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The causes of flow regime shifts in the semi-arid Hailiutu River, Northwest China

Z. Yang[1,2], **Y. X. Zhou**[2], **J. Wenninger**[2,3], **and S. Uhlenbrook**[2,3]

[1]China University of Geosciences (Beijing), 10029, Beijing, China
[2]UNESCO-IHE Institute for Water Education, P.O. Box 3015, 2601 DA Delft, The Netherlands
[3]Delft University of Technology, Department of Water Resources, P.O. Box 5048, 2600 GA Delft, The Netherlands

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Correspondence to: Z. Yang (z.yang@unesco-ihe.org)

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Abstract

Identifying the causes (climate vs. human activities) for hydrological variability is a major challenge in hydrology. This paper examines the flow regime shifts, changes in the climatic variables such as precipitation, evaporation, temperature, and crop area in the semi-arid Hailiutu catchment in the middle section of the Yellow River by performing several statistical analyses. The Pettitt test, cumulative sum charts (CUSUM), regime shift index (RSI) method, and harmonic analysis were carried out on annual, monthly, and daily discharges. Four major shifts in the flow regime have been detected in 1968, 1986, 1992 and 2001. Characteristics of the flow regime were analyzed in the five periods: 1957–1967, 1968–1985, 1986–1991, 1992–2000, and 2001–2007. From 1957 to 1967, the flow regime reflects quasi natural conditions with high variability and larger amplitude of 6 months periodic fluctuations. The river flow had been affected by the construction of two reservoirs in the period 1968–1985. In the period of 1986–1991, the river discharge decreased due to the combined influence of river diversions and increase of groundwater extractions for irrigation. In the fourth period of 1992–2000, the river discharge reached lowest flow values and variations corresponding to a large increase in crop area. The flow regime recovered, but not yet to natural status in the fifth period of 2001–2007. Climatic factors are not responsible for all these changes in the flow regime, but the changes are corresponding well to human activities.

1 Introduction

The temporal pattern of river flow over a period of time is the river flow regime, which is a crucial factor sustaining the aquatic and riverine ecosystems. Regime shifts are defined in ecology as rapid reorganizations of ecosystems from one relatively stable state to another (Rodionov and Overland, 2005). Flow regime shifts represent relatively sudden changes in temporal characteristics of river discharges in different periods. It is widely accepted that climate change and human activities are the main driving forces for hydrological variability (e.g. Milliman et al., 2008; Zhao et al., 2009; Xu, 2010). However, distinguishing the causes for the flow regime shifts is still a major challenge in hydrology.

Studies show that flow regime shifts in river basins can be ascribed to the changes in climatic variables, land cover and land use, river regulations, and other human activities; for example, soil and water conservation measures. The climatic variables were considered as the major driving factors for long-term changes in river discharge (Wolfe et al., 2008; Masih et al., 2010), which were also used for predicting the impacts of climate changes on stream discharge in the future (e.g. Thodsen, 2007). The changes in land cover (Costa et al., 2003; Poff et al., 2006,) and land use (Tu, 2005; Rientjes et al., 2010; Masih et al., 2011) would eventually alter the river discharge by influencing the runoff generation and infiltration processes. The construction of dams can significantly reduce the high flows and increase the low flows (Maheshwari et al., 1995; Magilliganan and Nislowb, 2005). The hydrological response also depends on a combination of precipitation, evaporation, transpiration, basin permeability and basin steepness (Lavers et al., 2010) or runoff generation in headwater catchments, impoundments in small dams and increased extractions for irrigated crop production (Love et al., 2010). These studies mainly focused on the relationship between the mean annual stream flow and the corresponding factors by performing different statistic tests on indictors of hydrological alterations or comparing modeled and measured discharge.

In China, the relations between the stream flow, precipitation and temperature were investigated in the Tarim River (Chen et al., 2006), Yellow River (Fu et al., 2007; Hu et al., 2011a), Wuding River (Yang et al., 2005) and Lijiang River (He et al., 2010). Zhao et al., (2009) studied the streamflow response to climate variability and human activities in the upper Yellow River Basin, and suggested that the climate effects accounted for about 50 % of total streamflow changes while effects of human activities on streamflow accounted for about 40 %. But the type of human activities was not identified. Furthermore, the changes in river discharge induced by soil and water conservation measures were examined in the Loess Plateau (Li et al., 2007; Lin et al., 2009) and Wuding River

(Xu, 2010). The effects of dam construction (Yang et al., 2008) and operation (Yan et al., 2010) on flow regimes in the lower Yellow River were assessed by analyzing the indicators of hydrological alterations (Richter et al., 1996), which suggested that dams effect the stream flow by increasing the low flows and decreasing the high flows.

Much of the present studies focus on the relations among the changes in climate and their linkage with the streamflow regime. However, the regime shift of the river discharge can also be caused by the human activities, but very often these factors cannot be distinguished (e.g. Uhlenbrook, 2009). Although some studies on climate change, dam regulation, human activities of soil and water conservations, and their effects on the river discharge have been conducted in the Loess Plateau of the Yellow River and its tributaries, no study focused so far on the regime shifts caused by human activities vs. climate controls in the sandy region in the middle section of the Yellow River Basin.

This paper reveals the flow regime shifts by means of detecting changes in annual, monthly, and daily characteristics of the river discharge and connects with changes in climate, water resources development, and land use in the sandy region of the middle section of the Yellow River Basin. The results provide a better understanding of the hydrological response to climate and human activities in a semi-arid area.

