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LONG-TERM STREAMFLOW RESPONSE TO CLIMATIC VARIABILITY IN THE LOESS PLATEAU, CHINA[1]

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ABSTRACT: The Loess Plateau region in northwestern China has experienced severe water resource shortages due to the combined impacts of climate and land use changes and water resource exploitation during the past decades. This study was designed to examine the impacts of climatic variability on streamflow characteristics of a 12-km^2 watershed near Tianshui City, Gansu Province in northwestern China. Statistic analytical methods including Kendall's trend test and stepwise regression were used to detect trends in relationship between observed streamflow and climatic variables. Sensitivity analysis based on an evapotranspiration model was used to detect quantitative hydrologic sensitivity to climatic variability. We found that precipitation (P), potential evapotranspiration (PET) and streamflow (Q) were not statistically significantly different ($p > 0.05$) over the study period between 1982 and 2003. Stepwise regression and sensitivity analysis all indicated that P was more influential than PET in affecting annual streamflow, but the similar relationship existed at the monthly scale. The sensitivity of streamflow response to variations of P and PET increased slightly with the increase in watershed dryness (PET/P) as well as the increase in runoff ratio (Q/P). This study concluded that future changes in climate, precipitation in particular, will significantly impact water resources in the Loess Plateau region an area that is already experiencing a decreasing trend in water yield.

(KEY TERMS: climate variation; trend analysis; streamflow; Loess Plateau.)

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INTRODUCTION

The Loess plateau in northwestern China has a semi-arid to arid continental climate influenced by East-Asian monsoonal climate. Since the latter half of the 20th Century, the region has been experiencing a climatic warming and drying trend (Liu *et al.*, 2006). Severe ground-water exploitation has accelerated the shortage of water resources. The average amount of water resource available per person in the region was 541 m^3/year, or roughly about 5% of the

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world average, and the water use for arable land irrigation for the region was 2620 m^3/ha/year, only about 7% of the world average (Su, 1996). Since the 1990s streamflow of the Yellow River decreased by up to 65% compared with the average value of the 1950s-1990s, and one of the hydrologic stations along the Yellow River, Lijin Station, has observed zero flow for 226 days in 1997 (Liu and Zhang, 2004).

Several factors were believed to explain the zero flow phenomena, including the human activities and the climate changes. Climate changes alone generally accounted for 43-75% of the zero flow phenomena (Liu and Zhang, 2004). Liu and Zheng (2003) and Liu and Zhang (2004) reported that comparing the 1990s with the period of the 1950s to 1960s streamflow in the upper reach of the Yellow River decreased by 5.75 billion m^3/year (around 16.5%) due to the reduced precipitation, which accounted for 75% of the actual observed reduction. For the middle reach of the Yellow River, streamflow decreased by 63.1 billion m^3/year (21.8%), which accounted for 43% of the actual observed reduction. Using a linear regression technique and correlation analysis, Jiang *et al.* (2003) and Lu *et al.* (2003) examined the relationships between precipitation and streamflow of the upper and middle reaches of the Yellow River. They concluded that precipitation was a major factor in affecting streamflow at a large temporal scale. Using a global circulation model (GCM), Wang *et al.* (2003) evaluated the influence of future climate change in next 30 years on water resources in northwestern China. The study suggested that the annual precipitation in the region of the Yellow River would increase by 1.6% and temperature increase by 2.0-2.38°C over the next 30 years. These climate changes would cause an increase in evapotranspiration (ET) by 15% and a decrease in runoff by 5.7-24%. Using a monthly water balance model, Wang and Wang (2000) and Wang *et al.* (2002) analyzed the influences of precipitation and temperature on streamflow in the upper and middle reaches of the Yellow River. They concluded that runoff was more sensitive to variations in precipitation than to temperature.

ET is a major component of the water balance for terrestrial ecosystems. But in an arid or semi-arid area, actual ET is usually restricted by the water availability, even though much higher potential ET (PET) is observed in arid ecosystems (Baird and Wilby, 1999). A few studies have examined the sensitivities of runoff variation to changes in climatic and energy flux variables, including precipitation (Wigley and Jones, 1985; Dooge *et al.*, 1999; Sharma *et al.*, 2000; Milly and Dunne, 2002; Miller *et al.*, 2003; Jones *et al.*, 2006), temperature (Sharma *et al.*, 2000; Miller *et al.*, 2003; Jones *et al.*, 2006), PET (Jones *et al.*, 2006), net radiation (Milly and Dunne, 2002), and CO_2 (Wigley and Jones, 1985). Liu and Zhang (2004) found that the decrease in flow of the Yellow River was partly associated with climate warming. However, much of the research on climate change impacts, still focuses on precipitation effects with less attention to other climatic factors. Compared with temperature, PET is more preferred in sensitivity based analysis because it is a more direct measure of moisture loss from regions such as the Loess Plateau that is water limited rather than energy limited. It is unclear whether the influence of the increased PET with a rise in temperature would mask the effect of precipitation increase on streamflow. The influence of changes in P and PET on streamflow variation was not well understood.

