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# Assessing the impact of climate variability and human activities on streamflow from the Wuding River basin in China

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## Abstract:

Located in the Loess Plateau of China, the Wuding River basin (30 261 km$^2$) contributes significantly to the total sediment yield in the Yellow River. To reduce sediment yield from the catchment, large-scale soil conservation measures have been implemented in the last four decades. These included building terraces and sediment-trapping dams and changing land cover by planting trees and improving pastures. It is important to assess the impact of these measures on the hydrology of the catchment and to provide a scientific basis for future soil conservation planning. The non-parametric Mann–Kendall–Sneyers rank test was employed to detect trends and changes in annual streamflow for the period of 1961 to 1997. Two methods were used to assess the impact of climate variability on mean annual streamflow. The first is based on a framework describing the sensitivity of annual streamflow to precipitation and potential evaporation, and the second relies on relationships between annual streamflow and precipitation. The two methods produced consistent results. A significant downward trend was found for annual streamflow, and an abrupt change occurred in 1972. The reduction in annual streamflow between 1972 and 1997 was 42% compared with the baseline period (1961–1971). Flood-season streamflow showed an even greater reduction of 49%. The streamflow regime of the catchment showed a relative reduction of 31% for most percentile flows, except for low flows, which showed a 57% reduction. The soil conservation measures reduced streamflow variability, leading to more uniform streamflow. It was estimated that the soil conservation measures account for 87% of the total reduction in mean annual streamflow in the period of 1972 to 1997, and the reduction due to changes in precipitation and potential evaporation was 13%. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS land use change; streamflow regime; streamflow trends; flow duration curves

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## INTRODUCTION

As a major tributary in the middle reach of the Yellow River, the Wuding River is known for its high sediment yield (Ludwig and Probst, 1998; Shi and Shao, 2000). Since the 1950s, significant land-use changes have taken place in the catchment to control soil erosion, maintain land productivity and improve environmental quality. The extent and rate of the changes are unprecedented. These changes include tree plantations, establishment of pasturelands, building of terraces and sediment-trapping dams. Although these measures have reduced soil erosion, they have also resulted in noticeable changes in the streamflow regime. Given the range of the conservation measures, it is difficult to isolate effects of the individual measures on streamflow.

Attempts have been made to quantify the impacts of these measures on streamflow using empirical methods, such as Zhan and Yu (1994) and Xu and Niu (2000). However, it is difficult to draw general conclusions from these studies because of their empirical nature. Although the areas of conservation measures are known, the exact locations are not, thus preventing the use of detailed, spatially distributed models. However, by analysis of patterns in precipitation–streamflow relationships, and knowing the relative area (but not exact locations) and timing of soil conservation measures, it is possible to examine the combined effects of soil conservation measures on catchment streamflow. To achieve this goal, it is important to understand the key processes that are affected by the conservation measures and, in turn, how they will modify streamflow. A widely used hydrologic method for estimating the impact of climatic factors (e.g. precipitation) on streamflow is based on relationships between annual precipitation and streamflow (Dai, 2002). Dooge *et al.* (1999) and Milly and Dunne (2002) proposed a framework to describe first-order estimates of the sensitivity of annual streamflow to precipitation and potential evaporation.

The purpose of this study was to detect changes in annual streamflow and evaluate the impact of climate and soil conservation measures on average catchment-scale water balance. This information can be used to evaluate