2 Materials and methods

2.1 Study area

The Hailiutu catchment is located in the middle section of the Yellow River Basin in Northwest China. The Hailiutu River is one of the branches of the Wuding River, which is the major tributary of the middle Yellow River (Fig. 1). The total area of the Hailiutu catchment is around 2645 km^2. The surface elevation of the Hailiutu catchment ranges from 1020 m in the southeast to 1480 m above mean sea level in the northwest. Most part of the Hailiutu catchment is surrounded and coved by Maowusu desert; the

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sand dunes cover almost all the catchment except for some floodplains located in the river valley. The Hailiutu River is located in the temperate, semi-arid monsoon climatic region. The long-term mean air temperature is 8.1 °C with the highest daily mean temperature value of 38.6 °C recorded in 1935 and the lowest value of −32.7 °C observed in 1954. The mean value of the annual sunshine hours is 2926 hours (Xu et al., 2009). The mean annual precipitation for the period 1985 to 2008 is 340 mm a^{-1}, the maximum annual precipitation at Wushenqi is 616.3 mm a^{-1} in 2002, and the minimum annual precipitation is 164.3 mm a^{-1} in 1999 (Wushenqi meteorological station monitoring data, 1985–2008). Due to the monsoon from southeast, most of the precipitation occurs in the summer and autumn. The mean annual pan evaporation (recorded from evaporation pan with a diameter of 20 cm) is 2184 mm a^{-1} (Wushenqi metrological station, 1985–2004). One tributary of the Hailiutu River, named Bulang, is situated at the middle part of the catchment. One hydrological station is located at the outlet of the Hailiutu catchment near Hanjiamao village with a mean discharge of 2.64 $m^3 s^{-1}$ for the period 1957–2007. The mean monthly discharges at Hanjiamao station vary from 0.86 $m^3 s^{-1}$ in April to 11.6 $m^3 s^{-1}$ in August (Fig. 2). There are two reservoirs constructed; one at the upstream of the Hailiutu River and the other one at the Bulang tributary for local water supply. The information about the construction of the reservoirs and water diversions is listed in the Table 1.

2.2 Data

There are four meteorological stations situated in and around the Hailiutu catchment (Fig. 1), and one hydrological station with daily discharge measurements from 1957 to 2007 at the outlet of the catchment. Daily precipitation at meteorological stations, air temperature from 1961 to 2006 at Yulin and Hengshan, monthly evaporation from 1978 to 2004 at Yulin, and monthly evaporation from 1985 to 2008 at Wushenqi were collected for analyses. Time series of annual mean discharge, annual maximum discharge, annual mean monthly minimum and standard deviation of annual mean monthly discharge at Hanjiamao hydrological station were selected for detection of

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the flow regime shift. The climatic variables such as annual precipitation, annual total heavy precipitation (daily rainfall $>10\,\text{mm}\,\text{d}^{-1}$), number of days of heavy rainfall, average air temperature from April to October, and annual evaporation were analyzed for possible climate changes. The crop area statistics from 1949 to 2007 in the Yuyang district of which part of the area is located in the Hailiutu catchment was available for analysis as an indicator of groundwater extraction for irrigation. Direct observations of extraction rates were not available.

2.3 Methods of regime shift detection

Among all the methods of detection of the regime shifts or the change points, detection of shifts in the means is the most common type (Rodionov, 2005). In this paper, the Pettitt test (Pettitt, 1979), cumulative sum chart (CUSUM) with bootstrap analysis (Taylor, 2000a, 2000b), regime shift index (RSI) calculated by a sequential algorithm of the partial CUSUM method combined with the t-test (Rodionov, 2004) for detecting the shifts in means of hydrological and climatic variables were carried out.

The Pettitt test is a non-parametric trend test for identification of a single change point in the time series data, which is often used to detect abrupt changes in hydrological series (e.g. Love et al., 2010). The tests were carried out by the software Datascreen (Dahmen and Hall, 1989) at a probability threshold of $p = 0.8$. The time series data were manually divided into sub-series in order to detect the change points in different periods. Abu-Taleb et al. (2007) used the CUSUM and bootstrap analysis for examining annual and seasonal relative humidity variations in Jordan, which begins with the construction of the CUSUM chart for the data sets, then calculates the confidence level by performing a bootstrap analysis for the apparent changes. A sudden change in the direction of the CUSUM indicates a sudden shift in the average. Rodionov (2004) proposed a sequential algorithm that allows for early detection of a regime shift and subsequent monitoring of changes in its magnitude over time. Start with initial subdivision of the data at certain point with the predefined cut-off length, the RSI method estimates the regime shift by statistically testing the mean of the previous subsets and subsequent data sets. Then continuously increases the number of the subsequent data sets and recalculates the means until the difference of the means is statistically significant. The regime shift is established when the means are statistically different. This data point is considered as a possible start point of the new regime. The Student's t test assuming unequal variances at the significance level of 0.05 was employed for the validation of the regime shift in the means of the hydrological variables, climatic variables, and crop area in this study.

Among the methods introduced above, the Pettitt test is widely used for examining the occurrence of a single change point in the time series, while multiple change points can be detected by CUSUM and RSI methods.

The periodic characteristics of hydrological variables can be analyzed by harmonic series (Zhou, 1996). Harmonic analyses for monthly discharges and standard deviations of the discharge were applied for different periods based on the preliminary analyses of the flow regime shift. The periodicity, magnitude and phase shift of the harmonic components were investigated in order to detect shifts in the periodic characteristics. Finally, flow duration curves (FDC) of different periods were constructed for investigating the changes of daily discharge characteristics.

