river basin by dividing the catchment into sub-basins using the DEM (digital elevation model). The HBV model consists of the following four kernel modules: snow melting, soil moisture calculation, hydrological response, and flow routing. Compared with other hydrological models, the HBV model has the advantages of a simple structure, relatively few parameters, a physically based mechanism of runoff yield, and ease of application (Liu *et al.* 2021a, 2021b). The model inputs include daily precipitation, air temperature, and potential evaporation (often substituted by the observed E601 evaporation). The model outputs include the simulated daily rainfall–runoff process of each sub-basin, and the simulated discharge at the outlet hydrometric station of the study basin.

Based on the simulated and observed discharge, the NSE coefficient and relative error (RE) of mean runoff are used to evaluate the model's performance. The NSE ranges from '1' to negative infinity, with the best simulations having an NSE approaching 1 (Nash & Sutcliffe 1970). The NSE is defined as:

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n} (Q_{oi} - Q_{si})^2}{\sum_{i=1}^{n} (Q_{oi} - Q_{\mathrm{m}})^2}$$

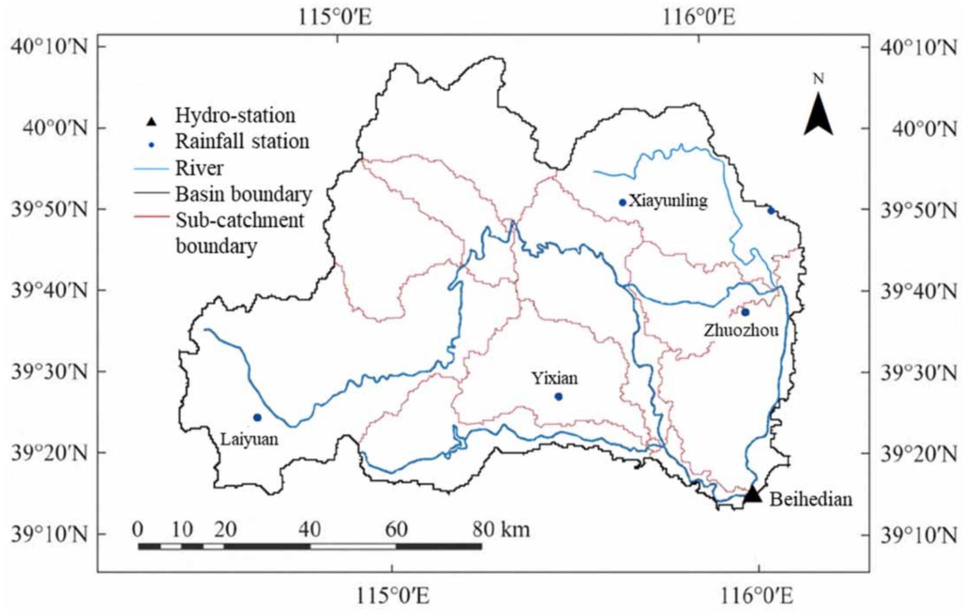


Figure 1 | River systems of the Nanjuma River and locations of hydro-meteorological stations.

where NSE is the Nash–Sutcliffe model efficiency coefficient, Q_{oi} is the observed runoff, Q_{si} is the simulated runoff, Q_{m} is the mean of observed runoff, and n is sample number.

Mann–Kendall test

Influenced by changes in climate and human activities, data series of streamflow may vary with time while presenting a certain tendency. It is of importance to detect the variation trend of hydrological series for understanding the impact of human activities. The Mann–Kendall (M–K) nonparametric trend test (M–K method) is a commonly used method to detect the variation trend of time series (Mann 1945; Wang *et al.* 2013). Based on an assumption of stability of a time series, the method does not require the samples to follow a certain statistical distribution. The defined M–K statistic approximately follows a standard normal distribution with a positive/negative value indicating an increasing/decreasing trend. A significant variation trend is detectable when the absolute M–K statistic is greater than 1.96 at the significance level of 0.05.

RESULTS AND DISCUSSION

Variation of hydro-meteorological elements in a changing environment

Variations of catchment average annual precipitation and observed runoff at the Beihedian station from 1961 to 2017 are given in Figure 2. Figure 2 shows that (1) both the annual precipitation and annual runoff presented declining trends from 1961 to 2017 with linear trends of −0.69 and −0.93 mm/a, respectively. (2) In comparison with the annual precipitation, the observed annual runoff showed a large variability with the maximum of 493 mm occurring in 1996 and the flow dried up in 2002–2003, 2007–2008, 2010–2011, and 2015. The ratio of the maximum precipitation (in 1973) to the minimum (in 1965) is about 2.87. The M–K test results indicate that the annual runoff exhibited a significant decreasing trend with the M-K value of −5.48 while the decreasing trend in the annual precipitation is insignificant (with the M-K value of −0.99) at the confidence level of 0.05.

