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Responses of baseflow in Kuye catchment to the LUCC on the Loess Plateau of China

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Abstract: The variability of baseflow is a comprehensive reflection of land use/cover changes (LUCC) and an important hydrological characteristic considered in maintaining sustainable development of an ecosystem. Daily streamflow data from 1959 to 2005 at Wenjiachuan gauge station in Kuye catchment on the Loess Plateau were used to analyze baseflow responses to the LUCC. Chapman-Maxwell digital filter was used to separate daily streamflow into baseflow and surface flow. Both nonparametric Mann-Kendall test and Pettitt test were adopted to detect the trend of the baseflow and identify its change point. Double mass curves method was also employed to verify the change points. Results are as follows:

(1) The average annual baseflow in Kuye catchment was 24.7 mm, accounting for 38% of total runoff. A significantly negative trend of the annual baseflow was detected in the last 50 years. The average change rate was 0.628 $mm.a^{-1}$, which was about 2.5% of the average annual baseflow. Two change points occurred in the years of 1980 and 1996.

(2) Baseflow regimes, as represented by daily baseflow curves, showed an increasingly dramatic reduction across the high, median and low percentiles of the time and an increase of zero-baseflow days in the catchment. The variability of baseflow represented by baseflow duration curves increased period by period.

(3) By considering statistical insignificance detected in annual precipitation, the change of baseflow in Kuye catchment was greatly related to soil conservation measures implemented from the 1970s to 1980s and coal mining development after 1996.

Key words: *Trend, Change point, Baseflow, LUCC, Loess Plateau*

1 INTRODUCTION

The Loess Plateau in the middle reaches of the Yellow River of China is the most erosive area in the world (Chen and Luk, 1989). To reduce severe soil erosion, a series of soil conservation practices have been implemented in the area since the late 1950s, including engineering measures (terraces and dams) and biological measures (plantations and pasturelands). Kuye catchment located in the north part of the Loess Plateau is one of the main sediment sources of the Yellow River. On the other hand, the catchment is rich in coal and thus coal mining is a key local industry (Tang, 1990; Jiang et al., 2010). Soil conservation practices and coal mining in the catchment lead to large-scale land use/cover changes (LUCC).

The LUCC has profound effects on many aspects of environment, including hydrology (Farley et al., 2005; Scanlon et al., 2007; Zhang et al., 2001). There are many researches on the effects of the LUCC on annual runoff (Liu and Zhong, 1978; Bosch and Hewlett, 1982; Zhang et al., 2001; Huang and Zhang, 2004; Farley et al., 2005; Brown et al., 2005; Zhang et al., 2008). Soil conservation measures, such as afforestation, can reduce annual runoff by delaying peak flow and reducing surface runoff through increasing rainfall interception and evapotranspiration (Saghafian et al., 2008; Zhang et al., 2001). However, the effect of soil conservation measures on baseflow regime is not uniform. Huang and Zhang (2004) showed that soil conservation measures reduced surface runoff and baseflow by the rates of 1.30 and 0.48 mm a^{-1}, respectively, while the ratio of annual baseflow to total runoff (BFI) increased from 0.53 in the contrast period to 0.61 in the treated period. Dou et al. (2009) reported the same results from their study in the Wuding catchment. Compared to the contrast period, the average annual runoff, surface runoff, and baseflow in controlling period were reduced by 60%, 65%, and 55%, respectively. Correspondingly, the BFI had a significant increase from 0.57 to 0.63. However, some researches gave the different result, for example, an increased trend of baseflow following afforestation was detected in the semiarid region of Tanzania (Sandström, 1995). Understanding the responses and extent of baseflow regime changes to the LUCC is helpful to develop appropriate strategies for catchment management on the Loess Plateau.

The specific objective of this study was to (1) detect the trend of annual baseflow and its change point in Kuye catchment in the last 50 years; (2) find the change extent of baseflow by daily flow duration curves; and (3) relate the changes to the LUCC in Kuye catchment.

2 STUDY AREA DESCRIPTION

Kuye River is a tributary of the Yellow River. Kuye catchment is located in the north part of the Loess Plateau, a transition zone from the sandy area in the northwest to the loess hilly-gully region in the southeast (Fig. 1). The drainage area of the catchment is 8706 km^2. The area covered by sand in the catchment is about 40% of the total area. The length of the main channel is 242 km with an average gradient of 2.58‰.