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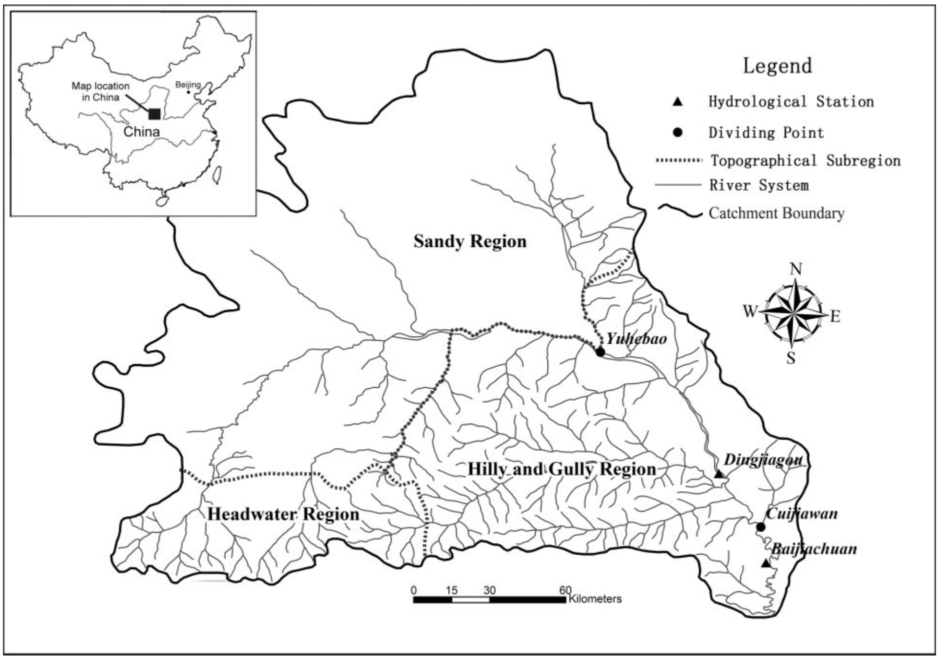

Figure 1. Location map of the study area in the Loess Plateau

the effectiveness and outcomes of the soil conservation measures implemented in the last four decades and guide future measures to be implemented in the region.

## MATERIALS AND METHODS

### *Study area and data*

The Wuding River basin is located in the Loess Plateau of China and it is a tributary of the Yellow River (Figure 1). The basin covers an area of 30 261 km$^2$ and the main channel length is 491·2 km, with an average slope of 1·97‰. The climate is semi-arid; average annual precipitation in the catchment varies between 350 to 500 mm, of which 75% falls between June and September. Average annual potential evaporation varies between 1100 and 1400 mm. The northwestern part of the basin is characterized as sandy areas with gentle slopes, and the southeastern part is typically steep hillslopes with incised channels. The sandy region covers 54·3% of the total catchment area and is mainly dry grassland. The channel density is low in this region. Because of the high infiltration rate, this region generates little overland flow and most runoff is baseflow. As a result, the erosion rate is relatively low (3000 t km$^{-2}$ year$^{-1}$) compared with the other parts of the basin. Overland flow is the dominant runoff generation mechanism in the southern part of the catchment, due to high rainfall intensities and low infiltration rate. The erosion rate is amongst the highest in the Loess Plateau (20 000 t km$^{-2}$ year$^{-1}$).

The gauging station at Baijiachuan was selected as it is located at the outlet of the basin. Streamflow was computed using a velocity–area method from automatic measurements of velocity using a current meter (LS68-2) and water depth at a natural cross-section. Daily precipitation was measured at 11 rain gauges across the basin and spatially averaged precipitation data were used in the analysis. The study period is 1961 to 1997.

The Wuding River basin has had a series of soil conservation measures since 1958 to control soil erosion. During the period of the 1950s to the 1970s, small-scale conservation measures were implemented gradually and the total area affected was very limited (see Table I). After the 1970s, the conservation measures were accelerated and intensified, and the total area affected reached 12 803 km$^2$ by 1996, or over 43% of the total basin area. The conservation measures included building terraces and sediment-trapping dams and changing land cover by planting trees and improving pastures. The information

Table I. Areas affected by the different conservation measures in the Wuding River basin (Zhang *et al.*, 2002)

| Year | Terraces | | Trees | | Pasture | | Dams | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| | km$^2$ | % | km$^2$ | % | km$^2$ | % | km$^2$ | % | km$^2$ | % |
| 1959 | 61·53 | 0·21 | 452.71 | 1·53 | 255·5 | 0·86 | 1·4 | 0·00 | 771.14 | 2·60 |
| 1969 | 285·6 | 0·96 | 1 254.61 | 4·24 | 197·54 | 0·67 | 43·65 | 0·15 | 1 781.4 | 6·01 |
| 1979 | 591·33 | 2·00 | 4 184.23 | 14·13 | 598·46 | 2·02 | 134·21 | 0·45 | 5 508.23 | 18·60 |
| 1989 | 976·07 | 3·30 | 8 893.78 | 30·02 | 905·97 | 3·06 | 180·91 | 0·61 | 10 956.73 | 36·99 |
| 1996 | 1 248·17 | 4·21 | 10 530.3 | 35·55 | 831·54 | 2·81 | 193·59 | 0·65 | 12 803.6 | 43·22 |

