Hydrological responses to climatic changes in the Headwater Catchments of the Yellow River Basin

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Abstract

Hydrological cycle changes in the headwater catchments of the Yellow River Basin have been detected with special reference to precipitation elasticity of runoff. The results had shown that in 1990s, the precipitation, potential evapotranspiration, actual evapotranspiration and runoff was 5%, 0.9%, 10% and 21% less than that of the baseline period (1960-1990). The precipitation elasticity of runoff is around 2, implicating that 5% reduction in precipitation may result in 10% reduction of runoff. Therefore, besides the impacts of precipitation change, the other factors such as land use and land cover change may also play an important role in the decrease of runoff in 1990s.

Keywords: Hydrological cycle, climatic change, elasticity coefficient, headwater catchments, the Yellow River Basin

Introduction

The headwater catchments of the Yellow River refers to the region between 95°50′45″E to 103°28′9″E, and 32°12′11″ to 35°48′7″N with the Tongnag station as the outlet of the catchments (Figure 1). The combined drainage area of the catchments is about 121,972 km^2 (15 % of the whole Yellow River Basin), while the river length is about 1,553 km. The altitude of most area is between 3,480 and 4,680 m above sea level. There are about 2,000 km^2 of lakes, swamps and grassland in the region. The annual average runoff is 20.5×10^9 m^3 y^{-1} (35 % of total runoff for Yellow River). In terms of climate, the catchments are described as a semi-humid region of the Tibetan Plateau sub-frigid zone. Annual average daily temperature varies between –4 and 2 °C from southeast to northwest. The annual average precipitation is about 534 mm. Up to 75-90% of the total annual precipitation falls in the wet season (June – September) caused by the Southwest monsoon from the Bay of Bengal. Precipitation tends to decrease from southeast (~ 800 mm) to northwest (~ 300 mm). There are permanent snow packs and glaciers in southern Animaqing, Bayankala, and northern Qilian Mountains.

The headwater catchments of the Yellow River contribute over 35% of water resources for the whole basin, known as the "water tower" of the Yellow River Basin. Hydrological consequence due to climatic changes in the region has attracted increasing research efforts in recent years. In this research, we tend to detect the long-term changes of hydrological cycle in the region, with special reference to climatic elasticity of stream flow.

Methodology

For changes of hydrological cycle in the headwater catchments in the Yellow River Basin, factors including precipitation (P) , potential evapotranspiration (E0), actual evapotranspiration (Ea), runoff (R) and baseflow (Q) have been taken under consideration. The long term precipitation and runoff data series are gauged records from 1960 to 2000, while the other factors are estimated by the method introduced following.

- **Potential evapotranspiration**

Potential evaporation defined as the evaporation from a continuously saturated imaginary surface is estimated according to the method proposed by Xu et al. (2005). Parameters of the imaginary surface are described in Kondo and Xu (1997) include a surface roughness of 0.005 m, albedo *ref* = 0.06, surface emissivity ε = 0.98, evaporation efficiency β = 1. Thus, the estimation of potential evapotranspiration is based on the following expressions:

$$R^{\downarrow} = \varepsilon\sigma Ts^4 + H + \lambda E + G \tag{1}$$

$$H = c_p \rho ChU_1 (Ts - Ta) \tag{2}$$

$$\lambda E_p = \lambda \rho \beta ChU_1 (q_{sat}(Ts) - q_a) \tag{3}$$

where $R^{\downarrow}$ is net radiation at the ground surface, σ is the Stefan-Boltzman constant (5.670×10^{-8} W m^{-2} K^{-4}). c_p is the specific heat of air, ρ is the air density, *Ta* is the air temperature, λ is the latent heat of vaporization, $q_{sat}(Ts)$ is the saturation specific humidity of *Ts*, and q_a is the specific humidity. The surface temperature T_s is calculated iteratively to satisfies the heat balance equations (1) and (2) indicated above. With a given *Ts*, *Ep* can then be estimated according to (3), while the exchange speed ChU_1 is defined as.

$$ChU_1 = \max(0.0027 + 0.0031 \times U1, 0.0036 \times (Ts - Ta)^{\frac{1}{3}}) \tag{4}$$

Besides the method described above, the FAO reference evapotranspiration based on Penman-Monteith equation also used in this research.

- **Actual evapotranspiration**

Since the objects of this research are to define long-term changes of hydrological cycle in the headwater catchments of the Yellow River Basin, annual actual evapotranspiration (Ea) is estimated according to Bagrov (1953) and Zhang (2001), described as a function of potential evapotranspiration and precipitation (P).:

$$\text{Bagrov:} \quad \frac{dE_a}{dP} = 1 - \left(\frac{E_a}{E_p}\right)^N \tag{5}$$

$$\text{Zhang:} \quad \frac{E_a}{P} = \frac{1 + w\dfrac{E_p}{P}}{1 + w\dfrac{E_p}{P} + \left(\dfrac{E_p}{P}\right)^{-1}} \tag{6}$$

where N and w is parameter of Bagrov and Zhang model respectively.

- **Precipitation elasticity of runoff**

The concept of elasticity coefficient is learnt from economy referring to the quotient of two changing rates. For precipitation elasticity of runoff (ε), it can be described as:

$$\varepsilon = \frac{dQ/Q}{dP/P} \tag{7}$$

where, Q is runoff. Analytically, if there is an explicit expression of the relationship between runoff and precipitation, dQ/dP can then be determined to calculate the elasticity at given (P, Q).

