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| | | | 霍林河流域径流量变化及驱动机制研究 | 内蒙古师范大学创新基金项目 | 王晓珍, 夏莹莹, 王娜, 于本金 | 是 | 2020.5-2021.12 | 项目主要采用月、年及年代际等不同时间尺度，研究霍林河流域气候过程，通过对流域的气象数据分析，探讨以霍林河流域为例的干旱 - 半干旱地 区的气候变化的规律和趋势。对在全球环境变化的背景下我国北方生态脆弱地区气候的变化具有重要的意义。 |

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# Quantitative impacts of climate change and human activities on runoff in the Huolin River catchment

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## ABSTRACT

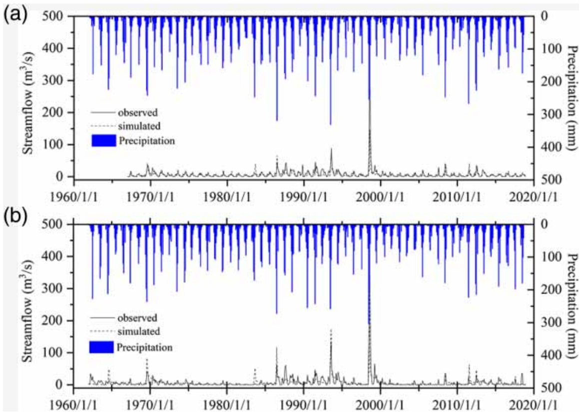
The Huolin River is located in the monsoon marginal zone in Northeast China. It is an important source of the wetland system on the Northeast Plain. Recently, a dramatic reduction in the observed river runoff has resulted in a record high level of dried-up days in the Huolin River catchment (HRC). In this study, we used the hydrological simulation approach of the Soil and Water Assessment Tool (SWAT) model to evaluate the influences of climate change and human activities on runoff in the HRC. The SWAT model effectively simulated the streamflow changes in the HRC with a high accuracy. The $R^2$ values were 0.71 and 0.69 for the calibration and validation periods, respectively. In addition, the Nash-Sutcliffe efficiency (NSE) index reached 0.69 and 0.66 for the calibration and validation periods, respectively. The simulation results demonstrated that the variations in runoff have mostly been caused by combined influence of climate change and land use/land cover (LULC) changes, but the contributions of these factors varied in each period. The climate factors contributed 84.5% of runoff fluctuations before 2000, while the effect of LULC changes gradually grew to 63.6% after 2000. The increase in the influence of LULC changes was mainly apparent in the considerable growth of the areas of the arable land and construction land, which increased by 607 and 113 $km^2$, respectively. This study provides an effective scientific basis for establishing long-term water management in catchment scale and regional social and economic development under the changing environment.

**Key words:** land use/land cover, semi-arid region, SWAT model, water shortage

## HIGHLIGHTS

- The SWAT model has strong feasibility and applicability in monthly runoff simulation of the HRC.
- Climate change played a dominant role in the runoff variation in the HRC before 2000.
- The decrease in runoff in HRC is the result of a combination of climate change and human activities.

## GRAPHICAL ABSTRACT



## 1. INTRODUCTION

Water resources are the most precious and irreplaceable natural resources in the world. Water is essential for maintaining human society and natural environmental systems, and it is also a vital link between them (Pedro-Monzonís *et al.* 2015; Milly *et al.* 2018; Pokhrel *et al.* 2021). Recently, it has been established that the uneven distribution of water resources has produced environmental challenges such as regional water shortages, increased dried-up days and frequent droughts (Su *et al.* 2018; Martin *et al.* 2020; Amiri & Gocic 2021a). In addition, the conflict between supply and demand for water resources has become more prominent, leading to the vulnerability and uncertainty of ecosystems (Haddeland *et al.* 2013; Li *et al.* 2021). For example, China's total freshwater volume is $2.81 \times 10^{12}$ $m^3$, ranking sixth in the world. Although the total volume is large, the water resources per capita are only 25% of the world average (Piao *et al.* 2010). The distribution of water resources in China, a 'less in the north and more in the south' pattern, does not match the distribution of population, arable land, minerals, and economic development (Zhang *et al.* 2015). Under global warming conditions, the frequency and intensity of floods and drought directly linked to water resources gradually increase, and the situation will be more severe in the future, especially in northern China (Sheffield *et al.* 2012; Dai 2013; Su *et al.* 2018; Gu *et al.* 2020). This could adversely influence the expected effects of important projects such as grain production in northern and northeastern China, the South–North Water Transfer Project and the ecological restoration and construction of national watersheds (Jiang 2009; Nakayamaa & Shankman 2013; Xu *et al.* 2020).

River runoff is an important component of the hydrological cycle, and runoff variations have a considerable impact on water resources (Tao *et al.* 2003; Yan *et al.* 2017). According to earlier studies, river runoff in many parts of the world has exhibited a significant decreasing trend (Huang & Zhang 2004; Dai *et al.* 2009; Martin *et al.* 2020) and 60% of rivers in the world cease to flow for at least 1 day per year (Messager *et al.* 2021). It is well accepted that climate change coupled with intensive human activities has directly and indirectly affected runoff (Huntington 2006; Dai *et al.* 2009; Haddeland *et al.* 2013). Precipitation is the principal runoff replenishment source, and its frequency, intensity, and distribution directly affect the amount of runoff (Zhang *et al.* 2011; Amiri & Gocic 2021b). A change in precipitation of 1% will result in a change in runoff of 1.3% in northern China (Lu *et al.* 2013). Temperature affects runoff through two approaches. Warming can increase runoff through melting of permafrost and glaciers, in cold regions; however, the increase in temperature also enhances catchment evapotranspiration, thus reducing runoff (Cao *et al.* 2011; Milly *et al.* 2018; Gocic & Amiri 2021). This is also one of the main reasons for the decrease in runoff in arid regions. Certainly, rainfall–runoff processes are also largely regulated by surface conditions such as vegetation, antecedent soil moisture, and geographic location (Berghuijs *et al.* 2016; Manoj *et al.* 2022). Although many studies have emphasized the importance of these factors in hydrological processes, the understanding of these effects is still limited due to regional differences. Land use/land cover (LULC) changes such as afforestation/deforestation, urbanization, and wetland reclamation have led to increased extreme hydrological events. Other human activities, for example, arable land expansion and urbanization, have also added to uncertainties in the vegetation and ecosystem structure changes (Li *et al.* 2018; Chen *et al.* 2019). Effective methods of controlling excessive human activity are still lacking. Given these trends, it is critical to quantify the amount of climate and anthropogenic contributions to watershed runoff change and to identify potential driving forces, which are integral to the development of sustainable management strategies.

Recent research has primarily used empirical statistics (Wang *et al.* 2012; Zhao *et al.* 2014), elasticity-based approaches (Li & Quiring 2021), and hydrological modeling (Farsi & Mahjouri 2019; Zhang *et al.* 2020) to examine the effects of climate and human impacts on runoff. Empirical statistical methods facilitate calculations, but the physical mechanisms of hydrological cycle events cannot be well represented (Wu *et al.* 2017). Elasticity-based approaches require an accurate estimation of the potential evapotranspiration; otherwise, the quantitative results will be adversely affected. The most promising technique for assessing the hydrological response is hydrological modeling, which provides a framework for understanding and predicting the relationships among climate change, human activities, and water resources. The different spatiotemporal scales of the underlying physical processes are represented in the models (Zeng *et al.* 2015; Wu *et al.* 2017). However, hydrological models have limitations such as their complex structure, time-consuming construction, and demand for a large number of input datasets. The Soil and Water Assessment Tool (SWAT) is one of the most commonly used distributed hydrological models. It is used to model ecological, hydrological, and environmental processes under diverse climatic and management settings (Gassman *et al.* 2007; Wu *et al.* 2013; Hovenga *et al.* 2016; Wang *et al.* 2017). The SWAT model has been applied to the analysis of runoff in cold and arid regions in northwestern China, and it has been determined that climate change had a greater impact on runoff than LULC changes, such as in the Tarim River (Li *et al.* 2021), Heihe River (Yang *et al.* 2016), and Jing River basins (Yin *et al.* 2017). In northeastern China, relevant research has revealed that LULC changes had a significant influence on river runoff in the Nenjiang River (Li *et al.* 2019), Huifa River (Zhang *et al.* 2012), and Naoli River basin (Liu *et al.* 2015). Given that climate change and human activities are the primary factors influencing runoff, the local conditions should be taken into consideration.

The Huolin River is a tributary of the Nenjiang River in northeastern China, which has become a typical betrunked river with drastically decreased runoff and an increasing frequency of dried-up days. Based on an examination of the average annual runoff, that the runoff is decreasing in the Huolin River catchment (HRC) (Bian *et al.* 2004; Dan *et al.* 2021). Wavelet function analysis also supported the declining trend in runoff and forecasted that the catchment will undergo a larger scale dry period over the next few years (Lu *et al.* 2005). The multi-timescale variability of runoff has been investigated that the dual actions of flow evolution of natural factors and human disturbances exerted influences of different degrees on the flow signals during different periods (Lu *et al.* 2006). Changes in the LULC and landscape patterns in the HRC have also garnered a great deal of attention (Lu *et al.* 2007, 2015; Li & Liu 2011, 2012; Zhang 2014). The relevant results indicate that land use types have exhibited different trends in the HRC, and the wetland landscape has become highly fragmented. Most studies have focused on the hydrologic response to climate change or land use change in the watershed. However, research on hydrological modeling and quantitative attribution is scarce in the study area. Therefore, hydrometeorological and land use data from different periods and hydrological models were used in this study to quantify how these changes affect the hydrology in the HRC. The objectives of this study were (1) to assess the applicability and reliability of the SWAT model in semi-arid regions and (2) to quantify the impacts of climate change and human activities on the hydrological changes in the HRC using the SWAT model. The novelty of this paper lies in the quantitative estimation of the contribution of climate change and human activities to runoff in the HRC. This research improves our understanding of runoff fluctuations in typical inland catchments and provides a reference for water resource management in semi-arid China.

## 2. MATERIALS AND METHODS

### 2.1. Study area

The HRC is located in northeastern China (119°18′–124°17′E, 44°55′–45°53′N). It has an area of 36,623 km$^2$ and accounts for ~12% of the Nenjiang River basin (Wu *et al.* 2018). The HRC can be divided into three sections based on the digital elevation model (DEM). The upstream section, with a maximum elevation of 1,422 m, is a primarily mountainous area covered in forests. The Tuleimaodu station is the outlet of the upstream runoff. The upstream section contains roughly 20 rivers with individual lengths of >10 km, including four primary tributaries (Table 1). The midstream section consists of hilly plains covered by grassland, and it contains two major tributaries. With a total area of 10,221 km$^2$, the upstream and midstream sections were taken as the study in this research (Figure 1). They are pastoral regions with a population density of approximately 22 people per km$^2$ by the end of 2018. The floodplain downstream below the Bayanhushu station has been significantly altered by human activities, and since there are no replenishing tributaries, the flow is drastically reduced and frequently dried up.

Since the HRC is situated in a semi-arid climate transition zone and a monsoon marginal zone (Dan *et al.* 2013), it is subject to the effect of the East Asian Summer Monsoon in summer, which brings heat and moisture; while it is subject to the Mongolian High Pressure System in winter, which brings dryness and cold. The average annual temperature of the catchment is 3.1 °C, its annual average precipitation is 385.5 mm, and its annual pan evaporation is 2,032 mm.

