Research on the attribution identification of source runoff variation in the Yellow River Source Region based on water and energy balance model

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Abstract. The Yellow River source region runoff has a huge impact on the Yellow River Basin. Based on the data of meteorological and hydrological elements from 1960 to 2015 and the principle of water and energy coupling equilibrium in the basin, this paper analysis the influence of climate and underlying surface changes on runoff, and derives its differential. Firstly, the variation law of runoff in the Yellow River source is analysed based on the long series of runoff data. Then the influence of climate change and the underlying surface changes on runoff is studied by the principle of watershed and energy coupling equilibrium. And the influence of changes in meteorological elements is further refined into runoff changes caused by precipitation changes and potential evapotranspiration combined with the coefficient of climate elasticity. Finally, analysis results show that a 1% increase in elasticity factor precipitation, potential evaporation, and the perennial average basin surface parameters, will result in an increase in 1.97% runoff, a decrease in runoff of 0.97% or 1.18%. The contribution of runoff reduction was 24.0% for precipitation change and 18.0% for evaporation. And for the Yellow River source region, the contribution of climate change scenarios and human activity factors to runoff changes is close to 4:6. Compared with other stations, we can find that the closer to the source of the river, the greater affected by climate change, and the closer to the middle reaches, the greater the impact of human activities.

1. Introduction
As the effects of global climate change, the increase in temperature causes the water cycle to intensify, and the distribution of water on the surface, which in turn affects the development of human society and the ecological environment. It mainly analyzes the influence of regional precipitation, temperature, evaporation and other hydrological factors caused by climate change on the amount of regional surface water resources, which can reflect the dominant characteristics of water cycle at large spatial and temporal scales. Therefore, by studying the impact of climate change on water resources, it can provide a basis for the protection and utilization of water resources and comprehensive management. It is one of the hotspots in the global climate change and utilization of water resources research [1,2]. The change of surface water resources is mainly affected by different climate scenarios, which follows the “climate scenario-hydrological simulation-impact assessment” approach [3-7]. Among them, the distributed hydrological model is an important tool currently used to evaluate the change of water resources caused by climate change, but in the modeling process, detailed
meteorological, hydrological, underlying conditions, socio-economic and other data are needed, which is difficult to scale at large scale. It is promoted and applied, and there are many parameters that need to be determined, and there are problems with the same effect. In addition, the distributed hydrological model is more suitable for the monthly scale and daily scale, and is not suitable for the long-term mean simulation. How to establish a regional annual scale hydrological model and simulate the process of climate change's influence on regional water resources under different scenarios is the key to study the influence of climate change on water resources.

Water energy balance equation is an expression that explains the relationship between regional precipitation, evaporation and energy from a macro perspective. Experts at home and abroad have carried out related research in combination with this equation [8-11]. At the same time, relevant scholars have also obtained fruitful results. Other scholars have also carried out a lot of research using the hydrothermal balance equation, it is pointed out that the actual evaporation is closely related to the synchronization of rainfall and potential evaporation, and proposed hydrothermal coupling that can be applied to any time scale. With the deepening of people's research on climate change, the research on the influence of climate change on regional water resources based on the principle of water and energy balance equation has become one of the current research hotspots. Based on water energy balance model considering the underlying factors, the relevant scholars analyzed the empirical formulas for constructing different climate change scenarios and different human activities on the change of runoff based on the long series of hydrological runoff data from different basins [12-15]. The above research shows that the water-energy balance equation can be used to analyze the impact of climate change scenarios on regional water resources, so that the parity of regional water resources relates climate change to regional underlying surface conditions and can analyze the macroscopic law of water resources change from a larger scale.

If the annual precipitation increases by 1%, the annual runoff of the basin is a percentage change from the multi-year average. The elasticity coefficient of the underlying surface of runoff can be defined as the change quantity of runoff in a basin or region caused by the change of unit area of the underlying surface. The change in the underlying surface of the basin here mainly refers to different human activities [16]. However, there is no comprehensive index to quantitatively describe the change of the underlying surface of the basin. Although the distributed hydrological model can quantitatively simulate the influence of underlying surface changes on runoff, the runoff variation analysis based on distributed hydrological model is also questioned due to the complexity and uncertainty of the model. Based on the daily meteorological and hydrological monitoring data of the Yellow River source from 1960 to 2015, and the principle of watershed and energy coupling equilibrium. Firstly, this paper establishes the water-energy balance equation that reflect the impact of climate change scenarios and underlying surface changes on surface runoff. Secondly, we derives the differential form, combined with the climate elastic coefficient, to describe the water cycle constitutive relationship of the region on a simplified scale on the annual scale. Finally, the impacts of precipitation and temperature changes caused by climate change on the amount of water resources in the Yellow River source are analyzed from a macro perspective.

