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## Runoff and sediment load of the Yan River, China: changes over the last 60 yr

F. Wang<sup>1,2,3,4</sup>, X. Mu<sup>1,2,4</sup>, R. Hessel<sup>3</sup>, W. Zhang<sup>2,4</sup>, C. Ritsema<sup>3</sup>, and R. Li<sup>1,2,4</sup>

<sup>1</sup>Institute of Soil and Water Conservation, Northwest A&F University, Yangling 712100, Shaanxi, China

<sup>2</sup>Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of water Resources, Yangling 712100, Shaanxi, China

<sup>3</sup>Alterra, Wageningen UR, P.O. Box 47, 6700 AA Wageningen, The Netherlands

<sup>4</sup>University of Chinese Academy of Sciences, Beijing 100049, China

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Correspondence to: F. Wang (wafe@ms.iswc.ac.cn)

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### Abstract

Runoff and sediment load changes are affected by climate change and human activities in an integrated way. Historical insight into these effects can not only improve the knowledge of river processes, but also promote more effective land and water management. In this study, we looked at runoff and sediment change in the Yan River Basin, Loess Plateau, China, using data sets on land use and land cover (LUC), monthly data of precipitation and temperature, and observed data on runoff and sediment load from 1952 to 2010 at the Ganguyi Hydrologic Station. Available data on soil and water conservation structures and their effect were also studied. Five main findings emerged from the data analysis. (1) The annual runoff and sediment load varied greatly during the last 60 yr and both had coefficients of variation that were much larger than those of precipitation and temperature. (2) Annual runoff and sediment load both showed a significant trend of linear decline over the period studied. The climate data showed a non-significant decline in precipitation over the same period, and a very significant increase in temperature; both can help explain the observed declines in runoff and soil loss. (3) Based on a mass curve analysis with anomalies of normalized runoff and sediment load, 4 stages in the change of runoff and soil loss were identified: 1951 to 1971 (Stage I), 1972 to 1986 (Stage II), 1987 to 1996 (Stage III) and 1997 to 2010 (Stage IV). (4) When years were paired based on similar precipitation and temperature condition (SPTC) and used to assess the impacts of human activities, it was found that 6 sets of paired years out of 12 (50 %) showed a decline in runoff 8 (67 %) a decline in sediment load and 9 (75 %) a decline in sediment concentration. The other sets show an increasing change with the time. It showed the complexity of human impacts. (5) Human impacts relating to LUC change and soil and water measures in this basin were significant because of both the transfer of sloping cropland into non-food vegetation or terraces and the siltation in the reservoirs and behind check dams. Data indicated that about 56 Mt of sediment was deposited annually from 1960–1999 as a result of the soil and water conservation structures, which is significantly more than the 42 Mt

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that is, on average, leaving the Yan River Basin as sediment load each year. Although the effects of climate change and human action could not be separated, analysis of the data indicated that both had a significant impact on runoff and sediment loss in the area.

## 5 1 Introduction

The Yellow River is China's second largest river, and derives its name from the sediment suspended in its waters. These sediment contents pose a major problem because sedimentation in the lower course of the river has raised the river bed to several meters above the surrounding landscape (Douglas, 1989; Zhang et al., 1990; Zhu et al., 10 1997), and reservoirs are being filled with sediment (e.g. Wan and Wang, 1994). The Chinese government is committed to combatting these problems and much attention is being directed at decreasing the erosion rates on the Loess Plateau, as it is the source of about 90% of all the sediment that enters the Yellow River (Douglas, 1989; Wan and Wang, 1994). The Loess Plateau has some of the highest erosion rates on 15 the entire planet. Jiang et al. (1981) estimated that erosion rates may be as much as  $18\,000\text{ t km}^{-2}\text{ yr}^{-1}$  for the hilly loess region of the Wuding River Basin, which is one of the main Loess Plateau tributaries of the Yellow River. Sediment concentrations in runoff on the Loess Plateau of over  $1000\text{ kg m}^{-3}$  have been recorded regularly (e.g. Jiang et al., 1981; Zhang et al., 1990; Wan and Wang, 1994).