According to the variation in annual runoff, the data series could be roughly divided into three phases: 1961–1979, 1980–1999, and 2000–2017. The first phase can be characterized as a natural alternation of wet and dry in the annual runoff, where the runoff varies from 400 to 100 mm. Runoff in the second phase shows a more considerable disparity and variability, ranging from 500 to 20 mm. The third phase has a steady low stream flow with an annual runoff under 30 mm in all years and zero flow in several years.

Previous studies show that the Hai River Basin has been increasingly influenced by human activities since the late 1970s (Bao *et al.* 2012; Yan *et al.* 2020). The Hai River Basin could be treated as a quasi-natural state before 1980 as it was only slightly influenced by human disturbance. After 1980, the recorded runoff gauged at key hydrometric stations on the Hai

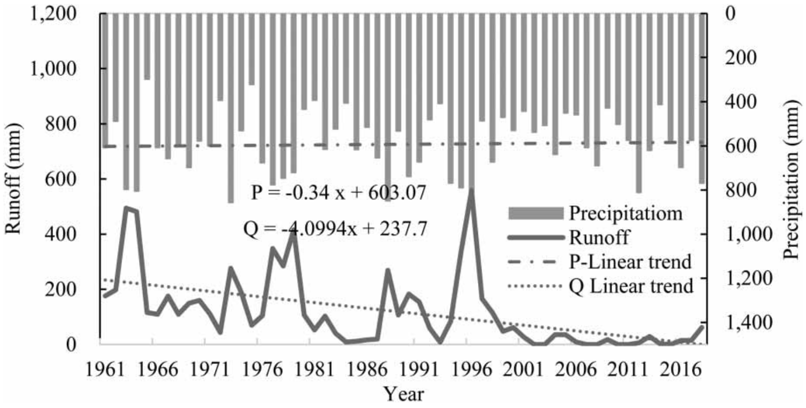


Figure 2 | Rainfall–runoff processes from 1961 to 2017 for the Nanjuma River Basin.

River decreased by more than 50% relative to the previous period while the precipitation approximately reduced by 10% (Wang *et al.* 2020). The sensitivity analysis indicated that a 10% change in precipitation will lead to an 18–25% change in the runoff the for Hai River basin (Wang *et al.* 2017), which is much lower than the observed runoff reduction, illustrating a huge human influence on stream flow in the 1980s and beyond.

From the features of runoff processes in Figure 2, the following three phases can be defined: natural phase (1961–1979), moderate human-disturbance phase (1980–1999), and intensive human-disturbance phase (2000–2017). The relationships between precipitation and runoff in different phases are shown in Figure 3. It can be seen from Figure 3 that the observed runoff highly correlates with precipitation in the first and the second phases in a nonlinear manner, while the runoff weakly correlates with precipitation in the third phase. Statistical results show the Spearman correlation coefficients of precipitation and runoff in the three stages as 0.58, 0.40 and 0.01, respectively. The points of a runoff against precipitation in the first phase scatter in the upper area of the figure while those in the second and third phases are in the lower areas, which means runoff yield in the natural phase is much higher than that in the moderate and intensive human-disturbance phases for the same precipitation situation, implying runoff reduction due to impact of human activities.

Hydrological modeling in different human-disturbance phases

To evaluate the performance of a hydrological model, a data series with good consistency and longer time span covering at least 7–8 consecutive years is needed (Guan *et al.* 2019). Previous analysis shows that the consistency of the recorded

