Actual evapotranspiration estimation in the upper reaches of the Jinghe River basin with the Advection-Aridity model

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ABSTRACT: Evapotranspiration is the largest component of water loss from storage and has a major influence on all hydrological processes. Based on meteological and hydrological in the upper reaches of the Jinghe River basin, Advection-Aridity model was applied to estimate the actual evapotranspiration from 1966 to 2012. The results showed that the average annual actual evapotranspiration is 529.4 mm in the study area, and the variation of actual evapotranspiration was described as four phases. Model calculation results can reflect the regional evapotranspiration loss and provide the basis for the regional soil moisture and green water analysis.

INTRODUCTION

Evapotranspiration is a key process within the Earth's surface water and energy balance. The concept of the complementary relationship between actual and potential evapotranspiration proposed by Bouchet (1963) provides a new way of calculating regional evapotranspiration. The most widely known models based on the hypothesis of the complementary relationship are the Advection-Aridity (AA) model (Brutsaert and striker, 1979), Complementary Relationship Areal Evapotranspiration (CARE) model (Morton, 1983) and the Granger and Gray (GG) model (Granger, 1989). The advantages of these models are that they estimate actual evaportanspiration from observations of the overpassing air without the requirement for factors or assumptions associated with the soil-vegetation system (Xu，2005). Using the meteorological and hydrological data in the Yellow River basin, combined with satellite remote sensing information and digital elevation model, the AA, CARE, and GG models were applied to evaluate the calculation precision in different time scales and climate zones, and the results showed the estimated monthly actual evapotranspiration from AA model was more reasonable and perfectly(Liu, 2004). The Advection-Aridity (AA) model was selected in this study to estimate actual evapotranspiration in the upper reaches of Jinghe River basin, this study also aims to character the change in actual evapotranspiration in the study area from 1966 to 2012.

STUDY AREA AND DATA

Study area

The Jinghe River is one of the top ten drainages in the Yellow River basin, located in the Loess Plateau in the northwestern China. The upper reaches of the Jinghe River basin (106°11′~107°21′E，35°15′~35°45′N) occupies an area of 3 164 km^2, the highest land surface elevation is 2 911 m of the Liupanshan mountain in the western part of the region, while the minimum altitude is 1 100 m. The annual mean temperature is 8.9℃. The annual precipitation is about 586mm, as influenced by the monsoon climate, the precipitation is concentrated in the wet season, and the percentage of precipitation falling during June and September varies from 53% to 85%．

Data

Daily meteorological records of 4 national meteological stations from 1966 to 2012 from the National Climatic Centre of the China Meteological Administration were used in this study (Fig. 1). The meteorological data included daily precipitation, maximum, minimum and mean air temperatures, wind speed, relative humidity, and sunshine duration. The monthly streamflow (1973～2012) at the Jingchuan station and the monthly precipitation data at 34 rainfall gauges from 1966 to 2012 were provided by the Yellow River Hydrological Bureau (Fig. 1).
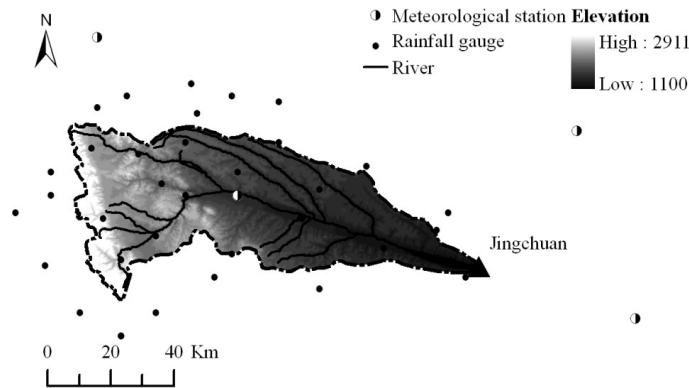
Figure 1. Map of the study area

methodology

The complementary relationship hypothesis

The concept of the complementary relationship between actual and potential evapotranspiration proposed by Bouchet (1963) states that over areas of a regional size and away from sharp environmental discontinuities, there exists a complementary feedback mechanism between actual (ET_a) and potential evapotranspiration (ET_p). This relationship can be expressed as

$$dET_a + dET_P = 0 \tag{1}$$

in which ET_a is the actual evapotranspiration, ET_p is the potential evapotranspiration, dET_p and dET_a are the changes in the potential evapotranspiration and the actual evapotranspiration caused by change in the availability of water. Eq. 1 states that the increased of ET_p is equal to the decrease of ET_a.

