Impacts of climate change and human activities on runoff in the Luan River Basin

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Abstract. The M-K test and double accumulation curve method were applied to analyze the impact of human activities and climate change on the runoff changes in the study area. The results show a significantly decreasing runoff trend in the study area, with the calculation model of climate change impact and double accumulation curve models. We can get that the impact of human activities is 36.28 mms in the process of runoff change in the Luan River Basin. Its contribution rate is 62.59%, much larger than the impact of climate change, 37.41%. The effect of human activities is the main factor leading to the decrease of runoff in the Luan River Basin.

Keywords: Climate change; human activities; M-K test; double accumulation curve; Luan River Basin.

1. Introduction

Climate change is a severe challenge to the survival and development of humanity today and a major global issue of universal concern to the international community, and actively addressing climate change has become an international consensus and development trend [1-2]. Water resources are the most immediate and essential area affected by climate change [3]. Hydrological cycle research in changing environment has become one of the hot spots in water science research today [4-5]. Under the background of global climate change, it is of great practical significance to study the processes and influence factors of river basin runoff change in river basin water resources planning and management.

In recent years, scholars from various countries have conducted many studies on the attribution analysis of river runoff and the evaluation of climate change impacts. However, due to the limitation of research methods and data, more attention has been paid to the qualitative impact of runoff and climate change on runoff in previous studies [6-7]. However, little research has been done on the quantitative analysis of human activities and climate change on runoff. How to scientifically and quantitatively define the impact of both on river runoff is not only a scientific issue in the field of environmental change impact research but also an essential topic of research and concern for the scientific community at home and abroad [8-9].

As an essential water system in Haihe River Basin, the Luan River Basin has a wide range of watersheds, and the trend of aridity and water resources is becoming increasingly scarce. Scientific and quantitative analysis of runoff variation in the Luan River Basin is not only an essential element in evaluating water resources in the basin, but also a basis for scientific management and rational exploitation of water resources. Therefore, this paper applies sensitivity analysis and double cumulative curves to study the impact of human activities and climate changes on runoff change in the Luan River Basin to clarify their respective impacts and contributions. Sensitivity analysis can measure the influence range of various uncertain factors on watershed runoff, which is beneficial in analyzing the main influencing factors. Staff focus on these critical factors. In studying the consistent evolution of hydrometeorology, the double accumulation curve can be used to analyze the impact of human activities on runoff simply, intuitively, and with low deviation.

2. Materials and Methods

2.1. study area

The study area is located at 38°15′-43°40′ N latitude and 114°40′-118°45′ E longitude, which is the second largest river in Hebei Province and one of the four major water systems in Haihe River Basin (Fig 1). The basin has a typical temperate continental climate, with an average annual temperature of 5-12℃, hot and rainy summers, dry spring and autumn, and cold and dry winters, with an average annual rainfall of 400-700mm. The climate is such that the basin has an uneven intra-annual distribution of runoff, with 70% of the water concentrated in the July-September flood season, and the inter-annual variation in abundance and depletion is considerable, with anomalies of consecutive excellent and bad years [10-11]. The area is economically developed, densely populated, and water-intensive. Moreover, the ecological and environmental conditions are not optimistic or tend to deteriorate more seriously. Hence, it has been classified as a severe water shortage area. The water resource system in the study area has a low ability to adapt to natural changes (e.g., climate change), and it is one of the most vulnerable areas of the water resource system in China. Therefore, it is urgent to restore the water ecology and environment of the Luan River, and it is important to study the response to hydrological cycle processes to future climate change.

The precipitation distribution of the study area has large variability, with the average annual precipitation above Panjiakou reservoir being about 370 mm and up to 742 mm in the area below. The basin's annual flat inlet runoff depth is about 110 mms, with uneven intra-annual distribution and excessive inter-annual variation in abundance and depletion, about 72 mm in the area above Panjiakou and about 223 mm in the area below.

