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# Sediment load reduction in Chinese rivers

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## Abstract

In this paper, the changes in the annual runoff and sediment transport have been assessed by using the long term observation data from 10 gauging stations on 10 large rivers across China from far north to far south. It is found that the annual sediment yield has generally had a decreasing trend in the past half century. According to the changes in annual runoff and the sediment yield per area, rivers in China can be classified into the following three groups: 1) rivers with decreasing annual sediment transport and stable runoff; 2) rivers with both decreasing annual sediment transport and runoff and 3) rivers with greatly reduced annual sediment transport and decreasing annual runoff. The results indicate that, in all southern rivers (to the south of the Huaihe River including the Huaihe River), there has been little change in average annual runoff but a dramatic decrease in annual sediment transport. In the northern rivers, however, both the annual sediment yield and the runoff show significant evidence of reduction. To further investigate the recent changes in annual runoff and sediment transport, the short-term observation data from these 10 gauging stations in the recent 10 years have been assessed. Results show that both the annual sediment transport and the runoff have decreased significantly in the northern rivers in the past 10 years. Using the Yellow River at the Lijin Station as an example, the average annual runoff for the last 10 years is only 1/3 of the long term average value and the average annual sediment yield of the last 10 years is only 1/4 of the long term average value. More unusually, in the Yongding River the annual sediment yield has approached zero and the runoff has decreased significantly. In addition, the impacts of human activities on the changes in both runoff and sediment transport have been discussed.

**Key Words:** China, Runoff, Sediment load, Large rivers, Sediment yield, Yangtze River, Yellow River

## 1 Introduction

Soil erosion is a worldwide problem that threatens an important and non-renewable resource – farmland. Soil erosion involves the detachment and movement of soil particles by both wind and water, but the latter is more significant. The soil erosion process can be accelerated by human activity, such as the removal of surface vegetation, forest harvesting, rangeland grazing, surface mining and urbanization. Tillage implements, forest harvesting equipment, mining activities and construction equipment all disturb the soil structure, which can also reduce the soil's resistance to detachment. In addition to removing a valuable resource, soil erosion leads to increased sediment input to nearby rivers and thus deposition in the river systems including reservoirs.

Sediment transport in rivers is particularly important for the global geochemical cycle and the transport of organic carbon from the land to the oceans by rivers (Ludwig et al, 1996). Sediment transport in rivers

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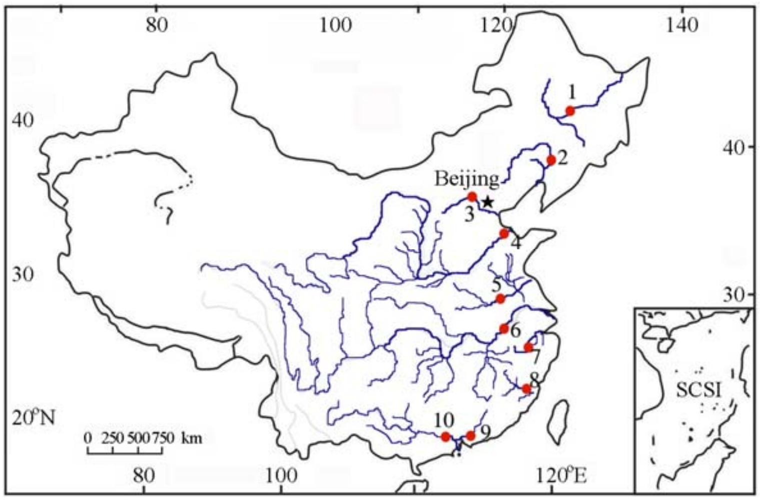
depends on both sediment properties and hydraulic parameters. Particle shape affects the incipient motion of sediment (Wang and Dittrich, 1999) and hydraulic parameters influence the sediment transport capacity and the river dynamics (Wang and Wu, 2001). Furthermore, land use may exert a significant influence on runoff and sediment yield (Lu and Huang, 2003; Sui et al. 2000 and 2005, Wang and Wang, 1999).

As pointed out by Walling and Fang (2003), the land-ocean transfer of sediment by rivers is a key component of the global denudation system and provides a general measure of the rate of denudation of the continent. With the growth of interest in global change, many researchers have attempted to assess the changes in runoff and sediment transport by rivers. Existing research results indicate that sediment transport by rivers has tended to decrease globally in recent years. Walling (2003, 2006) carried out extensive investigations to assess the changes in annual runoff and sediment loads measured at the furthest downstream gauging stations of 142 world rivers. He showed that rivers with an increasing annual runoff, decreasing annual runoff and stable annual runoff accounted for 8.5%, 22.5% and 69.0% of the total, respectively. In the case of sediment transport, rivers with an increasing annual sediment load, a decreasing annual sediment load and a stable annual sediment load accounted for 2.8%, 47.9% and 49.3% of the total, respectively.

Many rivers in China, especially the Yellow River, have sediment problems. With the booming economy and industrial development as well as urbanization, several characteristics of the watersheds, such as the percentage of vegetation cover (including secondary vegetation), may be dramatically changed. As a result, the rainfall- runoff process should be different from its original condition and sediment transport by the river systems should change. The purpose of the research was to assess the changes in annual runoff and sediment transport for 10 important large rivers in China, by using long-term observation data released in the China Gazette of River Sedimentation (WMR, 2001-2005, 2006).