20 To effectively combat erosion on the Loess Plateau, it is important to have insight into the historical development of runoff and sediment yield, and causes of significant changes. In particular, it is important to know to what degree the main causes are related to climate or to human activity, e.g. through land use change and through building of reservoirs. Where human activity is a main contributing factor, there will be 25 opportunities for reducing discharge and soil loss through modified activity, for example changes in land use.

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Ren and Zhu (1994) showed how different kinds of information (written records, Yellow River delta volumes) indicate that the serious soil erosion on the Loess Plateau started around 1000 AD. Xu (2001) found that bank breaching of the Yellow River increased in frequency from the 10th century AD onwards. According to him, breaching 5 frequency depends on sediment load, which apparently increased due to increased erosion on the Loess Plateau following destruction of the natural vegetation. On the other hand, Long and Xiong (1981) reported that historic literature from the Eastern Han Dynasty (25–220 AD) already recorded very high sediment contents: “the silt occupied six tenths of the volume in one barrel of water sampled”. According to Peng 10 et al. (2010) sediment yield started to increase around 3000 BP (1050 BC) because of cultivation and deforestation, but abruptly increased further around 1000 AD to levels that were maintained until the 1950's.

Monitoring of the Yellow River and its tributaries on the Loess Plateau started in the 1950's and has shown a gradual decrease over the years in runoff as well as sediment 15 load (e.g. Peng et al., 2010). Several authors have recently studied changes in discharge, sediment load and climate and have tried to quantify the contribution of climate variability and human action to the observed changes. Li et al. (2009) studied the Hei River Basin and reported that over the period 1981–2000 climate variability influenced discharge and sediment yield more than land use change. However, this might be due 20 to the relatively limited changes in land use during this period; while much larger land use changes have occurred since 2000 as a result of the “Grain for Green” project (Feng et al., 2010; Wang et al., 2010; Miao et al., 2011). Other studies have indicated that land use changes, i.e. human activity, can have significant effects on runoff and soil loss on the Loess Plateau (e.g. Hessel et al., 2003; Zhang et al., 2004; Feng et al., 25 2010). And Peng et al. (2010) reported that the main reason for a decrease in sediment load in the Yellow River is the conservation measures that have been implemented in the middle reaches of the basin since the 1950's; again human activity. None the less, there are climate trends that could also explain the observed decreases in runoff and sediment load. Li et al. (2009) observed a decrease in rainfall and an increase

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in temperature over the period 1981–2000, and Wang et al. (2012) also reported decreasing rainfall and increasing temperature on the Loess Plateau, over the period 1961–2010. Finally, Miao et al. (2011), who studied the whole Yellow River Basin and found a general increase in the influence of human activity over time – even outweighing the influence of climate in the period 2000–2008, also observed varying degrees of influence from climate and human impact for different decades since 1960, and for different parts of the Yellow River. These studies show that climatic variability/change and human action are both important factors to take into account to understand trends in discharge and sediment load on the Loess Plateau. Which of these factors outweighs the other is likely to depend on the area and time period that are studied.

In this paper we look at runoff and sediment yield developments over the last approximately 60 yr in the Yan River, one of the main Loess Plateau tributaries of the Yellow River. As previously mentioned, monitoring of rainfall, discharge and sediment content in the Yan River Basin started in 1952; and satellite images that can be used to derive information on land use are available from 1980. These and other data sources are used to analyze the trends and the impact that climate and/or human activity has had on the changes.

The aims of this paper are (1) to show how discharge and sediment yield from the Yan River varied over the last 59 yr; (2) to compare discharge and sediment load with rainfall data and land use and cover change data to identify causes for the observed changes; (3) to discuss implications for watershed management.

## 2 Materials and methods

### 2.1 Study area

The Yan River is a first-order branch of the Yellow River, China. The Yan River Basin (36° 21′–37° 19′ N, 108° 38′–110° 29′ E) is located in the middle of the Loess Plateau and the area of the whole basin is 7687 km<sup>2</sup>. The basin contains parts of 5 counties,

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namely Jingbian County, Zhidan County, Ansai County, Baota District and Yanchang County of Yan'an City, Shaanxi Province (Fig. 1).