**Table 1** | Main tributaries of the Huolin River

| | Tributaries | Drainage area (km$^2$) | Length (km) | Stream gradient (‰) |
|---|---|---|---|---|
| Upstream | Kunduleng River | 3,878.4 | 198 | 3.02 |
| | Dundewusu River | 647.7 | 62.5 | 4. 91 |
| | Zhunzhelimu River | 424.2 | 44.8 | 7.37 |
| | Xieshengtu River | 423.9 | 43.9 | 6.04 |
| Midstream | Chaoertu River | 504.7 | 46.6 | 5.46 |
| | Emute River | 1,451.2 | 84.3 | 6.41 |

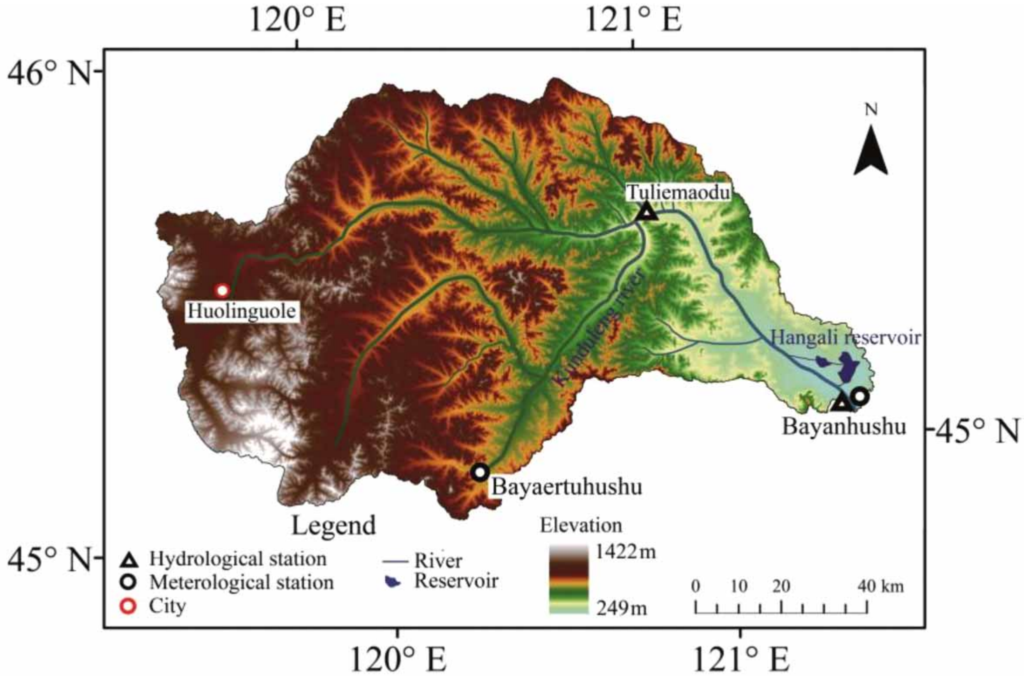



**Figure 1** | Meteorological and hydrological stations in the upstream and midstream of the HRC.

## 2.2. Methods

### 2.2.1. Model data input

The data required to run the SWAT model include meteorological, hydrological, landform, soil property, and LULC data (Table 2) (Gassman *et al.* 2007; Golmohammadi *et al.* 2014).

The SWAT requires daily precipitation and maximum/minimum air temperature data as meteorological inputs. The daily observed meteorological data at Bayaertuhushu and Bayanhushu stations were obtained from the Inner Mongolia Meteorological Bureau. The Bayaertuhushu station is located at the headwater of the Kunduleng River (Supplementary figure, Figure S1), which accounts for 70% of the Huolin River runoff and is the most important tributary in the catchment (Sun *et al.* 2015). The Bayanhushu station is located in a key position where the midstream and downstream sections meet. The meteorological data from these two stations can fully reflect the climatic processes in the catchment. The daily runoff data for Tuliemaodu and Bayanhushu stations, which are the outlets for the upstream and midstream sections, respectively, were obtained from the Inner Mongolia Hydrological Bureau.

**Table 2** | Data item and data source of the model

| Data type | Data name | Year | Data specification | Data source |
|---|---|---|---|---|
| Elevation data | DEM | 2009 | 30 m | http://www.gscloud.cn |
| Land use type data | Landsat TM image data | 1977, 1990, 2000, 2010, 2018 | 30 m | http://www.gscloud.cn |
| Soil type data | HWSD (version 1.1)<br>Inner Mongolia soil type map | 2009<br>1992 | 1:1,000,000<br>1:1,500,000 | http://data.tpdc.ac.cn |
| Meteorological data | Gauged daily temperature and precipitation data | 1960–2018 | Bayaertuhushu, Bayanhushu | Inner Mongolia Meteorological Bureau |
| Hydrological data | Gauged daily runoff data | 1967–2018<br>1956–2018 | Tuliemaodu<br>Bayanhushu | Inner Mongolia Hydrological Bureau |

Based on the Harmonized World Soil Database (HWSD), the Inner Mongolia soil type map, and the field sampling, the soil type data were established to classify the HRC soil types into nine categories (Supplementary figure, Figure S2). At least 10 samples of each soil type were collected using the random sampling method to measure the soil properties, including the particle-size distribution, bulk density, organic carbon content, and available water capacity. Each sampling was divided into two layers (0–30 cm and 30–100 cm of depth intervals) during the 2 years of field surveys in 2019 and 2020. The mean measured data for the 2 years were used to adjust the soil property parameters in the HWSD to obtain more accurate simulation results.

The LULC maps were obtained via visual interpretation of Landsat images of the catchment. The land use in the HRC was divided into six types, namely arable land, woodland, grassland, water area (including rivers, lakes, and reservoirs), construction land (including mining areas and transportation land), and bare land (Supplementary figure, Table S1). During the 2019 fieldwork, 130 reference samples of various LULC types were gathered. A random sampling design (Hu *et al.* 2013) was implemented, and 500 random samples in Landsat images were collected based on the LULC classifications for 2018, 2010, 2000, 1990, and 1977. The random samples were combined with visual interpretation of high-resolution Google Earth images taken at the same time, and average user and producer accuracies of 90 and 88% were achieved, respectively. Finally, the arable land, water area, and construction land were all consistently plotted with a high accuracy. However, the mapping of woodland and grassland was often less accurate than other land use types like water or construction land. This could be due to the following reasons. First, some of the woodland samples were probably mixed with the arable land. Second, the similarity between the spectral and phenological characteristics of the mixed woodland and grassland samples resulted in increased mapping errors for these classifications. Third, due to the relatively coarse spatial resolution of the multispectral scanner/thematic mapper (MSS/TM) images, fine-scale land change processes may have been ignored.

The landforms, topography, and physical properties of soil remained relatively stable during the past 59 years and did not change significantly. Thus, we focused on the effects of factors such as precipitation and LULC on the surface runoff in the HRC.

### 2.2.2. Model setup and calibration/validation

Based on these datasets, the basin was divided into multiple sub-basins and hydrological response units (HRUs) according to the minimum threshold ratios of land use, soil type, and slope (Gassman *et al.* 2007; Golmohammadi *et al.* 2014). The HRC was divided into seven sub-basins (Supplementary figure, Figure S3) and 478 HRUs in this study. The SWAT model used the observed monthly discharge data from Tuliemaodu and Bayanhushu hydrological stations during 1960–2018. The periods of 1960–1961, 1962–1982, and 1983–1998 were used as the model warm-up, calibration, and validation periods, respectively.

The SWAT model is based on the principle that the water balance equation (Equation (1)) is a proxy for all processes that occur in a catchment (Arnold *et al.* 2012; Mutenyo *et al.* 2013):

$$W_t = W_o + \sum_{i=1}^{t} (P_d - Q_s - E_a - W_s - Q_{gw}) \quad (1)$$

where $W_t$ is the final soil water content (mm), $W_o$ is the initial soil water content (mm) on day $i$, $P_d$ is precipitation (mm), $Q_s$ is the land surface runoff (mm), $E_a$ is evapotranspiration (mm), $W_s$ is the seepage flow (mm), and $Q_{gw}$ is the return flow (mm) on day $i$.

Sensitivity analysis, calibration, and validation were conducted using the Sequential Uncertainty Fitting (SUFI-2) algorithm through its interface with the SWAT calibration and uncertainty procedure (SWAT-CUP). The performance and efficiency of the model in simulating the observed streamflow were assessed using the coefficient of determination ($R^2$), Nash–Sutcliffe efficiency ($NSE$) index, and relative error ($RE$) (Equations (2)–(4)). These indices were calculated as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{t} (Q_m - Q_s)^2}{\sum_{i=1}^{t} (Q_m - \overline{Q_m})^2} \quad (2)$$

$$R^2 = \frac{\left[\sum_{i=1}^{t}(Q_s - \overline{Q_s})(Q_m - \overline{Q_m})\right]^2}{\sum_{i=1}^{t}(Q_s - \overline{Q_s})^2 \sum_{i=1}^{t}(Q_m - \overline{Q_m})^2} \tag{3}$$

$$RE = \frac{\sum_{i=1}^{t}(Q_s - Q_m)}{\sum_{i=1}^{t} Q_m} \times 100\% \tag{4}$$

where $t$ is the number of time series steps, $Q_s$ and $Q_m$ are the simulated and measured runoff values at the time step, respectively. $\bar{Q}_s$ and $\bar{Q}_m$ are the simulated and measured average runoff values, respectively. The model calibration was aimed at achieving a satisfactory model efficiency with $[\mathrm{NSE}] \geq 0.5$ (Moriasi *et al.* 2007, 2015; Mutenyo *et al.* 2013). The SWAT model simulation was determined to be 'satisfactory' if $NSE > 0.5$ for the monthly time step simulation.

#### 2.2.3. Quantitative analysis of climate change and human activities

The following principle can be used to quantify the contributions of climate change and human activities to the runoff changes during different periods (Wang *et al.* 2009, 2016):

$$\Delta Q_T = Q_{HR} - Q_B \tag{5}$$

$$\Delta Q_H = Q_{HR} - Q_{HN} \tag{6}$$

$$\Delta Q_C = Q_{HN} - Q_B \tag{7}$$

$$\eta_H = \frac{\Delta Q_H}{\Delta Q_T} \times 100\% \tag{8}$$

$$\eta_C = \frac{\Delta Q_C}{\Delta Q_T} \times 100\% \tag{9}$$

where $\Delta Q_T$ is the total change in runoff (Equation (5)). $\Delta Q_H$ and $\Delta Q_C$ are the runoff changes caused by human activities and climate change, respectively (Equations (6) and (7)); $Q_B$ is the baseline runoff; $Q_{HR}$ and $Q_{HN}$ are the recorded and natural runoff values, respectively, in the human-disturbed period; $\eta_H$ and $\eta_C$ are the relative contributions of the anthropogenic and climatic factors to the total runoff change, respectively (Equations (8) and (9)). It is hypothesized that the runoff was only influenced by climate change, and there was no influence from any human activities during the baseline period. Based on previous studies (Hu *et al.* 2012; Liu *et al.* 2017), the period of 1962–1982 was selected as a baseline period because (1) the study area was covered by naturally vegetated land during this period, with arable land only accounting for 6% of the total area; (2) the low population density and livestock production lifestyle of the HRC has a low impact on the natural environment. In this study, we used positive values to represent impacts leading to an increase in runoff, and negative values to represent impacts leading to a decrease in runoff.

## 3. RESULTS

### 3.1. SWAT model parameter calibration and verification

The observed precipitation and temperature data for 1960–2018 were processed. The data for 1960–1982 were used to calibrate the model, and the data for 1998–2018 were used to validate the model. The first 2 years of each simulation were used as the model warm-up time. We calibrated the SWAT model at the catchment level using the observed river discharge at Tuliemaodu and Bayanhushu stations. Before running the calibration, the sensitivity of the parameters was analyzed using the Latin hypercube one-factor-at-a-time (LH-OAT) method of SWAT (van Griensven *et al.* 2006). This approach combines the advantages of the global and local sensitivity analysis methods and can efficiently provide a rank ordering of the parameter importance (Sun & Ren 2013). Based on the sensitivity, the top-ranked 12 sensitive parameters (Supplementary figure, Table S2) were optimized using the SUFI2 algorithm in the SWAT-CUP. The results revealed that these parameter designs and model outputs were consistent with the runoff variability in the HRC.

