

# Anthropogenic impacts on suspended sediment load in the Upper Yangtze river

Jie Wei · Xiubin He · Yuhai Bao

Received: 16 August 2010 / Accepted: 7 April 2011 / Published online: 22 April 2011  
© Springer-Verlag 2011

**Abstract** Climate change and human disturbance drive catchment erosion and increase riverine sediment load sensitively in small and medium-sized watersheds. This is not always true in large basins, where aggregation and buffering effects have dampen the ability to determine the driving forces of sedimentation. Even though there are significant responses to sedimentation in large river basins, it is difficult to get a precise quantitative assessment of specific drivers. This paper develops a methodology to identify driving forces that change suspended sediment load in the Upper Yangtze river. Annual runoff and sediment load data from 1954 to 2005 at the Yichang gauging station in the Upper Yangtze basin, daily precipitation data from 60 meteorological stations, and survey data on reservoir sediment were collected for the study. Sediment load/rainfall erosivity ( $S/R$ ), is a new proxy indicator introduced to reflect human activities. Since the mid-1980s,  $S/R$  in the Upper Yangtze has dramatically declined from 0.21 to 0.03 ( $\times 10^{10} \text{ t ha h MJ}^{-1} \text{ mm}^{-1}$ ), indicating that human activity has played a key role in the decline of the suspended sediment load. Before the mid-1980s, a higher average  $S/R$  is attributed to large-scale deforestation and land reclamation. A significant sediment decrease occurred from 1959 to 1961 during an extreme drought condition, and an increase in sedimentation in 1998 coincided with an extreme flood event, which was well recorded in the  $S/R$  curve. This indicates that the  $S/R$  proxy is able to

distinguish anthropogenic from climate impacts on suspended sediment load, but is not necessarily indicative in extreme climate events. In addition, typical drivers of riverine sediment load variation including soil conservation projects, reservoirs construction, and land use/cover change are discussed.

**Keywords** Anthropogenic impact · Catchment erosion · Rainfall erosivity · Riverine sediment · The Upper Yangtze river

## Introduction

Sediment load represents an important measure of soil erosion, transportation, deposition, and various intensities of human activities in river basins (Douglas 1967; Lane et al. 1997; Syvitski et al. 2005; Lesschen et al. 2007). Within small and medium-sized catchments, the riverine sediment load is sensitive to catchment erosion in the context of climatic change and human intervention. Walling and Fang (2003) and Walling (2006) demonstrate the response of sediment flux to various anthropogenic activities in small and mid-sized catchments. For example, the increased sediment load in the Lancang river between 1963 and 1990 is a reflection of intense land clearing and land use change during the 1970s and 1980s. On the other hand, the potential for conservation practices and management strategies reduced sedimentation of the Sanchuan river on the Chinese Loess Plateau. Studies of large basin rivers such as the Colorado (Meade and Parker 1985), Mississippi (Kesel et al. 1992), Nile (Stanley and Warne 1998), Yangtze river (Higgitt and Lu 1999; Yang et al. 2006a), and Yellow rivers (Yang et al. 1998; Xu and Cheng 2002; Wang et al. 2007) demonstrate that aggregation and

J. Wei (✉)  
Geography and Tourism College,  
Chongqing Normal University, 400047 Chongqing, China  
e-mail: wei\_jie@mails.gucas.ac.cn

X. He · Y. Bao  
Institute of Mountain Hazards and Environment,  
Chinese Academy of Sciences, 610041 Chengdu, China

buffering effects of multiple human activities complicate the process of sediment yield and delivery, and the resulting signals make it difficult to assess the main drivers of sedimentation (Walling 2006). It is critical to elucidate the specific drivers of sediment responses based on watershed-level human activities in order to provide important information for land management decision-making (Walling 2006).