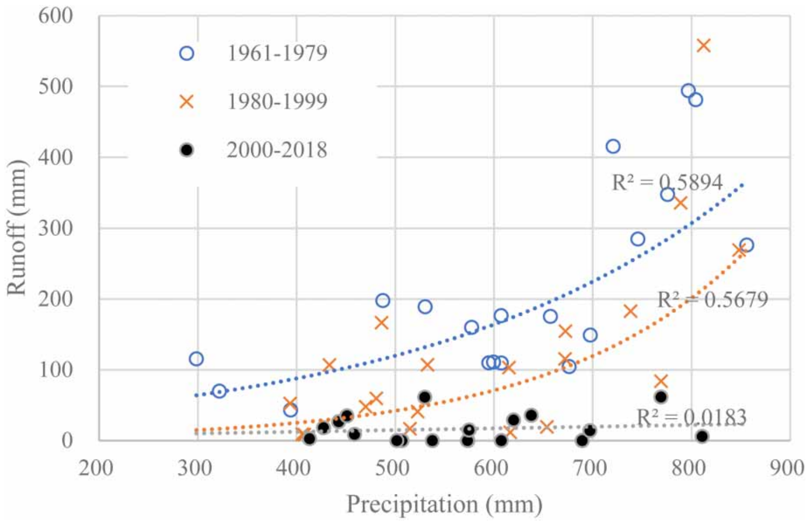


Figure 3 | Precipitation–runoff relationship during different periods in the Nanjuma River.

discharge series of the Nanjuma River Basin from 1961 to 2017 was destroyed due to environmental changes. We, therefore, calibrated the HBV model based on the three segment phases identified in Section 2.1. For the data series of each segment phase, the first year is taken as the warm-up period to minimize the effect of the initial state condition, which is usually given based on expert knowledge. The data in the last 3–5 years are usually used to validate the model. The rest of the data series is used for model calibration. The calibration and validation periods of each segment data series are given in Table 1.

We took the NSE as the objective function. The model parameters under different human influences were calibrated and are given in Table 2. The model performance on discharge simulation is statistically given in Table 3.

Table 2 shows that the calibrated model parameters in the first natural phase are close to those in the second period in which human activities moderately influenced hydrological processes. However, there is a large difference between parameters in the natural phase and those in the third phase when intensive human activities strongly influenced the stream flow.

Table 3 indicates that (1) the HBV model performs better on monthly discharge simulation than on daily discharge simulation. The NSEs on monthly scale are much higher than those on the daily scale for all three phases. (2) The HBV model works the best on discharge simulation in the first phase when the catchment was in the quasi-natural state. Both daily-scale NSEs in the calibration and validation periods exceed 0.6, while monthly-scale NSEs in both periods are 0.88 and 0.71, respectively. The relative errors of simulations in the calibration and validation periods are quite small, −3.6 and 2.7%, respectively, representing a good performance of the HBV model in the Nanjuma River. (3) The HBV model is acceptable for discharge simulation with daily-scale NSEs over 0.45 and monthly-scale NSEs over 0.55 when the catchment was moderately influenced by human activities, but the RE of simulations is larger than those in the natural state. (4) The HBV model

Table 1 | Definition of calibration and validation periods for the three different human-disturbance phases of the study basin

Phase definition	Description	Warm-up period	Calibration period	Validation period
1961–1979	Natural state	1961	1962–1974	1975–1979
1980–1999	Moderate human influence period	1980	1981–1994	1995–1999
2000–2017	Strong human influence period	2000	2001–2012	2013–2017

Table 2 | Description of the HBV model parameters and the optimized parameters for the three segment phases of the Nanjuma River Basin

Parameters	Description	Range of parameters	1961–1979	1980–1999	2000–2017
BETA	Soil index	0.5–6	2.6	2.4	2.4
KUZ2	Outflow coefficient of the lower storage	0.05–0.1	0.067	0.053	0.05
UZ1	Threshold value of surface runoff	0–100	5.68	4.79	7.8
KUZ1	Outflow coefficient of the upper storage	0.01–1	0.026	0.019	0.01
PERC	Maximum infiltration rate.	0–100	3.00	12	37
KLZ	Water retention coefficient	0–0.8	0.007	0.04	0.32

Table 3 | Performance of the HBV model on daily and monthly discharge simulation under different human disturbances in the Nanjuma River Basin

Data series		1961–1979		1980–1999		2000–2017	
Description		Natural state		Moderate human influence		Strong human influence	
Periods		Calibration	Validation	Calibration	Validation	Calibration	Validation
NSE	Daily scale	0.81	0.63	0.51	0.48	0.14	−0.21
	Monthly scale	0.88	0.71	0.64	0.57	0.31	0.17
RE (%)		−3.6	2.7	4.8	17.9	16.9	27.8