### 3.2. Simulation results of the SWAT model

The measured and simulated monthly runoff values at Tuliemaodu and Bayanhushu stations are shown in Figure 2. In general, the simulated runoff curves follow the same trend as the measured runoff curves. The SWAT model can reflect the seasonal distribution of natural runoff well. Except for a few years with deviations, in most years the simulated flood peaks matched the actual measurements well. The runoff simulation accuracies for the calibration and validation periods are presented in Table 3. For both the calibration and the validation periods, the *NSE* and $R^2$ values were greater than 0.6, and the relative errors were less than 20%. For example, the model underestimated the flood peak in August 1998, that is, the simulated value was only 352 $m^3$/s, while the measured flood peak was 456 $m^3$/s. However, other peak years such as 1986 and 1993 exhibited overestimation. The possible reasons for this are that (1) the study area is located in a semi-arid region in which the precipitation is unevenly distributed and varies tremendously at the seasonal and interannual scales. In addition, 53% of the annual precipitation is less than 400 mm, and using this as a model input would underestimate the flood runoff from short-duration storms. The precipitation in the high flow years was 3.5 times higher than in the low flow year, resulting in a 100-fold difference in runoff. (2) The elevation difference in the upper and midstream sections is more than 1,000 m, and the mountain valleys are narrow and easily form flood runoff. (3) The soil texture in the mountainous area is mainly sandy clay. The underdeveloped root system of herbaceous plants and the poor water conservation of the sandy clay caused the soil water content to fluctuate between 7 and 20%. These factors might have had an impact on the model simulation results and a significant impact on the accuracy of the model output. Generally, the performance of the SWAT model was deemed to be acceptable for monthly runoff simulation in the HRC.

The measured values were higher than the simulated values in the dry season in both the calibration and validation periods, indicating that the simulation accuracy of the SWAT model for partial dry years was low. Except for the mid-1980s when there were no flood peaks in the actual measurements due to the river break, peaks occurred in the simulation. In conclusion, model overestimation or underestimation of runoff due to extreme precipitation existed to varying degrees in hydrological models.

### 3.3. Contributions of climate change and human activities to runoff reduction

The time series was divided into three periods: 1962–1982, 1983–1998, and 1999–2018, based on the abrupt change points of observed runoff in the HRC (Dan *et al.* 2021). The baseline period was set as 1962–1982 when human activities were

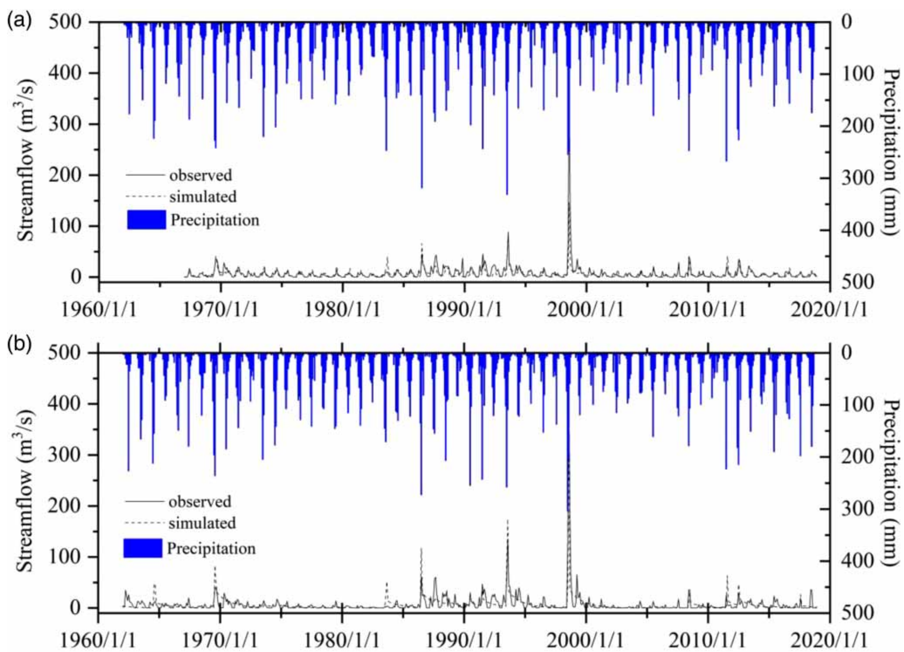



**Figure 2** | Comparison of the monthly precipitation, runoff simulated and measured value in the (a) Tuliemaodu and (b) Bayanhushu hydrological stations.

**Table 3** | Model performance for the simulation of monthly streamflow

| Statistical indicator | *NSE* | $R^2$ | $E_R$ (%) |
|---|---|---|---|
| Calibration (1962–1982) | 0.70 | 0.72 | 15.3 |
| Validation (1983–1998) | 0.64 | 0.66 | 17.6 |

relatively low, and the contributions of human activities and climate change to the change in runoff before and after the abrupt change points were derived (Table 4). The results of the SWAT model analysis revealed that the relative contributions of climate change and human activities were 84.5 and 15.5% during 1983–1998, 36.4 and 63.6% during 1999–2018, respectively. From 1983 to 1998, both the measured and simulated runoff increased by more than three times the average annual runoff compared to the baseline period before 1982, indicating that changes in the climatic factors caused the increase in runoff during this period, and the contribution of climate change to the increase in runoff was 84.5%. The observed mean annual runoff during 1999–2018 was approximately 7% lower than the mean annual runoff during the baseline period, indicating that human activities also caused a decrease in runoff. The contribution of human activities to the reduction in runoff was 63.6% after 2000.

## 4. DISCUSSION

### 4.1. Impacts of climate change on runoff

The climate factors such as temperature and precipitation are very important to runoff variations (Wang & Hejazi 2011). Precipitation is an important source of river runoff in northeastern China (Liang *et al.* 2011). The Huolin River is also a typical inland river in a semi-arid region, with precipitation-generated runoff serving as the primary source of water. Thus, over a long period, differences in precipitation may affect runoff variations. During the last 59 years, the annual precipitation exhibited severe fluctuations and a significant decreasing trend with a slope of −5.7 mm per decade. The uneven spatiotemporal distribution of annual precipitation changed significantly and could be divided into three periods (Figure 3(a)) based on the abrupt change points (Supplementary figure, Figure S4). During period I (1960–1982), the average precipitation was 388 mm, with the maximum (535 mm) and minimum (266 mm) values occurring in 1969 and 1972, respectively. This is consistent with the trend of precipitation in northeastern China (Sun *et al.* 2017). The weakening of northward moisture transport by the East Asian Summer Monsoon at mid-latitudes in the 1970s resulted in reduced precipitation in northern and northeastern China (Ding *et al.* 2008, 2009; Huang *et al.* 2013). During period II (1983–1998), the average annual precipitation was 467 mm. This was a wet period. Compared to period I precipitation increased by around 20% in period II. The annual precipitation in 1998 was 749 mm, resulting in a hundred-year flood in the HRC. In 1997, the year with the least precipitation, the precipitation was only 273 mm. This is associated with the significant intensification and westward expansion of the western Pacific subtropical high since the 1980s, especially in 1998 (Sun *et al.* 2000; Gao *et al.* 2014). During period III (1999–2018), the average annual precipitation was 350 mm. The runoff dried up during this time possibly due to the lack of precipitation, especially after 2000, when it dried up for 293 days in 2007, with almost no runoff at all. With a variation of 38 mm, the average amount of precipitation decreased by 10% from 1999 to 2018 compared to that during period I. The East Asian Summer Monsoon has weakened since 1999. This occurred concurrently with the shift of the Pacific Decadal

**Table 4** | Contribution rate of human activities and climate change to streamflow

| | | | | Anthropogenic factor | | Climatic factor | |
|---|---|---|---|---|---|---|---|
| Period | Observed value ($m^3$/s) | Simulated value ($m^3$/s) | Variation | Influence quantity | Contribution rate (%) | Influence quantity | Contribution rate (%) |
| 1962–1982 | 4.50 | 3.92 | | | | | |
| 1983–1998 | 14.25 | 12.74 | 9.75 | 1.51 | 15.5 | 8.24 | 84.5 |
| 1999–2018 | 4.17 | 4.38 | −0.33 | −0.21 | 63.6 | −0.12 | 36.4 |

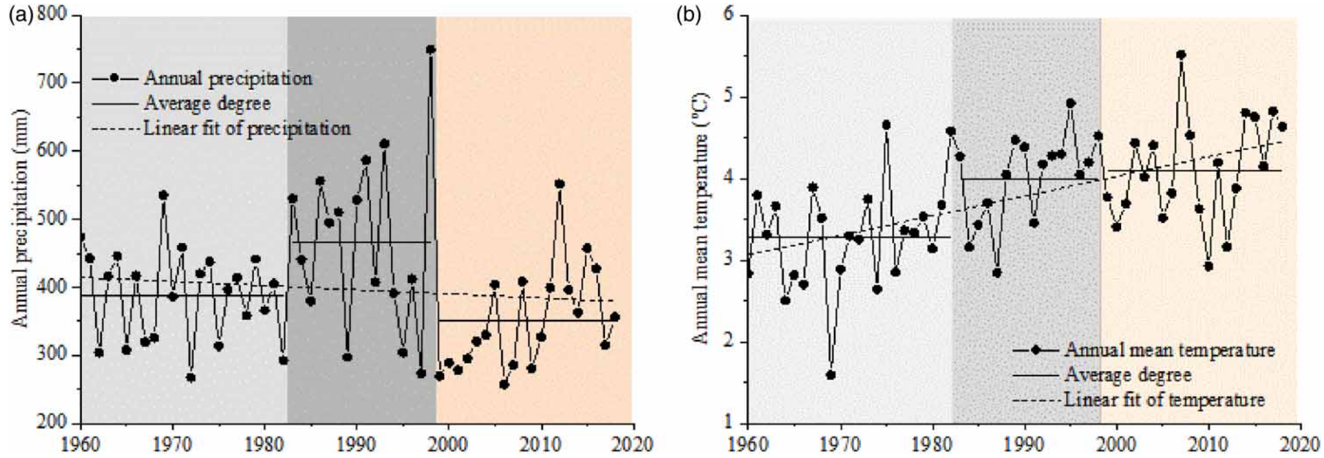



**Figure 3** | Temporal change of (a) annual precipitation and (b) the annual mean temperature in the upstream and midstream of the HRC.

Oscillation to the negative phase, which consequently resulted in a decrease in the local precipitation in summer (Han *et al.* 2015). Multiple factors affected the amount of precipitation, and their interactions and connections with the precipitation were complex, the physical mechanisms of which deserve further exploration in the future. Precipitation and runoff were well correlated in the HRC during each period. The Spearman correlation coefficients for the precipitation and runoff during the three periods were 0.59 ($\alpha = 0.01$) (1960–1982), 0.60 ($\alpha = 0.05$) (1983–1998), and 0.29 (1999–2018). This indicates that the natural period had the highest water yield capacity, while the human-induced period had the lowest capacity (Figure 4).

Temperature increases have led to an increase in the rate of evapotranspiration, aggravating the loss of streamflow and the catchment's hydrological cycle (Milly *et al.* 2018). Therefore, climate was the crucial component of runoff fluctuations and changes in the ecology in the watershed. The annual temperature exhibited a significant increasing trend, with a slope of 0.24 °C per decade (Figure 3(b)), increasing from 3.3 °C during 1960–1986 to 4.1 °C during 1987–2015. Thus, the temperature has risen dramatically since 1986, when an abrupt change occurred. The highest and lowest air temperatures were recorded in 1969 and 2007, with values of 1.58 and 5.51 °C, respectively. The cumulative deviation exhibited an increasing trend during this period, indicating that the temperature was increasing. The results presented here indicate that the HRC has experienced new and more severe dry conditions since 2000.

### 4.2. Impacts of human activities on runoff

Agricultural expansion, industrial development, and reservoir construction are examples of anthropogenic interventions in the catchment. These activities have predominantly influenced runoff by changing surface conditions. Since the 1970s, the influence of human activities in the HRC has increased due to the expansion of arable and construction land, while the areas of woodland and grassland have decreased (Supplementary figure, Table S3).