Yangtze river (Changjiang), the longest river in Asia and third longest in the world, has become a worldwide concern due to the impacts of the Three Gorges Project. The reach from the headwaters to Yichang is called the Upper Yangtze river. There has been an increasing number of publications focused on the sediment load dynamics and its relation to human activities in the Yangtze Basin, especially in the Upper Reaches (e.g., Gu and Douglas 1989; Higgitt and Lu 1999; Lu and Higgitt 1998, 1999; Zhang and Wen 2004; Lu 2005; Yang et al. 2006b). With one eighth of China's population residing in the Upper Yangtze river, intense human activity has led to a high degree of land use change, which has impacted suspended sediment load in the river. In the past two decades, the sediment load has sharply decreased (Yang et al. 2002; Zhang and Wen 2004; Lu 2005). Many documents describe the decreases of sediment load in the Yangtze river as being caused by human activities, but none has elucidated the linkage between sediment load variations and the multiple potential drivers such as climate change and anthropogenic activities. On the basis of the sediment yield mechanism, long-term precipitation and sediment load, the current study has developed a proxy indicator of sediment load/rainfall erosivity (S/R) to indicate anthropogenic impacts on riverine sediment load. Two ways of anthropogenic impacts in terms of sediment yield and transportation are investigated in the Upper Yangtze basin.

### The Upper Yangtze basin

Originating in the Qinghai–Tibetan Plateau, the Yangtze river extends 6,300 km to the East China Sea with a watershed drainage of 1.8 million km<sup>2</sup> (Fig. 1). The Upper Yangtze at 4,300 km, has a total drainage area of 1 million km<sup>2</sup> and a population of 155 million. The study area extends 12 latitudes (24–36°N) and 22 longitudes (90–112°E) with an altitude range between 400 and 5,100 m. There are distinct climatic variations within the basin due to mountainous terrain. From East to West, the mean annual temperature is –4 to 18°C, with several rainy centers and a mean annual precipitation variation between 200 and 1,500 mm (Wen et al. 2002). Thirty-five percent of the basin is affected by soil erosion, which has resulted in