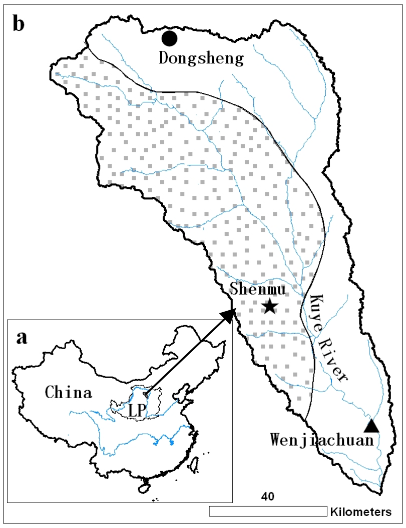

Fig. 1. Kuye catchment (b) and its location on the Loess Plateau, China (a). The symbols triangle, round point, and star indicate the locations of Wenjiachuan gauge station, city, and county, respectively. The shaded part in the catchment indicates the area covered by sand.

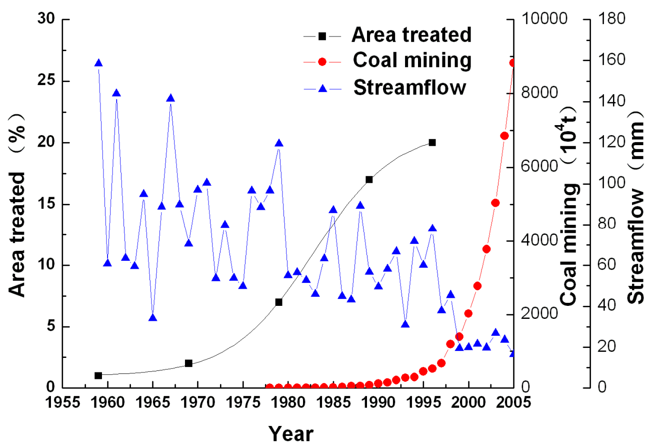

Fig. 2. Annual streamflow, the area controlled with soil conservation measures, and coal mining in Kuye catchment.

Kuye catchment is characterized with arid and semi-arid continental monsoon climate. Average annual precipitation is 387 mm, of which 70-80% occurs as high intensity rainfall from June to September. Vegetation in the catchment belongs to the typical steppe zone. High intensity summer rainstorms, erosive loessal soils, sparse vegetation, and intensive human activities contribute to the problems of heavily dissected landscape, severe soil erosion, and sedimentation in the catchment. Average sediment yield from the catchment is as high as 35,000 $t.km^{-2}.a^{-1}$ (Jiao, 2002; Sui et al 2009).

A series of soil conservation practices, including terraces, check-dams, plantations, and pasturelands, have been implemented in Kuye catchment since the late 1950s, especially the 1970s (Fig. 2; Table 1). Coal mining in the catchment began in 1978 and the annual amount of coal mining rose dramatically after 1990, especially 1996 (Fig. 2). The average annual amount of coal mining was about 0.29×10^6 t in 1980s and up to 5.2×10^6 t in 1990s. In the first five years of the 21st century, the average annual amount of coal mining increased rapidly to 54.52×10^6 t (Jiang et al., 2010). The development of coal industry aggravates water resources and even dries up water resources during the dry season in the catchment (Wang et al., 2008).

Table 1. Cumulative areas with soil conservation measures in Kuye catchment [a]

Year	Terrace		Afforestation		Pasture		Check-dam	
	(km^2)	SP [b](%)	(km^2)	SP [b](%)	(km^2)	SP [b](%)	(km^2) [c]	SP [b](%)
1959	5	9.26	27	50.00	22	40.74	0	0.00
1969	33	17.93	97	52.72	52	28.26	2	1.09
1979	66	11.02	415	69.28	110	18.36	8	1.34
1989	67	4.67	1004	69.92	353	24.58	12	0.84
1996	99	5.89	1184	70.39	380	22.59	19	1.13

Note: [a], refer to Ran et al (2000). [b], SP means the structure percentage of the area with each measure over the total controlled area in that year. [c], Values in this column mean the silted land areas by check-dams.