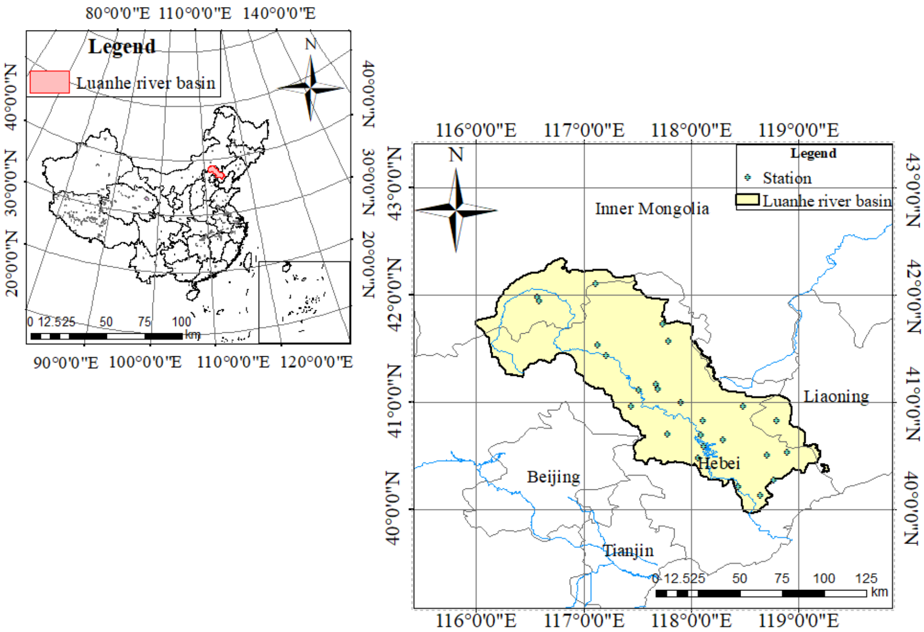

Fig 1: Approximate position of Luan River Basin.

2.2. Data collection

The hydrological process data onto the basin required for this study were mainly obtained from the Hydrological Yearbook of the People's Republic of China for the Haihe River Basin-Luanhe River Basin as well as the Haihe River Basin Water Resources Bulletin, and the locations of the hydrological stations are shown in Fig 1. To study the influence of various factors on runoff variation, data of six hydrological stations and six meteorological stations from 1968 to 1977 were collected, including mean watered level, mean flow, precipitation, evaporation, and mean temperature.

The measured runoff is close to the natural runoff because there are fewer water diversions of the control basin than six stations, which is negligible. The selected sites belong to the typical sites in the upper and middle portions of the Luan River Basin, which can represent the overall situation of the region spatially. The time series is also long enough to meet the research needs. The data are obtained from the hydrological system compilation data, similar to the meteorological data. The joint test of the Brown-Forsythe test [12] and M-K test [13] showed that the meteorological data of each meteorological station had no noticeable abrupt changes and random changes. Meanwhile, the data were more consistent and reliable, representing the regional climate conditions.

2.3. Methodology

2.3.1. Calculation method of potential evapotranspiration

The potential evapotranspiration in this study was calculated by applying the Penman-Monteith equation [14], whose expression is

$$E_0 = f \cdot E_\omega = f\,\frac{\Delta R_n + \gamma E_a}{\Delta + \gamma} \tag{1}$$

After transformation, i.e.

$$E_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma\,\frac{C}{T+273}\,\mu_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34\mu_2\right)} \tag{2}$$

Among them.

$$\Delta = 2503\,\frac{e^{\frac{17.27T}{T+273.3}}}{\left(T+237.3\right)^2} \tag{3}$$

Where: E_0 is the potential evapotranspiration. E_ω is evaporation from water surface; f is the seasonally varying empirical conversion factor from the water surface to soil evapotranspiration; Δ is the slope of saturated vapor pressure; R_n is total radiation; G is heat influx of soil; γ is the dry and wet table constant; e_s is saturated vapor pressure; e_a is actual vapor pressure; μ_2 is the wind speed at 2m height; C is the unit conversion factor, which takes the value of 900.

2.3.2. Mann-Kendall trend test

In the M-K test, the original hypothesis H_0 is that the time series data (x_1, x_2..., x_n) are n independent samples with the same random variable distribution; the checking hypothesis H_1 is a two-sided test. For all r, $q \leq n$, $r \neq q$, x_r, and r_q with different distributions, the statistical variable S of the test is calculated as follows:

$$S = \sum_{r=1}^{n-1}\sum_{q=r+1}^{n} \operatorname{sgn}(x_q - x_r) \tag{4}$$

Among them,

$$\operatorname{sgn}(x_q - x_r) = \begin{cases} +1 & (x_q - x_r > 0) \\ 0 & (x_q - x_r = 0) \\ -1 & (x_q - x_r < 0) \end{cases} \tag{5}$$

Mean 0, variance 0, and S is a normal distribution. Var(S) = n· (n-1) · (2n+5)/18. Equation (6) is used to calculate the standard normal statistic variates when n>10.