For $Q=aP^b$, it can be easily derived that the elasticity coefficient is b. However, if the relationship between runoff and precipitation is unknown or implicit, the coefficient can be estimated based on the observed data as:

$$\hat{\varepsilon} = Median(\frac{\Delta Q_i / \overline{Q}}{\Delta P_i / \overline{P}}) \tag{8}$$

Moreover, for observed data, the coefficient can be regarded as the regression coefficient between $\Delta Q_i / \overline{Q}$ and $\Delta P_i / \overline{P}$, which can be estimated according to least-square estimation (LSE).

Results

- **Changes of hydrological cycle**

The previous research has shown there is no significant long term tendency of annual runoff in the headwater catchments of the Yellow River Basin, but the hydrological cycle in 1990s had shown great difference to the previous periods (Zheng, et al, 2006). Therefore, in this research, the period from 1960 to 1990 is set as the baseline to be compared with hydrological cycle in 1991-2000. Table 1 shows the difference of these two periods.

As shown in table 1, in 1990s, precipitation, potential evapotranspiration and observed runoff of the headwater of YRB is about 5%, 0.9% and 21% less than that of the baseline period (1960-1990) respectively. Actual evapotranspiration from Bagrov model reduced about 1.7%, while in Zhang's model, it reduced about 21.%. Using the results from Bagrov model and Zhang's model, we can further estimate runoff basing on the water balance equation Q=P-Ea, which showed that in 1990s the runoff is about 10% less than the baseline period. tion.

Table 1 Changes of hydrological cycle elements in the headwater catchments of the YRB

Period	1960-1990	1991-2000	Difference	Relative Diff.(%)
P (mm)	513.5	487.7	-25.8	-5.0
Ep(mm)	351.4	348.3	-3.1	-0.9
Ea-Bagrov(mm)	320.1	314.7	-5.4	-1.7
Q-Bagrov(mm)	193.4	173.0	-20.4	-10.5
Ea-Zhang(mm)	308.7	301.6	-7.1	-2.3
Q-Zhang(mm)	204.8	186.1	-18.7	-9.1
Ea=P-Qm	332.9	345.0	12.1	3.6
Qm(mm)	180.6	142.7	-37.9	-21.0
Runoff Coef.	0.4	0.3	-0.1	-16.8

- **Climatic Elasticity of Stream Flow**

For the headwater catchments of the YRB, there is a rather good relationship between annual precipitation and runoff described as $Q=0.0006P^{2.0187}$(figure 1), which indicates that the precipitation elasticity of runoff is around 2.01. Regardless of the relationship, we can also derive the elasticity coefficient as the regression coefficient between dQ/Q and dP/P as depicted in figure 2. From figure 2, the elasticity coefficient is about 2.1, consistent with that from figure 1.

The elasticity coefficient of 2 implicates that 1% change of precipitation may result at 2% change of runoff in the headwater catchments of the YRB. Since precipitation in 1990s was about

5% less than baseline period, it may result in 10% reduction of runoff in 1990s. However, runoff in 1990s was about 20% less, which means that precipitation change contributes about 50% to runoff change in 1990s but other factors such as land use and land cover change may also play an important role in hydrological change in the headwater catchments of YRB.

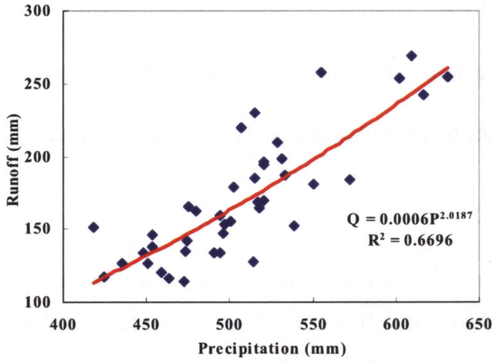

Figure 1 Relationship between annual precipitation and runoff in the headwater catchments of the YRB

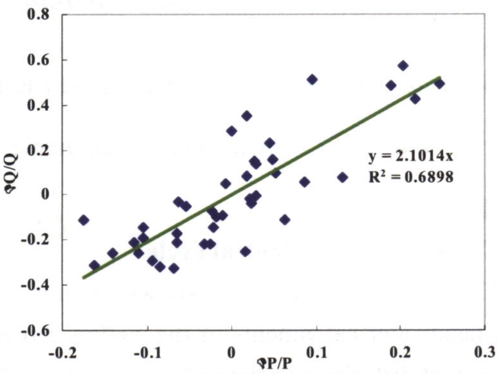

Figure 2 Relationship between changing rate of annual precipitation and runoff in the headwater catchments of the YRB

Conclusions

In this research, hydrological cycle changes in the headwater catchments of the Yellow River Basin have been detected. The results had shown that in 1990s, the precipitation, potential evapotranspiration, actual evapotranspiration and runoff was 5%, 0.9%, 10% and 21% less than that of the baseline period (1960-1990). The precipitation elasticity of runoff is around 2, implicating that 5% reduction in precipitation may result in 10% reduction of runoff. Therefore, besides the impacts of precipitation change, the other factors such as land use and land cover change may also play an important role in the decrease of runoff in 1990s.

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