regarding the different soil conservation measures was collected through censuses conducted in each village and aggregated to catchment level.

### *Statistical analysis*

To analyse the stationarity of the streamflow record, the non-parametric Mann–Kendall–Sneyers (Mann, 1945; Kendall, 1975; Sneyers, 1975) test was applied. The test is a sequential version of the Mann–Kendall rank statistic proposed by Sneyers (1975). Let $x_1, \ldots, x_n$ be the data points. For each element $x_i$, the numbers $n_i$ of elements $x_j$ preceding it ($j < i$) such that $x_j < x_i$ are computed. Under the null hypothesis (no trend), the test statistic

$$t_k = \sum_{i=1}^{i=k} n_i \tag{1}$$

is normally distributed with mean and variance given by

$$\bar{t}_k = E(t_k) = \frac{k(k-1)}{4}$$
$$\overline{\sigma} t_k^2 = \mathrm{var}(t_k) = \frac{k(k-1)(2k+5)}{72} \tag{2}$$

Let

$$u_k = \frac{t_k - \bar{t}_k}{(\overline{\sigma} t_k{}^2)^{1/2}} \tag{3}$$

be the normalized variable, which is the forward sequence, and the backward sequence $u_k^*$ is calculated using the same equation but with a reversed series of data.

When the null hypothesis is rejected (i.e. if any of the points in the forward sequence are outside the confidence interval), the detection of an increasing ($u_k > 0$) or a decreasing ($u_k < 0$) trend is indicated. The sequential version of the test used here enables detection of the approximate time of occurrence of the trend by locating the intersection of the forward and backward curves of the test statistic. If the intersection occurs within the confidence interval, then it indicates a change point (Demaree and Nicolis, 1990; Moraes *et al*., 1998).

### *Estimating the impact of climate variability on streamflow*

Hydrological sensitivity can be defined as the percentage change in mean annual streamflow occurring in response to a change in mean annual precipitation $P$ and potential evapotranspiration $E_0$. The water balance for a catchment can be written as:

$$P = E + Q + \Delta S \tag{4}$$

where $P$ is precipitation, $E$ is evapotranspiration, $Q$ is streamflow, and $\Delta S$ is change in catchment water storage. Over a long period of time (i.e. 10 years), it is reasonable to assume $\Delta S$ is zero.

Following Zhang *et al.* (2001), long-term average evapotranspiration can be estimated as

$$\frac{E}{P} = \frac{1 + w(E_0/P)}{1 + w(E_0/P) + (E_0/P)^{-1}} \tag{5}$$

where $w$ is a model parameter relating to vegetation type and was set to 0·50 in this study.

Perturbations in both precipitation and potential evapotranspiration can lead to changes water balance (Dooge *et al*., 1999). It can be assumed that a change in mean annual runoff can be determined using the following expression (Koster and Suarez, 1999; Milly and Dunne, 2002):

$$\Delta Q^{\mathrm{clim}} = \beta \Delta P + \gamma \Delta E_0 \tag{6}$$

where $\Delta Q^{\mathrm{clim}}$, $\Delta P$, $\Delta E_0$ are changes in streamflow, precipitation, and potential evapotranspiration respectively; $\beta$ is the sensitivity of streamflow to precipitation and $\gamma$ is the sensitivity to potential evapotranspiration.

The sensitivity coefficients can be expressed as

$$\beta = \frac{1 + 2x + 3wx}{(1 + x + wx^2)^2} \tag{7}$$

$$\gamma = -\frac{1 + 2wx}{(1 + x + wx^2)^2} \tag{8}$$

where $x$ is the index of dryness and is equal to $E_0/P$.