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & S < 0 \end{cases} \tag{6}$$

2.3.3. M-K mutation test

For the time series x with sample number n, construct a sequence.

$$s_r = \sum_{p=1}^{r}\sum_{q=1}^{p-1}\alpha_{pq} \quad (r = 2,3,\cdots,n) \tag{7}$$

Among them,

$$\alpha_{pq} = \begin{cases} 1 & x_p \le x_q \\ 0 & x_p \le x_q \end{cases} \quad (1 \le q \le p) \tag{8}$$

Define the statistic UF_r under the hypothesis of stochastic independence of time series.

$$UF_r = \frac{s_r - E(s_r)}{\sqrt{\mathrm{var}(s_r)}} \quad (r = 1,2,\cdots,n) \tag{9}$$

Eq.

$$E(s_r) = \frac{r(r+1)}{4} \tag{10}$$

$$\mathrm{var}(s_r) = \frac{r(r-1)(2r+5)}{72} \tag{11}$$

x is the eigenvalue. μ is the overall mean. σ is the overall standard deviation.

Reverse order is used to arrange the data sequence x, and the formula is then used to calculate it, while satisfying:

$$\begin{cases} UB_r = -UF_r \\ r^{'} = n+1-r \end{cases} \quad (r = 1,2,\cdots,n) \tag{12}$$

The line chart is drawn in the coordinate system based on two series of UF_r and UB_r value data. If there is a crossover between the two curves at the significance threshold, the time spot corresponding to the crossover point is the mutation point.

2.3.4. Calculation of climate change impact volume

Budyco [15] considers that the average multi-year evapotranspiration of a watershed is determined by precipitation and the potential evapotranspiration, and that evapotranspiration is a function of the two, which can be represented simply as

$$\frac{E}{P} = f\left(E_0 / P\right) \tag{13}$$

Where: E represents actual evapotranspiration; P represents precipitation. Chinese climatologist Fu et al [16] put a differential form of Budyco's hypothesis based on the physical implication of basin hydrometeorology, and the analytic equation of Budyco's hypothesis [17-20] was derived through dimensional analysis and mathematical derivation.

$$\frac{E}{P} = 1 + \frac{E_0}{P} - \left[1 + \left(\frac{E_0}{P}\right)^{\omega}\right]^{1/\omega} \tag{14}$$

Where: ω is a dimensionless parameter.

Based on the long time series water balance equation $P = E + Q$, equation (2) can be derived as the simulation equation for runoff Q.

$$Q = \left[P + E_0^{\omega}\right]^{1/\omega} - E_0 \tag{15}$$

Based on equation (3), the sensitivity of watershed runoff (Q) to climate change elements (X) can be obtained by applying the calculus for partial derivatives ($\partial Q/\partial X$).

$$\frac{\partial Q}{\partial P}=\left[1+\left(\frac{E_0}{P}\right)^{\omega}\right]^{(1/\omega-1)} \tag{16}$$

$$\frac{\partial Q}{\partial E_0}=\left[1+\left(\frac{P}{E_0}\right)^{\omega}\right]^{(1/\omega-1)}-1 \tag{17}$$

Where: ω is obtained by applying the least squares solution.

Milly and Dunne proposed a method to calculate runoff variations due to climate change based on the theory of Budyko's hypothesis [21-26].

$$\Delta Q_{climate}=\Delta Q_P+\Delta Q_{E_0}=\beta\Delta P+\gamma\Delta E_0 \tag{18}$$

Where: β and γ are the amount of impact on watershed runoff per unit of potential evapotranspiration and precipitation change, respectively, i.e., the sensitivity coefficient $\beta=\partial Q/\partial P$, and $\gamma=\partial Q/\partial E_0$.