3 DATA AND METHODS

3.1 Data Description

Daily streamflow data from 1959 to 2005 were obtained from the Water Resources Committee of the Yellow River Conservancy Commission. Annual precipitation data were obtained from the State Meteorology Bureau. Precipitation data averaged over the whole study area were used in the analysis (Wan et al., 2011). Census information on soil and water conservation measures and coal mining was described by Ran et al. (2000) and Jiang et al. (2010).

3.2 Methods

Chapman-Maxwell digital filter, an automated technique for baseflow separation, was used to separate daily total runoff into baseflow and surface runoff in Kuye catchment (Chapman and Maxwell, 1996). Trend of the annual baseflow was detected using the nonparametric approach of Mann-Kendall test (Mann, 1945; Kendall, 1975). Change point of the annual baseflow was tested by Pettitt approach and double mass curves (Pettitt, 1979; Searcy and Hudson 1960; Gan, 1998). Baseflow duration curves method was used to identify relative change in different stages (Smakhtin, 2001).

4. RESULTS AND DISCUSSION

4.1 Trend of Annual Baseflow and its Change Points

The average annual baseflow in Kuye catchment over the last 50 years was 24.7 mm, which accounted for nearly 38% of the total runoff. A decreasing trend of the annual baseflow was detected at the significance level of $p < 0.001$, statistically. The average change rate for decreased baseflow was found to be -0.628 $mm.a^{-1}$, which accounted for 2.5% of the average annual baseflow.

A change point of annual baseflow was detected in the year of 1980 at the significance level of $p < 0.001$ (Fig.3). The result was considerably consistent with that from the research by Zhang et al (2008). Furthermore, double mass curves method was used to test the consistency and the change point on the plot of the cumulative annual baseflow against the cumulative annual precipitation. Apparently, two significant change points can be detected in 1980 and 1996, as shown in Fig. 4. The year of 1980 agreed with the result from Pettitt's test and the year of 1996 was consistent with the time after which coal mining in the catchment was dramatically increased, as mentioned by Jiang et al.(2010).

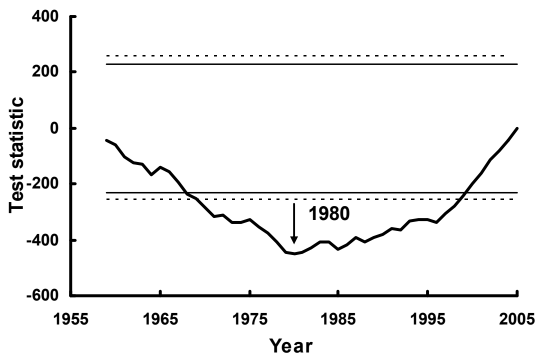

Fig. 3. Pettitt's test for detecting change point in annual baseflow in Kuye catchment. The horizontal lines in the graph represent the significance levels of 5% (dotted) and 10% (solid). When a minimum or maximum in the value of *Z* statistic occurs outside these lines, it indicates the time for a statistically significant change point.

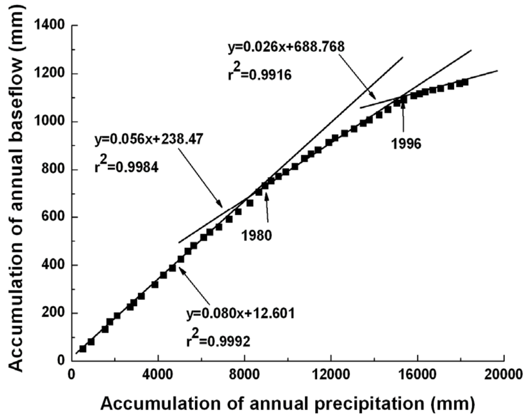

Fig. 4. The double mass curves on the plot of cumulative annual baseflow against the cumulative annual precipitation in Kuye catchment.

4.2 Changes of Baseflow Regime

Based on the change points detected by Pettitt test and double mass curves method, the whole time (from 1959 to 2005) was divided into three periods: pre-change point period from 1959 to 1979 (P1), post-change point period from 1980 to 1995 (P2), and period characterized with coal mining development from 1996 to 2005 (P3). Daily baseflow duration curves were derived and the relative changes in baseflow at high flow (exceeded 5% of the time), median flow (exceeded 50% of the time) and low flow (exceeded 95% of the time) were calculated in the P2 and P3 in comparison with the P1.