Integrating Eq. 1, gives

$$ET_a + ET_P = C \tag{2}$$

Where C is an integration constant, and can be estimated according to boundary conditions. In this context, ET_p is defined as the evapotranspiration that would take place from a moist surface under the prevailing atmospheric conditions, limited only by the amount of available energy. Under conditions where ET_a equals ET_p, this rate is referred to as the wet environment evapotranspiration (ET_w). The general complementary relationship is then expressed as

$$ET_a + ET_P = 2ET_w \tag{3}$$

Where ET_w is the wet environment evapotranspiration. As shown in Eq. 3, under dry conditions, there is no water supply from evapotranspiring surface, $ET_a = 0$ and $ET_p = 2ET_w$; under wet conditions, $ET_a = ET_p$, that is the potential evapotranspiration in a completely humid area equals to the wet environment evapotranspiration. This provides the possibility of estimating the actual evapotranspiration from routine climatological observations. This is done by computing potential evapotranspiration and wet environment evapotranspiration.

AA model

In this section the components of the complementary relationship are summarized for the AA model. In this model, ET_p is calculated by the Penman equation which combines information from the energy budget and water vapor transfer, and ET_w is calculated by the Priestly-Taylor equation based on derivations of the concept of equilibrium evapotranspiration under conditions of minimal

adcection, first proposed by Priestly and Taylor (1972). The expressions for ET_p, ET_w and ET_a in AA model are shown as follows.

$$ET_P = \frac{\Delta}{\Delta + g} \frac{R_n}{l} + \frac{g}{\Delta + g} e_a \qquad (4)$$

$$ET_w = a \frac{\Delta}{\Delta + g} \frac{R_n}{l} \qquad (5)$$

$$ET_a = (2a - 1) \frac{\Delta}{\Delta + g} \frac{R_n}{l} - \frac{g}{\Delta + g} e_a \qquad (6)$$

Where R_n is the net available energy at the surface, l is the latent heat of vaporization, Δ represents the slope of the saturated vapor pressure curve at air temperature, g is the psychrometric constant, e_a is known as the "drying power of the air", a is the Priestly and Taylor constant, an approximate value of $a = 1.26$ is suggested from Priestly and Taylor (1972) for water surfaces under condition of minimal advection and in the absence of inversions and condensation.

Changing trend analyses

(1) the non-parametric Mann-Kendall (MK) rank statistic method

To analyze the trend and test its significance for annual precipitation, potential evapotranspiration and runoff series, the non-parametric Mann-Kendall (MK) rank statistic method (Mann 1945; Kendall 1975) was applied. The Mann-Kendall test is suggested by the World Meteorological Organization, and has been widely used as an effective tool for analyzing the trends in meteorilogical and hydrological variables, such as water quality, temperature and precipitation (Hirsch and Slack et al. 1982; Liu and Zheng 2004; Xu and Takeuchi et al. 2005). It is robust to outliers and can be used to detect linear or nonlinear monotonic trends (Helsel and Hirsch 1997). The algorithm of Mann-Kendall test is briefly introduced as follows.

For a time series X= $\{ x_1, x_2, \ldots, x_n \}$, where $n > 10$, the standard normal statictic Z_C is estimated as follows:

$$Z_c = \begin{cases} (S-1)/\sqrt{\text{var}(S)} & S > 0 \\ 0 & S = 0 \\ (S+1)/\sqrt{\text{var}(S)} & S < 0 \end{cases} \qquad (7)$$

Where

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i) \qquad (8)$$

$$sng(x_j - x_i) = \begin{cases} +1, & x_j > x_i \\ 0, & x_j = x_i \\ -1, & x_j < x_i \end{cases} \qquad (9)$$

$$Var(S) = \frac{\left[n(n-1)(2n+5) - \sum_t t(n-1)(2t+5) \right]}{18} \qquad (10)$$

Where x_i, x_j are the sequential data values, $sng(\theta)$ is equal to 1, 0, -1 if θ is greater than, equal to, or less than zero, respectively, t is the extent of any given tie and denotes the summation of all ties. A time series has a significant trend, if $|Z_C| > Z_{(1-a/2)}$, at a confidence level of α. For example, at a 5% confidence level, $Z_{(1-a/2)} = 1.96$, if $Z_c > 1.96$ or $Z_c < -1.96$, it demonstrates that the null hypothe-

sis of no trend is rejected. And further, a positive value of Z_c indicates an increasing trend, and the negative value of Z_c corresponds to a decreasing trend.

(2) Accumulated difference curve

The accumulated difference curve was also applied to analyze the runoff change (Hao and Chen et al. 2008). A downward gradient suggests a decreasing trend in runoff and vice versa, and a horizontal gradient indicates the runoff is approaching the average annual runoff. A continuous downward or upward gradient suggests that water deficiency or wet years has existed for a long period of time, respectively.