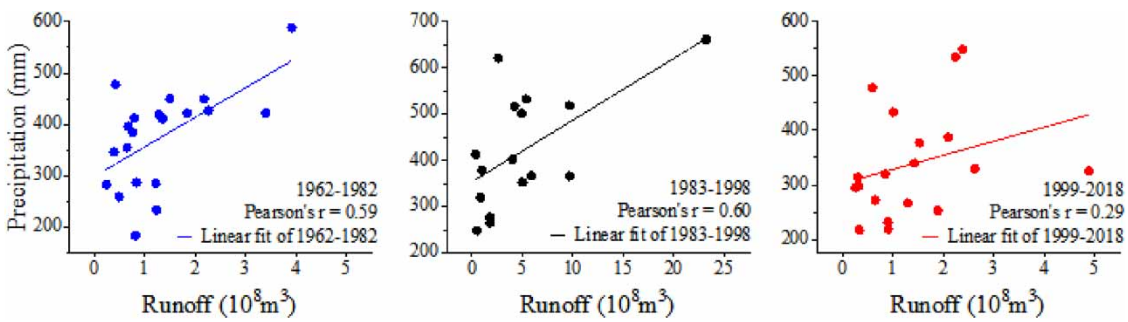



**Figure 4** | Relationship between runoff and precipitation in the upstream and midstream of the HRC during each periods.

### 4.2.1. Agricultural expansion

From 1977 to 2018, the area of arable land increased by 607 $km^2$, and its proportion of the total area increased rapidly from 6 to 12% (Figure 5). The arable lands were mainly distributed in the tributary valley of the HRC, which contained 158 $km^2$ of irrigated land. Of this area, 54 $km^2$ of irrigated land was distributed in the midstream section between the two hydrological stations, and the rest was distributed in the downstream section below the Bayanhushu station. (Table 5). Field research revealed that the expansion of irrigated land in these regions primarily occurred after 2000. The total water consumption for irrigation was approximately $5{,}280 \times 10^4\ m^3$, of which approximately $1{,}814 \times 10^4\ m^3$ was consumed in the midstream section, accounting for 6% of the normal annual runoff. Combined with the decreasing precipitation trend in the HRC, agriculture expansion had a significant impact on reducing runoff in recent 20 years.

### 4.2.2. Coal mining development

The area of construction land increased by 113 $km^2$, increasing from 0.6 to 1.6% of the total study area. The expansion of construction land was concentrated in the upstream section of the HRC (Figure 6). The expansion area was a coal mining area in Huolinguole City. As a resource-based city, the open-pit coal mines led to an increase in construction land area from 18.85 $km^2$ in 1977 to 118 $km^2$ in 2018. In particular, the expansion of coal mines after 2000 resulted in groundwater depletion, which influenced the generation of runoff. Coal mining is an extremely water-intensive activity that cuts off rivers and destroys underground aquifers. According to a survey of the Huolinhe coal mine, the annual productivity of the Huolinhe coal mine increased from 0.47 Mt in 1984 to 57 Mt in 2010 (Wei 1992). The coal mining capacity decreased significantly after 2010 due to the implementation of regular policies, and it has remained at around 30 Mt in recent years (Supplementary figure, Table S4). Studies have shown that the water consumption per ton of coal produced in Inner Mongolia is approximately 0.95 $m^3$ (Ren *et al.* 2020). Thus, the annual water consumption for mining in the HRC has been approximately $0.3 \times 10^8\ m^3$ in recent years (Figure 5). This water consumption accounted for about 10% of runoff in the HRC.

### 4.2.3. Reservoir construction

The development and use of water resources, such as dam and reservoir construction, may also have had an impact on runoff (Zhang 2014). The Hangali reservoir in the midstream section is the largest reservoir in the HRC, which covers an area of 38.8 $km^2$ and the total water storage of $0.925 \times 10^8\ m^3$. The reservoir was put into operation around 1982, which may help partially explain the abrupt change in the amount of runoff. During the water-abundant season, the reservoir typically holds water for one month every year, and the average water inlet rate of intake sluice is 18 $m^3$/s. The average annual water diversion of the reservoir is $0.46 \times 10^8\ m^3$, accounting for 17% of the annual average runoff. The overflow water from the reservoir is dumped back into the main channel of the Huolin River. The midstream impoundment of reservoirs intercepts the river's supply to the wetlands and has a serious negative influence on the ecosystems downstream.

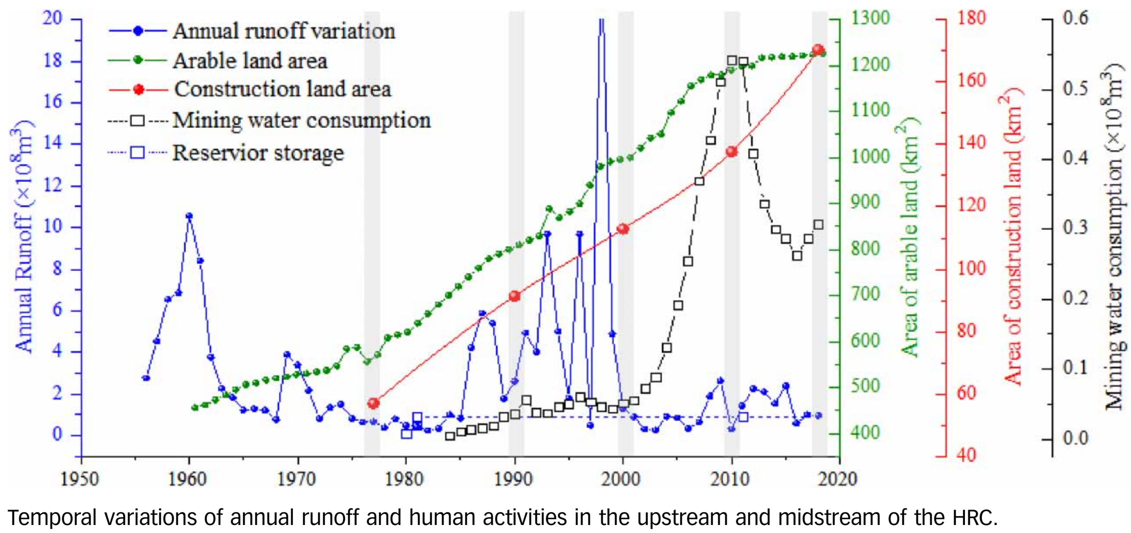



**Figure 5** | Temporal variations of annual runoff and human activities in the upstream and midstream of the HRC.

**Table 5** | Irrigation area in the upstream and midstream of the HRC

| | Irrigation area | Area ($km^2$) | Quality | Water consumption ($10^4$ $m^3$) |
|---|---|---|---|---|
| Midstream | Tu-Ba | 12.67 | Dryland | 423.06 |
| | Duerji | 22.07 | Dryland | 736.93 |
| | Kaoshan | 19.6 | Dryland | 654.46 |
| Downstream | Budunhua | 33.4 | Dryland 26.73; paddy field 6.67 | 1,115.25 |
| | Xitaiben | 70.4 | Dryland 21.33; paddy field 49.07 | 2,350.70 |
| | | 158.14 | | 5,280.4 |

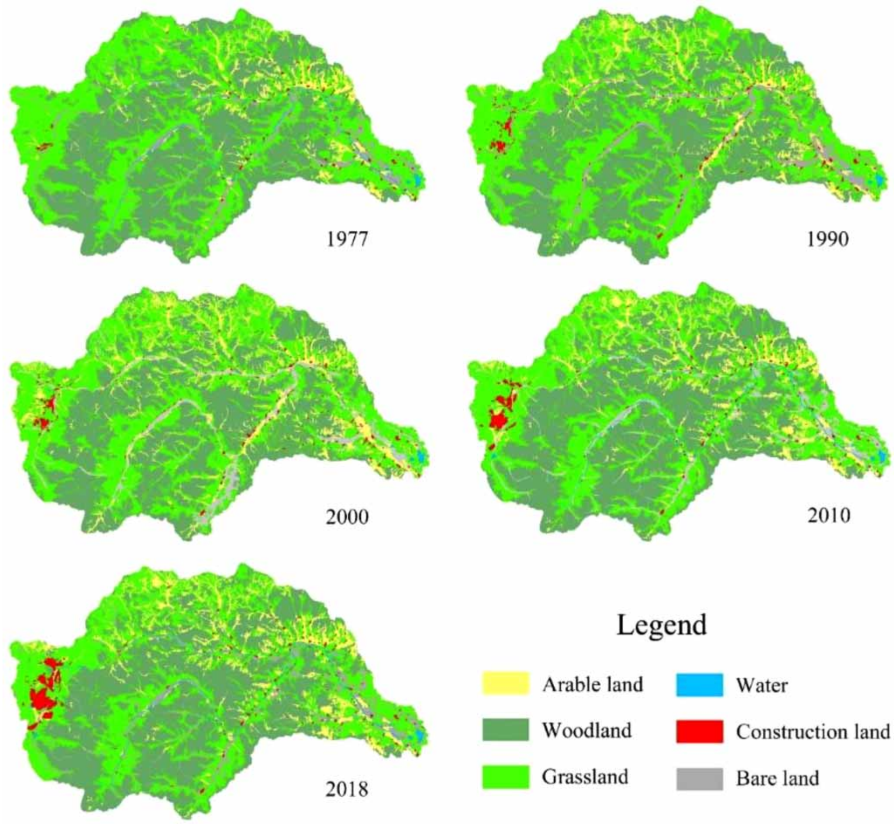



**Figure 6** | A spatial–temporal pattern of LULC in the upstream and midstream of the HRC.

### 4.3. Comparison of climate and anthropogenic contributions

The HRC has abundant forest and mineral resources, but it is extremely lacking in water resources. Climate change played a dominant role in runoff changes in the HRC during the baseline period. However, as human activities intensified, the runoff became significantly influenced by land use changes. In particular, after 2000, the effects of human activities were particularly noticeable. Reservoirs and agricultural irrigation were the major consumption activities that directly reduce runoff in the midstream section. The results revealed that the contribution of human activities to runoff changes in the midstream section was 63.6%, which was less than that in other regions of northeastern China. The results of a previous study pointed out that the contribution of human activities to runoff in the Liao River (Jiang & Wang 2016), Nenjiang River (Zhai & Tao 2017), and Songhua River basins (Wang *et al.* 2015; Liu *et al.* 2017; Xin *et al.* 2019) was generally more than 80%, while the combined contribution of the climatic factor was less than 20%. However, our results are credible because (1) the population density and urbanization level of the study area were low; (2) only 12% of the total arable land was irrigated; and (3) there was only one medium-sized reservoir built in the midstream section. Although the impact of human activities may be intensifying, climate change is crucial to changes in this region, which played a significant role during the baseline period.

The SWAT model in this study can be effectively used to simulate runoff in the HRC, but the simulation accuracy still needs to be improved. We primarily concentrated on the contributions of changes in the climatic and anthropogenic factors rather than on forecasting future runoff variations due to the complicated precipitation–runoff systems and data limitations in the research area. Although it has been widely employed in many studies, this method has some limitations. There is still a lack of applications for modeling long-term groundwater table fluctuations, aquifer storage changes, and water loss through surface evaporation. These variables may even change how the runoff is distributed.

## 5. CONCLUSIONS

The supply and demand of water resources are increasingly in conflict due to the reduced runoff in the HRC. The warm and dry climate trend in the HRC has affected the river runoff, and the increase in population and the intensity of economic activities have further aggravated the water shortage, which has been particularly prominent in the last 20 years. In this study, the impacts of climate change and human activities on the surface runoff in the HRC in northeast China were assessed using the SWAT model. The main conclusions of this study are as follows.

- The SWAT model performed well in simulating the runoff in the HRC. In the calibration period, the $R^2$ and $NSE$ values were 0.72 and 0.7, respectively; in the validation period, they were 0.64 and 0.66, respectively. The SWAT model offers a high degree of viability and application in simulating the monthly runoff in the HRC, which can provide a scientific basis for basin water resource planning.
- Compared with the baseline period in the HRC, the precipitation decreased from 14.27 and 3.1 mm per decade, and the temperature increased 1.58 and 2 °C in human-disturbed period. In addition, the anthropogenic influence in the HRC has increased due to the expansion of the arable land and construction land, and the decrease in woodland and grassland in recent 20 years.
- During 1983–1998, the contributions of climate change and human activities were 84.5 and 15.5%, respectively; while during 1999–2018, they were 36.4 and 63.6%, respectively. Climate change contributed more in the 1980s, while human activities contributed more after 2000. The decrease in runoff in the HRC was the result of a combination of climate change and human activities.