Sustainable water resource management in the water-stressed region requires a clear understanding of the impacts of climate change on water yield. There is still uncertainty regarding how watershed hydrology will respond to climate change and variability and land use change in the Loess Plateau region (Li *et al.*, 2007). Small watersheds are best suited for understanding the processes of hydrological responses to either land use change or regional climate variability. Therefore, this study focused on the combined influences of P and PET change on streamflow variation with the following specific objectives: (1) to investigate the relationship among streamflow, P, PET, and ET using a small scale watershed and (2) to differentiate the effects of P and PET change on change in streamflow.

METHODS

Watershed Characteristics and Databases

The Luergou Watershed (E105°41′-105°45′, N34°30′-34°35′) is located south of Tianshui City, Gansu Province in northwestern China. The watershed has a total area of 12.0 km^2 with an elevation ranging from 1,720 to 1,200 m (Figure 1). The land use survey of 1982 indicated that the watershed was dominated by grassland (24%), forested land (24%), sloping crop land (23%), and crop lands on terraces (13%). The other 16% of the land cover was composed of shrub, orchard, bare soil, sparse wood, and residential areas. In the 1990s, grassland cover increased by 4%, forest land increased by 1%, and terrace agriculture increased by 2%, the other land use including sloping crop land, shrub, and residential areas decreased.

The average annual precipitation was 570 mm/year over 1982-2003 and over 80% of rainfall occurred from

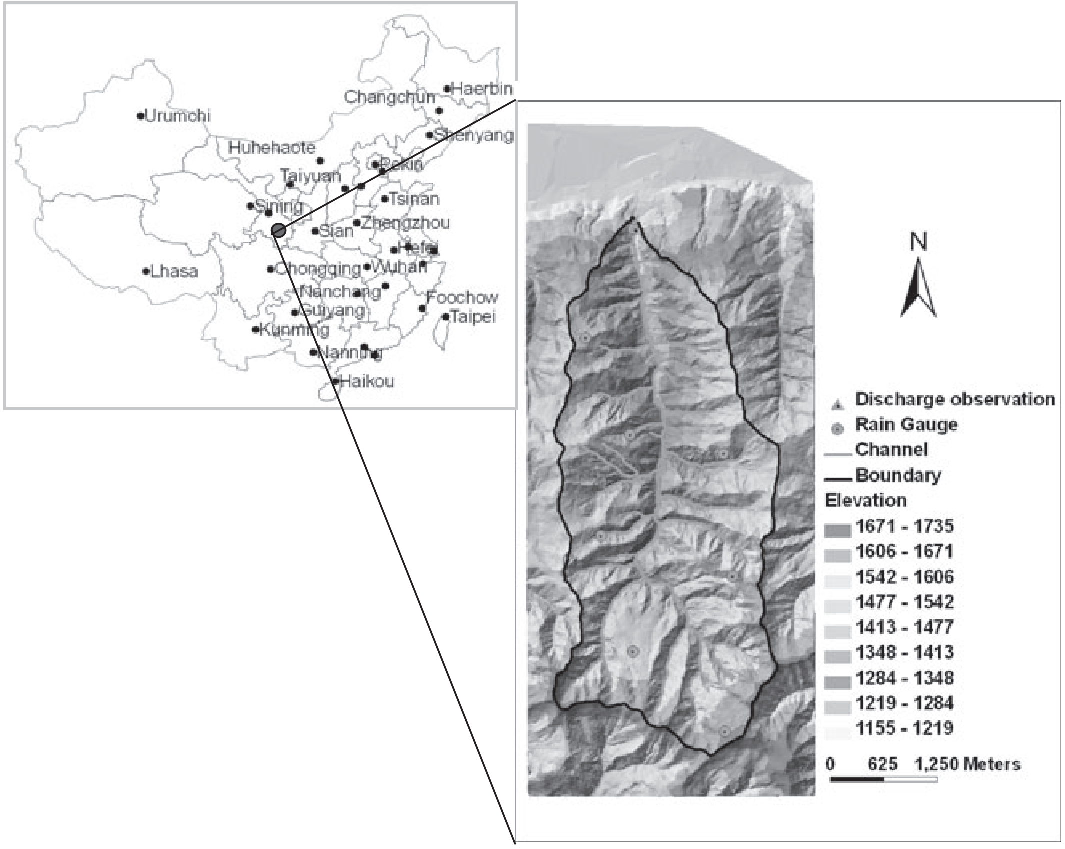

FIGURE 1. Topography and Location of Luergou Watershed.