2. Study area and methodology

2.1. Study area
The Yellow River source is located in the northeast of qinghai-tibet plateau, Qinghai province. The study area is above the Tangnaihai Station in the Yellow River basin [17], which is shown in figure 1. The meteorological and hydrological data required for the study are: observation data of 19 meteorological stations in the basin and surrounding areas from 1960 to 2015. The data set includes meteorological elements such as solar radiation, temperature, precipitation, runoff, relative humidity and wind speed. The meteorological data comes from the National Meteorological Science Data Sharing Service Platform, and its web site is http://data.cma.cn. The runoff monitoring data of the Yellow River source is the natural runoff from January 1 1960 to December 1 2015 in Tangnaihai.
2.2. Calculation of the elastic coefficient of runoff

Based on the principle of watershed and energy coupling equilibrium, this study established an analytical method that can reflect the influence of climate change and the underlying surface changes on runoff. Under certain climatic and vegetation conditions, the long-term hydrological and climatic characteristics of the basin are subject to the principle of water and energy balance [18], which was later named by the international counterpart as the Choudhury-Yang formula [19]. The water-hydrodynamic coupling equilibrium equation of the basin, the expression is as follows:

\[
E = \frac{P \times ET_0}{(P^0 + ET_0^{1/\omega})^{1/\omega}}
\]  

(1)

In the formula, \(E\) is the perennial average evapotranspiration, \(P\) is the perennial average precipitation, \(ET_0\) is the perennial average evapotranspiration, and \(\omega\) is the parameter reflecting the characteristics of the underlying surface of the basin. This includes terrain, soil and vegetation [20-22].

It is considered that \(P\), \(ET_0\) and \(\omega\) are independent variables in the above formula. Combined with the perennial average water balance equation of the region, for example, \(P = E + R\), the Annual change in runoff \(R\) can be expressed as the following all-differential form:

\[
dR = \frac{\partial f}{\partial P} dP + \frac{\partial f}{\partial ET_0} dET_0 + \frac{\partial f}{\partial \omega} d\omega
\]  

(2)

Schaake [23] expresses the precipitation elastic coefficient (\(\varepsilon_P\)) of runoff as \(\varepsilon_P = \frac{dR/R}{dP/P}\). Similarly, the potential evapotranspiration coefficient of runoff can be defined as \(\varepsilon_{ET_0} = \frac{dR/R}{dET_0/ET_0}\), and the elastic coefficient of underlying surface of runoff \(\varepsilon_\omega = \frac{dR/R}{d\omega/\omega}\). According to the definition of these elastic coefficients, by dividing (2) by the perennial average runoff depth \(R\), you can get:

\[
dR = \varepsilon_P \frac{dP}{P} + \varepsilon_{ET_0} \frac{dET_0}{ET_0} + \varepsilon_\omega \frac{d\omega}{\omega}
\]  

(3)
Using the differential form of the hydrothermal coupling balance, the precipitation elastic coefficient of the runoff can be obtained from the definition of the elastic coefficient. ($\varepsilon_p$), Potential evapotranspiration elastic coefficient of runoff ($\varepsilon_{ET}$), and the elastic coefficient of the underlying surface of the runoff ($\varepsilon_{\omega}$), let $\phi = \frac{E_0}{P}$, they are as follows:

$$\varepsilon_p = \frac{1}{1 + \left(\frac{E_0}{P}\right)\omega} - \frac{1}{1 + \left(\frac{E_0}{P}\right)\omega}^{1/\omega+1}$$ (4)

$$\varepsilon_{ET} = \frac{1}{1 + \left(\frac{E_0}{P}\right)\omega} - \left(1 + \left(\frac{E_0}{P}\right)\omega\right)^{-\omega}$$ (5)

$$\varepsilon_{\omega} = \ln \left[1 + \left(\frac{E_0}{P}\right)\omega\right] + \left(\frac{E_0}{P}\right)\omega \ln \left[1 + \left(\frac{E_0}{P}\right)\omega\right]^{1/\omega+1}$$ (6)

From equations (4) to (5), the three elastic coefficients of the annual runoff in the basin can be based on the perennial average precipitation ($P$) of the basin, the perennial average potential evaporation ($E_0$), and the perennial average basin surface parameters ($\omega$). It is postulated that these three parameters reflect the annual average runoff hydrological and climatic characteristics of the basin.