3 Detection of regime shifts

3.1 River flow regime changes

Change point detection

Change points were detected at 1968, 1985, 1991 and 2000 for annual mean discharge at Hanjiamao station from 1957 to 2007 by Pettitt test. The first change point moved slightly to the year 1967 with CUSUM method, the other three change points were the same. Three change points were found by RSI method at the year 1967, 1988 and 2000 for the annual mean discharge. For the annual maximum discharge at Hanjiamao

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station, the three change points at the year 1971, 1988 and 2000 were detected by Pettitt test and CUSUM method, only one change point at 1971 was found by the RSI method. Four change points at 1967, 1985, 1991, and 1998 were also found in annual mean monthly minimum discharge series by the Pettitt test, and almost the same four change points were detected by the CUSUM method except that the first change point was in 1965. The change points at 1960, 1965, 1991 and 1998 were found by the RSI method. The three change points at the year 1971, 1990 and 2000 were detected by all the three methods in the annual standard deviation of the mean monthly discharge. In order to verify whether the difference in the means between two series are statistically significant, the Student's t-test (assuming unequal variance) at significant level 0.05 were carried out for all the detected change points. Because the number of annual discharge series in two parts was too small, the monthly mean discharge series was used to perform the Student's t-test. The change points for shifts in means are listed in Table 2. Figure 3 presents the detection results of flow regime shift at Hanjiamao hydrological station.

Harmonic analysis

The harmonic analysis results using monthly mean discharge time series from 1957 to 1967 show that the peaks start in March and repeat every 6 months with amplitude of 0.52 $m^3 s^{-1}$. A 12 and 6 months periodicity with the amplitude of 0.47 $m^3 s^{-1}$ and 0.26 $m^3 s^{-1}$ were found in the period 1968–1985 with two peaks in February and October. An annual periodicity with amplitude of 0.58 $m^3 s^{-1}$ exists in the period of 1986–1991, while an annual periodicity with amplitude of 0.35 $m^3 s^{-1}$ was found in the period 1992–2000. In the last subset of monthly mean discharge from 2000 to 2007, a 12 months periodicity was found with the amplitude of 0.71 $m^3 s^{-1}$. An one peak discharge at December was found in the last three periods.

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There are two periods of 12 and 6 months in mean monthly standard deviation of discharge time series from 1957 to 1971, the amplitudes of the two harmonics are $0.8\,m^3\,s^{-1}$ and $0.44\,m^3\,s^{-1}$, respectively. The peaks occur in January and August. Only one 12 months periodicity with amplitude of $0.39\,m^3\,s^{-1}$ and peak in July was found in the period 1972–1990, the similar harmonic characteristics were found in the period 1991–2000 except for the amplitude of $0.15\,m^3\,s^{-1}$. The two harmonics with the same periodicity and peaks as in the period of 1957–1971 were found in the period 2001–2007 except for the smaller amplitude of $0.46\,m^3\,s^{-1}$ and $0.25\,m^3\,s^{-1}$ for the two harmonics. The Table 3 and Fig. 4 illustrate the regime shifts in harmonic changes of the monthly discharge and standard deviation at Hanjiamao station.

Figure 5 illustrates the flow duration curves (FDC's) in the five different periods according to the analysis results for the annual data. The high flows, median flow, and low flows in the first period from 1957 to 1967 are significantly larger than those in other periods. Less difference were found among the high flows in the second, third, and fifth periods, while the high flow is lowest in the fourth period from 1992 to 2000. The median flow (50 % value) in the second period of 1968–1985 is the second largest value among the medians in different FDCs, whiles the median flow and in the fourth period 1992–2000 is lowest. The low flows in five periods show a similar pattern as the medians.

3.2 Past climate and land use changes

The correlation coefficients among monthly precipitation at four meteorological stations are more than 0.88 (Table 4), the correlation coefficients between monthly pan evaporation at two stations are also higher than 0.53, and the correlation coefficient between the annual average air temperature at Yulin and Hengshan is 0.98. The high correlation coefficients indicate that the precipitation, evaporation, and air temperature at the meteorological stations are spatially more homogeneous and consistent.

The results of regime shift detection of climate variables and crop area in Hailiutu catchment are shown in Table 5 and Fig. 6. No significant shifts were found in the annual precipitation, total heavy precipitation (daily rainfall >10 mm d^{-1}), number of days of the heavy precipitation, and evaporation time series by all three methods at the meteorological stations. The change points at 1985 and 1997 were found in the average air temperature from April to October at Yulin and Hengshan meteorological stations by Pettitt test, while the 1997 was the only change point detected by the CUSUM and RSI methods.

Three change points were detected at 1972, 1990, and 1998 by the Pettitt test in the crop area from 1957 to 2007, almost the same three change points were found by CUSUM and RSI methods except for a little difference at the first and second change point.

4 Analysis of the results

4.1 Characteristics of flow regime changes over time

The detection of regime shift in annual mean discharge at Hanjiamao station from 1957 to 2007 provides integrated information about how the river water has been affected by changes in all causing factors. The flow regime can be divided into five groups identified in the analysis of annual mean discharge. Two periodic components of annual and semi-annual periodic fluctuations dominate in monthly mean discharge series, which reflect a small discharge peak in winter with maximum baseflow from groundwater discharge and a large discharge peak in summer originating from seasonal rainfall. The flow regime in the first undisturbed discharge series from 1957 to 1967 represents quasi natural variations with a mean discharge value of 3.49 $m^3 s^{-1}$, 6 months periodicity, and the comparable high daily discharges. In the second period from 1968 to 1985, the flow regime can be characterized with a lower mean discharge value of 2.72 $m^3 s^{-1}$, 12 and 6 months periodicity, and lower daily flows, which implies that the discharge had been affected. In the third period of 1986-1991, the mean discharge decreased to 2.3 $m^3 s^{-1}$. The magnitude of the summer peak discharge became smaller than

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the winter peak. The daily flows continuously declined in the fourth period of 1992–2000. The discharge reached lowest levels with a mean value of 1.92 $m^3 s^{-1}$, lowest amplitude of harmonic components, and lowest daily flows. The discharge recovered comparably to the previous but not to natural level in the fifth period of 2001–2007 with a mean value of 2.41 $m^3 s^{-1}$, 12 months periodicity, and comparable higher daily flows.