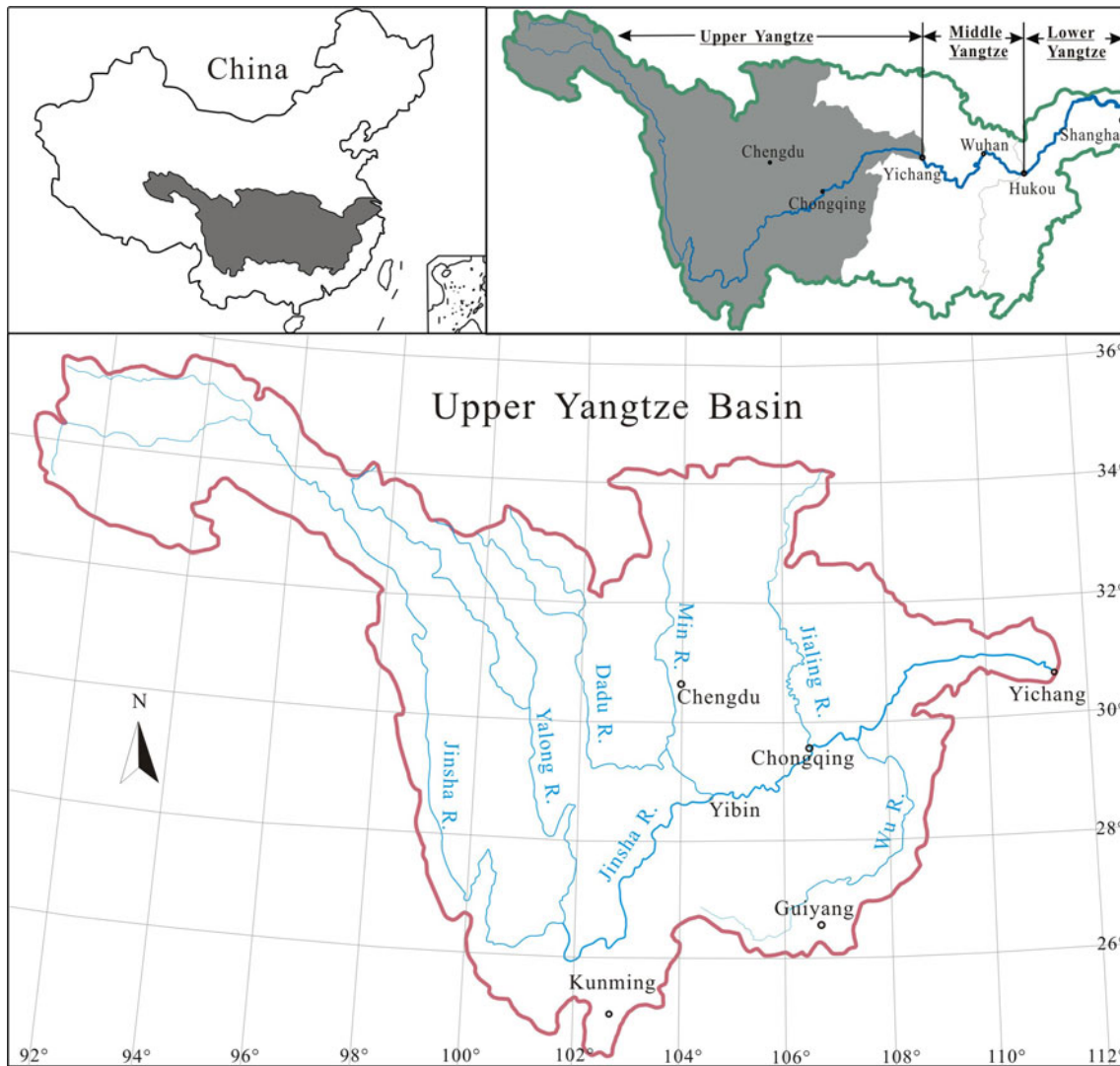
degradation of water quality and the riparian ecosystem (Wen et al. 2002). The Jinsha river comprises the uppermost 3,300 km of the river and is joined by tributaries of the Yalong, Dadu, Min, Tuo, Jialing, and Wu rivers. Due to steep gradient geomorphologic characteristics, severe rainstorm events, and rapid socio-economic development in the uppermost reaches, the Jinsha and Jialing rivers are the main source of sediment load in the Upper Yangtze river (Zhang and Wen 2004). These two rivers cover 64% of the Upper Yangtze basin area, and 77% of the sediment load. Serious erosion has captured attention from the authorities and the public. Since 1989, the Central Government has launched a number of sediment control programs in this area such as vegetation restoration, which has led to positive results in sediment load decrease.

### Methods and materials

#### Methods

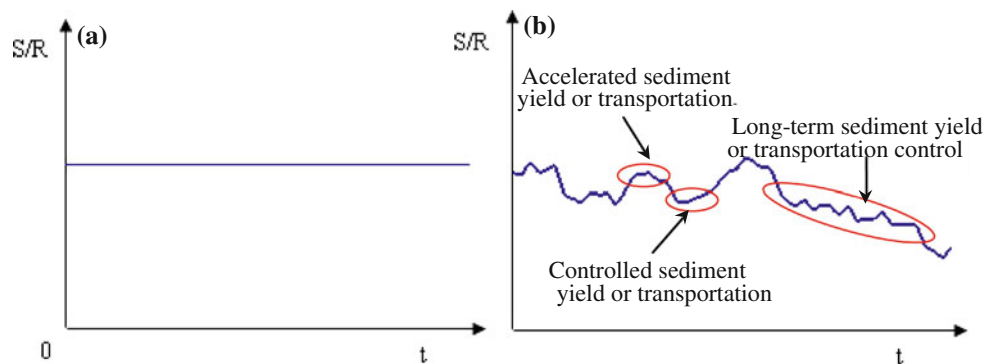
Sediment generation is mainly driven by rainfall, accelerated by human disturbances, and controlled by conservation practices (He et al. 2006). Therefore, sediment load can be expressed as a function of rainfall and human activities. Furthermore, the sediment load/rainfall erosivity (S/R) is a proxy indicator that illustrates anthropogenic impacts on sediment flux. We assume that the indicator is a constant when there is no human disturbance or activities. The increment in S/R indicates enhanced human activities, and vice versa (Fig. 2). This enables us to distinguish human impacts from the rainfall impacts.