2.3.5. Double accumulation curve

Assuming X is the base period variable, Y is the tested variable, and N is the number of years of observation, a new year-by-year cumulative series is obtained for X and Y by accumulating each in chronological order, i.e.

$$X'_p=\sum_{p=1}^{N}X_p \tag{19}$$

$$Y'_p=\sum_{p=1}^{N}Y_p \tag{20}$$

In this study, cumulative precipitation is used as the base period variable by which the effects of human activities can be discerned. It is performed as follows.

(1) Based on the relationship curves of accumulated precipitation $\sum P$ and accumulated runoff $\sum Q$, the time point at which human activities affect runoff is judged, and the time point is used as the boundary to divide the Base Periods and Change Periods into two periods.

(2) Linear regression of the data in the columns $\sum P$ and $\sum Q$ for each year of the base period, and fit the equation of the relationship between them.

$$\sum Q=a\sum P+b \tag{21}$$

(3) Applying the above fitting equation, ∑P of the Change Periods is substituted into the equation to obtain the deep simulation value of accumulated runoff in the Change Periods $\sum Q'$, and $\sum Q'$ is considered as the runoff without the influence of human activities under the same condition as the sub-base period.

(4) Based on the principle of superposition of cumulative values, the calculation method of this principle is applied in reverse. According to the simulated value $\sum Q'$ inverse, the year-by-year runoff depth simulation value Q' is obtained. Then the measured value and average runoff in Change Periods influence human activities on runoff in the basin.

3. Discussion

3.1. M-K test analysis

From Fig 5, it can be seen that the values of the Mann-Kendall test [27-28] statistic *UF* and *UB* for annual runoff in the studied region exceed the critical value corresponding to the confident level of 0.05 (*Y*=1.96 and *Y*=-1.96), indicating a clear trend of runoff variation. The value of *UF* is smaller than 0, indicating a clear trend of annual runoff decrease from 1968 to 1977. Furthermore, the *UF* and *UB* curves in the test results show a crossover point in 1972, indicating that an abrupt change in the runoff variation in this area occurred in 1972. In 1972, the research period can be divided into the Base Periods (1968-1972) and the Change Periods (1973-1977).

3.2. Effects of climate variation on runoff in Luan River Basin

Fig 3 shows the comparison of E_0 and *P* in different research periods in the Luan River Basin. The analysis results show that the precipitation in this area decreases while the E_0 does not change much during these years. The $\bar{P}$ in the Base Periods is 614.2mm while in the Change Periods is 634.4mm, and the variation in *P* decreased by 20.2mm; The $\overline{E_0}$ in the Base Periods is 968.4mm while in the Change Periods is 970.8mm. Moreover, the variation in E_0 increased by 2.4mm.

Based on the sensitivity analysis of runoff to climate change in this area, the sensitivity coefficient β of runoff to precipitation is 0.3361, and the sensitivity coefficient γ of potential evapotranspiration is -0.1235. Based on the analysis of the change in E_0 and *P* between the Base Periods and Change Periods, the change of *P* is -20.2mm. Simultaneously, the change of E_0 is -2.4mm. Based on Eq(14), the impact of climate change on runoff is 21.68mm, of which the impact on precipitation is 21.21mm, and the impact on E_0 is 0.47mm.

3.3. Impact on human activities on runoff in Luan River Basin

As shown in Fig 4, the correlation between cumulative precipitation and cumulative runoff is divided into two distinct phases with the year 1972 as the boundary, and the slope of the fitted straight line changes significantly in 1972, which indicates that human activities started to have a significant impact on the watershed runoff in that period. The distance between the deviation point and the original fitting line extension indicates the degree of human activity interference. The fitted linear regression equation between cumulative precipitation $\sum P$ and cumulative runoff $\sum Q$ for the base period is $\sum Q = 0.1586\sum P + 127.34$, the coefficient of determination of the equation R_2 is 0.9937. Besides, the number of observation years *N* is ten years. To produce the simulated cumulative runoff, the accumulated precipitation in the Change Periods is added to the fitting equation, and the simulated yearly runoff Q′ in the Change Periods is inverted. The results show that the simulated annual average runoff in the Change Periods is 110.628 mm when the measured annual average runoff is 74.348 mm, indicating that the runoff change ΔQ_{human} caused by human activities is 36.28 mm.