The findings of this study provide a foundation for the sustainable use of water resources in the HRC. The results of this study also offer theoretical support for decision-makers to prevent the adverse effects of climate change in northeastern China. In future research, it is suggested to collect more data and use different LULC simulated models to predict the future climate scenarios and LULC scenarios, respectively.

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## 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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Original Article

# Runoff variation and its response to climate change in Huolin River catchment, Northeast China

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**Abstract:** The Huolin River catchment (HRC) is located in the semi-arid region of Northeast China, which is very sensitive to climate change. The runoff in HRC is closely related to the recovery of local vegetation in the Greater Khingan Mountains and the survival of downstream wetlands. Dramatic runoff fluctuations and increasing no-flow days confirmed the water crisis in this area. Hence, it is extremely urgent to study the current situation and characteristics of runoff. In this study, hydrological and meteorological data of HRC during 1956-2018 were analyzed to elucidate the processes, characteristics, trends of the river runoff and revealed its response to climate change. The Mann-Kendall test and linear regression method showed that runoff in the HRC demonstrated a downward trend over the study period with a marked annual variation. The runoff in the high flow years was 100 times that of the low flow years, showing a typical continental climatic river characteristic. There are two runoff peak flows in the intra-annual runoff distribution in March and July, whereas two runoff valleys occurred around May and September to February. The runoff positively correlates with precipitation in summer and temperature in early spring. Snowmelt influenced by rising temperatures in April and precipitation in July is the main driving factor for the two peaks flow. Evaporation rose with precipitation decline and temperature increased, which may influence the runoff decrease. The annual runoff is well synchronized with the annual precipitation, and precipitation change is the main driving factor of variation and abrupt change points of annual runoff in the catchment. This study would be beneficial for water resource management in developing adaptation strategies to offset the negative impact of climate change in HRC.

**Keywords:** Precipitation-runoff system; Mann-Kendall test; Abrupt change; Regional response; Semi-arid area

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## 1 Introduction

Water shortage is a crucial factor restricting economic and social development, which not only seriously affects people's living environment and quality of life, but also dramatically threatens the stability of the natural ecosystem and has become a "bottleneck" in the local sustainable development (Milly et al. 2005; Kummu et al. 2016; Yin et al. 2018). As a significant component of the hydrological cycle, river runoff reflects the abundance and shortage of regional water resources and the changing characteristics of the hydroclimatic environment in the catchment (Xu 2011; Yang et al. 2020). The climate model (Milly et al. 2005) and runoff rebuilding based on wavelet analysis (Labat et al. 2004) showed that the surface runoff increased. De Grey River in Australia (Aryal et al. 2020), San Joaquin watershed, United States (Ficklin et al. 2009), Brahmani River, India (Islam et al. 2012), and Huaihe River, China (Zhang et al. 2013) also confirmed an increasing trend of runoff. However, for more researches found runoff in different catchments showed a downward trend, such as Turkey (Kahya and Kalaycı 2004), Northeast Brazil catchments (Montenegro and Ragab 2010), Goulburn River, Australia (Patil et al. 2020), and Northern China (Wang et al. 2010; Jiang et al. 2011; Gao et al. 2016). Thus, the runoff variation and its climatic impact need to be addressed better to understand water resources management in catchment scale.

Under global change conditions, the hydrological cycle is intensifying, and regional differences in runoff are more noticeable, particularly evident in China. Observed hydrological data in southern and northwest China showed an increasing trend of runoff (Li et al. 2011a; Li et al. 2011b; Zhang et al. 2011), such as Yangtze River (Chen et al. 2014; Su et al. 2017) and the Tarim River (Tao et al. 2011; Chen et al. 2019). While the results in northern and northeast China showed a declining trend of runoff (Dai et al. 2009; Yu et al. 2019; Aryal et al. 2020), such as Yellow River (Piao et al. 2010; Tian et al. 2019), Haihe River (Yang and Tian 2009; Bao et al. 2012; Xu et al. 2020) and Songhuajiang River (Ren et al. 2002; Li et al. 2014). Especially in northeast China, a unique hydrological process is formed by special geographical and climatic conditions. The decreasing surface runoff, breaking subwatershed streamflow, and declining groundwater level is the response of water resources to climate change (Liu et al. 2012), which reflects uncertain water supply and growing demand (Jiang and Wang 2016). Spatio-temporal distribution in the Songhuajiang River has found that the runoff showed a downward trend and significantly decreased after 1990 (Meng and Mo 2011; Miao et al. 2011; Mu et al. 2012). The dramatic drop of the annual and seasonal runoff in the Nenjiang River basin is attributed to temperature coupled with precipitation (Tang et al. 2009; Xu et al. 2009; Feng et al. 2011). Further, the same downward trend was observed in the Liaohe River basin, and the results show it is related to the change of summer precipitation in the watershed (Sun et al. 2012; Tu et al. 2012). However, some researchers believed that the runoff in different sections was mainly affected by human activities (Ma et al. 2015; Jiang and Wang 2016; Zhang et al. 2017; Tian and Wang 2018), such as the building of a dam in the upstream, much drilling, and irrigation (Yang and Tian 2009). Although climate change and anthropogenic factors contribute differently to runoff variation, the former is the most fundamental and critical driver particularly pronounced in mountainous areas with low population density and underdeveloped agriculture.

The Huolin River is located in a monsoon transition zone in Northeast China. It is a non-perennial inland river, the headwater of the Horqin, Xianghai wetlands, and Chagan lake, susceptible to the effect of climate change (Lu et al. 2007a). Moreover, the Huolin River catchment (HRC) is vulnerable to droughts and floods due to extreme climate change. HRC suffered its most severe monsoon flood in 1998, adversely affected 239 thousand people, with a total economic loss of 2.7 billion Yuan (Li et al. 1999). Therefore, it is necessary to elucidate further the climate changes impacts on hydrological processes in the region. Most previous studies have focused on the 1998 flood process (Li et al. 1999; Li and Xia 2003; Liu et al. 2013) of the Huolin River and the changes of a wetland landscape in the downstream (Lu et al. 2007b; Li and Liu 2011; Li and Liu 2012; Zhang 2014; Lu et al. 2015), and lack of systematic studies of runoff changes in recent decades. The main objectives of this study are 1) investigate the response of river runoff changes in small and medium watersheds in the monsoon marginal zone under global warming conditions; 2) address the linkage of runoff variation to changes of precipitation and temperature.

## 2 Materials and Methods

### 2.1 Study area

The Huolin River originates from the Delutelehan Mountain of the Greater Khingan Mountains in Inner Mongolia, China (Fig. 1a). It is a tributary of the Nenjiang River in Northeast China. It flows east in the upstream, where there is an abundant runoff, then turns southeast and crosses Bayanhushu hydrological station, finally flow into Chagan lake in the western Songnen Plain (Fig. 1b), with a total length of 560 km and a drainage area of 36,623 $km^2$ (Lu et al. 2007a). The west of Tuliemaodu hydrological station is the upstream and main runoff producing zone accounts for 88% of the total runoff, composed of more than twenty tributaries over the length of 10 km, including four main tributaries such as Kunduleng River, Dundeusu River, Dongzhelimu River, and Xieshengtu River, with the length of 198, 62.5, 44.8 and 43.9 km, respectively. Kunduleng River accounts for about 70% of the flow and becomes the main water supply of the Huolin River (Sun et al. 2015). The midstream between Tuliemaodu and Bayanhushu are hilly plain areas with two main tributaries, Chaoertu River and Emute River, which account for 11.8% of the total runoff. Upper Bayanhushu Station, the main flow-producing area of the Huolin River, covers an area of 10,355 $km^2$, the land use/cover is dominated by forest land (40.1%) and grassland (40.8%), accounting for about 81% of the total area, while the remaining 19% is arable land (10%), construction land (2%), water area (1%), and bare land (6%), respectively in 2018. The major part of the upstream and midstream is pastoral areas, with the population density of about 22 people per square kilometer by the end of 2018. Therefore, the impact of human activities in this area is relatively slight. The downstream of Huolin River is the Xianghai wetland area with irregular river channels and no tributaries to supply the runoff, dried-up for now except extreme flood event years such as 1998.

HRC is located in the semi-arid region influenced by the southeast monsoon in summer and controlled by Mongolian High in winter. The multi-year surface temperature, precipitation, and pan evaporation are 3.08°C, 385.5 mm, and 2032 mm, respectively. The highest monthly mean temperature and precipitation occur in July (Fig. 2), reaching 24°C and 130 mm. The precipitation is concentrated in the flood season from June to September, accounting for 85.3% of the annual precipitation. The highest monthly mean pan evaporation occurred in May, accounting for 17% of the annual total, followed by June and April, accounting for 14.2% and 12.5%, respectively. From November to the following March is the freezing period.

### 2.2 Data

Daily runoff data was collected from the Hydrological Bureau, Inner Mongolia Autonomous Region of China. Relevant hydrological parameters, seasonal distribution, and time scale are shown in Table 1. Tuliemadu and Bayanhushu hydrological stations (Fig. 1b) are the upstream and midstream drainage outlets of HRC, respectively. The daily temperature, precipitation, evaporation data from four meteorological stations (Fig. 1b) in the HRC were obtained from the Inner Mongolia Meteorological Bureau (Table 2). Due to the difference in the build-up time of gauging stations, the starting time of the observation data is not the same. The Tuliemaodu meteorological station stopped observing in 2010. The data from these hydroclimatic stations could reflect the runoff fluctuation and the process of climate change over the river basin.

### 2.3 Method

To analyze runoff variation trends and its response to climate change in the HRC, a representative hydrological station along the river channel was selected for analysis. First, to evaluate the variation trends of runoff over the six decades, the Mann-Kendall (MK) test (Mann 1945; Kendall 1975) was applied. As a non-parametric method, the MK method is extensively used to analyze hydroclimatic time series (Yang and Tian 2009; Bao et al. 2012; Aryal et al. 2020). Linear regression was computed for comparison with the runoff variation trends. Second, abrupt change is examined using the sliding T test combined with the MK test. Third, to better understand the runoff characteristics in HRC, we also did some statistical analysis of the intra-year distribution, number of dried-up days, etc. Finally, to clarify the impacts of different climatic elements on hydrological responses, we analyzed Pearson's Correlation Coefficient. To test for the possibility that summer runoff variation is driven by precipitation,

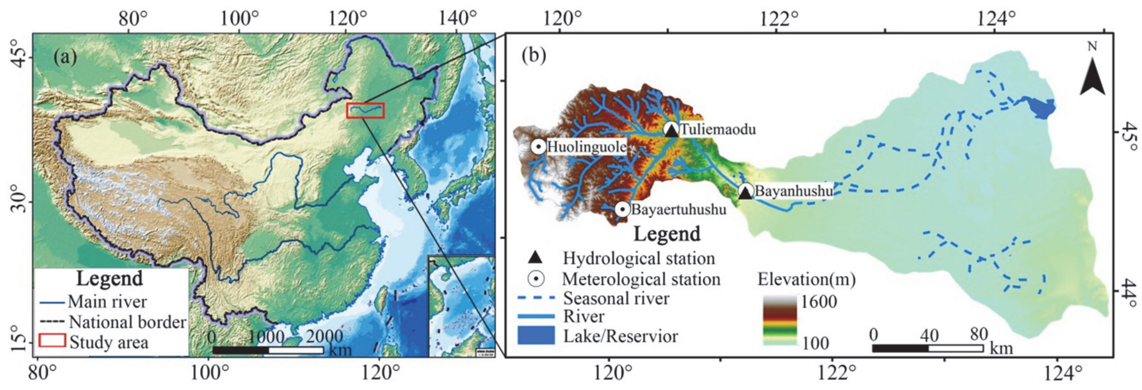


**Fig. 1** Geographical map of the study area. (a) the location of the Huolin River catchment; (b) hydrological and meteorological stations in the Huolin River catchment.