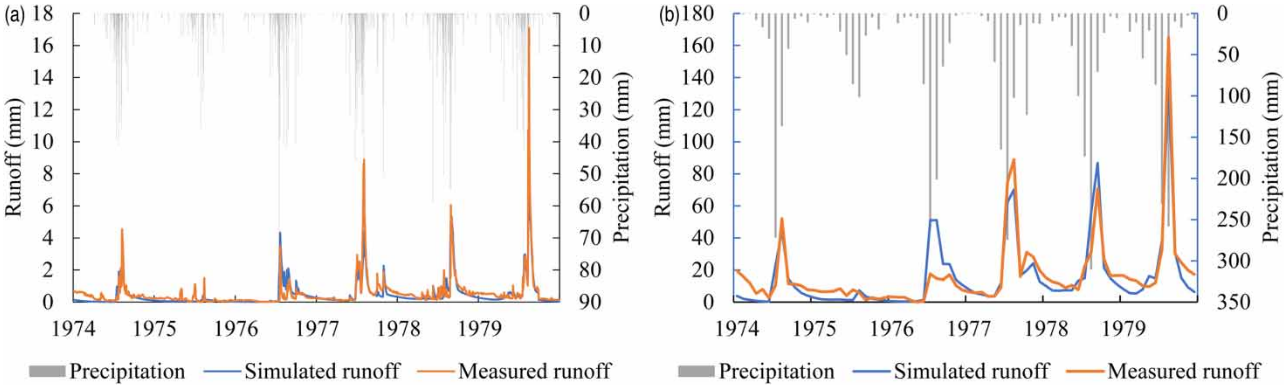


Figure 4 | Observed and simulated discharges at daily scale (a) and monthly scale (b) from 1974 to 1979 at the Beihedian station.

has a mediocre performance for simulating hydrological processes on both daily and monthly scales when the catchment was strongly disturbed by intensive human activities. In the period 2000–2017, NSEs on both daily and monthly scales are quite small and even below zero while REs are beyond 15%. It is also found that the HBV model overestimates discharge when the catchment was moderately or strongly influenced by human activities.

The daily-scale NSEs in the calibration period (1961–1974) and validation period (1975–1979) of the natural phase are 0.81 and 0.63, respectively. For further evaluation of the HBV model, performance on discharge simulation in dry years and wet years during the natural phase, the recorded and simulated discharges on daily and monthly scales from 1974 to 1979, which covers 1 year in the calibration period and all years in the validation period (NSE is relatively low), were plotted and are shown in Figure 4.

Figure 4 shows that the hydrographs of observed and simulated runoff fit nicely on daily and monthly scales, which means the HBV model performs well for discharge simulation in the natural phase. The HBV model may overestimate or underestimate peak discharge while low flow is generally underestimated with the exception of that in several dry months. In addition, the absolute simulation error of high discharge is higher than that of low discharge, but the RE of high-flow simulation is relatively low with comparison with that of low-flow simulation. However, an NSE is sensitive to simulation of high flow. A good simulation of high flow can effectively increase the NSE.

To evaluate the applicability of the HBV model in the moderate and intensive human-disturbance phases, the monthly simulated and recorded runoffs at the Beihedian station during 1980–2017 were calculated and are shown in Figure 5. The results show that (1) only several peak discharges were observed during 1980–2017. The HBV model can simulate

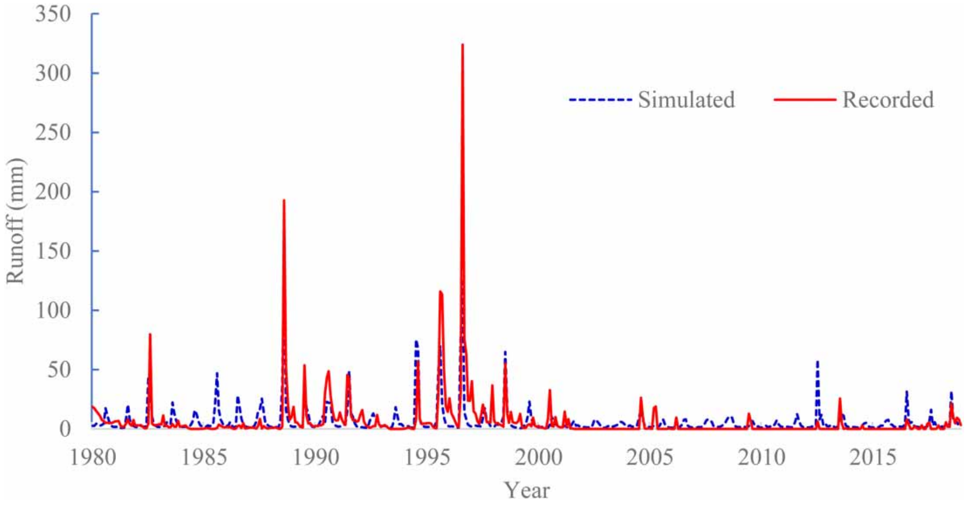


Figure 5 | Monthly simulated and recorded runoff at the Beihedian station from 1980 to 2017.