Results

The Priestly and Taylor constant a is associated with regional characteristics according to the results from Xu (2005), and can be further calibrated with the principle of water balance. The annual mean actual evapotranspiration is 518 mm according to the water balance equation using the measured runoff of Jingchuan hydrological station and precipitation data of 34 precipitation stations in and around the river basin. The value of a is the optimal value when the water balance closure error is zero, then the optimal value of a in AA model for the upper reaches of Jinghe river basin is 0.96.

The value of actual evapotranspiration was between 478.4mm and 582.3mm in the upper reaches of the Jinghe river from 1966 to 2012 as shown in Fig. 2, and the average annual actual evapotranspiration was 529.4 mm. The maximum actual evapotranspiration occurred in 1968, while the minimum was in 1989.

In the upper reaches of Jinghe River basin, the actual evapotranspiration had a decreasing trend. The Mann-Kendall test result showed that the decreasing trend of annual actual evapotranspiration was not remarkable at the 0.05 significance level.

The accumulated difference curve of actual evapotranspiration in the study area showed that it underwent four stages (Fig. 3), an increasing trend between 1966 and 1978, and a subsequent decrease trend from 1979 to 1992, then an increasing trend from 1993 to 2006, and a subsequent decrease trend between 2007 and 2012. When the accumulated difference curve showed an increase trend, the actual evapotranspiration in this period was larger than the average annual actual evapotranspiration; vice versa, the actual evapotranspiration is smaller than the average annual actual evapotranspiration when the accumulated difference curve had a decrease trend. Then we can see that the actual evapotranspiration was larger than the average annual value for the two periods from 1966 to 1978 and from 1993 to 2006, and it was smaller in the periods from 1979 to 1992 and 2007 to 2012.
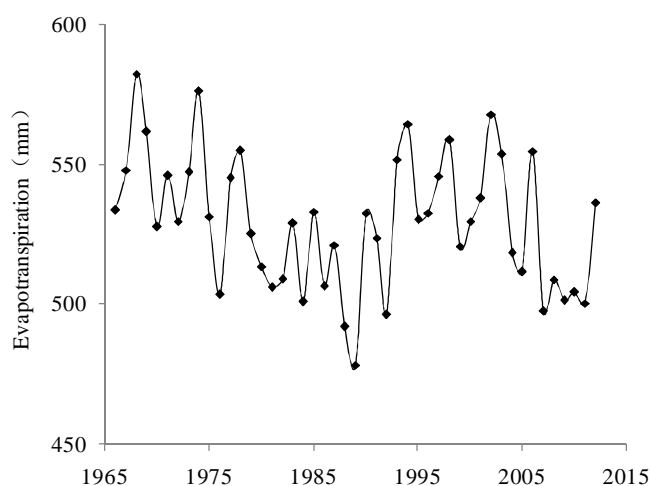

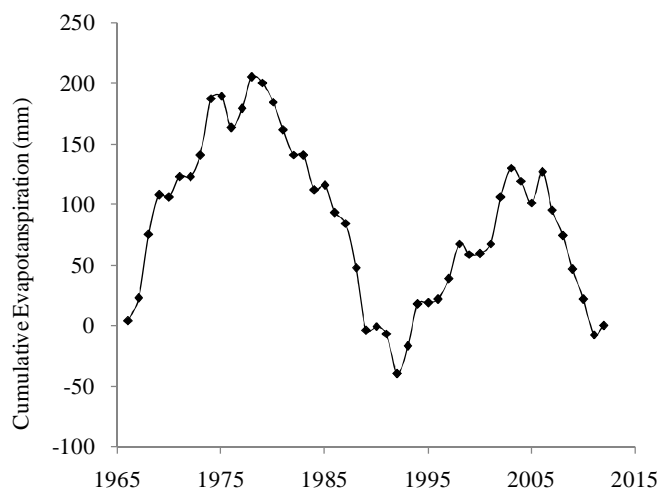Figure 2. Variation of the actual evapotranspiration in the study area from 1966 to 2012.

Figure 3. Accumulated difference curve of the actual evapotranspiration from 1966 to 2012.

conclusions

It is shown that the Advection-Aridity model can be applied in the upper reaches of Jinghe river basin, and the estimated average annual actual evapotranspiration is 529.4 mm. The variation of actual evapotranspiration was described as four phases, it had an increasing trend during the two periods from 1966 to 1978 and from 1993 to 2006, while in the periods from 1979 to 1992 and 2007 to 2012, it had a decreasing trend.

Acknowledgments

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