May to October (Figure 2). The intense summer storms were a major force causing overland flow and severe soil erosion. Due to higher rainfall intensity and erosion-prone loess soils, the average annual soil erosion rate of the watershed was over 25 t/ha/year between 1982 and 2000 (Zhang *et al.*, 2005).

Throughout the whole observation period, rainfall was measured by eight automatic rain gauges located within the watershed, and the arithmetic mean of daily precipitation was calculated to represent area precipitation. Streamflow was observed at the outlet of the watershed by measuring stage level and flow velocity using the floating method (Mosley and Mckerchar, 1993). Air temperature was measured at a local meteorological station approximately 1 km outside of the study watershed. Daily PET was calculated by the temperature-based Hamon's method. Details of the Hamon's method can be found in Hamon (1963) and Lu *et al.* (2003, 2005).

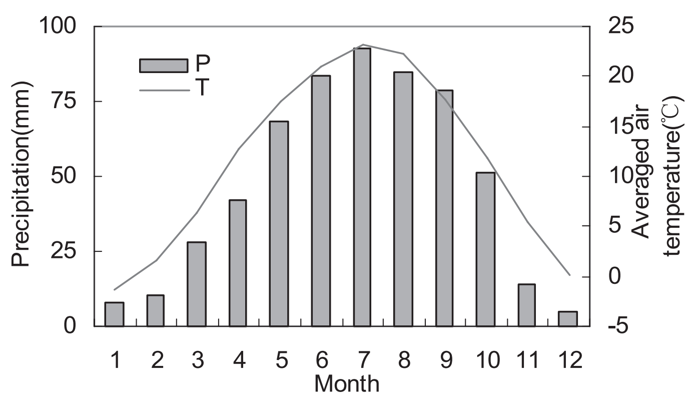

FIGURE 2. Averaged Monthly Rainfall and Air Temperature During 1982-2003.

Nonparametric Kendall's Trend Test

Nonparametric Kendall's test was employed to detect trends of precipitation, PET, ET, and streamflow over the observation period. Kendall's test was first adopted by Hirsch *et al.* (1982) from the Mann-Kendall's test (Kendall, 1975) and was later used by Gan (1998) to analyze the hydroclimatic trends in the Canadian prairies. Kendall's test was used as the analytical tool of choice because: (1) the model works for nonnormalities involving seasonality, missing values, censoring, or unusual data reports; and (2) the model has a high asymptotic efficiency (Berryman *et al.*, 1988; Gan, 1998; Fu *et al.*, 2004).

Kendall's test was applied on both annual and monthly basis. The statistic Z of Kendall's test was estimated by the following formula:

$$Z = \begin{cases} \frac{S-1}{(\mathrm{Var}(s))^{1/2}} & \text{if } S > 0 \\ 0 & \text{if } S = 0, \\ \frac{S+1}{(\mathrm{Var}(s))^{1/2}} & \text{if } S < 0 \end{cases} \quad (1)$$

where

$$\mathrm{Var}(s) = n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)/18 \quad (2)$$

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sgn}(x_j - x_k), \quad (3)$$

where

$$\mathrm{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0, \\ -1 & \text{if } x_j - x_k < 0 \end{cases} \quad (4)$$

where x is the observed variable (e.g., monthly streamflow, precipitation, PET); k = 1, 2, 3,…,n − 1; j = k + 1, k + 2,…, n; n is the number of independent and random samples; t is the extent of any given tie; and α is the significant level ranging 0.01-0.05.

The null hypothesis, H_0, was that there was no significant warming/cooling or wetting/drying (i.e., Z) trend, and was accepted if $-Z_{\alpha/2} < Z < Z_{\alpha/2}$, where $Z_{\alpha/2}$ are the standard normal deviates $Z_{\alpha/2} = 1.96(\alpha = 0.05)$ and $Z_{\alpha/2} = 1.65(\alpha = 0.01)$. Alternatively, it was accepted that H_1 or Z was statistically significant if $Z < -Z_{\alpha/2}$ or if $Z > Z_{\alpha/2}$ (Gan, 1998).