2.3. Runoff change attribution identification

According to the mutation point, the whole research period is divided into two parts. The annual average runoff of period 1 is deeply recorded as $R_1$, and the annual average runoff of period 2 is deeply recorded as $R_2$. The difference in the average annual runoff depth is expressed as:

$$\Delta R = R_2 - R_1$$ (7)

The variation of runoff depth ($\Delta R$) is derived from the change of meteorological elements and the change of the underlying surface of the basin. The change of runoff can be written as:

$$\Delta R = \Delta R_p + \Delta R_{ET}$$ (8)

Among them, $\Delta R_p$ is changes in runoff caused by climate change, and $\Delta R_{ET}$ is the changes in runoff caused by the change of the underlying surface of the basin. This study further refines the effects of changes in meteorological elements into runoff changes ($\Delta R_p$) caused by precipitation changes and runoff changes ($\Delta R_{ET}$) caused by potential evapotranspiration changes. According to the climatic elastic coefficients ($\varepsilon_p$ and $\varepsilon_{ET}$) of the runoff and the elastic coefficient ($\varepsilon_{\omega}$) of the underlying surface, the runoff changes due to different factors can be assessed as follows:
\[ \Delta R_p = \varepsilon_p \frac{R}{P} \Delta P, \quad \Delta R_{ET_0} = \varepsilon_{ET_0} \frac{R}{ET_0^0} \Delta ET_0^0, \quad \Delta R_i = \varepsilon_i \frac{R}{\omega_i} \Delta \omega_i \]  
(9)

Among them, \( \Delta P = P^2 - P^1 \) and \( \Delta ET_0 = ET_0^0 - ET_0^1 \) denote the difference between the average annual precipitation and the potential evapotranspiration for two periods. \( \omega^1 \) and \( \omega^2 \) represent the underlying surface conditions of the basin 1 and the period 2, respectively, and can be obtained through the perennial average \( P \) of the two periods, \( ET_0 \) and \( E \) are inversely calculated by the equation (1).

3. Results and discussion

Through the calculation and analysis of the Yellow River source precipitation, potential evaporation and runoff depth, figure 2 shows that from 1960 to 2015, the precipitation trend decreased slightly, the annual difference was large, and the potential evapotranspiration increased significantly (8.7 mm/10a), at the same time, the runoff depth shows a decreasing trend (5.2 mm/10a).

![Figure 2. Precipitation (a), potential evaporation (b) and runoff depth (c) change trend.](image)

As shown in figure 3, in the past 50 years, the year of sudden runoff was 1990. According to calculations, the average annual runoff depth from 1991 to 2015 was 149.9 mm, a decrease of 16.4% compared with 1990. At the same time, it is calculated that the precipitation runoff coefficient of the Yellow River source area before 1990 is 0.30. After 1990, the coefficient is reduced to 0.26, and the runoff formed under the same precipitation conditions is reduced.

![Figure 3. Mutation test of runoff.](image)

The precipitation-runoff relationship was separated from the year of the catastrophe in 1990, and the precipitation-runoff relationship from 1960 to 1990 and from 1991 to 2015, respectively, as shown in figure 4, further indicates that the runoff decreased after 1990. However, the relationship between precipitation and runoff did not change much during the two periods.
Using the elastic coefficient, the characteristics of meteorological hydrological variables in the source region of the Yellow River are further analyzed, as shown in table 1. There are 3 hydrological stations are used in table 1. The purpose of discussing Tou Daoguai station and Hua Yuankou station is to analyze the impact of climate change and human activities on the upper and middle reaches of the Yellow River. The absolute value of the elastic coefficient is $P$, the middle value is $ET_0$, and the smallest is $\omega$. For Tangnaihai station which represents the source region of the Yellow River, a 1% increase in $P$, $ET_0$ or $\omega$ will result in an increase in 1.97% runoff, a decrease in runoff of 0.97% or 1.18%. For Tou Daoguai station which represents the upper reaches of the Yellow River, a 1% increase in $P$, $ET_0$ or $\omega$ will result in an increase in 1.85% runoff, a decrease in runoff of 0.85% or 1.67%. For Hua Yuankou station, which represents the middle reaches of the Yellow River, a 1% increase in $P$, $ET_0$ or $\omega$ will result in an increase in 2.42% runoff, a decrease in runoff of 1.42% or 2.11%.