4.2 Causes of flow regime shifts

The climatic variables such as precipitation, evaporation, and the human activities are normally correlated with the observed discharge variability. Hu et al., (2011b) found no significant changes in the rainfall in the past 50 yr at some of the stations in the source region of the Yellow River, while decreasing trends were found in some other meteorological stations (Hu et al., 2011a). Thus, the decrease of the stream flow at most of the hydrological stations in the source region of the Yellow River can be ascribed to the decrease of the rainfall except for those where no changes were found in the meteorological stations. In this study, no significant change points were detected in the annual precipitation, the heavy rainfall (daily rainfall >10 mm d^{-1}), and the number of heavy rainfall days. Higher air temperature especially in the growing season would result in higher evaporation demands and eventually have negative effects on the discharge. The average air temperature from April to October increased from 1997 at a significance level of 0.05, but no significant changes in the annual pan evaporation could be found. Thus no correlation between the climatic variables and flow regime shifts was found in this catchment, and the human activities such as construction of hydraulic engineering works, water diversion, and groundwater exploitation for water supply are mainly responsible for the observed changes in discharges.

The hydraulic works such as reservoirs may significantly reduce surface runoff and, hence, are expected to have great impact on the discharge variability and particularly on the annual maximum streamflow (Li et al., 2007). The change point in the annual maximum discharge was detected with three methods at 1971 when the two reservoirs were constructed in the main river and tributary. In the subsequent period of

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1972–1985, the standard deviation decreased due to the combined effects from the reservoirs and groundwater exploitation. The maximum discharge and standard deviation were slightly increased in the period of 1986–1990 when less operation of the hydraulic engineering works during the initial stage of policy that the farmers could cultivate individually (Zhang et al., 2009). In the fourth period of 1991–2000, the maximum discharges are lowest due to the combined effects of reservoirs and construction of several water diversions for irrigation. The increase of maximum discharge and the standard deviation in the fifth period indicate a reduction of water diversion.

The low flows during the dry season are sensitive to changes in the groundwater system because the groundwater discharge dominates in the dry season. The groundwater abstractions started in the 1970's based on the analysis of annual mean monthly minimum discharge. The intensive groundwater exploitation is responsible for the lowest minimum discharge time series in the period of 1991–1998. The increase of the minimum discharge in the fifth period indicates a possible reduction of groundwater extraction.

The changes of crop area in Yuyang district can represent the changes in the amount of water diverted from river and groundwater exploitation for irrigation. The crop area has been influenced by the policy for cultivation and agriculture during the last 51 yr (Fig. 7). The crop area remained at a certain level from 1957 to 1971 when the crop land development and degradation processes were balanced. The crop area gradually decreased from early 1970's when the cultivated land was converted to terraces for agriculture with the policy of emulating Dazhai on agriculture campaign (Bi and Zheng, 2000). The policy of distributing the cultivated land to farmers was established in early 1980's, which eventually stimulated the farmers to enlarge the crop area (Zhang et al., 2009). The crop area was increased during 1989-1998 for the agriculture production according to the policy of non-staple food supply in urban districts in 1988 (Wang and Xu, 2002), which implies that intensive water diversion works and groundwater extraction wells were established to secure the irrigation for the crop land. The Chinese government has implemented a program to return the crop land to forest or grassland

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for ecosystem rehabilitation since 1999 (Li and Lv, 2004), which resulted in a decrease of crop area from 2000 to 2007. Figure 7 connects the local/regional land policies with the changes in crop area and observed flow regime shifts in Hailiutu River. It is clear that there is no decrease of the river flow despite a sharp increase in air temperature since 1997. However, the river flow regime changes are corresponding well to major historical landuse policy changes in the catchment.

4.3 Regression analysis

The multiple regression analysis was applied for investigating the relations between river discharge, climate parameters and crop area in the Hailiutu catchment. Based on the results of detection for flow regime shifts, the flow regime has been disturbed since 1968. The annual mean discharge at the Hanjiamao station, annual precipitation and air temperature at the Yulin station, and crop area in Yuyang district from 1968 to 2006 were selected for the analysis. Table 6 shows the correlation coefficients among the variables. It is clear that the annual mean discharge is positively dependent of the precipitation, but negatively dependent of crop area and air temperature.

The regression equation was found as follows:

$$Q = 85.7 + 0.011 \times P - 2.127 \times T - 0.723 \times A_{\text{crop}}$$

Where the Q is the annual mean discharge in mm a^{-1}, P is annual precipitation in mm a^{-1}, T is annual average air temperature in °C, and A_{crop} is the crop area in km^2. The multiple regression analysis (Fig. 8) yielded a coefficient of determination of 0.67, indicating that 67 % of the variation in the annual mean discharge can be explained by the combined variation of the precipitation, crop area and air temperature. The crop area is an indirect indicator of irrigation water use by river diversions and groundwater extractions. The air temperature is an indirect indicator of the total evaporation. The regression could be likely improved if the actual data of water diversion and groundwater extraction would be available.