Sensitivity Analysis

Sensitivity analyses were conducted to quantify the different effects of P and PET on streamflow variation. The sensitivity analysis approach was based on a simplified hydrological model or a conceptual model, and was widely employed to explore relative contributions of climate variables to runoff change (Wigley and Jones, 1985; Dooge *et al.*, 1999; Milly and Dunne, 2002). Jones *et al.* (2006) proposed a bilinear relationship that links runoff change to climate change, and this relationship has been used, in here, to detect the individual effect of P and PET on runoff (Li *et al.*, 2007)

$$\delta Q = A * \delta P + B * \delta PET, \quad (5)$$

where δP is the change in mean annual precipitation, δPET is the change in mean annual PET, δQ is the change in mean annual runoff, and the annual runoff was estimated with precipitation (P) minus actual ET, $Q = P - ET$.

All changes in P, PET, and Q are expressed as a percentage. A and B are the model coefficients. Once A and B were calculated, the individual influence of P and PET on water yield was determined quantitatively.

To predict streamflow under a changing climatic condition, a rational ET model proposed by Zhang *et al.* (2001) was used that was established on the basis of data observation from over 300 small watersheds across a large climatic gradient around the world. Zhang's model has closely related ET to P and PET. Thus, combined with a water budget equation ($Q = P -$ ET), runoff variation can be determined under the changed climate conditions given specific land surface characteristics. Zhang's model has the following form:

$$ET = \left(\frac{1 + w\frac{PET}{P}}{1 + w\frac{PET}{P} + \left(\frac{PET}{P}\right)^{-1}} \right) * P, \quad (6)$$

where P is the mean annual precipitation (mm); PET and ET are potential evapotranspiration and actual evapotranspiration (mm), respectively; and w is an empirical parameter reflecting plant water use, land cover/soil conditions and the PET methods used (Zhang *et al.*, 2001; Sun *et al.*, 2005; Li *et al.*, 2007). Zhang *et al.* (2001) found that w coefficients of 0.5 for grass and 2.0 for forests provided the best predictions of ET. The higher the w, the more water the ecosystem needs, given the same P and PET (Zhang *et al.*, 2001). Our previous studies (Wang, 2007) concluded that Zhang *et al.*'s (2001) model performed well in estimating annual ET for this watershed after calibrating the w parameter.

For each year between 1982 and 2003, 19 climatic scenarios have been developed to drive the ET model to test the sensitivity of streamflow to P and PET, respectively. These included varying annual precipitation by 0, −5, −10, −15, and +10%, of the measured value, and by varying annual PET by 0, +5, +10, and +15% of the calculated value. A total 418 of scenario runs were performed for the entire analysis. The sensitivity coefficients of A and B in Equation (5) were determined by the least squared error method.

RESULTS

Dynamics of P, PET, Actual ET, and *Q*

The long-term average annual precipitation was 573 mm, and ranged from 364 to 881 mm. A large portion (547 mm or 96%) of the average annual precipitation recorded during this study period was lost as ET, and only a small amount (26 mm or 5%) of P left the watershed. Storm flow occurred mostly in the summer months between May and September, following a similar pattern of precipitation (Figures 2 and 3), and they often existed for several days.

General linear regression analysis found that annual precipitation did not show a statistically significant trend ($p = 0.37$), although precipitation had an annual reduction of 5 mm/year with a high annual variation of Cv of 0.26 (Figure 4). Reductions in precipitation corresponded to a statistically significant increase of annual mean daily temperature ($p < 0.0001$), and annual PET ($p < 0.0001$) was increased by 6 mm/year, with a much lower variation Cv (0.06). Despite the warmer and drier climate, annual streamflow did not show statistical significant decreasing trend ($p = 0.14$) with an annual decrease of 2 mm and a much higher Cv (1.21). Also, ET, calculated as precipitation minus discharge showed no trend ($p = 0.50$) with a changing rate of only −3 mm/year and a moderate Cv of 0.21.