## 2 STUDIED RIVERS AND DATA BASE

Ten important large rivers located across China (as shown in Fig. 1) have been selected to assess the changes in runoff and sediment transport. From the far north to the far south, these 10 rivers include: the Songhua River (at Harbin Station), the Liaohe River (at Tieling Station), the Yongding River (at Yanchi Station), the Yellow River (at Lijin Station), the Huaihe River (at Bengbu Station), the Yangtze River (at Datong Station), the Qiantang River (at Lanxi Station), the Minjiang River (at Zhuqi Station), the



Gauging stations on studied rivers:
1. Harbin station on the Songhua River
2. Tieling station on the Liaohe River
3. Yanchi station on the Yongding River
4. Lijin station on the Yellow River
5. Bengbu station on the Huaihe River
6. Datong station on the Yangtze River
7. Lanxi station on the Qiantang River
8. Zhuqi station on the Minjiang River
9. Boluo station on the Dongjiang River
10. Gaoyao station on the Xijiang River

**Fig. 1** The studied rivers and gauging stations

Dongjiang River (at Boluo Station) and the Xijiang River (at Gaoyao Station). Nine out of these 10 rivers enter the East Sea or the South Sea of China. The Songhua River, a tributary of the Heilong River (Amur River), flows northeast into Russia and then discharges into the ocean.

For each river, the data for the gauging station furthest downstream released in the China Gazette of River Sedimentation have been used. As shown in Table 1, the period of record ranges from 29 years to 56 years. The data series at most gauging stations are more than 50 years long. The drainage areas range from 18,233 km$^2$ (the Qiantang River at Lanxi) to 1,705,383 km$^2$ (the Yangtze River at Datong). The drainage area of the Yellow River at the Lijin Station is 752,032 km$^2$.

**Table 1** Long term and recent 10 year average annual runoff and sediment yield at 10 gauging stations across China

| Station/River | Drainage area (km$^2$) | Data period | Annual runoff per area (l/s.km$^2$) | | | Annual sediment yield per area (t/km$^2$.yr) | | |
|---|---|---|---|---|---|---|---|---|
| | | | Long term ave. $Q_{RI}$ | Recent 10-yrs ave. $Q_{RI10}$ | $Q_{RI10}/Q_{RI}$ | Long term ave. $S_L$ | Recent 10-yrs ave. $S_{L10}$ | $S_{L10}/S_L$ |
| Harbin/Songhua R. | 389769 | 1955-2005 | 3.45 | 2.96 | 0.86 | 16.7 | 12.3 | 0.74 |
| Tieling/Liaohe R. | 120764 | 1954-2005 | 0.80 | 0.45 | 0.56 | 103.5 | 23.4 | 0.23 |
| Yanchi/Yongding R. | 43674 | 1963-2005 | 0.48 | 0.24 | 0.50 | 3.1 | 0.0 | 0.01 |
| Lijin/Yellow R. | 752032 | 1952-2005 | 1.32 | 0.46 | 0.35 | 1034.5 | 256.1 | 0.25 |
| Bengbu/Huaihe R. | 121330 | 1950-2005 | 6.99 | 6.47 | 0.93 | 75.5 | 42.8 | 0.57 |
| Datong/Yangtze R. | 1705383 | 1950-2005 | 16.80 | 17.56 | 1.05 | 242.7 | 164.7 | 0.68 |
| Lanxi/Qiantang R. | 18233 | 1977-2005 | 28.75 | 28.16 | 0.98 | 108.7 | 87.9 | 0.81 |
| Zhuqi/Minjiang R. | 54500 | 1950-2005 | 31.13 | 32.09 | 1.03 | 110.1 | 42.9 | 0.39 |
| Boluo/Dongjiang R. | 25325 | 1954-2005 | 28.89 | 27.64 | 0.96 | 97.0 | 57.6 | 0.59 |
| Gaoyao/Xijiang R. | 351535 | 1957-2005 | 19.86 | 20.40 | 1.03 | 193.4 | 134.1 | 0.69 |

Precipitation depth is one important factor affecting the magnitude of runoff and thus the sediment transport by a river system. For this study, long term annual precipitation depths from some climate stations in the associated watersheds have been assessed. As shown in Table 2, the data series at most climate stations are more than 50 years long. Table 2 gives the average long term and short term (in the past 10 years) annual precipitation depths. Table 2 also gives ratios of the average precipitation depths in the past 10 years to those of long term values for studied climate stations.

## 3 Results

In this paper, the annual runoff per area (annual average discharge per unit area, l/s.km$^2$) and the annual sediment yield per area (annual suspended sediment flux per unit area, t/km$^2$.yr) have been used to compare the changes in runoff and sediment flux associated with the 10 large rivers in China. To assess the changes in runoff and sediment flux for each river, trend analysis for the annual runoff and the annual sediment yield has been conducted. Additionally, the dependence of the annual sediment yield on the annual runoff has been explored for each river.

Conceptually, the changes of annual sediment transport depend mainly on the runoff pattern and the erodibility of a watershed. Precipitation depth is one important factor affecting the magnitude of the annual runoff. On the other hand, annual sediment transport in a river may be significantly changed by the impact of human activities such as water and soil conservation programs, sediment trapping dams (mainly used in the Yellow River watershed), as well as reservoir construction and hydropower development in the watershed.

Based on trend analysis of the time series of the annual runoff and the sediment yield for these 10 rivers, the changes in both annual runoff and sediment transport were found to vary from river to river. These changes depended on the nature and magnitude of human impact, including changes in vegetation cover and the installation/operation of hydraulic structures on the rivers. Overall, the annual sediment yield in all rivers decreased over time but the annual runoff showed no evidence of a significant decrease for some rivers. Based on the changes in annual runoff and sediment yield shown in Fig. 2, the 10 large rivers in China can be subdivided into the following three groups: 1) rivers with decreasing sediment transport and stable runoff; 2) rivers with both decreasing sediment transport and decreasing runoff and 3) rivers with greatly reduced sediment transport and decreasing runoff.