Another way to estimate the impact of climate variability on streamflow is to use rainfall–runoff models (Jones *et al*., 2006). Following Zhang *et al.* (1998) and Dai (2002), annual streamflow for catchment can be estimated as

$$Q_1^{\mathrm{c}} = a + bP_1(\sigma_1{}^2)^{\mathrm{c}} \tag{9}$$

where $Q_1^{\mathrm{c}}$ is the calculated annual streamflow, $P_1$ is the annual precipitation, and $\sigma_1^2$ is the variance of the monthly precipitation; $a$, $b$, and $c$ are constants calibrated for the baseline period. The subscript '1' represents the baseline period when the catchment is under stable conditions, i.e. no changes in catchment properties, such as land use and land cover.

A change in observed mean annual streamflow $\Delta Q^{\mathrm{tot}}$ can be result from climate variability $\Delta Q^{\mathrm{clim}}$ and human activities $\Delta Q^{\mathrm{ha}}$. For a catchment that has undergone major land-use change, it can be assumed that a response in streamflow will occur and the change can be gradual (a trend) or abrupt (a step change). For assessing the effect of human activities on streamflow, the sequential version of the Mann–Kendall rank statistic was used to detect the approximate time of the change in streamflow. Then the total streamflow record was divided into two periods. The first period represents the baseline when no significant human activities occurred, and the second period represents changed streamflow and is associated with significant human activities. Equation (9) was first used to estimate annual streamflow during the first period as the baseline conditions. Similarly, Equation (9) was applied to the second period to calculate annual streamflow that would occur if there were no significant land-use change. Finally, the effects of climate variability, in this case precipitation on streamflow, can be estimated using the expression

$$\Delta Q^{\mathrm{p}} = Q_2^{\mathrm{c}} - Q_1^{\mathrm{c}} \tag{10}$$

where $Q_1^c$ and $Q_2^c$ are the calculated annual streamflows during the first and second periods of the record respectively.

### *Flow-duration curve*

A flow-duration curve (FDC) represents the relationship between the magnitude and frequency of streamflow. An FDC is constructed from daily streamflow data over a time interval of interest and provides a measure of the percentage of time a given streamflow is equalled or exceeded over that interval. Each value of discharge $Q$ has a corresponding exceedance probability $p$, and an FDC is simply a plot of $Q_p$, the $p$th quantile or percentile of stream flow, versus exceedance probability $p$, where $p$ is defined by

$$p = 1 - p\{Q_p \leq q\} \tag{11}$$

The quantile $Q_p$ is a function of the observed streamflow; and since this function depends upon observations, it is often termed the empirical quantile function (Vogel and Fennessey, 1994).

## RESULTS AND DISCUSSION

### *Changes in annual streamflow*

The Mann–Kendall–Sneyers test was applied to the annual streamflow data over the period 1961 to 1997. The test showed a significant downward trend starting 1972. Figure 2a shows graphically the forward and backward application of the test. The intersection of the curves indicates an abrupt change in annual streamflow occurring in 1972 at the 5% significance level. The test was also applied to streamflow during the flood period (July–October) and non-flood period (November–June). The results showed that a change point also occurred in 1972 (Figure 2b and c). To investigate the effect of precipitation on streamflow, we also carried out the test for annual precipitation and no change point was identified (Figure 2d). Although the soil conservation measures started in the 1950s, the extent of the implementation was very limited, with only selected experimental subcatchments being targeted until the 1970s. As shown in Table I, the area affected by the soil conservation measures accounted for 6% of the total catchment area by 1969. The soil conservation measures were intensified during the 1980s and 1990s, and the total area affected reached 43% of the total catchment area by 1996. The identification of 1972 as a change point in annual streamflow appears consistent with the soil conversation history.