The rainfall erosivity, R, a factor in the universal soil loss equation (USLE) and revised universal soil loss equation (RUSLE) models, is the potential ability of the rain to cause erosion (Xin et al. 2010). Wischmeier and Smith (1978) defined R as the scalar product of rainfall energy and the maximum 30-min rainfall intensity. This classic expression of R has been widely tested and used in many countries and regions (e.g., Yu and Rosewell 1996a, b; Loureiro and Coutinho 2001; Yin et al. 2007). However, this method requires difficult to obtain continuous precipitation data, and a high volume of manual processing (Yu et al. 2001; Silva 2004). Subsequently, a number of studies have established a correlation between R and precipitation variables, such as average annual precipitation (e.g., Renard and Freimund 1994), average monthly precipitation (e.g., Renard et al. 1997; Yu 1998), and average daily precipitation (e.g., Zhang 2003). In south China, R is determined by the amount of rainfall rather than its intensity; therefore, it is feasible to compute the R using the simple approach developed by Zhang (2003):



**Fig. 1** Location map of the study area

**Fig. 2** The linkage between S/R and anthropogenic impacts on the sediment load. **a** Without human activities (changes); **b** various soil conservation beneficial human activities



$$R = \sum_{i=1}^{24} M_i \tag{1}$$

$$M_i = \alpha \sum_{j=1}^k (D_{ij})^\beta \tag{2}$$

where  $R$  is the annual rainfall erosivity ( $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{a}^{-1}$ );  $M_i$  is the half-month rainfall erosivity ( $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{a}^{-1}$ );  $i$  is the sequence of the half-month and it ranges from 1 to 24 in one calendar year;  $k$  is the number of rainy days in the half-month; and  $D_{ij}$  is the

daily precipitation in the half-month (mm). According to the definition of an erosive rainfall event, rainfall  $\geq 10.0$  mm could be the baseline for catchments in Southern China (Xie et al. 2000). Parameters  $\alpha$  and  $\beta$  are regressed as:

$$\beta = 0.8363 + 18.144/P_d + 24.455/P_y \quad (3)$$

$$\alpha = 21.586\beta^{-7.1891} \quad (4)$$

where  $P_d$  is the average of those daily rainfalls greater than 10.0 mm (erosive storm) and  $P_y$  is the mean annual precipitation of those daily rainfalls greater than 10.0 mm.

In the present paper, annual rainfall erosivity for each station was calculated based on Eqs. (1–4). Annual rainfall erosivity for the Upper Yangtze basin was calculated by weighting it by its area:

$$R_r = w \times R \quad (5)$$

where  $R_r$  is the regional average annual rainfall erosivity;  $w$  is the weight expressed by the percentage of the area each station, and  $R$  is the annual rainfall erosivity of each station. The area represented by each station was calculated using the Thiessen Polygon method (Thiessen 1911).