**Table 2** Long term and recent 10 year average annual precipitation depth at climate stations in the associated watersheds

| Rivers | Climate stations | Data period | Long term ave. $P_L$ (mm) | Recent 10-yrs ave. $P_{10}$ (mm) | $P_{10}/ P_L$ |
|---|---|---|---|---|---|
| Songhua | Nenjiang | 1951 - 2006 | 482.5 | 427.7 | 0.89 |
| Songhua | Mudanjiang | 1951 - 2006 | 545.9 | 515.2 | 0.94 |
| Liaohe | Chifeng | 1951 - 2006 | 367.0 | 357.8 | 0.97 |
| Liaohe | Siping | 1951 - 2006 | 635.6 | 582.8 | 0.92 |
| Yongding | Huailai | 1954 - 2006 | 390.6 | 352.6 | 0.90 |
| Yellow | Dari | 1956 - 2006 | 542.81 | 543.16 | 1.00 |
| Yellow | Lanzhou | 1951 - 2005 | 313.84 | 289.46 | 0.92 |
| Yellow | Yulin | 1951 - 2006 | 396.93 | 373.13 | 0.94 |
| Yellow | Zhengzhou | 1951 - 2006 | 639.88 | 656.02 | 1.03 |
| Huaihe | Zhumadian | 1958 - 2006 | 975.2 | 1018.9 | 1.04 |
| Huaihe | Bozhou | 1953 - 2006 | 808.4 | 886.6 | 1.10 |
| Yangtze | Tuotuohe | 1957 - 2006 | 279.4 | 309.7 | 1.11 |
| Yangtze | Qumalai | 1957 - 2006 | 402.5 | 401.0 | 1.00 |
| Yangtze | Yushu | 1953 - 2006 | 480.6 | 476.3 | 0.99 |
| Yangtze | Ganzi | 1951 - 2006 | 645.3 | 657.3 | 1.02 |
| Yangtze | Xichang | 1951 - 2006 | 1020.0 | 1085.4 | 1.06 |
| Yangtze | Chengdu | 1951 - 2003 | 904.4 | 815.1 | 0.90 |
| Yangtze | Shapingba | 1951 - 2006 | 1087.3 | 1103.5 | 1.01 |
| Yangtze | Youyang | 1951 - 2006 | 1350.6 | 1355.7 | 1.00 |
| Yangtze | Changde | 1951 - 2006 | 1350.0 | 1453.3 | 1.08 |
| Yangtze | Zijiang | 1951 - 2006 | 1264.5 | 1272.0 | 1.01 |
| Yangtze | Lingling | 1952 - 2006 | 1431.1 | 1502.7 | 1.05 |
| Yangtze | Ji'an | 1952 - 2006 | 1506.4 | 1603.6 | 1.06 |
| Yangtze | Nanchang | 1951 - 2006 | 1612.6 | 1744.8 | 1.08 |
| Yangtze | Yichang | 1952 - 2006 | 1154.4 | 1121.1 | 0.97 |
| Yangtze | Wuhan | 1951 - 2006 | 1263.6 | 1277.4 | 1.01 |
| Yangtze | Nanjing | 1951 - 2006 | 1051.7 | 1093.0 | 1.04 |
| Qiantang | Quzhou | 1951 - 2006 | 1669.4 | 1653.8 | 0.99 |
| Minjiang | Yong'an | 1951 - 2006 | 1565.0 | 1600.1 | 1.02 |
| Dongjiang | Heyuan | 1953 - 2006 | 1939.6 | 1920.6 | 0.99 |
| Xijiang | Wuzhou | 1951 - 2006 | 1481.0 | 1457.4 | 0.98 |

### 3.1 Rivers with decreasing sediment transport and stable runoff

As shown in Fig. 2, for all southern rivers (including the Huaihe, Yangtze, Qiantang, Minjiang, Dongjiang and Xijiang rivers) and the Songhua River which is located in the largest national forest region in the far north of China, the annual runoff is essentially stationary. As indicated by the trend functions $Q_{RI}(T)$, the trend coefficients are small. However, the trend lines for the annual sediment yield for the southern rivers are all characterized by a clear downward trend.

### 3.1.1 The Huaihe River at the Bengbu station

The annual sediment load of the Huaihe River shows an overall tendency to decreases through time, although the runoff record provides evidence of only a very slight decrease. As shown in Fig. 2, a significant increase in the annual sediment yield occurred between 1960 and 1965. This high value is likely to reflect the “conversion of forest to farmland” process that occurred during this period. This resulted in increased soil erosion and an increased annual sediment yield for the Huaihe River. As shown in Fig. 2, there is a good linear relationship between the cumulative annual runoff and the cumulative annual sediment yield before 1978. In the 1980’s, both annual runoff and sediment transport were fairly high but they decreased significantly in the 1990’s. By the end of the1990’s, annual runoff and sediment transport had increased again. The changes of annual runoff during this period were closely related to the variation of annual precipitation over the Huaihe River watershed (Wang and Wang, 2002).

As shown in Fig. 3, the annual precipitation depth in the Huaihe River watershed has slightly increased. After 1975 and especially after 1990, several water and soil conservation programs, which covered an area of $10.44 \times 10^3$ km$^2$, were established in the Huaihe River watershed. This resulted in a significant decrease in the annual sediment yield. The long term average annual runoff per area for the Huaihe River is 6.99

l/s.km$^2$ and this has decreased to 6.47 l/s.km$^2$ in the past 10 years. The annual sediment yield of the Huaihe River is fairly low. The long term average annual sediment yield per area of the Huaihe River is only 75.5 t/km$^2$.yr. However, in the past 10 years, the average annual sediment yield per area of the Huaihe River was reduced to 42.8 t/km$^2$.yr. The annual sediment yield is closely dependent on the annual runoff.