The climate region of the Yan River Basin is north temperate continental monsoonal, with average annual precipitation varying from 500 to 550 mm and average annual air temperature ranging from 8.5 to 11.4 °C (Wang et al., 2010). The study area is covered by thick erosion-prone loess, a type of fine silt soil (Fu and Gulinck, 1994). Soil loss is severe throughout the basin and causes enormous sedimentation and high flood risks downstream, including in the Yellow River (Hessel et al., 2003). The landform is heavily dissected due to long-term soil erosion and the gully density (the total length of channel per km<sup>2</sup>) ranges from 2.1 to 4.6 km km<sup>-2</sup> (Wang et al., 2005).

The Ganguyi Hydrologic Station (GHS, 109° 48′ E, 36° 42′ N) is located in Ganguyi Town, Baota County. Its control area is 5891 km<sup>2</sup>, including Jingbian County (256 km<sup>2</sup>), Zhidan County (708 km<sup>2</sup>), Ansai County (2699 km<sup>2</sup>) and Baota District (2228 km<sup>2</sup>) (Fig. 1). The average annual runoff and sediment load were 203.5 million m<sup>3</sup> and 41.5 million t, respectively from 1952–2010. The average sediment concentration was 204 kg m<sup>-3</sup> and the sediment load module was 7040 t km<sup>-2</sup> a<sup>-1</sup> (Ministry of Water Resources of China, 2011).

### 2.2 Data

A 59-yr dataset of precipitation, temperature, runoff and sediment load from 1952 to 2010 was analyzed. Climate data were obtained from the 6 county level meteorological stations of Yan'an City which is located in the middle of the Yan River Basin (Fig. 1). Precipitation (including total precipitation of each year (a.pptn) and precipitation in the rain-season from May to October (r.pptn), in mm) and annual mean, maximum and minimum air temperature ( $t$ ,  $t_{\max}$ ,  $t_{\min}$ , respectively; in °C) were the spatially averaged data based on the daily records of stations upstream area of GHS (A-GHS) using the Thiessen polygon method. The observation and data management was according to the Specifications for surface meteorological observation of China (China Meteorological Administration, 2003). The annual runoff (in million m<sup>3</sup>, M m<sup>3</sup>) and sediment

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higher than Stage I and the mean for the whole period. All the mean characteristics in Stage II were less than those for the whole period, except for precipitation which was nearly the same as the whole period mean. The mean a.pptn in Stage IV was 464.0 mm, about 8% less than that for the whole period, and the mean temperature was 1.2 degrees higher than the whole period. Mean  $R$ ,  $SC$  and  $S$  were  $145.9 \text{ Mm}^3$ ,  $97.6 \text{ kgm}^{-3}$  and  $16.5 \text{ Mt}$ , respectively, all less than the mean values for the whole period, the decreases being 28.3%, 45.1% and 60.2%, respectively.

For runoff, sediment load and sediment concentration, the differences between the different stages were very different. The mean annual runoff in Stage IV was  $145.9 \text{ Mm}^3$  just 63.4% of that in Stage I. The sediment load in Stage I was  $58.48 \text{ Mt}$ , about 3.5 times of that in Stage IV. The mean sediment concentrations in Stage I and III were  $231.3 \text{ kgm}^{-3}$  and  $226.6 \text{ kgm}^{-3}$ , and in Stage II and IV  $148.5 \text{ kgm}^{-3}$  and  $97.6 \text{ kgm}^{-3}$ , respectively. The reduction from Stage I to Stage IV was  $133.7 \text{ kgm}^{-3}$  between Stage IV and I (about 58%).

In Stage I and III, the mass curves are, on the whole positive, meaning that the annual values are usually more than the mean annual value for the whole period. The differences in the mean annual value of each parameter are quite small (2.28% for runoff, 2.04% for sediment concentration and 6.11% for sediment load). The mean annual values in Stage II and IV are less than their long-term mean annual values.