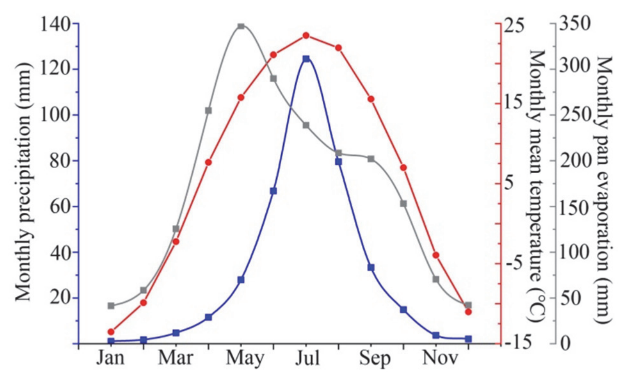


**Fig. 2** Multi-year annual distribution of precipitation, temperature and evaporation of Huolin River catchment.

**Table 1** Detailed information and relevant parameters of the hydrological stations

| Hydrological stations | Drainage area ($km^2$) | Channel length (km) | Mean annual ($10^8$ $m^3$) | Coefficients variations | Extreme values ($m^3$/s) | | Seasonal runoff distribution (%) | | | | Data period |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Max | Min | Spring | Summer | Autumn | Winter | |
| Tuliemaodu | 8000 | 198 | 2.38 | 0.87 | 9.1 | 0.4 | 23.7 | 47.6 | 25.4 | 3.3 | 1967-2018 |
| Bayanhushu | 10355 | 295.7 | 2.70 | 1.31 | 23.2 | 0.2 | 22.3 | 46.9 | 29.2 | 1.6 | 1956-2018 |

**Table 2** Detailed information and relevant parameters of the meteorological stations

| Meteorological stations | Position | | Mean annual values | | | Annual extreme values | | | | | | Data period |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Longitude (°) | Latitude (°) | $T$ (°C ) | $P$ (mm) | $E$ (mm) | Max.$P$ (mm) | Min.$P$ (mm) | Max.$T$ (°C ) | Min.$T$ (°C ) | Max.$E$ (mm) | Min.$E$ (mm) | |
| Huolinguole | 119.65 | 45.55 | 1.9 | 340.4 | 1792.7 | 654.7 | 193.3 | 3.5 | 0.9 | 2145.3 | 1469.7 | 1973-2018 |
| Tuliemaodu | 120.89 | 45.53 | 2.1 | 412.2 | 1601.6 | 946.9 | 256.0 | 4.4 | 0.3 | 1970.1 | 1269.0 | 1956-2010 |
| Bayaertuhushu | 120.33 | 45.07 | 3.2 | 421.0 | 1739.7 | 735.4 | 221.8 | 5.5 | 0.9 | 2068.0 | 1374.4 | 1956-2018 |
| Bayanhushu | 121.48 | 45.06 | 6.2 | 381.8 | 2057.8 | 661.0 | 183.1 | 8.7 | 3.5 | 2523.7 | 1462.6 | 1956-2018 |

**Notes:** $T$, temperature; $P$, precipitation; $E$, evaporation.

we compared July runoff values with corresponding monthly precipitation in Tuliemaodu and Bayanhushu stations during 1956-2018. Significant correlation between the two variables lends confidence to the presumption that summer runoff is correlative with variations in precipitation events. Similarly, we examined the correlation between temperature and runoff from March to April.

### 2.3.1 Mann-Kendall test

The MK test statistic ($S$) and significance test ($Z_c$) are given as:

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{\text{var}\ (s)}}, S > 0 \\ 0, S = 0 \\ \frac{S+1}{\sqrt{\text{var}\ (s)}}, S < 0 \end{cases} \quad (1)$$

in which

$$S = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} sgn\,(x_k - x_i) \quad (2)$$

$$var[S] = [n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)]/18 \quad (3)$$

Where $x_k$ and $x_i$ are the sequential data value; $n$ is the length of the data set.

$$sgn(\theta) = \begin{cases} 1, \theta > 0 \\ 0, \theta = 0 \\ 1, \theta < 0 \end{cases} \quad (4)$$

$t$ is the extent of any given time. In a two-sided test for trend, the $H_0$ is accepted if $|Z_c| < Z_{a/2}$ is at the level of significance. $|Z_c|$ critical values of 1.64, 1.96, and 2.58 were used for the probabilities of 95%, 97.5%, and 99.5%, respectively.

The MK test is also noteworthy for its capability to estimate the magnitude of the trend. The Kendall slope, defined as the median overall combinations of record pairs for the whole data set, is an unbiased estimator of trend magnitude. The MK slope (Burn 1994; Gan 1998) is

$$\beta = Median\left(\frac{x_i - x_j}{i-j}\right) \quad (5)$$

wherein $1 < j < i < n$. A positive value of $\beta$ indicates an upward trend, whereas a negative value of $\beta$ indicates a downward trend.

### 2.3.2 Sliding T test

The idea of the sliding T test is based on the time series significance test. In other words, the sliding T test conducts mutation analysis by comparing whether the mean difference of different subsequences is significant (Wei 2007). If the difference is greater than the given significance level, the two sequences exist with obvious qualitative changes (Du et al. 2018). They can be calculated from the equations below:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s(\frac{1}{n_1} + \frac{1}{n_2})^{1/2}} \quad (6)$$

$$s = \sqrt{\frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{n_1+n_2-2}} \quad (7)$$

where $s_1$ and $s_2$ are the variances of $x_1$ and $x_2$, respectively; $n_1$ and $n_2$ are the lengths of the two sequences; $t$ meets the distribution of $v = n_1 - n_2 - 2$. According to the description and analysis of testing methods and previous testing experience, the sliding T test is relatively suitable for identifying mean type abruptly. In counting, the lengths of two contrast sequences are usually equal. Therefore, $n$ of sequence length can be varied repeatedly to improve the accuracy of the results.

## 3 Results

### 3.1 Long time trends of runoff

At a long time scale, annual runoff shows a similar variation trend in Tuliemaodu and Bayanhushu hydrological stations (Fig. 3a). The MK trend test results showed that the annual runoff decreased with a value of -0.38 and -1.89 ($\alpha$=0.1), respectively (Table 3). The linear regression trends also showed the same downward tendency in the Bayanhushu hydrological station at a rate of -0.27×10$^8$ m$^3$/10a ($p$<0.05). If we eliminate the effects of the maximum value in 1998 from the long term trend of runoff sequence, the Z value of the MK test can reach -0.48 and -2.07 ($\alpha$=0.05), respectively, which means a more significant downward trend in both two hydrological stations.

Combined with the cumulative anomaly of runoff increment (Fig. 3b), it can be observed that the runoff processes tend to be last long in low flow years and

**Table 3** Mann-Kendall trend test and linear regression of annual runoff in two stations in Huolin River catchment

| Stations | Time | Linear regression | | MK test | |
|---|---|---|---|---|---|
| | | *b* | *p* | *Zc* | *β* |
| Tuliemaodu | 1967-2018 | 0.0004 | <0.05 | -0.387 | -0.00014 |
| Bayanhushu | 1956-2018 | -0.027 | <0.05 | -1.892* | -0.00145 |

**Note**: "*" delineates significance at $\alpha$=0.1.

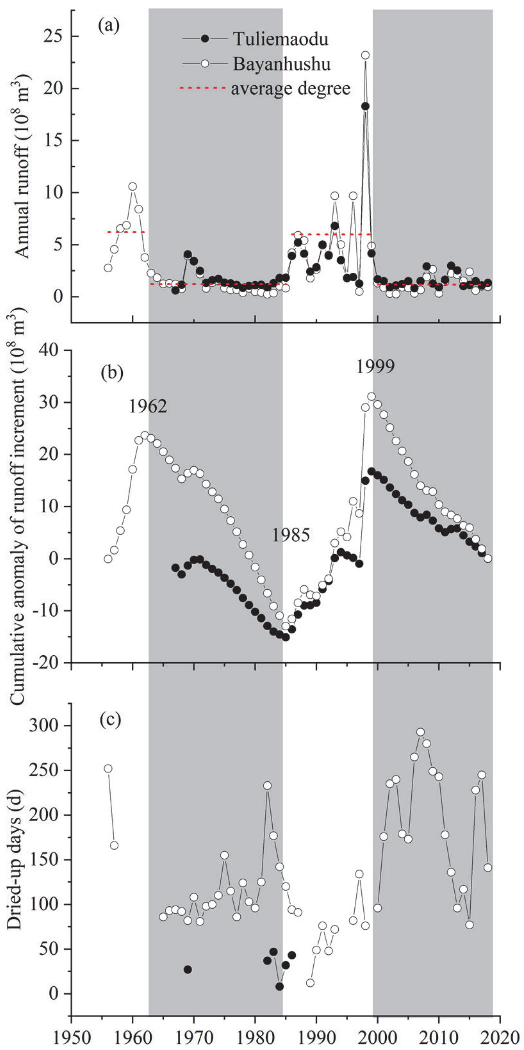


**Fig. 3** (a) Annual runoff record; (b) cumulative anomaly of runoff increment; (c) dried-up days of Tuliemaodu and Bayanhushu stations.

short in high flow years. The average annual river runoff at Tuliemaodu and Bayanhushu stations were $2.38\times10^8$ and $2.7\times10^8$ m$^3$, respectively. There are 35 years accounting for 67.3% in Tuliemaodu station and 45 years accounting for 71.4% in Bayanhushu station are below the average level. It means that about 70% of the years are low water with a dry climatic condition. The others are higher than the average level, namely, only 17 years accounting for 32.7% in Tuliemaodu station and 18 years for 28.6% in Bayanhushu station.

While the coefficients variations (Cv) of runoff in midstream (1.31) is larger than upstream (0.87), indicating that the fluctuation of runoff variation is higher in midstream. That is runoff in upstream was more stable, which is also supported by the number of dried-up days (Fig. 3c). The difference between upstream and midstream runoff is mainly attributed to a decrease in water supplies to midstream tributaries and increased evaporation.

In the period 1956-2018, there was a huge difference in the extreme runoff. In 1998, the most runoff abundant year, the annual precipitation and runoff were 661 mm and $23.2\times10^8$ m$^3$, respectively. The annual runoff is 8.6 times of average value. An extreme drought occurred in 1982, with only 283.2 mm of annual precipitation, while the annual runoff was merely $0.237\times10^8$ m$^3$, accounting for 8.7% of the average value. Nearly 100 times difference exists in runoff between the highest and lowest flow years. Consequently, the Huolin River runoff variation is greatly influenced by climate change, especially changes in precipitation, and exhibits the typical characteristics of an inland river.

### 3.2 Abrupt changing points of runoff

In the Bayanhushu hydrological station, the MK test results showed that the UF and UB curves intersected in 1964 and decreased significantly after 1976, the downward trend turned into an upward trend in 1982 (Fig. 4a). The sliding T test results further validate the accuracy of the abrupt change point occurred in 1964 and 1982. Same as above mentioned the abrupt change point in 1976, 1982, and 1999 was detected in Tuliemaodu station (Fig. 4b). Thus, the two stations have similar abrupt change points except 1964 and 1976. The difference may be explained by the different lengths of the time series of the two stations, with the Tuliemaodu station having eight years fewer measurement data than the Bayanhushu station, so we consider 1964 to be more reliable. Combining the results of previous studies (Miao et al. 2011; Mu et al. 2012), the length of the time series and practical situations, we adopted 1964, 1982, and 1999 as the abrupt change point in the catchment scale. Hence, the runoff is divided into four periods with three change points, and the mean runoff results of each period are calculated in Table 4. The whole runoff sequence shows the process of "alternation of drying and wetting" pattern.