The depths of the average annual baseflow in the P1, P2, and P3 were found to be 33.6, 21.4, and 11.4 mm, respectively. Compared to the P1, the reduction extents in the P2 and P3 reached 36.3% and 66.1%, respectively. Fig. 5 shows the daily baseflow curves for the three periods in Kuye catchment. In the P2, the high baseflow was lowered by nearly 30%; the median baseflow by 38%; and the low baseflow by 55%. In the P3, the baseflow at the 5th and 50th percentiles decreased by nearly 57% and 68%, respectively, and the baseflow at the 95th percentile decreased to null. The number of zero baseflow days tends to increase in the P3.

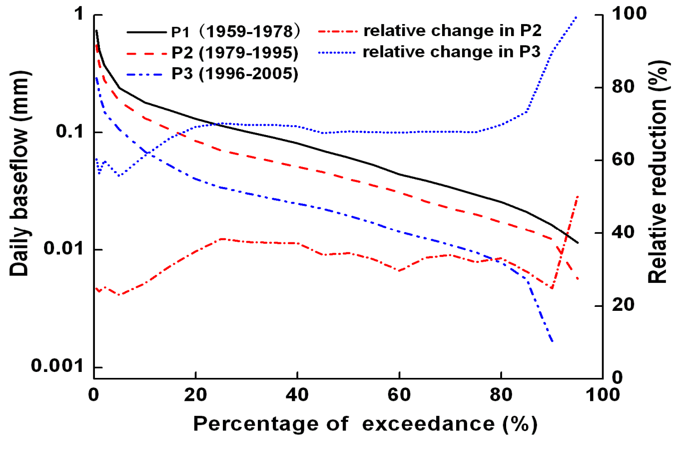

Fig. 5. Daily baseflow curves in the P1, P2, and P3 in Kuye catchment and the relative changes in the two latter periods as compared to the first period.

To further understand the changes in daily baseflow, the ratio of the high baseflow or low baseflow to the median baseflow, as an index, were introduced to represent the baseflow variability. The depths of the median baseflow given by daily baseflow curves in the three periods were 0.06, 0.04, and 0.02 mm, respectively. The high baseflow index increased from 4.0 in the P1 to 4.5 in the P2 and 5.4 in the P3. However, the low baseflow index decreased from 0.19 in the P1 to 0.14 in the P2 and 0 in the P3. That means the baseflow distribution in flow spectrum tends to be more and more variable in different periods with soil conservation practices and coal mining development in Kuye catchment.

4.3 Probable Reasons for Baseflow Changing

In general, precipitation and human activities are two main factors influencing hydrological regimes in a catchment. Precipitation is the only source of streamflow and human activities are another active factor influencing the changes of baseflow.

The trend of annual precipitation in Kuye catchment was tested using Mann-Kendall method (Fig.6). A small decreasing trend of statistical insignificance was found. The residuals estimated by Sen's slope estimation distributed randomly. No change point was detected by Pettitt test (Fig.7). Generally, average annual baseflow has a good relation with average annual precipitation in a catchment. In consideration of the annual precipitation change in Kuye catchment, the trend and the change points of annual baseflow probably resulted from the LUCC by soil conservation measures and coal mining.

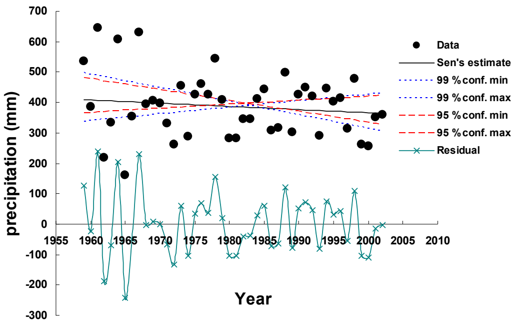

Fig. 6. The trend of annual precipitation in Kuye catchment detected by Mann-Kendall test. The lines indicating 95% and 99% of confidence levels and the residual estimated by Sen's slope estimation are also given in the graph.