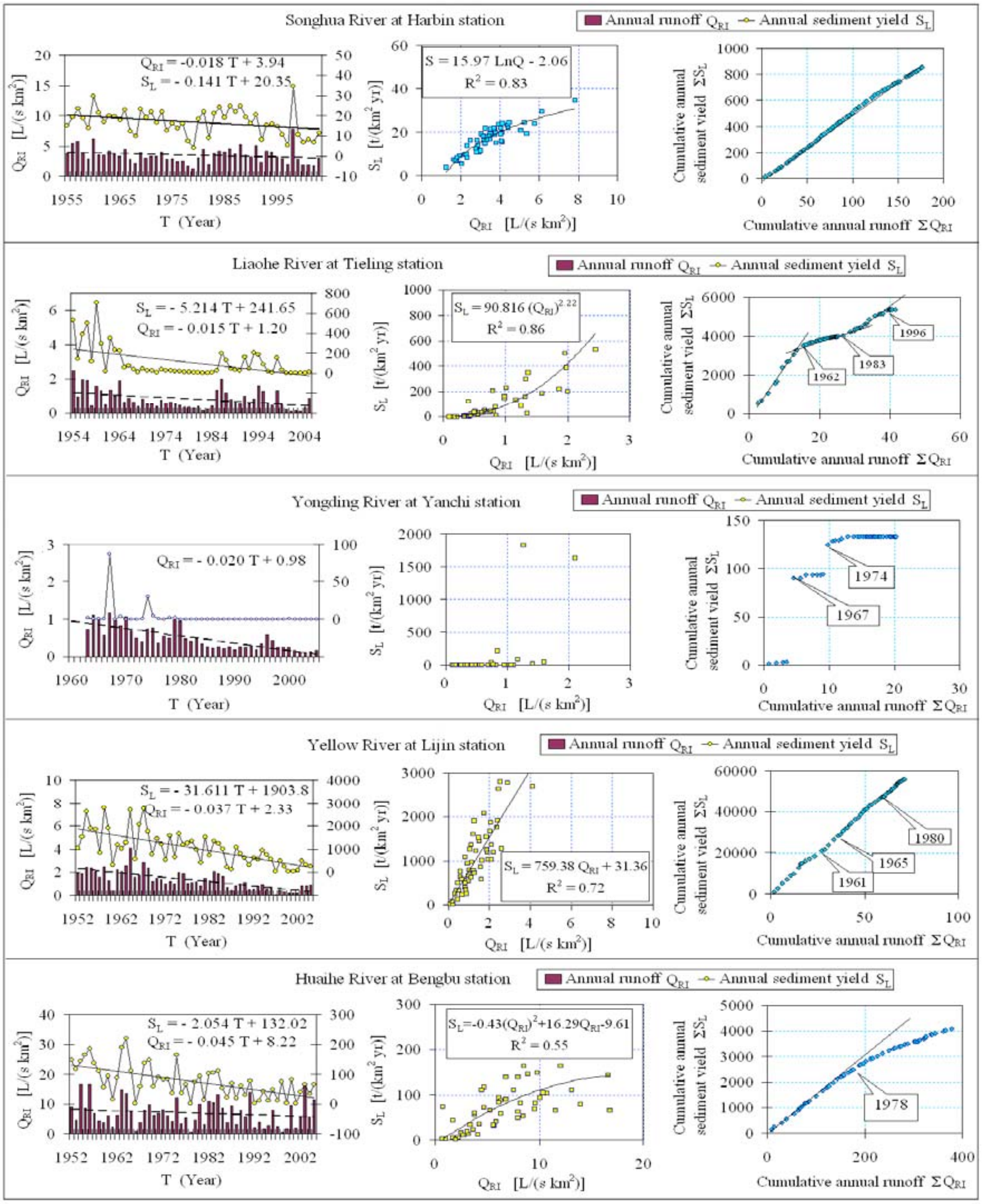


**Fig. 2** Changes in annual runoff and sediment yield

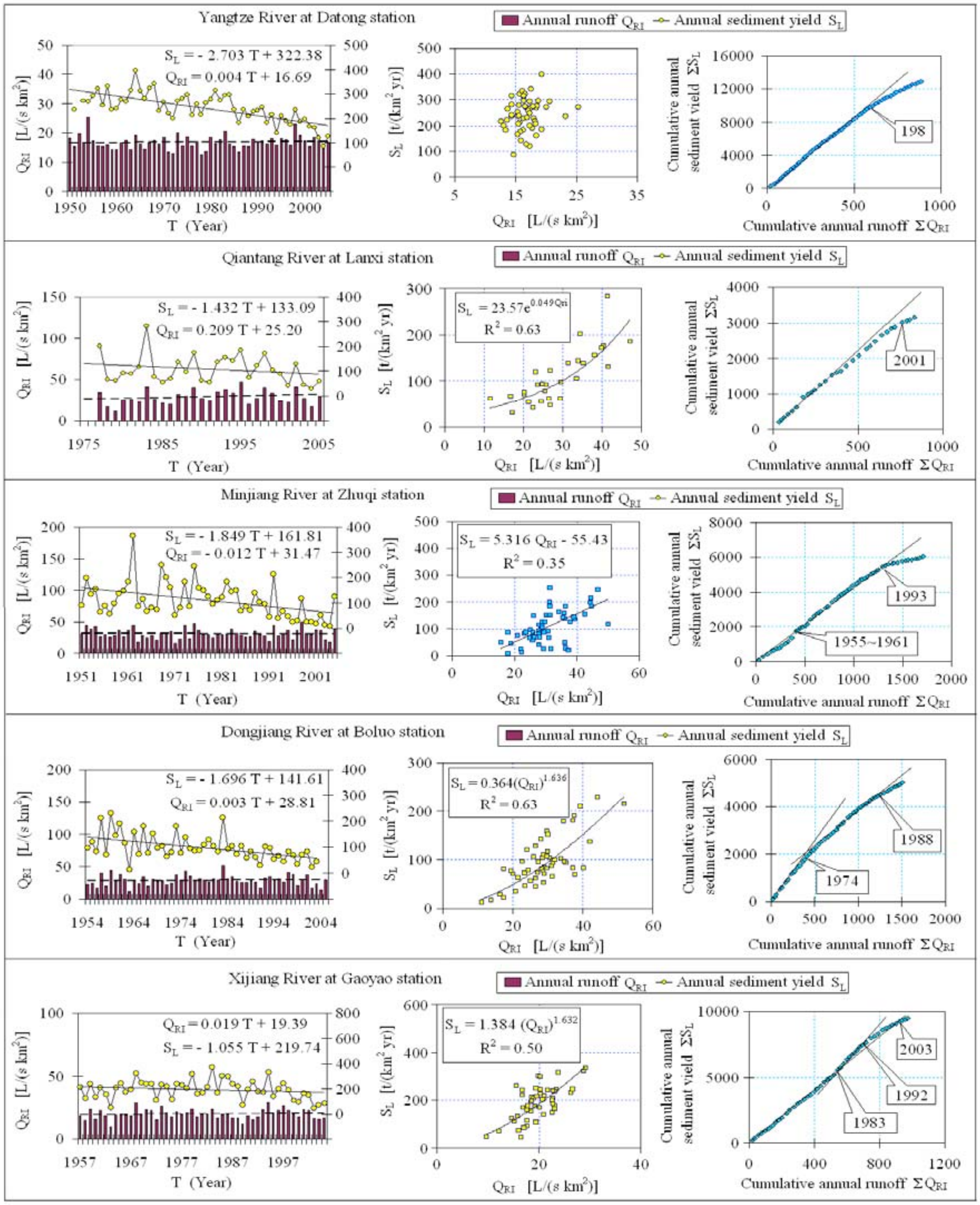


**Fig. 2** Changes in annual runoff and sediment yield (cont.)

### 3.1.2 The Yangtze River at the Datong station

The Yangtze River is the largest river in China. The long term average (1950-2005) annual runoff and sediment transport at Datong are $903 \times 10^9$ m$^3$ and $414 \times 10^6$ t. Table 1 shows the long term average annual runoff per area for the Yangtze River is 16.8 l/s.km$^2$ but this increased to 17.56 l/s.km$^2$ in the past 10 years. It can be seen in Fig. 3 that the annual precipitation depth in the Yangtze River watershed has a tendency of slightly increase. Table 2 contains annual precipitation depths of 16 climate stations in the Yangtze

River watershed. One can conclude that the annual precipitation depths at most climate stations in the Yangtze River watershed generally increased in the past 10 year. This is likely to be responsible for the slight increase in the annual runoff. This result confirms the finding of Yang *et al* (2005) based on the discharge records between 1950 and 2004 at the Datong station on the Yangtze River, although Yang *et al* (2004, 2005) claimed that the discharge at the Datong station should have had a significant decreasing trend from 1865 to 2004 based on the analysis on the regression relationship between the discharge at the Datong station and those at the upstream Hankou station.