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5 Conclusions

The flow regime shift detection and harmonic analysis show that the flow regime of the Hailiutu River has been changed dramatically over the last 51 yr. Five historical periods can be distinguished with different flow regimes. The first period from 1957 to 1967 represents in general the natural variation of the river flow with higher annual mean discharge, large annual maximum discharge, large standard deviation of mean monthly discharges, 6-month periodicity of two flow peaks (one in winter and one in summer) per year, and the high daily flow variability. The flow regime is modified in the second period from 1968 to 1985 mainly by the construction of reservoirs and water diversion works, which resulted in lower annual mean discharge, significantly reduction of summer flow peak, smaller standard deviation of mean monthly discharges, and low daily flows. In the third period of 1986–1991, the discharge continuously decreased due to the combined impacts by the river water diversion and the increase of the groundwater extraction. The summer flow peak is vanished because of river water diversion, leaving only the winter flow peak caused by groundwater discharge. The winter flow peak is shifted earlier possibly due to the irrigation return flow in the river valley. The annual mean discharge, annual maximum discharge, and the annual average standard deviation of mean monthly discharge were lowest in the fourth period of 1992–2000 due to a large increase of crop land with intensive water diversion and groundwater extraction for irrigation. The flow rate and variation recovered, but not yet to natural levels in the fifth period of 2001–2007, which can be attributed to the decrease of water extraction as a result of the implementation for the policy of returning farmland to forest and grassland in the catchment.

The analyses show that there are no significant climate changes in the Hailiutu River catchment. Only the average air temperature of April to October was increased since 1997, but has not caused significant changes in the flow regime. On the contrary, historical landuse policy changes had always had the footprint in the flow regime changes. Reservoirs and river water diversions are the main causes of reduction and

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disappearance of summer flow peaks. Groundwater extraction for irrigation reduces river base flow and contributes to the decrease of the annual mean discharge. The shift of winter peak flow one month earlier is most likely due to the irrigation return flow in the river valley. The river flow regime changes might have consequences on riparian ecosystems and downstream water use. The sustainable water resources development and management in the Hailiutu river catchment must consider the interactions of groundwater and river flow, and the consequences on the vegetation and downstream water use. Future research work should analyze effects of groundwater extraction on river flows and groundwater dependent vegetation in the catchment.

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Table 1. Hydraulic engineering works in the Hailiutu catchment.

No.	Name	Year of construction	Elevation (m a.m.s.l)	Type	Water use
1	Chaicaoba	1970	1072	Diversion dam	Irrigation for 53 ha crop land
2	Tuanjie	1971	1218	Reservoir	Water supply for power plant; Irrigation for 33 ha crop land
3	Maluwan	1972	1124	Diversion dam	Irrigation for 187 ha crop land
4	Geliugou	1972	1166	Reservoir	Irrigation for 33 ha crop land
5	Caojiamao	1989	1184	Diversion dam	Irrigation for 93 ha crop land
6	Hongshijiao	1992	1082	Diversion dam	Irrigation for 113 ha crop land
7	Shuanghong	1995	1101	Diversion dam	Irrigation for 100 ha crop land
8	Wanjialiandu	1995	1043	Diversion dam	Irrigation for 133 ha crop land
9	Wujiafang	1997	1150	Diversion dam	Irrigation for 60 ha crop land
10	Weijiamao	2008	1130	Diversion dam	Irrigation for 67 ha crop land

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Table 2. Results of flow regime shift detection.

Time series	Timing of the change points
Annual mean	1957 — 1967 (CUSUM, RSI); 1968 (Pettitt); 1985 (Pettitt, CUSUM); 1988 (RSI); 1991 (Pettitt, CUSUM); 2000 (Pettitt, CUSUM, RSI) — 2007
Annual maximum	1957 — 1971 (Pettitt, CUSUM, RSI); 1988 (Pettitt, CUSUM); 2000 (Pettitt, CUSUM) — 2007
Annual mean monthly minimum	1957 — 1960 (RSI); 1965 (CUSUM, RSI); 1967 (Pettitt); 1991 (Pettitt, CUSUM, RSI); 1998 (Pettitt, CUSUM, RSI) — 2007
Annual mean monthly standard deviation	1957 — 1971 (Pettitt, CUSUM, RSI); 1990 (Pettitt, CUSUM, RSI); 2000 (Pettitt, CUSUM, RSI) — 2007

The black line represents the time from 1957 to 2007, the triangle symbols above the time line stands for change points detected at the year, the detection methods for the change points are summarized below the time line.

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Table 3. Harmonic characteristics of monthly discharge and standard deviation at Hanjiamao station.

Monthly mean	1957–1967	1968–1985	1986–1991	1992–2000	2000–2007
Periodicity (month)	6	12/6	12	12	12
Amplitude	0.52	0.47/0.26	0.58	0.35	0.71
Peak discharge occurs in	Feb–Mar Aug–Sep	Jan–Feb Oct	Dec–Jan	Dec–Jan	Dec–Jan
Standard deviation	**1957–1971**	**1972–1990**		**1991–2000**	**2001–2007**
Periodicity (month)	12/6	12		12	12/6
Amplitude	0.80/0.44	0.39		0.15	0.46/0.25
Peak discharge occurs in	Feb/Aug	Jul		Jul	Feb/Aug

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Table 4. Correlation coefficients of monthly precipitation at meteorological stations.

Correlation coefficients	P_{Yulin}	P_{Wushenqi}	P_{Henan}	P_{Hengshan}
P_{Yulin}	1			
P_{Wushenqi}	0.89	1		
P_{Henan}	0.88	0.84	1	
P_{Hengshan}	0.89	0.83	0.95	1

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Table 5. Regime shift detection results of climate variables and crop area.

Time series	Timing of the change points
Average temperature from April to October at Yulin	1957–2007: 1985 ▽ (*Pettitt*); 1997 ▽ (*Pettitt*, *CUSUM*, *RSI*)
Average temperature from April to October at Hengshan	1957–2007: 1985 ▽ (*Pettitt*); 1997 ▽ (*Pettitt*, *CUSUM*, *RSI*)
Crop area in Yuyang	1957–2007: 1970 ▽ 1972 ▽ (*Pettitt*, *CUSUM*, *RSI*); 1988 1989 1990 ▽▽▽ (*Pettitt*, *CUSUM*, *RSI*); 1998 ▽ (*Pettitt*, *CUSUM*, *RSI*)

The black line represents the time from 1957 to 2007, the triangle symbols above the time line stands for change points detected at the year, the detection methods for the change points are summarized below the time line.