4. Results

4.1. Characteristics of runoff changes in Luan River Basin

Fig 2 compares the annual average runoff of Luan River Basin during the two periods. The average runoff in the base period is 108.368mm, which is 74.348mm in the change period, which indicates that the runoff in the change period is decreased by 34.02mm compared to the base period, with a percentage reduction of 45.76%.

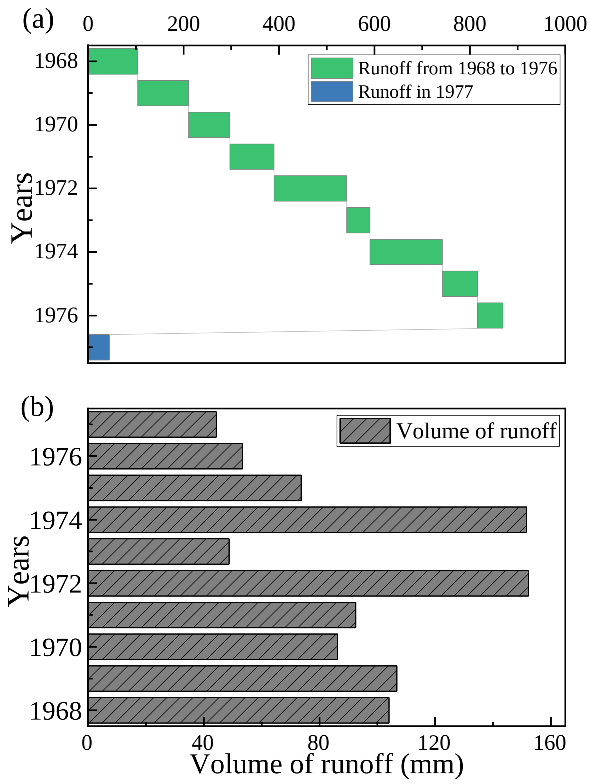

Fig 2: (a) Chart of flow increment in Luan River Basin during 1968-1977

(b) Comparison of the runoff between Base Period and Change Periods in Luan River Basin.

4.2. Analysis of relationship between Precipitation and Runoff in Luan River Basin by Double Accumulation Curve Method

The annual average precipitation, annual average runoff as well as the calculated annual average potential evapotranspiration in Luan River Basin are taken into equation (11). The result of ω in the study area is found to be 2.1392 by combining the least squares method. Bringing the ω value into formula (12) and formula (13), the precipitation of sensitivity coefficient Q/P to runoff is 0.3619, and the sensitivity coefficient Q/E_0 to potential evapotranspiration is -0.1418. It indicates that the sensitivity of the runoff of the Luan River Basin to climate change is that for every 1mm increase in precipitation, the runoff will increase by 0.3619mm; for every 1mm increase in potential evapotranspiration, the runoff of the watershed will decrease by 0.1418mm.

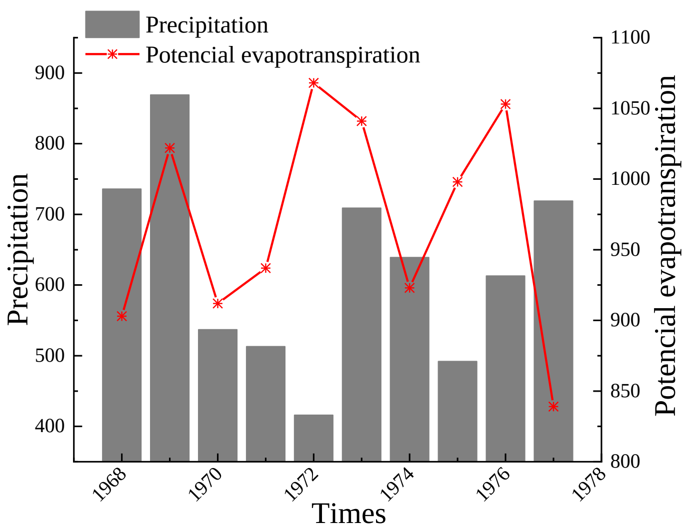

Fig 3: Comparison of potential evaporation and precipitation in Base Periods and Change Periods of Luan River Basin.

Simultaneously, according to the runoff and the annual precipitation of Luan River Basin from 1968 to 1977, the two data series are accumulated yearly to obtain a double accumulation graph for the study area.