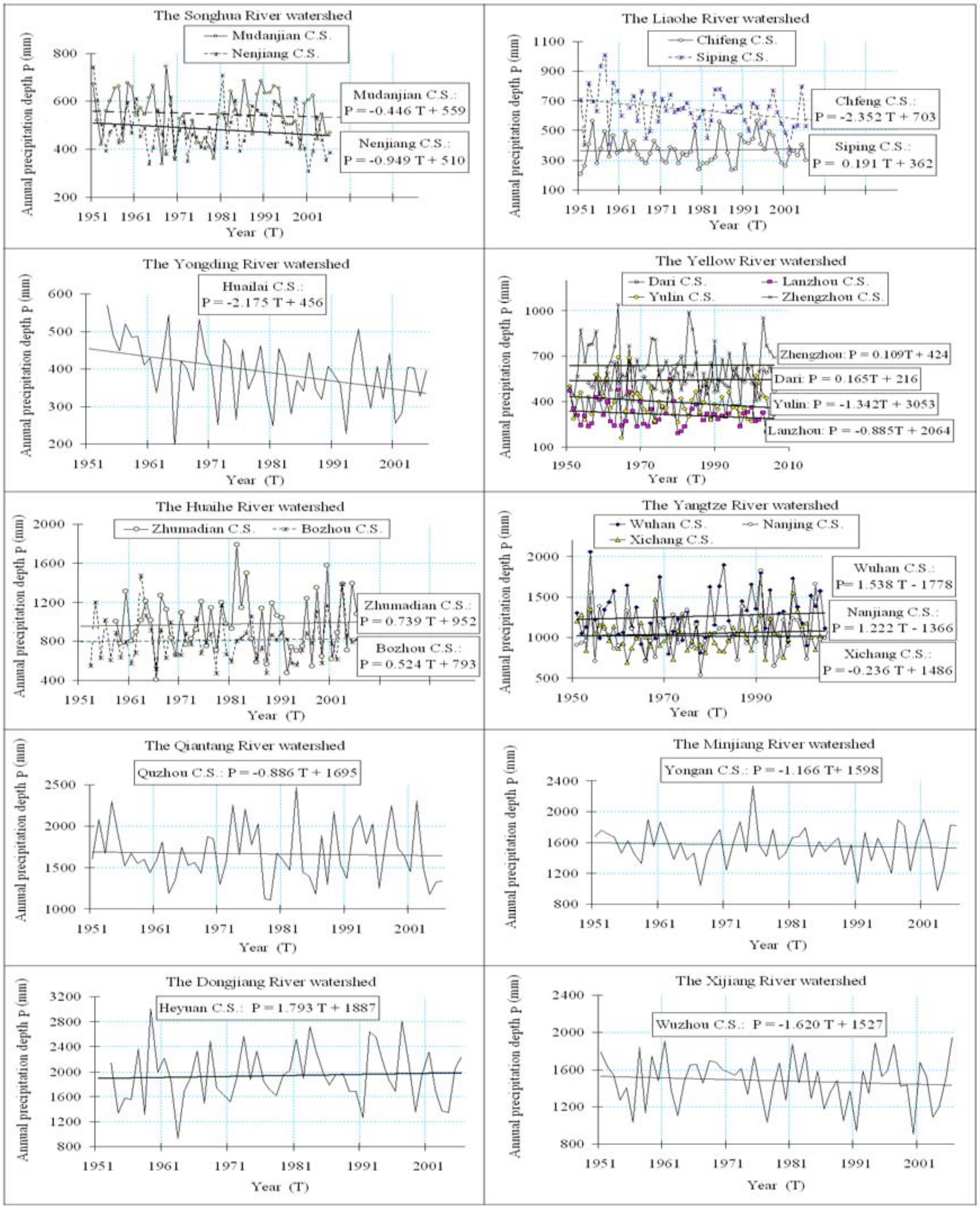


**Fig. 3** Annual precipitation depth of the climate stations in the associated watershed

The annual sediment yield per area of the Yangtze River is fairly high with a long term average value of 242.7 t/km$^2$.yr. However, in the past 10 years, the average annual sediment yield per area of the Yangtze River has dropped to 164.70 t/km$^2$.yr. As shown in Fig. 2, a significant increase in the annual sediment yield occurred between 1960 and 1967, during the "conversion of forest to farmland" process through clear-cutting. In 1967, the Danjiangkou Reservoir, which is located on the Hanjiang River - one of the largest tributaries of the Yangtze River, was completed and put into operation. The annual sediment yield of the Yangtze River therefore decreased after 1967. However, the Yangtze River experienced an increase in its annual sediment yield between 1977 and 1985. The high annual sediment yield of the Yangtze River during this period probably reflects the construction of the second largest hydropower project in China - the Gezhouba Hydropower Plant - between 1974 and 1988 and the high annual runoff depth during this period. After the mid 1980's the annual sediment yield at the Datong station gradually decreased. The decrease in sediment transport by the Yangtze River during this period may be related to: (a) the impact of water and soil conservation programs (the Project of Yangtze Upstream Water and Soil Conservation) which begun in 1988 (Xu, *et al*, 2006); (b) the installation of several reservoirs and hydro-power stations on the Yangtze River system and (c) increased sand mining ($50 \times 10^6$ t/year from 1990 to 2002) within the Yangtze River watershed. In 2003, the Three Gorges Reservoir on the Yangtze River, the largest hydropower project in the world, started to impound water. In 2003–2004, sediment loads at Yichang declined by 164 million tons relative to 2002. As pointed out by Xu *et al* (2006), by 2004, at Yichang and Datong stations, the Yangtze River transported only 12 percent and 33 percent, respectively, of its 1950–1986 loads. More than half of this decrease (65% and 60%) occurred prior to the Three Gorges Dam impoundment. Overall, the long term annual runoff of the Yangtze River shows a slightly increasing trend over the period of record. However, over the same period, the long term annual sediment yield shows a clear reduction through time. As shown in Fig. 2, there was a clear break in the trend of the plot of cumulative annual sediment yield versus cumulative annual runoff in 1989 and 2003. However, there is no clear relationship between the annual sediment yield and the runoff.