In the 4 stages (Table 2), the mean annual precipitations of Stages I, II and III are very similar with the differences being less than 21 mm (about 5%). However mean annual precipitation in Stage IV was 57.48 mm less than Stage III (about 11%). Meanwhile, the temperature increased in each stage from 9.02, to 9.52, 10.01 and 11.06 °C. This is similar to the increasing temperature trend for the whole Yellow River Basin (The Ministry of Water Resources and Ministry of Environmental Protection of China, 2010), but is very different from the trends for the whole of China (Piao et al., 2010), which, for the period 1960–2006, showed strong differences between northeastern (decrease), northwestern (increase) and southeastern China (increase).

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Changes in runoff, sediment load and sediment concentration in each stage were found to be much greater than changes in precipitation. Trying to account for this through consideration of only the differences in precipitation and temperature between the different stages is difficult, e.g. how an increase of just 3.3% in precipitation and 5.1% in temperature could induce an increase of 17.3% for runoff and 66.7% for sediment load (Stage III compared to Stage II). These data, therefore, suggest that factors other than climatic ones might also be of importance. Thus, the impacts of factors like LUC change and constructions in the Basin should also be considered and analyzed.

### 3.4 Relationship between river and meteorological factors

The relationships between river and climate factors are shown in Table 3. Runoff and sediment load and annual and rain-season precipitation are all very significant. However sediment concentration, which is a meaningful indicator for river quality because it determines the transportation and siltation of sediment in the river channel and reservoirs downstream (Terrio, 2008; Maren et al. 2009; Ma et al., 2012), has no good relationships with pptn. This suggests that this parameter is likely more affected by other factors than precipitation, like temperature and human activity.  $R$ ,  $SC$  and  $S$  all have a significant negative relationship with temperature. This is perhaps because the higher temperatures can induce increased evaporation and reduced runoff and sediment generation. Due to the strong correlation between sediment load and sediment concentration, sediment concentration would also be reduced. The relationships between precipitation and runoff or sediment load are usually non-linear because of all the processes that operate between precipitation and runoff generation, such as interception by vegetation and litter on the soil surface (Helvey and Patric, 1965; Huang et al., 2005), as well as infiltration and evaporation which are affected by multiple factors like weather, landform and soil and vegetation conditions. A comparison of runoff and sediment load between paired years with similar precipitation and temperature conditions (SPTC) allows better study of the changes because the same premise is set with

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just one additional assumption, that the evolution of natural landform and vegetation is slow enough to neglect over intervals of several decades.

### 3.5 Runoff and sediment load between paired years with SPTC

5 The changes in runoff and sediment load when investigated through SPTC analysis are shown in Table 4. A positive difference for  $R$ ,  $SC$  and  $S$  means the value of the later year is less than that of the earlier year of the two paired years. Such a decrease is considered an improvement in the integrated land surface condition of the basin because the goal of the main management practices in this semi-arid region is to retain more water and sediment on site, or to reduce runoff and sediment load in the river.

10 The difference of  $a.pptn$  and  $t$  between paired years in Table 4 is from 0.02%–0.97% and –0.87%–0.56% of the relative value of paired years, respectively, but the differences in  $R$ ,  $SC$  and  $S$  are very different. When comparing the later year with the earlier year in each set of paired years, there are 6 sets (4, 5, 6, 8, 10 and 12) of 12 paired years that showed that  $R$ ,  $SC$  and  $S$  reduced (directions negative for all three parameters), and 3 sets (2, 3 and 11) with  $R$ ,  $SC$  and  $S$  all increasing (positive direction), 15 2 sets (7 and 9) with a increasing direction in  $R$  and decreasing direction in  $SC$  and  $S$ , and 1 set (1) with  $SC$  having negative direction but both  $R$  and  $S$  having positive direction.

20 Since precipitation and temperature were very similar for the paired years, the effects on  $R$ ,  $S$  and  $SC$  can be attributed primarily to human activity. From the data it appears that in the middle and later years of the 1980's, human activity had more negative impacts on soil and water loss than in the early 1950s and 1960s (set 1, 2 and 3). On the other hand, the impact of human activities in the 1970s and early 1980s appear to have been positive when compared with the 1960s (set 4–9). The human impacts 25 in 1991 and 2007 were positive when compared with 1978 and 1998, respectively, but more negative in 1993 compared to 1981.