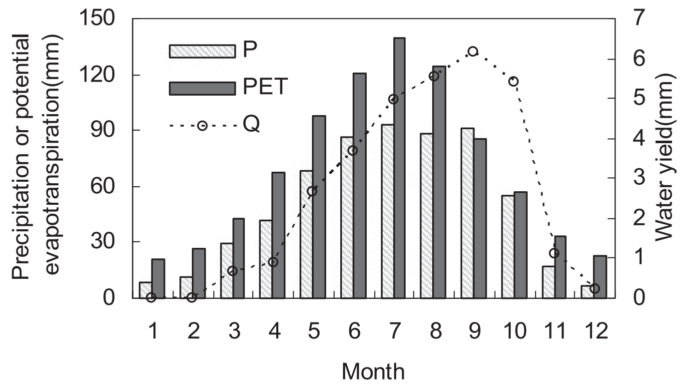

FIGURE 3. Monthly Distribution of Averaged P, Q, and PET.

To remove the noise of large variability on trend detection, nonparametric Kendall's trend tests were further applied as they have the capability of handling unusual data records. Kendall's tests confirmed that both P and Q did not have a significant trend at the 0.01 significance level. The results were consistent with that of the linear regression tests and Z was −0.26 for P and −0.64 for Q, respectively. Predicted PET was not statistically correlated with temperature data at the 0.05 significance p level. The discrepancy on the significant trend of PET between the results of linear regression test and Kendall's test was partially attributed to the limited number of samples ($n = 22$). It was assumed that the ability of trend identification with Kendall's test was correlated

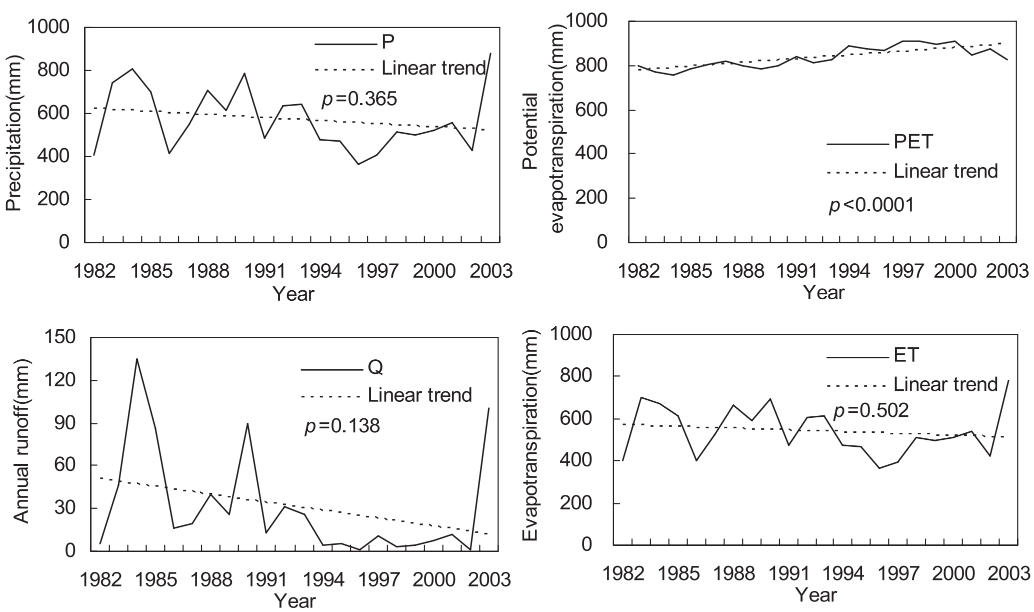

FIGURE 4. Annual Variation of P, PET, ET, and Q With Their Respective Linear Regression Line.

with the size of time series (Zhou, 2005). Similar to Kendall's test for P and Q, the estimated annual ET did not show significant trend ($p = 0.502$).

Kendall's trend test was applied at monthly scale to examine the seasonal climatic and hydrologic variations. It was found that except for January, September, October, and December, the other months had a slightly decreasing trend with regard to monthly precipitation, while monthly PET and Q presented an increasing and decreasing trend year round, respectively. Similar to P, monthly ET had a decreasing trend for the most of months except for August and September without trend detected. However, similar to the results of annual test, under either the level of 0.01 or 0.05, none of the variables was found having a significant trend by Kendall's tests.

Effects of Climate Variation on Streamflow

Previous studies suggested that no significant land use change occurred within the watershed during the study period (Wang, 2007). Therefore, the relationship between annual runoff and P and PET could be directly established using a stepwise linear regression technique. Contrary to the general expectation that runoff variation in the area of the Loess plateau was closely correlated with PET, we found that the annual PET was removed from a stepwise regression equation with adjusted correlation coefficient of 0.74 (Table 1). This means that, to a certain degree, the PET accounted for little variation of streamflow. Partial correlation analysis indicated that the correlation coefficient between annual P and streamflow was as high as 0.79, while the r^2 was only −0.32 between PET and streamflow.