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Table 6. Correlation coefficients among discharge, precipitation, air temperature, and crop area from 1968 to 2006.

Correlation coefficients	Q (mm a^{-1})	P (mm a^{-1})	A_{crop} (km^2)	T (°C)
Q (mm a^{-1})	1			
P (mm a^{-1})	0.42	1		
A_{crop} (km^2)	−0.71	−0.40	1	
T (°C)	−0.35	0.06	−0.01	1

Q is the annual mean discharge at Hanjiamao station, P and T are the annual precipitation and air temperature at Yulin station, A_{crop} is crop area in Yuyang district.

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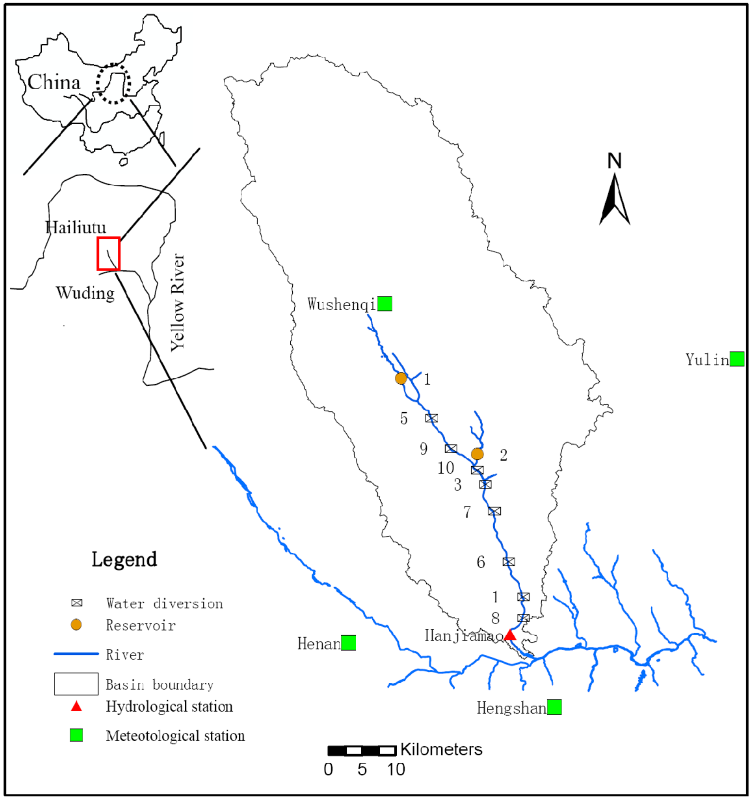

Fig. 1. Map of the Hailiutu catchment, the numbers nearby the stations are indices of hydraulic engineering works in the Table 1.

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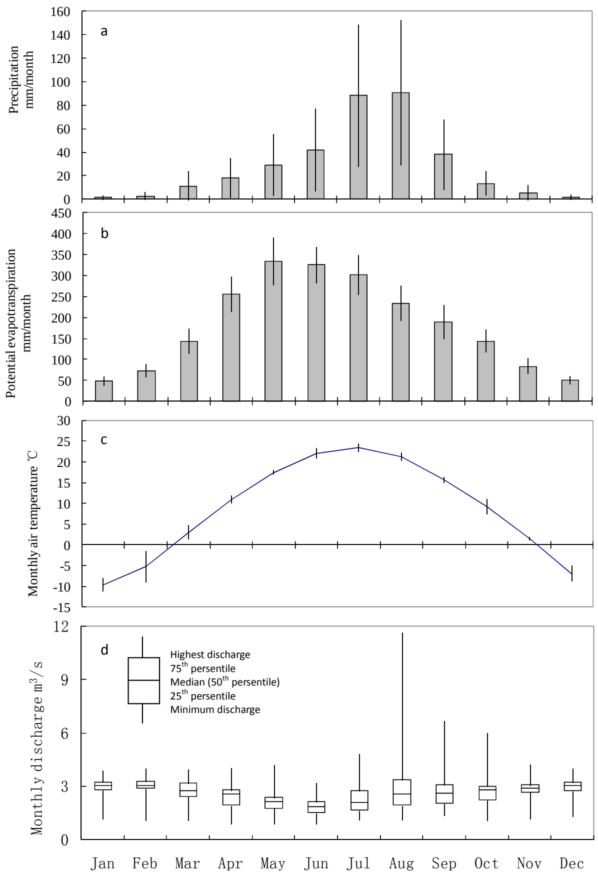

Fig. 2. **(a)** Mean monthly precipitation (1984–2005); **(b)** mean monthly pan evaporation (1984–2005); **(c)** mean monthly air temperature (2005–2008) at Wushenqi meteorological station; and **(d)** mean monthly discharge at Hanjiamao station (1957–2007), the error bars indicate the standard deviations for precipitation, potential evaporation, air temperature and the percentiles of the discharge.