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### 3.6 LUC change

Figure 5 provides a visual representation of the LUC for 4 counties in the area upstream of GHS in 1980 and 2010, and Fig. 6 provides details of the LUC for the same period. Forest, arable land and grassland are the main land use categories accounting for more than 99.20% of the whole area. Over the period studied, the area covered by forest increased continuously from 44.91 thousand ha in 1980 to 63.50 thousand ha in 2005, a conversion of 3.13% of the whole region to forest in 25 yr. The area used as arable land declined from 270.78 thousand ha in 1980 to 254.29 thousand ha in 2005, but not continuously as it increased by 2.17 thousand ha from 1985 to 1996. 10 The grassland area decreased from 274.82 thousand ha in 1980 to 272.38 thousand ha in 2005, almost all of which occurred from 1996 to 2000. The built-up land area nearly doubled because of the intensive houses and infrastructure development, but is still less than 2 thousand ha. More than half of the area converted to built-up area was converted from arable land. The actual area change in area of wetland and water body (Fig. 6) was less than 500 ha in the study period, but this is a decrease of 28% due to new arable land formation in the upstream parts of reservoirs and because of check-dam building across the gullies. The area of barren land remained stable at 250 ha.

20 Because of the very dissected landform in this region, all categories of land are distributed as small fragmented pieces (Fig. 5). The arable land along the Yan River and its branches had no clear change, but in the higher area, mainly the west and north parts of Zhidan County, Jingbian county and Ansai county, arable land use decreased, and patches of forest and grassland in that region expanded and even joined together (indicated by a dark purple color in the map for 2005).

25 A matrix based on the LUC change for three counties was developed to show the transfer between different kinds of land use categories in 1980 and 2005 (Table 5). This shows that 1.28 ha and 12.89 ha of forest changed into grassland and built-up land, and 14 497 ha of arable land and 4105 ha of grassland changed into forest. In

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been used in this paper do not provide proof about the relative importance of each of these factors because all these factors are operating simultaneously and perhaps even partly in dependence on each other. The data do provide some indications, but these can only be quantified if significant assumptions are made, such as for example the assumption made by Miao et al. (2011) that human influence in the 1950's could be neglected and that for the 1950's data a regression equation could therefore be developed that describes how runoff and sediment load would change solely under the influence of climate change. By extrapolating this equation to other decades, they were then able to separate the effect of human action from that of climate. In this study, we did not use such an assumption, but rather looked at indications that are found in the data, such as:

Decreases in runoff, sediment load and sediment concentration are larger than increases in temperature and decreases in rainfall. This, in itself, is not proof that other factors than temperature and rainfall are also at play, as relationships between temperature and rainfall and runoff and sediment load are not likely to be linear. However, the relatively low correlation between sediment concentration and precipitation as well as temperature (Table 3) does indicate that sediment concentration is partly controlled by other factors than climate.

The SPTC analysis of paired similar weather years shows that for years with similar rainfall and temperature, the later chronological year had lower runoff, sediment concentration and sediment load for 6, 9 and 8 out of 12 yr, respectively. Despite the caution that needs to be made about this method because of the large influence of individual events on yearly totals of runoff and sediment load, this also indicates that other factors than climate also play a role.

The LUC change data show an increase in forested land, and a decrease in arable land, which according to accepted knowledge would result in a decrease of runoff and sediment load at catchment scale.

Data on sedimentation at engineering structures of different scales show that significant amounts of sediment were captured. What the impact of this at catchment scale

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would be is however difficult to say, as the trapped sediment might also have deposited otherwise, while conversely new sediment might have been entrained by the clearer water that flowed out of, e.g. the reservoirs.

Hence, there are indications from the comparison of climatic data with runoff and sediment load that suggest that factors besides climate were involved in runoff and sediment changes, and there is also evidence that human activity (structures, land use) has decreased runoff and sediment load. Therefore, it can be expected that further human intervention by way of land management measures would be able to further influence runoff, sediment load and sediment concentration of the Yan River and other rivers on the Chinese Loess Plateau.