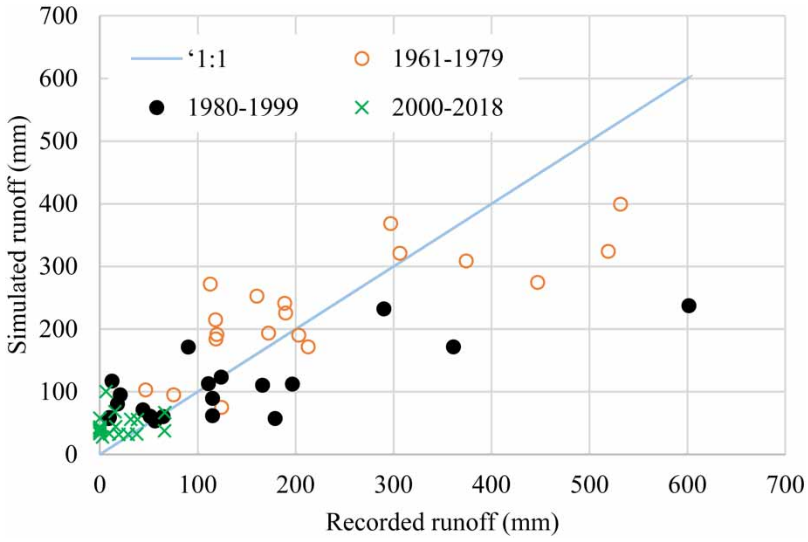


Figure 6 | Scatter of the recorded annual runoff against the simulated runoff for three different human-disturbance phases.

these peak discharges although these are largely underestimated for most cases. (2) In most of the years during 1980–2017, the HBV model reproduced peak discharges but they were not observed at the outlet station, particularly in the period after 2000, which means rainfall yielded runoff in the study basin, but the peak discharge did not appear at the outlet hydrometric station due to too much water withdrawal in the upper stream (Xu 2021).

The scatter of the recorded annual runoff against the simulated runoff are shown in Figure 6. The results indicate that (1) for the three phases, high flows (>300 mm) were underestimated while low flows (<100 mm) were overestimated in most cases. (2) The points of the recorded runoff against the simulated runoff were scattered around 1:1 line for the first phase of 1961–1979 which means the HBV model can simulate hydrological processes well when the basin was in the natural state. (3) For the second and third phases, the points are far away from the 1:1 line, and most of points in the third phase are above 1:1 line, which indicates that the HBV model poorly simulates discharge when a river basin is highly regulated by human activities.

DISCUSSION

The model structure can influence model performance for flow simulation (Kaleris & Langousis. 2017). Most HBV model applications are in cold regions because the model considers both mechanisms of runoff generated by rainfall and snowmelt (Lindström *et al.* 1997; Seibert 1997; Xu 1999; Ali *et al.* 2018). The Nanjuma River Basin is located in northern China where the temperature varies from −12 to 30 °C (Figure 7). Precipitation in the basin comes either as rainfall or snowfall, depending on whether the temperature is below or above 0 °C. Runoff yields in the basin, therefore, include both mechanisms of rainfall–runoff and snowmelt runoff, which are well considered in the structure of the HBV model (Engeland & Hisdal 2009). As a result, the HBV model simulates discharge well when the river basin under study was in the natural state.

The Nanjuma River Basin is in the East Asian Monsoon climate zone. Most of the high flows in the basin result from torrential rain in flood seasons, which often occurs abruptly and is highly heterogeneous in distribution in space. The density of rain gauges can influence model performance to some extent (Tegegne *et al.* 2017). Although the selected five meteorological stations are evenly distributed in the study basin and can monitor most of the large-scale rainfall information all over the catchment, it may miss local rainstorm information in some cases. It is, therefore, essential to increase the density of the hydrological monitoring network and acquire more information based on remote sensing, radar monitoring, etc., to improve the accuracy of peak discharge simulation in semi-arid regions.