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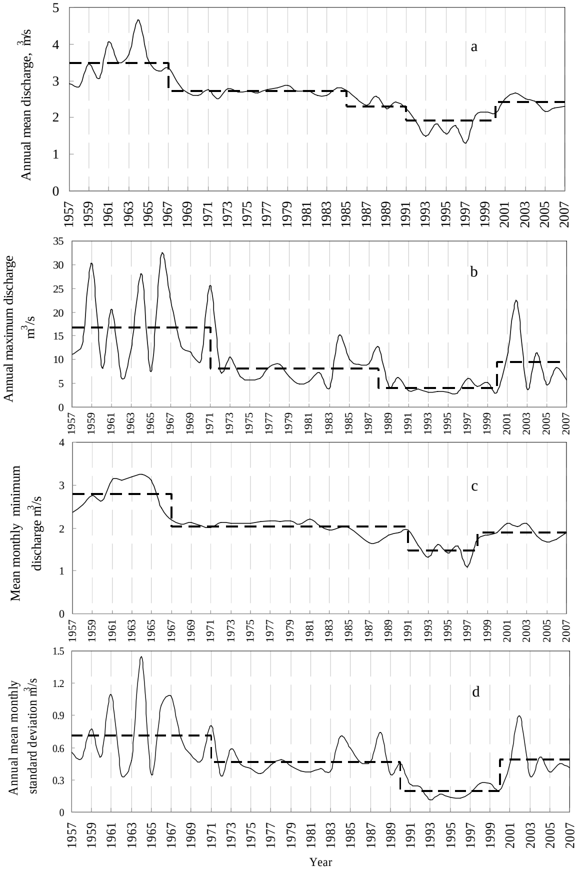

Fig. 3. The annual mean discharge **(a)**, annual maximum discharge **(b)**, annual mean monthly minimum discharge **(c)**, and the annual mean monthly standard deviation **(d)** at Hanjiamao station from 1957 to 2007, the grey lines are the annual time series data and the dotted lines are the mean of the data in different periods.

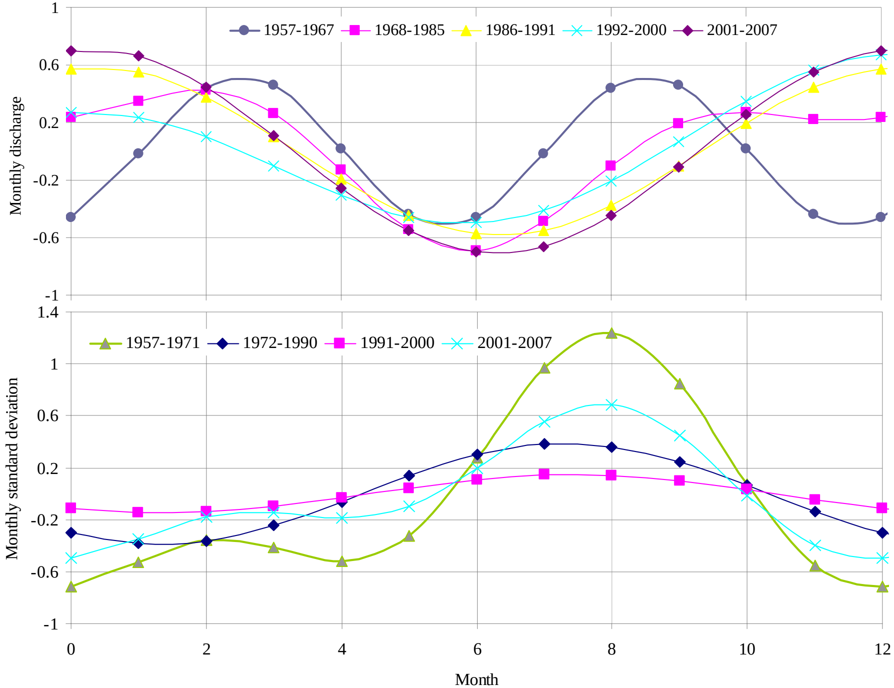

Fig. 4. Harmonic changes in monthly average discharge and standard deviation at Hanjiamao station for different periods.

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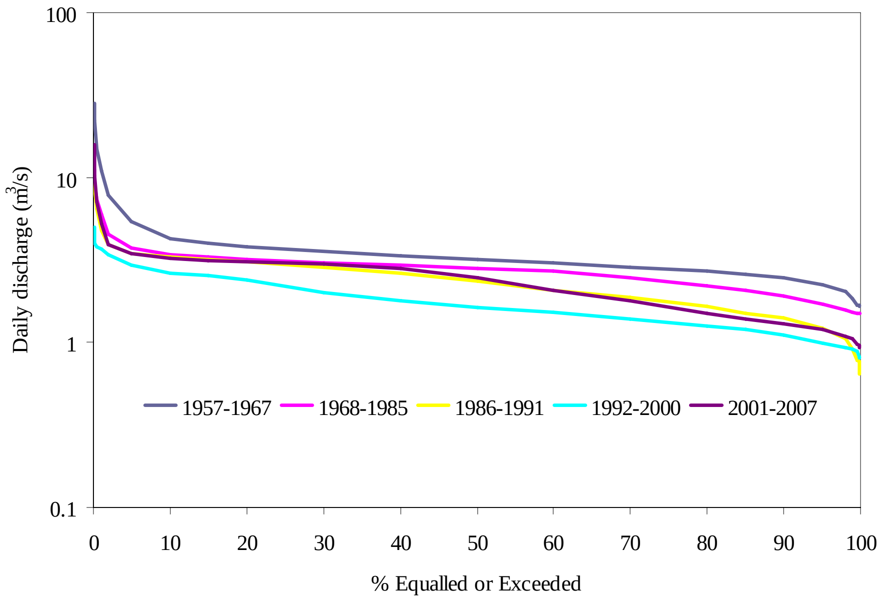

Fig. 5. Flow duration curves for mean daily discharges at Hanjiamao station in the 5 different periods.