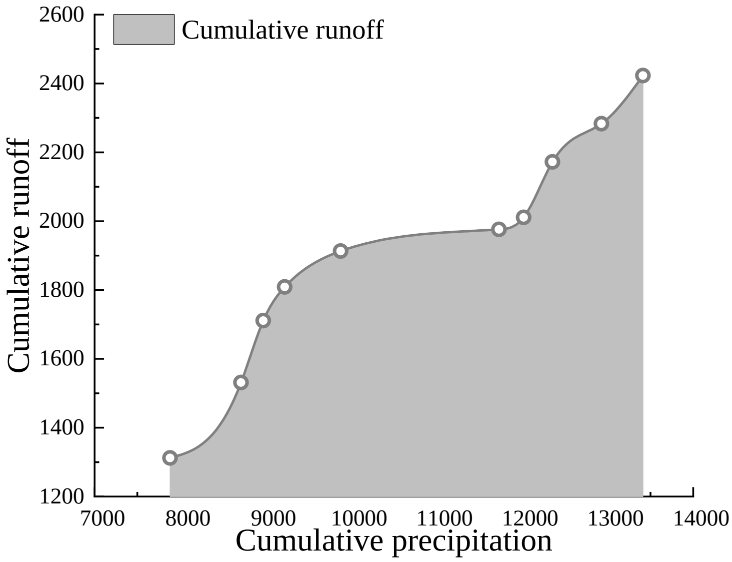

Fig 4: Precipitation-runoff double accumulation curve in the Luan River Basin.

4.3. Results of M-K test for runoff in Luan River Basin

Applying the M-K trend analysis, the statistic Z of the annual runoff in the Luan River Basin during 1968-1977 is -2.96, indicating a decreasing runoff trend in the study area. In addition, $|Z|>2.58$, indicating that the annual runoff in the studied region is not only decreasing, but also the decreasing trend is significant at the 0.01 level. Meanwhile, as shown in Fig 5, the M-K mutation test can be applied to examine the mutation of the annual runoff in the Luan River Basin.

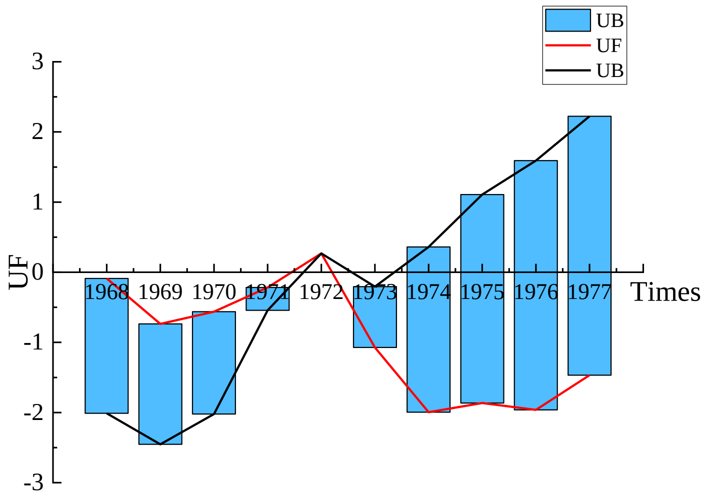

Fig 5: M-K mutation test for annual runoff in the Luan River Basin.

5. Conclusion

In this study, Luan River Basin was taken as the study area, and the impacts of interannual variation of runoff on climate change and human activities in the study area were analyzed, respectively. The main findings are as follows:

(1) In general, runoff increases with increasing precipitation and decreases with increasing average temperature. The annual runoff has generally shown a decreasing trend over the years, the precipitation has slightly decreased, and the temperature has generally shown an increasing trend.

(2) The sensitivity coefficient *Q/P* of runoff to precipitation is 0.3619, and the sensitivity coefficient Q/E_0 of potential evapotranspiration is -0.1418. The amount of climate change impact on runoff in the Luan River Basin is 21.68 mm.

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(3) In the runoff change process of Luan River Basin, the amount of human activity influence is 36.28mm, and its contribution is 62.59%, much larger than that of climate change, 37.41%. The influence of human activity is the primary factor resulting in the decrease of runoff in the Luan River basin.

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