### 3.1.3 The Qiantang River at the Lanxi station

The Qiantang River watershed has a very good vegetation cover. In the past half century, significant impacts from human activity have not been observed in this watershed. As shown in Fig. 2, the annual runoff of the Qiantang River experiences a slightly upward trend, although the annual precipitation depth in the Qiantang River watershed has a slight decrease, as shown in Fig. 3. However, the annual sediment yield shows a tendency to decrease slightly with time. As indicated in Table 1, the long term average annual runoff per area of the Qiantang River is 28.75 l/s.km$^2$ which is fairly high and this has decreased to 28.16 l/s.km$^2$ in the past 10 years. The long term average annual sediment yield per area of the Qiantang River is 108.7 t/km$^2$.yr and this has decreased to 87.9 t/km$^2$.yr in the past 10 years. There is a well-defined relationship between the annual sediment yield and the annual runoff.

### 3.1.4 The Minjiang River at the Zhuqi station

As the trend lines in Fig. 2 show, the long term annual runoff of the Minjiang River is essentially stationary, although the annual precipitation depth in the Minjiang River watershed undergoes a slightly decrease as shown in Fig. 3. As Table 2 indicates, the annual precipitation depth in the past 10 years has had a slight upward trend. However, the long term annual sediment yield decreased with time. After 1993, there was a clear decrease in sediment transport which can be attributed to the construction of the Shuikou Reservoir in the headwater region. Additionally, extensive sand mining (about 1 M t/yr) in recent years has also affected the annual sediment yield of the Minjiang River. The relationship between the annual sediment yield and the annual runoff for this river is weak. As indicated by the plot of the cumulative annual sediment yield, sediment transport of the Minjinag River was fairly low from 1955 to 1961 and after 1993. The long term average annual runoff per area of the Minjiang River is 31.13 l/s.km$^2$, which is the highest of these 10 rivers and it increased to 32.09 l/s.km$^2$ over the past 10 years. The long term average annual sediment yield per area of the Minjiang River is 110.1 t/km$^2$.yr and this has decreased significantly to 42.9 t/km$^2$.yr over the past 10 years.

### 3.1.5 The Dongjiang River at the Boluo station

The annual precipitation depth in the Dongjiang River watershed has a slightly increasing trend as shown in Fig. 3. However, as indicated in Fig. 2, the annual sediment yield in the Dongjiang River has exhibited a noticeable decrease since 1973. The Fengshuba Reservoir built in 1973, the expansion of the Baipen reservoir and the installation/operation of the Bapenzhu Hydropower Station on the Dongjiang River should be responsible for this decrease in sediment transport. A well defined relationship between the annual sediment yield and the runoff is shown for this river in Fig. 2. The long term average runoff per area of the Dongjiang River is 28.89 l/s.km$^2$ and this has decreased to 27.64 l/s.km$^2$ during the past 10 years. The long term average annual sediment yield per area of the Dongjiang River is 97.0 t/km$^2$.yr and this has decreased to 57.6 t/km$^2$.yr over the past 10 years.