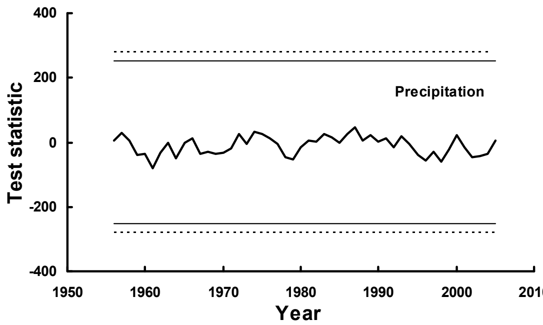

Fig. 7. Pettitt's test for detecting a change point in annual precipitaion in Kuye catchment. The dotted horizeontal lines represent the significance levels of 5% and the solid lines, 10%.

To control severe soil erosion, a great number of soil conservation practices have been implemented on the Loess Plateau since the 1950s, with a tremendous effort especially from the 1970s to 1980s (Fig.2). During the period, large-scale biological measures have been taken, such as afforestations and pasture improvement. As a result, the area of afforestation increased nearly 45 times, from 27 km^2 in 1959 to 1184 km^2 in 1996 and correspondingly the area of pasturelands, form 22 to 380 km^2 (Table 1). It is believed that afforestation can alter the water balance of a catchment by increasing evapotranspiration (Saghafian et al., 2008; Zhang et al., 2001), leading to reductions of runoff and baseflow especially in the dry season (Bosch and Hewlett, 1982; Li, 1983). Zhang et al. (2008) showed that afforestation reduced annual streamflow as tree use more water on the Loess Plateau. Therefore, the baseflow in Luye catchment was expected to have a decreasing trend with enhanced afforestation. Meanwhile, a great many terraces and check dams were constructed in the catchment. It is reported that there were 844 reservoirs constructed in 1988 and 662 check dams in the 1970s (Wang and Fan, 2002). The area of terraces increased from 33 km^2 in 1969 to 99 km^2 in 1996 (Table 1). Although the area of engineering measures was much less than that of biological measures, the implementation of engineering measures had immediate impacts on stream flow and flow regime compared to biological measures (Zhan and Yu, 1994; Zhang, 2008). Accordingly, the first change point in annual baseflow was mainly related to the implementation of soil conservation measures in the catchment, especially the construction of reservoirs and check dams.

Most importantly, a large scale of coal mining development was expected to have a great influence on the decrease in baseflow. From the work by Jiang et al. (2010), coal mining in Kuye catchment began in 1978, but acutely, the annual amount of coal mining rose greatly after 1996 (Fig.2). Harper and Olyphant (1993) showed that activities like coal mining destroyed the structure of aquifer, leading to a consequent groundwater leakage. Coal mining in Kuye catchment resulted in the dramatically decreased baseflow in nearly 10 years, which explains the change point of 1996 in the annual baseflow (Fig.5).

5 CONCLUSIONS

The daily streamflow data in Kuye catchment on the Loess Plaetau of China was analyzed to investigate the responses of baseflow to the LUCC. An automated baseflow separation technique, the Chapman-Maxwell digital filter, was used to get the daily baseflow data from 1959 to 2005.

Result from Mann-Kendall test showed that the annual baseflow had a negative trend with the statistical significance of $p < 0.001$. The change rate in the catchment was -0.628 mm.a^{-1} which accounted for about 2.5% of the mean annual baseflow. Pettitt test and double mass curves method gave two change points of the annual baseflow in 1980 and 1996, respectively.

Compared to the contrast period from 1959-1979, the relative change of the average baseflow in the second period from 1980 to 1995 and the third period from 1996 to 2005 were 36.3% and 66.1%, respectively. Analysis of baseflow duration curves indicated that in comparison with the period before 1980, the relative changes in the 5th, 50th, and 95th percentiles of time in the period from 1980 to 1996 were 30%, 38%, and 54%, respectively. The relative changes for the three flow regimes after 1996 reached 57%, 68%, and 100%, respectively.

The variability of baseflow distribution increased with time, as represented by baseflow duration curves. In consideration of statistical insignificance detected in annual precipitation, reasons for the baseflow changes in the Kuye catchment are much related to the soil conservation practices after the 950s, especially in the 1970s and 1980s, and coal mining development after 1996.

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