### 3.3 Runoff fluctuation pattern

There are significant differences between the high and low flow patterns during 1956-2018. The periods 1956-1963 and 1983-1998 were high flow. The

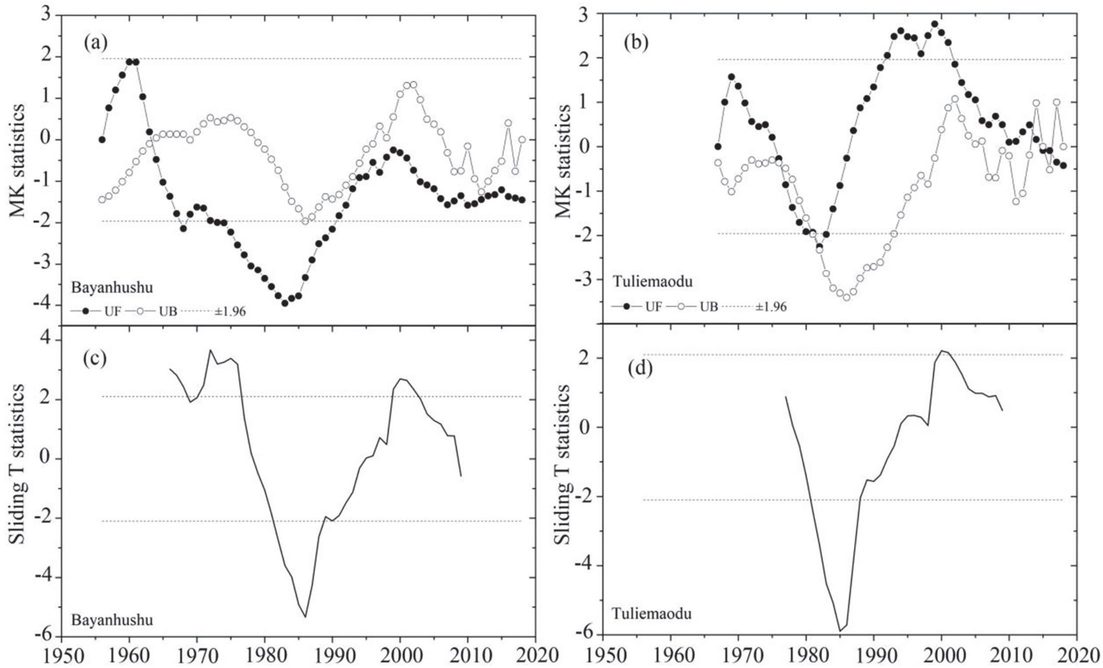


**Fig. 4** Mann-Kendall test of annual runoff in hydrological stations (a) Bayanhushu and (b) Tuliemaodu; sliding T test of annual runoff in hydrological stations (c) Bayanhushu and (d) Tuliemaodu.

**Table 4** Change point and mean runoff before and after abrupt change by Mann-Kendall test and sliding T test

| Stations | MK Test | Sliding T test | Runoff change | | *D* value |
|---|---|---|---|---|---|
| | | | Before | Post | |
| Tuliemaodu | 1976 | - | 1.91 | 1.03 | -0.88 |
| | 1982 | 1982 (-2.74**) | 1.03 | 4.13 | 3.10 |
| | 1999 | 1999 (2.21**) | 4.13 | 1.64 | -2.49 |
| Bayanhushu | 1964 | 1964 (3.03**) | 5.29 | 1.23 | -4.06 |
| | 1982 | 1982 (-3.41**) | 1.23 | 5.06 | 3.83 |
| | - | 1999 (2.70**) | 5.06 | 1.38 | -3.68 |

**Note**: "-", "**" represent not statistically significant, significantly in the level of $\alpha$=0.05; "*D*-value" means difference between average runoff before and after abrupt change.

former is a high flow that lasted eight years in the late 1950s, with an average runoff of 5.71×10$^8$ m$^3$, due to the average precipitation of 428 mm in HRC, making the longest-lasting and richest runoff period. Significantly, the runoff in 1960 reached 10.58×10$^8$ m$^3$, become the second peak in recent 63 years. The latter is the period of abundant runoff occurred from 1983 to 1998. Even though there were 2-3 years low flow years during this period, it kept a high water level with an average runoff of 5.06×10$^8$ m$^3$. In particular, extreme precipitation in the summer of 1998 resulted in a rapid rise of the river water level, becoming the highest runoff in the recent 63 years. During 1964-1982, the runoff shrank severely to only 1.26×10$^8$ m$^3$, which is only half of the regular year, due to reduce precipitation of 384 mm. The extreme drought year occurred after 2000 at the catchment, with an average runoff of 1.38×10$^8$ m$^3$ and average precipitation of 357 mm, may be led to persistent river dried-up in Bayanhushu hydrological station. In short, runoff shows a significant high-low-high-low process, namely the "Two Highs and Two Lows" pattern.

### 3.4 Intra-annual runoff variation

The intra-annual runoff distribution was extremely uneven. It has noticeable seasonal changes in abundance and drought, however, the runoff follows the "Double Peaks, Double Valleys" replacement pattern in regular year (Fig. 5a). The former peak flood is possibly caused by rising temperature and the infiltration of snow accumulation into the soil to supplement the runoff. It was a unique runoff characteristic of the rivers in

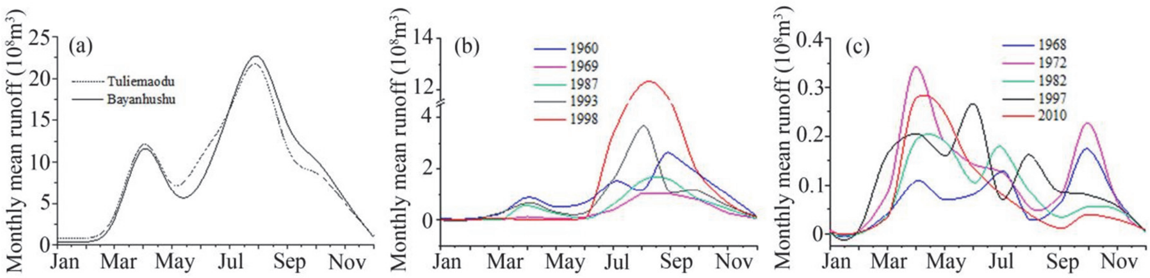


**Fig. 5** Intra-annual distribution of runoff (a) Multi-year average runoff in Tuliemaodu (1967-2018) and Bayanhushu stations (1956-2018); (b) Annual distribution of runoff in typical high flow years in Bayanhushu station; (c) Annual distribution of runoff in typical low flow years in Bayanhushu station.

the cold climate region and had a clear relationship between the peak runoff and land surface temperature. Since precipitation and runoff in the study area were concentrated in summer, accounting for 63.9% and 53% of the annual value, respectively. The second flood peak occurred in July due to the increase in precipitation. The valley runoff from November to March is a natural reduction due to the rivers freezing over when temperatures drop below zero, and the accumulated snow does not directly supply river runoff. In addition, in the second valley from May to June, there is an increase in evapotranspiration with a gradual increase in temperature leading to reducing runoff.

The intra-annual distribution of runoff in a typical abundance year is similar to an average year, with a "double peaks" pattern, showing an elongated or dislocated main peak in July (Fig. 5b). However, the drought year runoff was significantly reduced (Fig. 5c), and the "double peaks" are not prominent. It presents the multi-peak crisscross situation, although the runoff is very scarce. The intra-annual runoff distribution between abundant and drought years mainly depends on the difference in precipitation from July to September.

### 3.5 River dried-up days

River cutoff is the severe shortage of surface runoff and lowers groundwater table, which shows that water resource decreased and ecological environment is being severely worsened (Liu and Cheng 2000). In the upstream of HRC, the runoff remains relatively stable, water resources are also abundant, and the river flows all year round except for four years in the mid-1980s (Fig. 3c). However, the middle catchment suffered cutoff for 52 years, accounting for 83% of the recent 63 years. Especially after 2000, dried-up occurred more frequently and lasted longer. In 2007, the dried-up period lasted 293 days, becoming the most severe cutoff period. It is indicating that water shortage and water crisis occurred in HRC. Not considering the freeze-up period, the monthly dried-up peak mainly occurred around May, dried up lasted 80% of all year. This means that the midstream only has runoff for 20% of the entire year. The possible reasons are 1) there was a significant variation of annual precipitation, with a difference from 661 to 283.2 mm, and precipitation is the main supply of runoff; 2) it is easy for the river level to rise after a short period of heavy rainfall. Hence, river runoff decreases rapidly after rains, and water levels drop due to the lack of a stable and continuous water supply; 3) in general, in May of each year, there is a little precipitation, together with the rising temperature, leading to increase evapotranspiration, which has a negative impact on the runoff, and provoke the river dried-up.

## 4 Discussion

### 4.1 Relationships between precipitation and runoff

Surface runoff is part of the water balance process, and the runoff generation is closely connected with climate factors such as precipitation, temperature, and evapotranspiration which will influence global water regimes (Arnell 2004; Wang and Hejazi 2011). Especially in the semi-arid regions, it has been particularly pronounced (Yu et al. 2019; Aryal et al. 2020). As the primary source of water in the rivers of northern China, precipitation is significantly correlated with runoff (Zheng et al. 2009; Xie et al. 2018). The annual precipitation in HRC showed a downward trend (Fig. 6a-d), with an

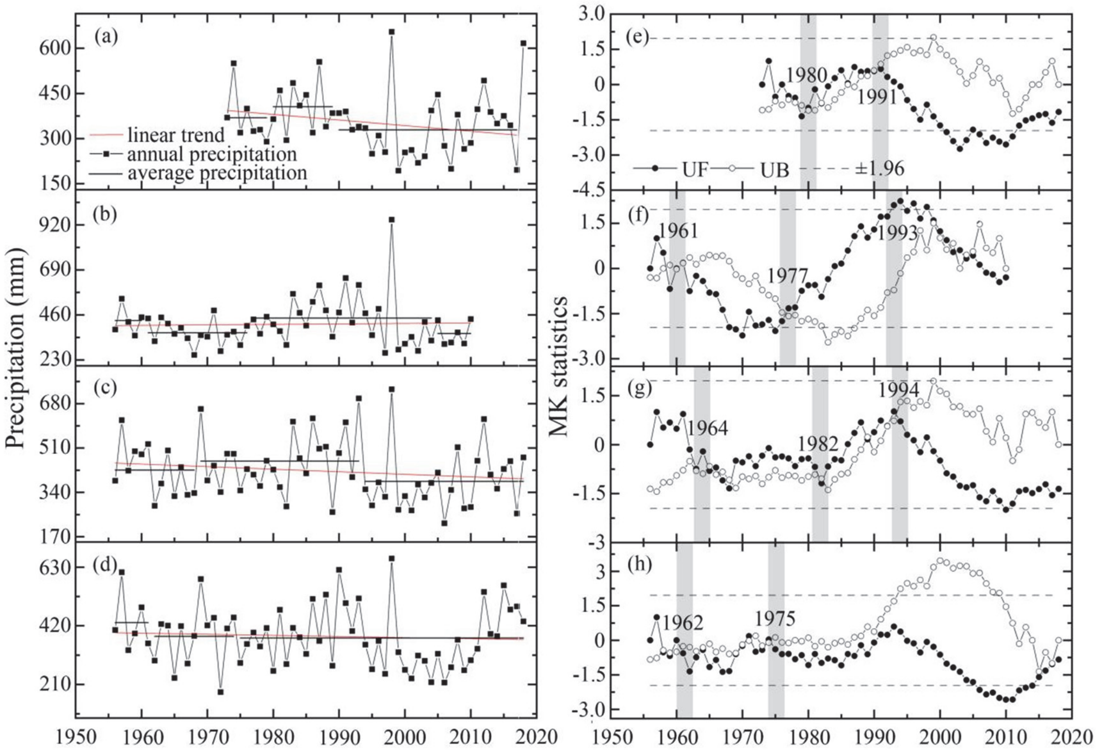


**Fig. 6** Annual precipitation variation in meteorological stations (a) Huolinguole; (b) Tuliemaodu; (c) Bayaertuhushu; (d) Bayanhushu. Mann-Kendall test of annual precipitation in meteorological stations (e) Huolinguole; (f) Tuliemaodu; (g) Bayaertuhushu; (h) Bayanhushu.

average rate of -14 mm/10a and a decrease of -32.4 mm in the recent 60 years, which was higher than -8.13 mm/10a in northeast China (Liang et al. 2011), indicating that there was a severe drought tendency in HRC (Dan et al. 2013). The annual runoff and precipitation have a similar variation, with precipitation abundant years corresponding to high flow years, for example, in 1960, 1969, 1993, and 1998. And severe drought years also correspond to little runoff, such as 1972, 1982, and 1989. Furthermore, the abrupt changing time of precipitation is consistent with runoff. The precipitation abrupt changed around 1961, 1963, and 1961 in Tuliemaodu, Bayaertuhushu, and Bayanhushu meteorological station, respectively (Fig. 6e-h). It is similar to the abrupt change time of runoff in 1964. Then, the abrupt change point of precipitation in 1981, 1977, 1982, and 1975 occurred when the runoff was abrupt in 1983. A significant increase of precipitation around 1994 occurred, and across the significance level around 1999 can be considered as an abrupt change point (Wei 2007), at the same time runoff abrupt change in upstream of HRC.