#### 4 Summary and conclusions

Global climate change has undoubtedly already influenced ecosystems and their functions and processes. In addition human activity has also undoubtedly influenced ecosystems and process. It can be very difficult to distinguish the impacts induced by climate change and human activities, yet this information can be of great value for developing management and adaptation strategies. In the Yan River Basin, the river runoff and sediment load declined dramatically over the last 60 yr. The non-significant decline in precipitation and significant increase in temperature can only partly explain these changes in runoff and sediment load.

The stages of river runoff, sediment load and climate change could be divided according to mass curve of anomalies of observed data, and the mass curves of normalized characteristics could put all change processes in one plot easily for better analysis. 4 clear stages of runoff and sediment load change were detected. Especially, the runoff and sediment load in Stage III (1987 to 1996) did not match the whole change processes, with runoff being 17–38 % higher than in neighboring stages, and sediment load being 66–70 % higher.

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The paired-year method can be useful to study the impacts of human activities, as it can be assumed that other factors that cause changes in runoff and sediment load, such as natural landform change, vegetation and soil evaluation are slow processes compared to the activities of human beings. As years with similar weather were selected, observed differences in runoff and sediment would therefore be due to human action.

The human impacts relating to LUC change and soil and water measures in this basin were very important both because of the transfer of sloping cropland into non-food vegetation or cultivable terraces, and because of siltation in reservoirs and behind check dams. Data for the study site show that about 2264.96 Mt in total or 56.62 Mt annual average of sediment were silted in the basin during 1960–1999. This value is larger than the amount of sediment that is, on average, leaving the Yan Basin, which was 41.50 Mtyr<sup>-1</sup> in the last 60 yr. This is one of the clearest indications that human activity had a significant impact on runoff and sediment loss.

Thus, both climate change and human activity are important factors in explaining the observed variation in runoff and sediment load. However, as the effect of both are integrated at catchment scale, accurate determination of exactly which part of the observed changes were due to climate change, and which to human management is extremely difficult if not impossible. Nevertheless, the results of this study clearly indicate that changes in human management of the Yan Basin would be likely to result in changes in runoff and soil loss at the scale of the whole basin.

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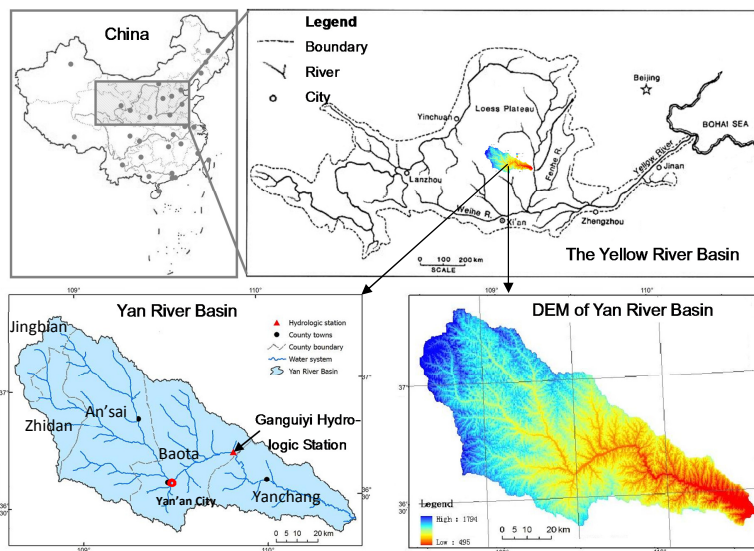




**Table 6.** Engineering measures of upstream area of GHS before 1999 (in ha).

Type	Character	Unit	Ansai County	Baota District	Zhidan County	Amount
Reservoir	Number	Set	1	1	–	2
	Control Area	km <sup>2</sup>	820.0	76.4	–	896.4
	Capacity	M m <sup>3</sup>	203.0	14.8	–	217.8
	Siltation	M m <sup>3</sup>	96.0	8.5	–	104.5
Key projects for gully control	Number	Set	17	26	–	43
	Control Area	km <sup>2</sup>	1.1	1.9	–	3.0
	Capacity	M m <sup>3</sup>	15.0	22.9	–	38.0
	Siltation	M m <sup>3</sup>	7.3	11.5	–	18.8
Check dam	Number	Set	688	3049	149	3886
	Siltation	M m <sup>3</sup>	275.2	1219.5	59.8	1554.5
		Mt	371.5	1646.4	80.7	2098.6
Amount of siltation	M m <sup>3</sup>	378.5	1239.5	59.8	1677.8	
	Mt	510.9	1673.4	80.7	2265.0	