Similar to the annual-scale analysis, there was no statistically significant step-wise correlations between PET and streamflow for most months except for April and October with a correlation coefficient of −0.624 and −0.647, respectively (Figure 5). Thus, PET was not as influential as P in effecting streamflow variation for most months.

TABLE 1. Variables Entered/Removed in Stepwise Linear Regression Model.

	P	**PET**	**Adjusted R^2**
April	E	E	0.57
May	E		0.24
June	E		0.44
July	E		0.61
August		E	0.31
September	E		0.56
October		E	0.44
Annual	E		0.741

Note: "E" denotes entered variable at $\alpha = 0.05$.

Sensitivity of Runoff to Changes in P and PET

Sensitivity analysis using scenario simulations indicated that runoff was more sensitive to P than to PET. The averaged values over the observation periods were 2.41 and −1.37 for A and B respectively, with a Cv of 0.02 for A and 0.03 for B. Not surprisingly, the changes in precipitation impact streamflow more than do changes in PET. That is to say that, a 1% increase in precipitation would result in a 2.4% increase in runoff, while a 1% decrease in PET would cause a 1.37% increase in annual runoff.

Sensitivities of streamflow to P and PET demonstrated regularly slight variation under different climatic condition. It could be found that both of the sensitivity coefficients of A and B (absolute value) all increased with an increase of the dryness index (Figure 6). This relationship was consistent with the results by Jones *et al.* (2006). As expected, sensitivities of A and B (absolute value) all decreased with an increase in runoff ratio (Figure 7).

DISCUSSION

Streamflow variation was directly related to catchment actual ET and P patterns. It is widely accepted that catchment ET is controlled by climate and land-surface characteristics.

As mentioned previously, when compared with the 1980s, the studied watershed was found to show a little improvement in land cover in the 1990s owing to the soil conservation efforts over the study period. Although increase in area of terraces and vegetation recovery was usually recognized to be influential in the interception of overland flow and sediment deposi-

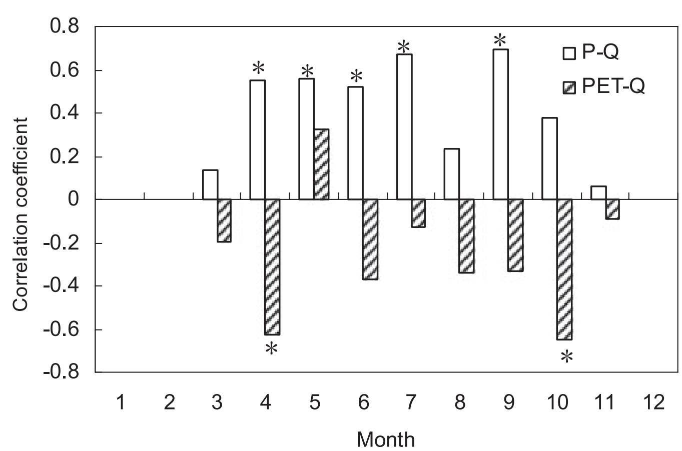

FIGURE 5. Correlation Coefficient for Each Month Between P and Q, and PET and Q.

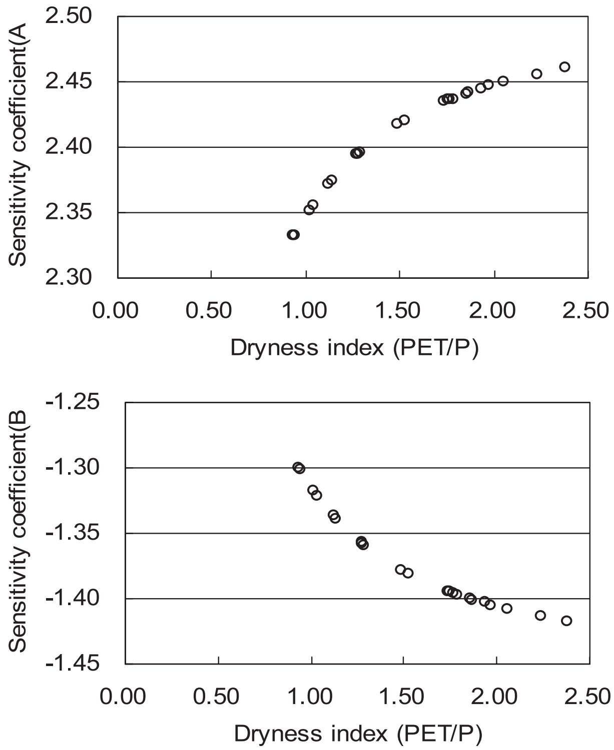

FIGURE 6. Scatter Plot of Sensitivity Coefficient Against Dryness Index.