Further, the attribution of runoff changes is identified. As shown in table 2, the contribution of runoff reduction is 24% for precipitation change, 18.0% for evaporation change, and 58.7% for underlying surface change. 0.7% in Tang Naihai station, and the contribution of climate change scenarios and human activity factors to runoff changes is close to 4:6. The contribution of runoff reduction is 25.4% for precipitation change, 8.7% for evaporation change, and 67.6% for underlying surface change 1.7% in Tou Daoguai station, and the contribution of climate change scenarios and human activity factors to runoff changes is close to 3:7. The contribution of runoff reduction is 28.6% for precipitation change, 4.7% for evaporation change, and 88.1% for underlying surface change 5.4% in Tou Daoguai station, and the contribution of climate change scenarios and human activity factors to runoff changes is close to 2:8. Form table 2, we can find that the closer to the source of the river, the greater affected by climate change, and the closer to the middle reaches, the greater the impact of human activities.

In table 2, $dR_P$ denotes runoff changes caused by precipitation, $dR_E$ denotes runoff changes caused by potential evapotranspiration, $dR_u$ denotes runoff changes caused by underlying surface, $dR$ denotes

| Station        | Catchment area (km²) | $P$ (mm) | $ET_0$ (mm) | $R_0$ (mm) | $ET_0 / P$ | $\omega$ | $\varepsilon_P$ | $\varepsilon_{ET_0}$ | $\varepsilon_\omega$ |
|---------------|---------------------|---------|------------|----------|----------|--------|-------------|----------------|-------------|
| Tang Naihai   | 121972              | 589.5   | 831.9      | 166.1    | 1.41     | 1.438  | -0.97      | -0.97         | -1.18       |
| Tou Daoguai   | 367900              | 380.9   | 964.3      | 88.8     | 2.53     | 1.130  | 1.85       | -0.85         | -1.67       |
| Hua Yuankou   | 730036              | 435.4   | 998.1      | 53.2     | 2.29     | 1.689  | 2.42       | -1.42         | -2.11       |

Figure 4. Precipitation-runoff relationship around 1990.
runoff depth difference, \(dR'\) denotes runoff depth change calculated, \(dO\) denotes difference between \(dR'\) and \(dR\). \(C_P\) denotes the contribution of precipitation to runoff changes, \(C_E\) denotes the contribution of potential evapotranspiration to changes in runoff, \(C_\omega\) denotes The contribution of underlying surface to changes in runoff, \(Co\) denotes The contribution of other factors to changes in runoff.

### Table 2. Runoff change attribution identification.

| Station       | \(dR_P\) | \(dR_E\) | \(dR_\omega\) | \(dR\) | \(dR'\) | \(dO\) | \(C_P\) | \(C_E\) | \(C_\omega\) | \(Co\) |
|---------------|----------|----------|--------------|---------|---------|--------|---------|---------|-------------|-------|
| Tang Naihai   | -7.0     | -5.3     | -17.2        | -29.4   | -29.6   | -0.2   | 24.0    | 18.0    | 58.7        | -0.7  |
| Tou Daoguai   | -4.9     | -1.7     | -13.1        | -19.3   | -19.7   | -0.3   | 25.4    | 8.7     | 67.6        | -1.7  |
| Hua Yuankou   | -11.5    | -1.3     | -18.8        | -27.6   | -31.6   | -4.0   | 28.6    | 4.7     | 88.1        | -5.4  |

4. Conclusions

This paper studies the variation of runoff in the Yellow River source under the influence of climate change based on water and energy balance model combined with the climate elasticity coefficient. Then the influence of meteorological factors is further refined into two parts: runoff variation caused by precipitation changes and runoff changes caused by potential evapotranspiration. On this basis, the impacts of climate change and human activities on runoff change are further analyzed. The following conclusions are drawn:

- In the Yellow river source, the year of sudden runoff was 1990. And a 1% increase in elasticity factor \(P\), \(ET_0\) or \(\omega\) will result in an increase in 1.97% runoff, a decrease in runoff of 0.97% or 1.18% in the Yellow River source.
- Contributions to runoff reduction: precipitation changes accounted for 24%, evaporation changes accounted for 18.0%, underlying surface changes accounted for 58.7%, other factors accounted for 0.7%.
- The contribution of climate change scenarios and human activity factors to runoff changes found form the analysis results, show that the closer to the source of the river, the greater affected by climate change, and the closer to the middle reaches, the greater the impact of human activities.

The research in this paper only demonstrates the extent of the impact of climate change and human activities on different regions of the basin, and further studies on the impact mechanism are still needed.

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