### 3.1.6 The Xijiang River at the Gaoyao station

As shown in Fig. 3, the annual precipitation depth in the Xijiang River watershed shows a slightly decreasing trend. Both the annual runoff and the sediment yield for this river are characterized by a quasi-stationary trend over the period of record, although the annual sediment yield fluctuates dramatically at times. As shown in Fig. 2, an obvious increase in the annual sediment yield occurred in the early 1980's. The construction of several reservoirs in this watershed is likely to be responsible for this increase. In 1992, the Yantan reservoir on the Xijiang River was completed and was put into operation. This resulted in a clear decrease in the sediment load of this river. Since 2003, the Longtan Reservoir has been under construction and this has resulted in a further decrease in sediment transport. The long term average annual runoff per area of the Xijiang River is 19.86 l/s.km$^2$, and this increased to 20.40 l/s.km$^2$ over the past 10 years. The long term average annual sediment yield per area of the Xijiang River is 193.4 t/km$^2$.yr and this has decreased to 134.1 t/km$^2$.yr during the past 10 years. There is a well-defined relationship between the annual sediment yield and the runoff for this river.

### 3.1.7 The Songhua River at the Harbin station

The Songhua River is located in the far north of China. However, since the majority of the Songhua River watershed is covered by dense forest and human impact is limited, there is no clear trend in the average annual runoff and the annual sediment yield for this river. However, both show some evidence of a slight downward trend, as shown in Fig. 2. The slight decrease in the annual precipitation depth in the Songhua River watershed as shown in Fig. 3 could be responsible for this. Although 2 hydropower plants (Baishan and Hongshi hydropower plants) were installed between 1981 and 1989 on the Second Songhua River – a major tributary of the Songhua River, no significant impacts have been observed on the annual sediment yield and annual runoff of the main river. The long term average annual runoff per area of the Songhua River is 3.45 l/s.km$^2$, this has decreased to 2.96 l/s.km$^2$ over the past 10 years. The long term average annual sediment yield per area of the Songhua River is 16.7 t/km$^2$.yr and this has decreased to 12.3 t/km$^2$.yr for the past 10 years. There is a strong relationship between the annual sediment yield and the annual runoff for this river. For instance, the high annual runoff in 1960, 1988, and 1998, resulted in a high sediment yield for these years.

### 3.2 Rivers with greatly reduced sediment transport and decreasing runoff - The Yongding River at the Yanchi station

One of the northern rivers included in the study, the Yongding River, is characterized by unique changes in runoff and sediment transport. The Yongding River is a sandy river, which is a main branch of the Haihe River system. As shown in Fig. 2, the annual sediment yield reduced markedly and approached zero between1968 and 1973 as well as after 1976. Overall, the annual runoff decreased significantly, especially after 1980. The long term average annual runoff per area of the Yongding River is only 0.48 l/s.km$^2$ which is very low and this has decreased further to only 0.24 l/s.km$^2$ over the past 10 years. The clear decrease in the annual precipitation depth in the Yongding River watershed as shown in Fig. 3 may be responsible for this. The long term average annual sediment yield per area of the Yongding River is only 3.1 t/km$^2$.yr which again is extremely low and this has decreased to about 0 t/km$^2$.yr over the past 10 years. Although the annual sediment yield remained very low and close to zero over most of the period of record, there were occasional peaks. In 1967, for example, the annual sediment yield per area was much higher and this can be accounted for by the releasing of impounded water from the Guanting Reservoir during a flood period in August 1967. In July 1974, high flows were again released during the high flood season to flush out deposited sediment from the Guanting Reservoir and this resulted in a high annual sediment yield. The Yongding River is a sandy river with serious soil erosion in its upstream reaches. The average annual runoff per area at Yanchi between 1952 and 1954 was 1.26 - 2.1 l/s.km$^2$ and the annual sediment yield per area was as high as 1834 and 1632 t/km$^2$.yr in 1952 and 1954 respectively (not shown in Fig. 2). However, the Guanting Reservoir, completed in 1954, intercepted most of the runoff and large quantities of sediment from upstream. The water discharge and sediment load of the river are now totally different from those under natural conditions as they are strongly influenced by human activities such as reservoir construction and water diversion.

### 3.3 Rivers with both decreasing sediment transport and decreasing runoff

For the northern rivers (including the Liaohe and the Yellow rivers), the trend lines presented in Fig. 2 show that both the annual runoff and sediment yield decreased markedly over the period of record.

#### 3.3.1 The Liaohe River at the Tieling station

Long term precipitation records at two climate stations in the Liaohe River watershed have been assessed. Annual precipitation depths in this watershed have a slightly downward trend. Overall, both average annual runoff and sediment transport were fairly high before 1964. Between 1964 and 1984, both the average annual runoff and sediment yield were fairly low. The annual sediment yield was quasi stationary during this period. Between 1985 and 1998, both average annual runoff and sediment transport showed significant fluctuations. After 1999, both average annual runoff and sediment transport were again fairly low, the annual sediment yield approaches a constant and the annual runoff does not change much during this period. As observed in Fig. 2, clear changes in the annual sediment yield occurred in 1962, 1983 and 1996. From the late 1960’s to the early 1980’s and after the late 1990’s, the Liaohe River watershed received less precipitation. The annual runoff and sediment yield in the Liaohe River are also affected by the impact of the Hongshan Reservoir. The Hongshan Reservoir started to impound water in 1962 and it trapped most of the sediment carried by the Laoha River – a sandy branch river of the Liaohe River. Therefore, the annual sediment yield decreased significantly since 1964. In 1985, the dead storage capacity of the Hongshan Reservoir was completely filled. From 1962 to 1999, the decrease in the storage capacity of this reservoir was $941\times10^6$ m$^3$, which accounts for 36.8% of the total storage capacity of this reservoir (Zhou and Zhaolun, 2005). The long term average annual runoff per area of the Liaohe River is 0.80 l/s.km$^2$ which is fairly low and this has decreased to 0.45 l/s.km$^2$ over the past 10 years. The long term average annual sediment yield per area of the Liaohe River is 103.5 t/km$^2$.yr and this decreased dramatically to a value of 23.4 t/km$^2$.yr for the past 10 years. The relationship between the annual sediment yield and the annual runoff is very strong.