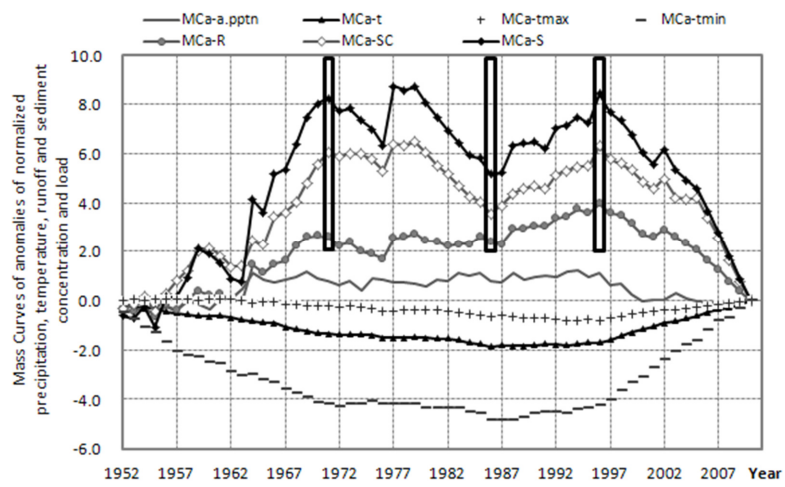
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**Fig. 1.** Location of study area (the Yan River Basin).

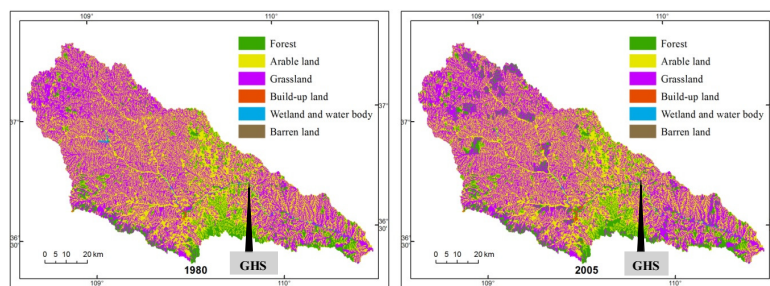
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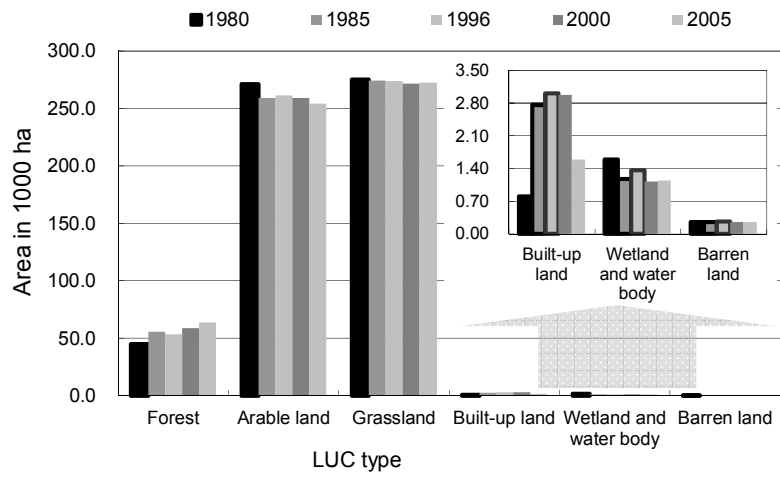
**Fig. 4.** Mass curves of anomalies of normalized characteristics of GHS in 1952–2010. (The boxes in the figure are the change points).

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**Fig. 5.** LUC of Yan River Basin from 1980 and 2005.

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**Fig. 6.** LUC change in the Yan River Basin from 1980 to 2005.