Based on the Mann–Kendall–Sneyers test, the period of the streamflow record was divided into two parts: a *baseline period* (1961–1971), representing streamflow under natural conditions, and a *changed period* (1972–1997), representing streamflow under the influence of the soil conservation measures. It is clear that annual streamflow during the two periods was significantly different, with reduced streamflow and variability in the second period (Figure 3). Flood-season streamflow showed a greater reduction of 49% compared

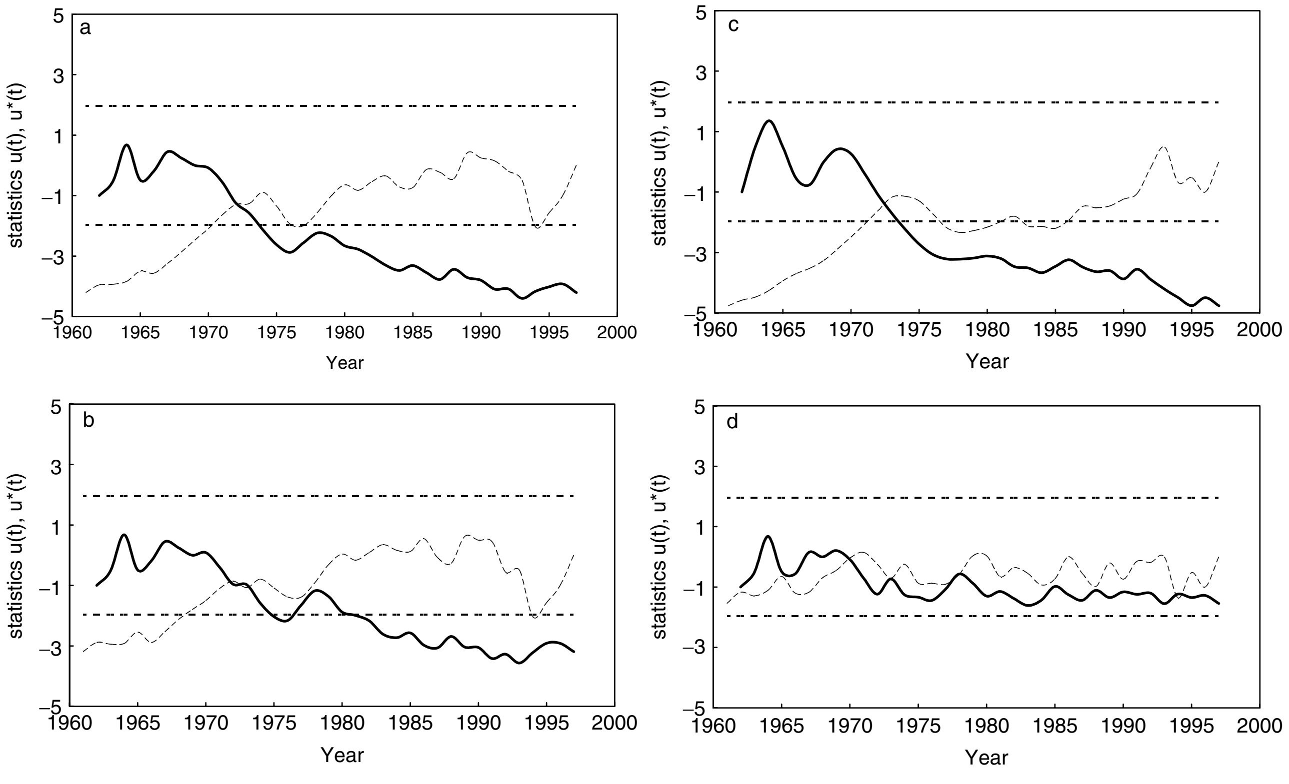

Figure 2. Mann–Kendall–Sneyers sequential trend test of (a) annual, (b) flood-season, (c) non-flood-season streamflow, and (d) annual precipitation with forward ($u_k$, solid line) and backward ($u_k^*$, dashed line). The horizontal dotted lines represent the critical values corresponding to the 5% significance level