#### 3.3.2 The Yellow River at the Lijin station

The Yellow River is well-known for its very high sediment load. Between 1952 and 2005, at the Lijin Station on the Lower Reach of the Yellow River, the average annual sediment transport was $0.78 \times 10^9$ t, with an average annual sediment concentration of 24.8 kg/m$^3$ (WMR, 2005). The Yellow River watershed is located in a semi-arid region. Based on the long term (about 50 years long) precipitation records from 77 climate stations in the Yellow River watershed, Xu and Zhang (2006) reported that there was no clear change in the annual precipitation over the sub-watershed of the Upper Reach of the Yellow River. For this study, long term data series of four climate stations were assessed. Annual precipitation depths in the headwater region and the Lower Reach sub-watershed have a slightly downward trend. However, a clear downward trend of annual precipitation depth in the Middle Reach sub-watershed of the Yellow River is observed, as shown in Fig. 3.

The main methodologies used for water and soil conservation in the Yellow River watershed include contour cultivation, enlargement of the vegetated area and construction of small sediment trapping dams in the easily eroded valleys. Before 1960, there was no hydropower development on the Yellow River. Additionally, no water and soil conservation programs had been conducted in the Yellow River watershed before 1960. Starting in the late 1960’s, extensive water and soil conservation programs have been carried out in the Yellow River watershed. As reported by Gu (1994, 2002), the area with water and soil conservation programs was only 8.0 thousand km$^2$ prior to 1959. This area increased to 15.8, 36.0, 79.2 and 171.3 thousands km$^2$ by 1969, 1979, 1989 and 1999 respectively. By 2005, 171 large reservoirs/hydropower stations had been constructed in the Yellow River watershed (WMR, 2006).

The Sanmenxia Reservoir exerts a very important influence on sediment transport in the Lower Reach of the Yellow River. As demonstrated by Fig. 2, the annual sediment yield at the Lijin Station on the Yellow River shows three clearly marked decreases in 1961, 1980 and 2000. Before 1960, the Yellow River was under essentially natural conditions. The sediment transport was high and the annual runoff was low. From 1960 to 1964, the Sanmenxia Reservoir was in operation for impounding water and trapping sediment. Thus, annual sediment transport downstream at the Lijin Station decreased dramatically. From 1965 to 1973, the operating mode of the Sanmenxia Reservoir was changed to provide flood detention and sediment flushing. Thus, both annual sediment transport and runoff at the Lijin Station increased during this period. From 1974 to 1985, the operating mode of the Sanmenxia Reservoir was further modified to provide for "storing clear water during low flow seasons and releasing turbid water during flood periods". Since 1980, water consumption by agriculture and industry has increased significantly. The annual water consumption by agriculture in the whole basin increased to 27.4 billion m$^3$ in 1980s from 12.5 billion m$^3$ in 1950s (Gu, 1994). Additionally, many soil and water conservation projects have been completed in the Loess Plateau in the Middle Reach of the Yellow River. Therefore, both annual sediment transport and runoff at the Lijin Station on the Lower Reach of the Yellow River decreased significantly after 1980. This trend in the annual runoff and sediment yield reflects the impact of reservoir operation and the increase in water consumption in the Middle and Upper reaches of the Yellow River. The annual runoff at the Lijin Station increased after 2002. This increase was caused by the operation of the Xiaolangdi Reservoir which is used to create high flows for scouring/dredging the channel of the Lower Reach. However, as shown by the trend lines in Fig. 2, both the annual runoff and sediment yield of the Yellow River demonstrate a clear downward trend overall. The long term average annual runoff per area of the Yellow River at the Lijin Station is only 1.32 l/s.km$^2$ and this has decreased further to 0.46 l/s.km$^2$ over the past 10 years. The long term average annual sediment yield per area of the Yellow River at the Lijin Station is 1034.5 t/km$^2$.yr, which is extremely high but this has decreased to 256.1 t/km$^2$.yr during the past 10 years. The relationship between the annual sediment yield and the annual runoff is very strong for this river.

## 4 Conclusions

In this paper, changes in annual runoff and sediment transport have been assessed by using the long term observation data from 10 gauging stations on 10 large rivers across China. It has been shown that annual sediment transport has generally been characterized by a decreasing trend over the past half century. Based on the changes in the annual runoff and the sediment yield, the large rivers in China included in this study can be classified into the following three groups: 1) rivers with decreasing sediment transport and stable runoff; 2) rivers with both decreasing sediment transport and decreasing runoff and 3) rivers with greatly reduced sediment transport and decreasing runoff.

From a long-term point of view, for all the southern rivers, there has been little change in annual runoff but a dramatic decrease in the annual sediment yield. Human activities, such as regulation of the flow by reservoirs, have had an impact on most southern rivers. In the northern rivers, however, both annual sediment transport and runoff show a tendency to reduce. The Yongding River is a sandy river which forms a main branch of the Haihe River. The annual sediment yield surprisingly approaches zero between 1968 and 1973 as well as after 1976 and the annual runoff decreases significantly, especially after 1980.

From a short-term perspective, the annual sediment yield of most rivers included in the study decreased significantly. In some northern rivers, the ratio of the short-term annual sediment yield to the long-term annual sediment yield is less than 50%, for example, 1% for the Yongding River, 23% for the Liaohe River and 25% for the Yellow River.

The results presented clearly demonstrate the impact of human activity on changes in runoff and sediment transport. In the Lower Reach of the Yellow River, the changes in runoff and sediment transport have been dramatically influenced by human activities, such as reservoir construction and the mode of operation of the reservoir, the increase in water consumptions and the introduction of soil and water conservation programs in the sub-watershed of the Middle and Lower reaches of the Yellow River. The long term average annual sediment yield per area at the Lijin Station on the Lower Reach of the Yellow River is 1034.5 t/km$^2$.yr which is extremely high. Due to the impact of human activity, including the operation of hydropower stations/reservoirs on the Yellow River, construction of sediment trapping dams, as well as soil conservation programs in the Yellow River watershed, the average annual sediment yield per area has decreased significantly over the past 10 years, to only 256.1 t/km$^2$.yr.

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