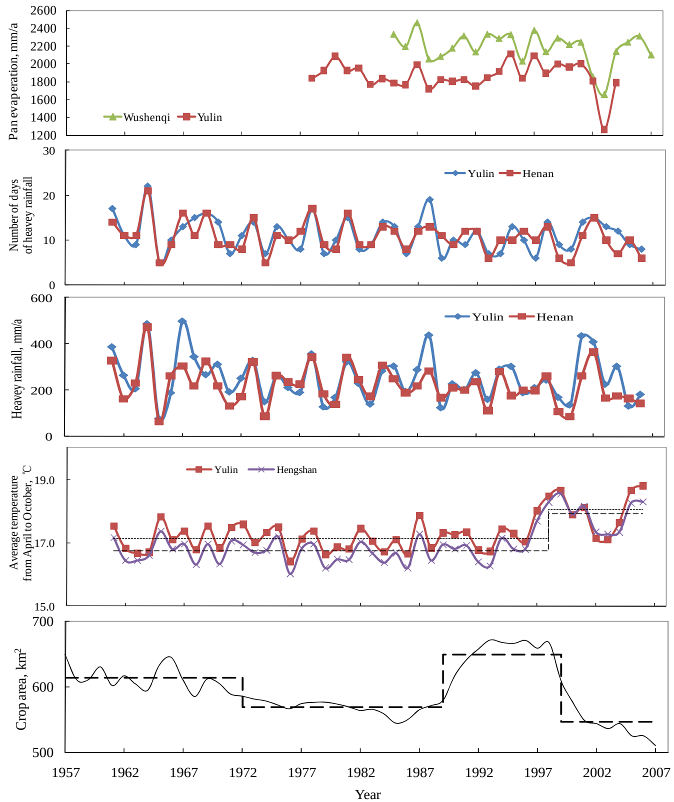

Fig. 6. Annual precipitation **(a)**, Heavy precipitation (>10 mm d^{-1}) **(b)**, number of days of heavy precipitation **(c)**, annual mean air temperature from April to October **(d)** at meteorological stations from 1961 to 2006. Annual pan evaporation **(e)** and annual crop area **(f)** in Yuyang district from 1957 to 2007, the dotted lines are the means of the data in different periods.

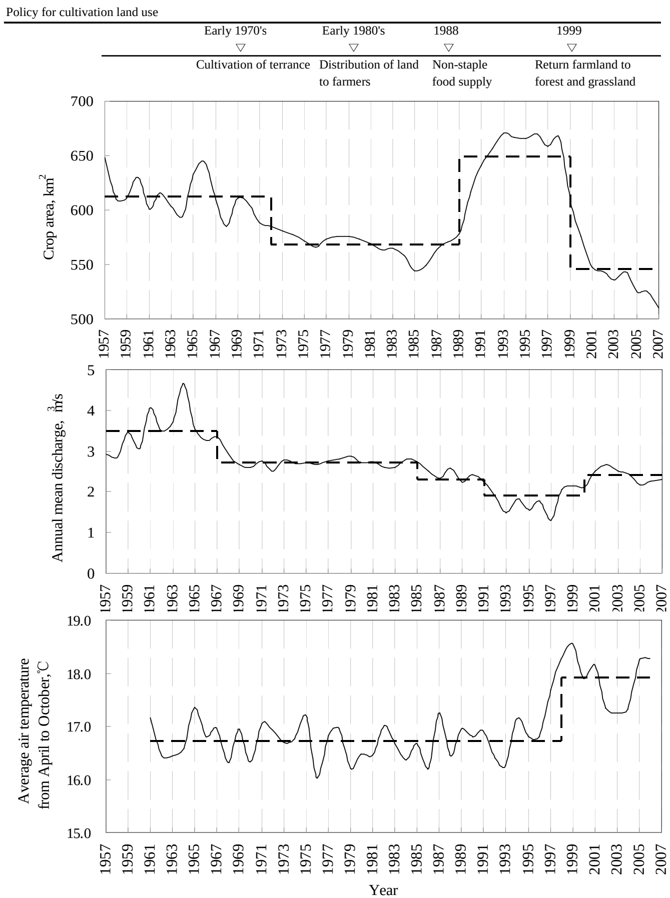

Fig. 7. Illustration of the causes for regime shifts; the cultivation policy, crop area, annual discharge, and air temperature form April to October at Yulin meteorological station.

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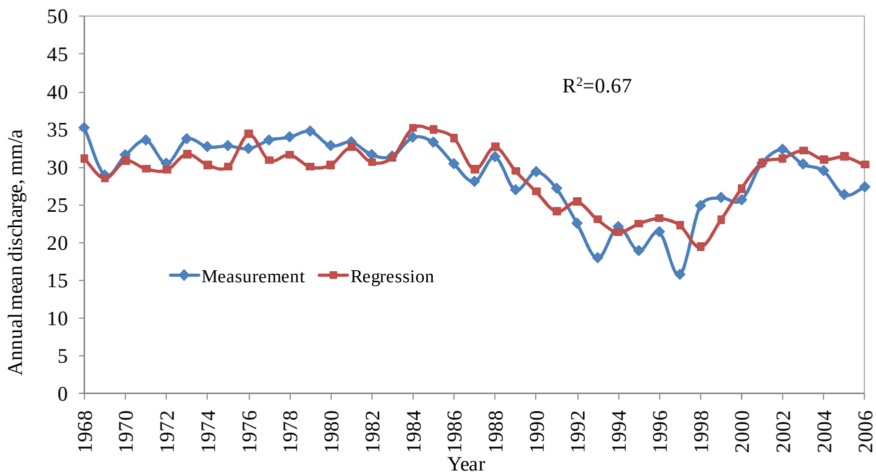

Fig. 8. Fit of prediction by multiple regression of the annual mean discharge at Hanjiamao station with the climatic variables at Yulin station and crop area in Yuyang district from 1968 to 2006.

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