The low flow in dry seasons mainly consists of subsurface flow and baseflow, which are generated from unsaturated and saturated soil zones. In this study, the NSE was taken as the objective function to calibrate the HBV model. Previous studies show that the accuracy of high-flow simulation can affect the NSE value to some extent (Guan *et al.* 2019). The NSE will

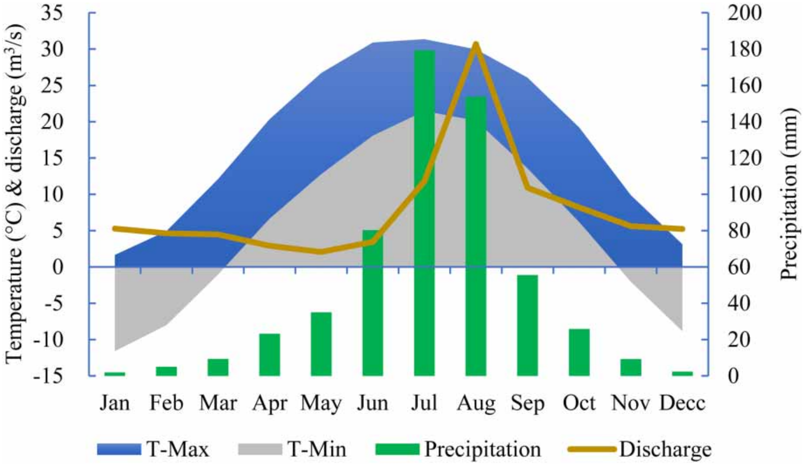


Figure 7 | Seasonal patterns of multiple-year average precipitation, runoff, maximum and minimum temperatures based on data series from 1961 to 2017.

probably be high when high flows are well simulated, while the NSE is not sensitive to changes in the accuracy of low-flow simulation. It is essential to select a suitable objective function if we take low flow as a focus.

Regional climate, topography, as well as human activities can also influence model performance for flow simulation. Numerous studies indicated that hydrological models perform better for the humid catchments than for the arid catchments, while hydrological modeling for plain catchment is a greater challenge than for mountain catchment (Yang *et al.* 2000; Wang *et al.* 2006; Vilaseca *et al.* 2021). In addition, intensive human activities make the mechanism of runoff yield more complex and thus change the hydrological regime (Liu *et al.* 2021a, 2021b). In this study, due to the influence of human activities, the HBV has been increasingly losing its capacity to capture real features of hydrological processes (Figure 7). It is urgent to enhance the research on mechanisms of human impact on hydrology to improve hydrological modeling and forecasting in a changing environment.

Environmental changes, particularly intensive human activities, are challenging the hydrological modeling. It may be helpful to strengthen the capacity of the HBV model in hydrological modeling by improving the model structure, selecting suitable objective functions, and using data from multiple sources. However, it is critical to quantify impacts of human activity and incorporate the quantified impacts in further studies.

SUMMARY AND CONCLUSIONS

In this study, taking the Nanjuma River Basin, a human-disturbed catchment, as a study case, we analyzed changes in the hydrological regime of the river basin under a changing environment, and investigated performance of the HBV model in different situations of human disturbances. Results can be concluded as follows:

The recorded streamflow decreased significantly under the influence of climate change and human activities. Characteristics of runoff variation and human activities in the river basin suggest the data series could be divided into three phases: the quasi-natural period from 1961 to 1979, the moderate human-disturbance period from 1980 to 1999, and the intensive human-disturbance period from 2000 to 2017.

The HBV model has a good performance in simulating hydrological processes on daily and monthly scales when the Nanjuma River catchment was in a natural state. The NSEs in both the calibration and validation periods are above 0.63 and the RE of simulation is less than 5%. Relatively, the model performs better in monthly discharge simulation than in daily discharge modeling.

The HBV model is acceptable for discharge simulation when the catchment is moderately influenced by human activities although the RE of simulation is greater than that in the natural state. The HBV model almost totally lost its capacity to capture hydrological features when the catchment was intensively regulated. It is, therefore, of great importance to study hydrological modeling under a changing environment in further study for supporting operational flow forecasting and water resources management.

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AUTHOR CONTRIBUTIONS

Yu.W. did formal analysis and wrote the original draft; Yanj.W. and Z.B. conceptualized and prepared methodology; J.J. and Yan W. did data curation and software analysis; Q.J. and X.D. led discussions and gave suggestions; C.L. and G.S. collected data and edited the article.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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