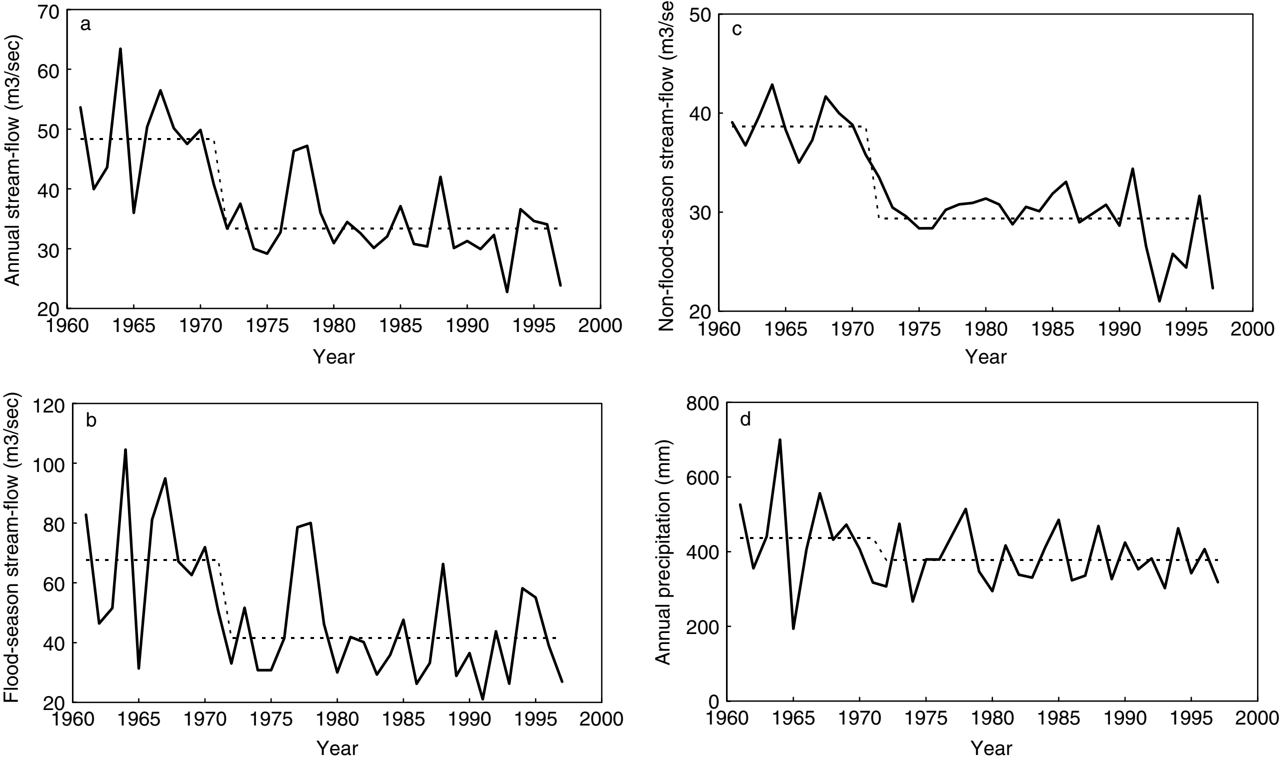

Figure 3. The variations in the characteristics of streamflows during the baseline and changed periods. The dotted lines represent the average streamflow for the two periods

with the annual streamflow (Table II). Non-flood-season streamflow was 36% lower during the later period. The coefficient of variation in annual streamflow was reduced by 12% in the second period (1972–1997).

The impact of the different soil conservation measures on streamflow is expected to vary. The engineering or structural works, such as terraces and dams, may significantly reduce surface runoff and, hence, are expected to have a greater impact on flood-season streamflow. For example, it is estimated that 1 $km^2$ of terrace in this basin could reduce annual runoff by 14 702 $m^3$ (Zhang *et al.*, 2002). Terraces are also likely to increase baseflow due to enhanced infiltration rate (Huang and Zhang, 2004). The impact of afforestation on annual streamflow has been studied and global data suggest that afforestation normally leads to a reduction in mean annual streamflow (Zhang *et al.*, 2001). Because there is insufficient documented information about the locations of the various soil conservation measures, we were unable to quantify the impact of the individual soil conservation measures. In the following sections, the impact of the soil conservation measures and climate variability on mean annual streamflow is examined using the methods described above.