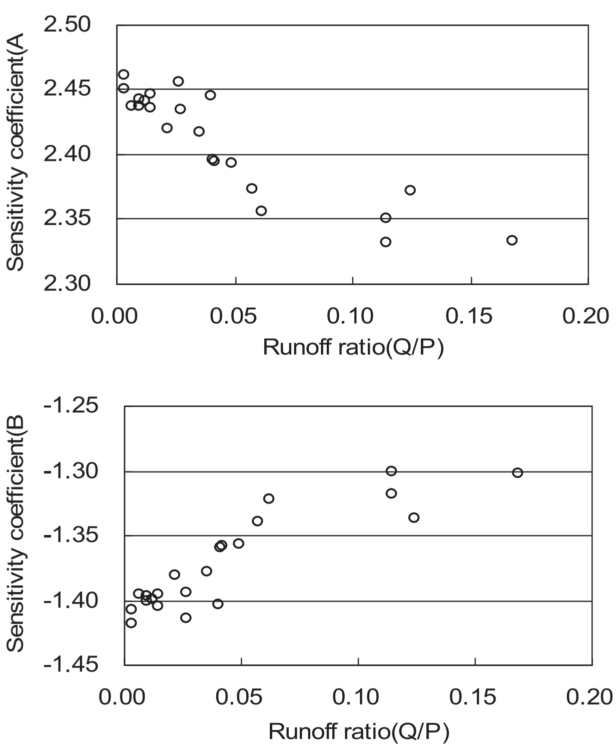

FIGURE 7. Scatter Plot of Sensitivity Coefficient Against Runoff Ratio.

tion, and had potential to decrease total water yield by increasing ET (Kang *et al.*, 2005), we reckoned that the land use and land cover change occurred in the research watershed were not significant enough to affect the water yield of the watershed, as the change in either terrace or shrub land or grassland or forested land was less than 4%. It is widely accepted that it is extremely difficult to detect the water yield change when change in vegetation cover was less than 20% (Bosch and Hewlett, 1982; Stednick, 1996). Therefore, the effect of land use change on annual water yield in this study might not be significant when discussing the relationship among P, PET, ET, and Q.

Although average annual ET of the watershed was estimated as high as 95% of the total precipitation, it does not necessarily mean that the actual ET of the watershed would increase with the increase in the PET. In fact, with the increase in PET, the annual actual ET decreased (Figure 8).

Given that the land use change was negligible in the study, both P and PET must be taken into account for the variation in predicting ET. When precipitation decreased, the water availability to evaporate loss decreased. Consequently, the ET declined even though the PET increased. It might be explicable in perspective of either physiology at stand level or the water balance at watershed scale. The behavior of the ratio of ET to P that asymptotically approach 1 with dryness increase in any of ET models (e.g., Pike, 1964; Budyko, 1974; Zhang *et al.*, 2001) states that the ET rise is restricted by the amount of precipitation. This is especially true for arid or semi-arid area. As Zhang *et al.* (2001) pointed out, for dry areas, ET was dominated by water availability and canopy resistance, while in wet areas ET was mainly controlled by advection, net radiation, leaf area, and turbulent transport. In this case study, the mean dryness index over the study period was

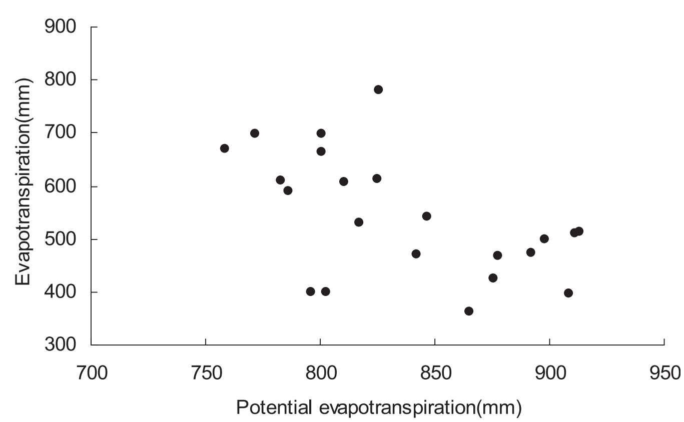

FIGURE 8. Scatter Plot of Actual Evapotranspiration Against Potential Evapotranspiration.

as high as 1.56, with a slightly increasing trend (Figure 9). Therefore, the annual ET for the watershed was largely controlled by the precipitation amount. The relationship between ET and precipitation increases as precipitation decreases.