The correlation analysis of runoff and precipitation in the HRC shows a significant correlation between them on an annual scale. The correlation coefficients were 0.67 in the upstream and 0.6 in the midstream, respectively. Meanwhile, the intra-annual distribution of precipitation and runoff was consistent, with higher river runoff in months with abundant precipitation and lower runoff in months with less precipitation, further indicating that fluctuations in precipitation within the basin are an important factor in the variation of runoff (Fig. 2). Precipitation in the basin is mainly concentrated from June to October, accounting for more than 80% of the annual precipitation, and correspondingly, the runoff during this period can also reach 70% of the annual flow. Precipitation and runoff in July account for 33% and 34% of the year, respectively. The correlation between them was most significant in July and gradually weakened from upstream to midstream with correlation coefficients $r$=0.75 and $r$=0.62, respectively (Fig. 7). Therefore, precipitation in the Huolin River is an essential factor influencing annual runoff variability, consistent with the entire northeast China (Ding et al. 2015; Wang et al. 2015).

Previous studies have shown a significant change in the intensity of the East Asian Summer Monsoon at mid-latitudes in the 1970s (Xu 2001; Yu and Zhou

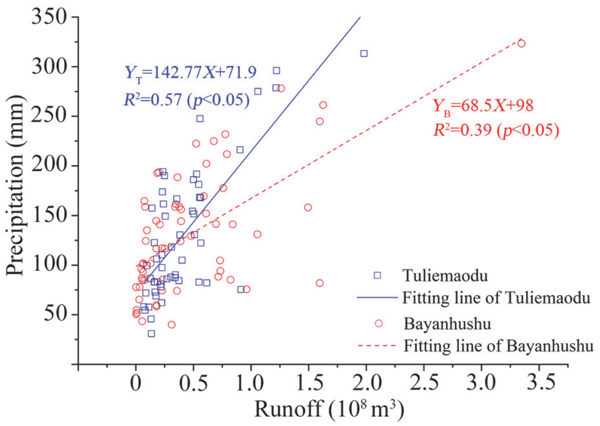


**Fig. 7** Scatter plot of daily precipitation and runoff in July in Tuliemaodu and Bayanhushu stations.

2007; Ding et al. 2008; Xu and Ma 2009; Ding et al. 2009; Huang et al. 2013). A weakening in the northward transmission of water vapor led to a decrease in rainfall in northern and northeast China (Jiang et al. 2008; Gao et al. 2014; Ding and Wang 2016). The declining time of the summer monsoon is consistent with the abrupt change time of precipitation and runoff in HRC, which led to severe drought events and dried-up increases after 2000. It reflected that the hydroclimatic elements in the study area are influenced by atmospheric circulation patterns and can respond to the changing characteristics of the large-scale climate system. In contrast, there is a significant correlation between precipitation and runoff on the decadal scale. Enhanced East Asian summer monsoon and precipitation result in increased runoff for 1956-1963 and 1983-1998. It further implies that precipitation fluctuation in the basin is an essential factor that causes runoff change, consistent with the conclusions of previous research (Xie et al. 2018).

### 4.2 Relationships between temperature and runoff

Global warming has intensified the hydrological cycle and made it prone to extreme drought events, especially after 2000. The average annual temperature of the four meteorological stations in HRC showed a significant rising trend (Fig. 8a-d), with a rate of 0.4°C/10a and an increase of 2.4°C in the past 60 years. It was higher than the temperature rise rate of 0.3°C/10a in northeast China (He et al. 2013), 0.25°C/10a in China (Ren et al. 2005), and 0.12°C/10a in the world (Ren et al. 2017; Sun et al.

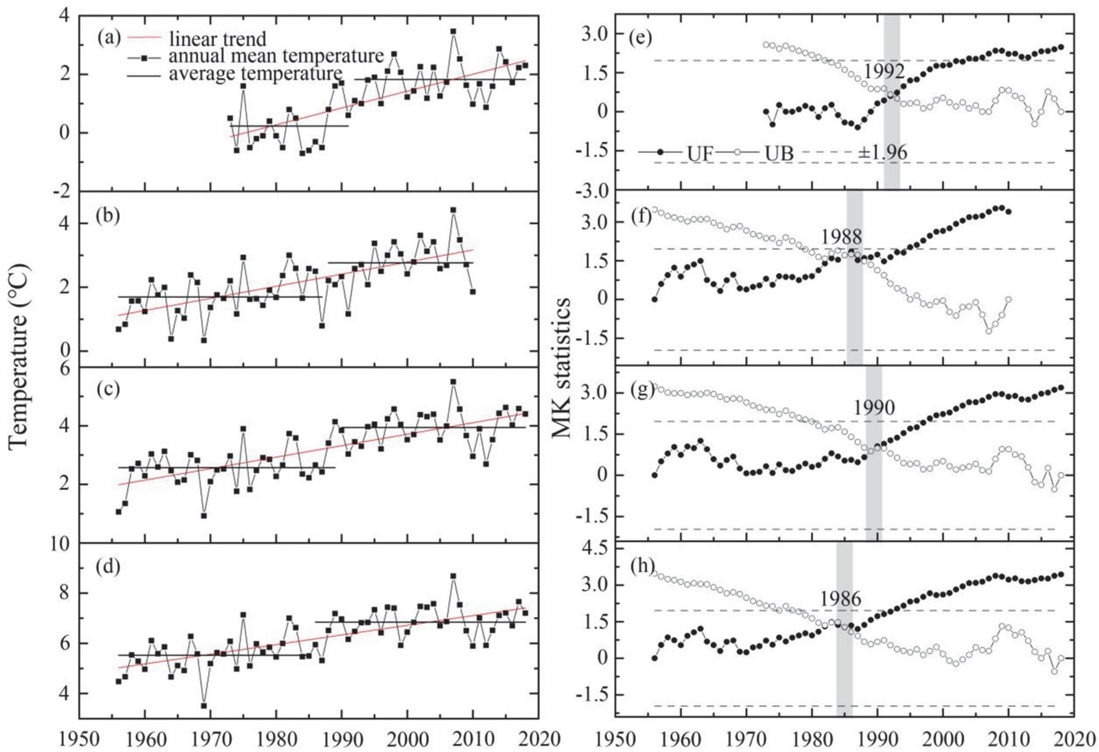


**Fig. 8** Annual average temperature variation in meteorological stations (a) Huolinguole; (b) Tuliemaodu; (c) Bayaertuhushu; (d) Bayanhushu. Mann-Kendall test of annual average temperature in meteorological stations (e) Huolinguole; (f) Tuliemaodu; (g) Bayaertuhushu; (h) Bayanhushu.

2017), indicating that this region is more sensitive to global change. The MK test shows that the abrupt change point of Huolinguole, Tuliemaodu, Bayaertuhushu, and Bayanhushu meteorological stations occurred in 1992, 1988, 1990, and 1986, respectively (Fig. 8e-h). The average temperature after abrupt was 1°C higher than before, indicating that the temperature increased significantly after the abrupt change point and may be transferred to severe drought, which has a negative effect on runoff generation.

The relationship between temperature and runoff is complex. In high latitude and cold regions, the runoff is controlled by air temperature through the indirect influence of snowmelt (Shen et al. 2018; Tang et al. 2019). In HRC, there is a positive correlation between temperature and runoff in early spring (Fig. 9). The small peak in runoff occurs around April 10th, and the difference in timing between the two stations is mainly due to the unfreezing time. When the temperature is between -5°C and 5°C, temperature and runoff are positively correlated. However, when the temperature is between 5°C and 12°C, temperature and runoff are negatively correlated in April, indicating that the evaporation effect increases gradually. Meanwhile, the supply of effective precipitation from March to May is only about 30 mm, with little impact on runoff generation. Furthermore, rapid warming after the 1980s may influence runoff by promoting evapotranspiration. In HRC, annual evapotranspiration was significantly negatively correlated with runoff, with correlation coefficients of -0.518 and -0.455 in the upstream and midstream, respectively. The negative correlation between them was most significant in July, with correlation coefficients of -0.68 and -0.6, followed by May with correlation coefficients of -0.58 and -0.39 in the upstream and midstream, respectively. All of the above passed the confidence test level of 0.01. It indicated that pan evaporation in the HRC has a significant reduction effect on the runoff.

Rising temperature also affect the actual evapotranspiration more by affecting the transpiration of vegetation (Steduto et al. 2003; Gundekar et al. 2008; Liu and Mcvicar 2012). Relevant studies indicate that an increase of 1°C in air temperature, surface evaporation will increase by

5%-6% (Philip and Biney 2002). It can be inferred that the increase in actual evapotranspiration

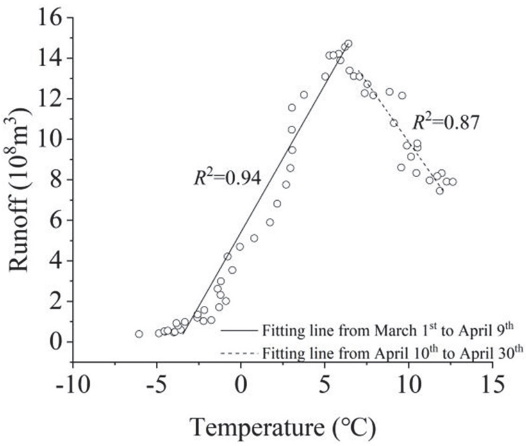


**Fig. 9** Scatter plot of daily temperature and runoff from March 1st to April 30th.

caused by the rise in air temperature accelerates the decreasing trend of runoff in the study area.

In summary, climate change is often the result of coupling changes in precipitation, temperature, and other climate factors. The decrease of precipitation is an essential factor in the reduction of runoff in HRC. Air temperature enhances the trend of runoff reduction by affecting evapotranspiration, which plays a vital role in the formation and development of regional drought. The reduced runoff in the catchment is also disturbed by human activities. However, in the upstream and midstream of the HRC, there is no town with more than 80,000 people, very little irrigated agriculture, low population density and economic activities. These have a slight impact on runoff.

## 5 Conclusion

Surface runoff is an essential component of water resources in arid and semi-arid regions, and an important part of the hydrological cycle, maintaining ecological environment and socio-economic development. Facing severe water challenges, it is crucial to improve the understanding of runoff changes and their driving factor. In this paper, the MK test and sliding T test are used to reveal the runoff variation and its response to temperature and precipitation in the HRC from 1956 to 2018. The main findings are summarized as follows:

(1) Under global warming, a decreasing runoff trend and severe water shortage are obvious in HRC, with an increase in dried up days. This region is prone

to extreme precipitation and drought events.

(2) Runoff process in the HRC can divide into four phases, with 1964, 1982, and 1999 as the abrupt change points. It shows an obvious high-low-high-low alternating process, namely a "Two Highs and Two Lows" pattern. Especially the drought after 2000 led to a severe scarcity of runoff, with river breaks and large areas of exposed riverbeds, clearly linked to climate change.

(3) The intra-annual runoff distribution is uneven. The two peak runoffs appear in April and July. The former peak runoff is possibly caused by rising temperature and snowmelt supplementing the runoff. The latter peak runoff was due to the increase in precipitation. The intra-annual runoff in a typical high flow year is similar to an average year. However, in the low flow year, the intra-annual runoff presents the multi-peak crisscross situation.

In conjunction with the hydro-climatic variables change, an ongoing water crisis and decreasing water resource amount has been portended in the HRC. These results could serve as a reference for regional water resources management and planning in semi-arid regions under global warming conditions. In addition to the climate change, anthropogenic impact such as land use and land cover change, and irrigation water capacity should be considered in the future studies.

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# 结 题 证 明

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负 责 人：丹丹

参 与 人：王晓珍 夏莹莹 王娜 于本金

特此证明

内蒙古师范大学研究生院

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