Table II. Summary of streamflow characteristics during the baseline and changed periods

| Period | Annual streamflow (mm) | CV | Streamflow (mm) | |
|---|---|---|---|---|
| | | | Flood season | Non-flood season |
| 1961–1971 | 51·4 | 0·33 | 29·1 | 32·3 |
| 1972–1997 | 35·5 | 0·29 | 14·9 | 20·6 |
| Change (%) | 30·9 | 12·3 | 48·9 | 36·3 |

### *Changes in streamflow regime*

The intra-annual variability of streamflow is controlled by the seasonal cycle of precipitation, temperature and catchment management. As shown in Figure 4, there have been significant changes in intra-annual variability of streamflow in the basin, with dramatic reductions in average monthly streamflow in the period 1972–1997. The absolute and relative reductions in streamflow were greatest in July and August and were smallest in the winter months. Streamflow in the basin showed strong seasonal patterns as result of seasonality in the precipitation. Flood-season streamflow accounted for 45% of the annual total streamflow, as the basin experienced high-intensity rainfall events. Large runoff or flood events also occur in spring as a result of snowmelt. In early autumn, rainfall in the area tends to be of long duration and low intensity, but covering large areas. As a result, streamflow generally has low peak flows, but a relatively large baseflow component. In winter, high-intensity rainfall is rare and runoff is mainly baseflow. The changes shown in Figure 4 are consistent with the work of Liu and Zhong (1978) and partly reflect the effects of afforestation in the basin (Brown *et al.*, 2005).

An FDC provides a simple, yet comprehensive, graphical view of the overall variability associated with streamflow and is the complement of the cumulative distribution

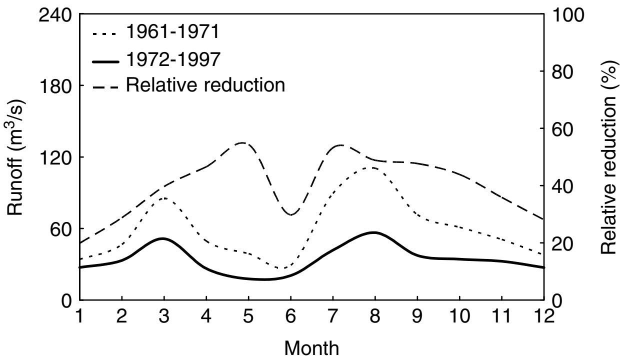

Figure 4. Average monthly streamflow for the baseline (1961–1971) and changed (1972–1997) periods

function of daily streamflow (Vogel and Fennessey, 1994; Brown *et al.*, 2005). Figure 5 shows the daily FDCs for the two periods described previously and the relative reduction in daily flow with the same percentile. The results indicate that there was a 31% reduction in most flows, but the reduction for low flows was up to 57%. The high-flow index $Q_5/Q_{50}$ can be defined as the ratio between daily streamflow exceeded 5% of the time, i.e. $Q_5$, and daily streamflow exceeded 50% of the time, i.e. $Q_{50}$. It was reduced by 11%. However, the change in low-flow index $Q_{95}/Q_{50}$, defined as the ratio between daily streamflow exceeded 95% of the time, i.e. $Q_{95}$, and daily streamflow exceeded 50% of the time, i.e. $Q_{50}$, is much more dramatic, with a 39% reduction. These results are consistent with the findings of Huang and Zhang (2004) for a catchment in this region. The observed change in the FDCs to some extent reflects the nature of the soil conservation measures in the basin, and the combined effect is to reduce the volume of annual streamflow and its variability, leading to a more uniform streamflow regime. The results also showed that the baseflow index of the basin remained constant over the whole period of record.