The effect of P and PET on ET variation or streamflow variation showed a little difference at annual scale *vs*. monthly scale. When downscaling to a monthly scale, the role of P did not necessarily override that of PET, and the dominant influence of P was obscure for several months. The variability in the role of P and PET might be associated with the integrated effect of seasonal leaf area change. Various demands for water were required to maintain the vegetation growth in different months. At the beginning and the end of growth season, the small leaf area and lower plant transpiration rates required less water use and the less dependence on water availability (from P). During this period, the importance of precipitation was reduced and the relative relationship strength of PET and ET increased. That also explained the partial correlation between PET and Q for April and October, and PET was not removed in stepwise linear regression. Therefore, we concluded that the monthly ET was generally dependent on the water availability, the atmospheric demand, and the plants leaf area index.

Sensitivity coefficient of A and B were all increased with the increase in dryness index. It was assumed that with global climate warming and increase in dryness in the study region, the effect of climate variability would be much obvious in water yield reduction. In our analysis, PET was estimated based on air temperature using Hamon's equation. Therefore, PET estimation was a function of T. Global circulation models suggested that surface air temperatures in the middle reach and the upper reach of the Yellow River region would increase 1-2.5°C and that precipitation amounts and patterns will also change during the next 50 years (Wang *et al.*, 2002). The increase in 1-2.5°C relative to the average annual surface air temperature of 11.6°C translates into equivalent increase in PET of 5.9% and 15.2%, respectively. By sensitivity-based analysis, we estimated that the predicted increases in surface air temperatures could increase annual streamflow by over 28% or decrease by 57%, depending on the degree and the direction of precipitation change (Table 2). Changes in precipitation are and will continue to be crucial to the availability of water resource of the watershed. As the dryness increases, the watershed would be more sensitive to climate variability.

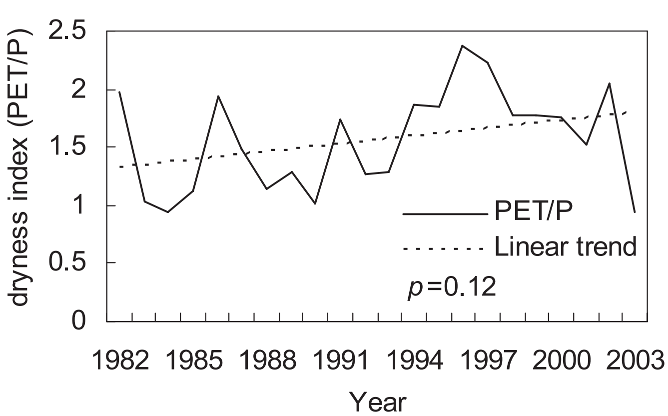

FIGURE 9. Annual Variation of Dryness Index (PET/P) With Linear Regression Line.

CONCLUSIONS

Despite small changes in land cover and a significant increase in surface air temperature between 1982 and 2003 in the Luergou Watershed, annual and monthly streamflow was not significantly different over this period of the time. However, a strong correlation between streamflow and climate variation was established. Dynamic variations in annual streamflow from the watershed were largely controlled by changes in P, and to a less extent by the surface air temperature and PET. As land cover changes at a monthly scale due to vegetation growth, the dominant role of P at the monthly scale could vary. The role of P and PET in influencing streamflow variation would vary in different months as plant water demand changes. Sensitivity analysis suggested that annual streamflow was more sensitive to P than to PET. The effect of climate change on runoff was slightly influenced by watershed dryness. It is expected that the study region will be more sensitive to precipitation change in the future under a warmer and drier climate and expected to decrease in water yield due to future climate change and an

TABLE 2. Estimation of Relative Change in Mean Annual Runoff (%) by Sensitivity Based Analysis for Various Scenarios.

	dT(°C)/dPET(%)	
dP(%)	**1.0/5.9**	**2.5/15.2**
0	−8.1	−20.8
5	4.0	−8.7
10	16.0	3.3
15	28.1	15.4
−5	−20.1	−32.8
−10	−32.2	−44.9
−15	−44.2	−56.9

increase in water use by restored vegetation cover (Sun *et al.*, 2006; McVicar *et al.*, 2007) and soil conservation practices (Li *et al.*, 2007).

ACKNOWLEDGMENTS

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