### *Effects of climate variability and human activities on streamflow*

Changes in streamflow for a given catchment can be the result of climate variability and human activities. However, quantification of the individual impacts is difficult, as most changes in streamflow are associated with changes in both climate and human activities. Milly and Dunne (2002) developed a method to estimate changes in streamflow due to changes in precipitation and potential evaporation. Application of this method to the Wuding River basin showed that the effect of climate variability on mean annual streamflow $\Delta Q^{\text{clim}}$ accounted for 12·7% of the total change in streamflow and that human activities are responsible for most of the change in mean annual streamflow (e.g. 87·3%). The other method used for estimating the impact of climate change on streamflow is based on the rainfall–runoff relationship as represented by Equation (9). The relationship was calibrated using the data during the baseline period and the coefficient of correlation is 0·94. Application of the relationship to both the baseline period (1961–1971) and changed period (1972–1997) yields the estimate of change in mean annual streamflow (Table III). The method assumes that, for a given catchment, the relationship between precipitation and streamflow will remain unchanged unless catchment properties have been modified. It should be noted that this method does not take potential evaporation into consideration and operates on annual time-scale. It is encouraging that the two methods provided a consistent estimate of percentage changes in mean annual streamflow. This gives us confidence in the methods used for quantifying the impact of climate variability and human activities on streamflow.

## CONCLUSIONS

Soil conservation measures have been implemented in the Wuding River basin at a scale that is unprecedented. An interesting question for hydrologists and catchment managers is to what degree the streamflow regime has been modified by these measures. The Mann–Kendall–Sneyers test was employed to analyse changes in annual streamflow for the period 1961–1997. An attempt was made to examine the impact of climate variability and human activities on streamflow. The following conclusions can be drawn from this study:

- A significant downward trend has been found for annual streamflow, with an abrupt change in 1972.

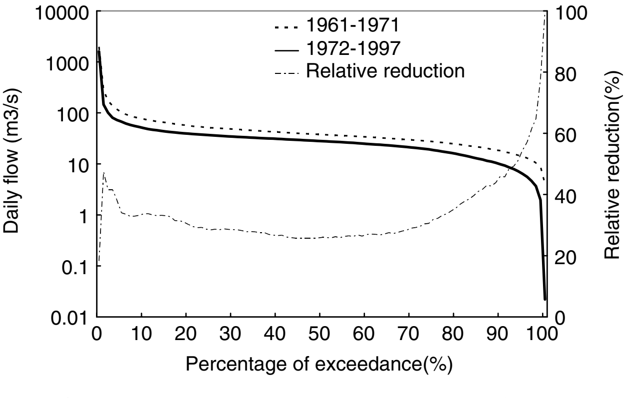

Figure 5. Changes in FDCs between the baseline (1961–1971) and changed (1972–1997) periods

Table III. Effects of climate variability and human activities on streamflow in the Wuding River basin as estimated using two different methods

| Period | $P$ (mm) | $E_0$ (mm) | $Q$ (mm) | $\Delta Q^{\text{clima}}$ (%) | $\Delta Q^{\text{hab}}$ (%) | $\Delta Q^{pc}$ (%) | $\Delta Q^{\text{had}}$ (%) |
|---|---|---|---|---|---|---|---|
| 1961–1971 | 391 | 1079 | 51·4 | | | | |
| 1972–1997 | 364 | 1051 | 35·5 | 15·7 | 84·3 | 12·9 | 87·1 |

[a] The change in mean annual streamflow due to climate variability as estimated using Equation (6).
[b] Estimated as $(1 - \Delta Q^{\text{clim}})$ and represents the change in mean annual streamflow due to human activities.
[c] Change in mean annual streamflow due to change in precipitation as estimated using Equation (10).
[d] Estimated as $(1 - \Delta Q)$ and indicates the change in mean annual streamflow due to human activities.

This downward trend corresponded with increased soil conservation measures in the basin. Annual streamflow during the period 1972–1997 was 31% compared with the baseline period (1961–1971).

- The streamflow regime of the basin showed a relative reduction of 31% for most percentile flows except for low flows, which showed a 57% reduction. Soil conservation measures reduced streamflow variability, and flood-season streamflow showed a reduction of 49%. Such a change appears to be beneficial in terms of soil erosion control, as most sediment load occurs during high flows.
- Soil conservation measures were estimated to be responsible for 87% of the total reduction in mean annual streamflow in the period 1972–1997. Climate variability accounted for 13% of the change in mean annual streamflow. The two methods used for assessing the impact of climate variability yielded consistent results.

## ACKNOWLEDGEMENTS

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