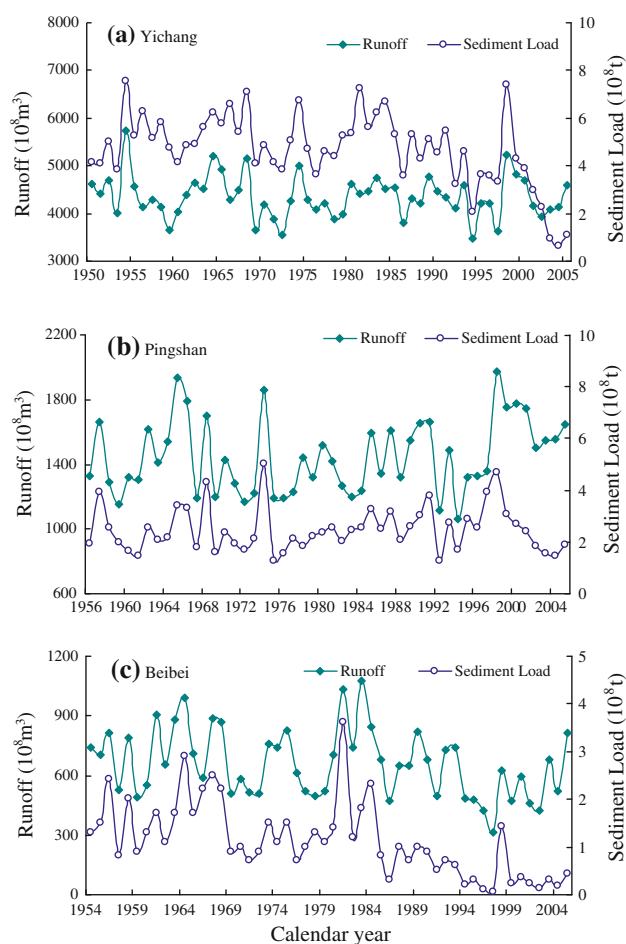
#### Data collection

The daily precipitation data in the Upper Yangtze basin was collected from the Chinese Meteorological Data Sharing Service System. The precipitation data was measured according to the Chinese national standard. We selected 60 meteorological stations that provided a series of data from 1954 to 2005, except for the Hanyuan station which was missing 2001 to 2005 data that was collected from the local administrative authority. Annual suspended sediment load and water discharge for the upper reaches was monitored by the Yichang hydrological station, the Jinsha river data was collected from the Pingshan hydrological station, the Min river data from the Gaochang station, the Jialing river was obtained from the Beibei station, and Wu river from the Wulong station, respectively. This sediment load and water discharge monitoring data (1954–2005) were provided by Yangtze Water Conservancy Committee.

## Results and discussion

### Sediment load and rainfall erosivity in the Upper Yangtze river

As shown in Fig. 1, the Yichang hydrological observation station is the virtual end point of the Upper Yangtze reach; therefore, the water discharge and sediment load data is



**Fig. 3** Variations in annual runoff and sediment load of hydrological observation stations of Yichang, Pingshan, and Beibei

assumed to represent the water discharge and sediment load in the entire Upper Yangtze basin. The Jinsha and Jialing rivers are regarded as the first two large tributaries in the upper reaches in terms of sediment yield. The Jinsha river has a drainage area of  $48.51 \times 10^8$  km<sup>2</sup>, a mean annual water discharge of  $1,446 \times 10^8$  m<sup>3</sup> and a mean sediment load of  $2.49 \times 10^8$  t, which accounts for 33.1 and 53.0% of that in the Upper Yangtze river, as recorded at the Yichang gauging station. The Jialing river drains a catchment of  $15.61 \times 10^8$  km<sup>2</sup> and has a mean annual water discharge of  $657 \times 10^8$  m<sup>3</sup> and a mean sediment load of  $1.11 \times 10^8$  t, which accounts for 15.1 and 23.6% of the Upper Yangtze river. The sum of mean annual water discharge and sediment of the Jinsha and Jialing rivers accounts for 48.2 and 76.6% of the Upper Yangtze river, which demonstrates that sources of runoff and sediment of the Yichang station varied.

The water discharge of Yichang gauging station changed slightly but sediment declined notably during the calendar year (Fig. 3a). After the mid-1980s, the sediment load has gradually been decreasing. At the Pingshan station

**Table 1** Spearman rank-order analysis for water discharge and sediment load in the Upper Yangtze river

Station	<i>N</i>	<i>c</i>	<i>r</i> <sub>runoff</sub>	Degree of water discharge variation	<i>r</i> <sub>sediment</sub>	Degree of sediment variation
Pingshan	50	0.280	0.233	U	0.095	U
Beibei	52	0.274	-0.357	O	-0.690	O
Yichang	56	0.264	-0.105	U	-0.427	O

*N* is the number of years for water discharge and sediment recorded; *c* is the critical value for judging whether the variations are obvious.  $c = u_{0.975} / \sqrt{N - 1}$ , where  $u_{0.975} = 1.96$ ; *r*<sub>runoff</sub> and *r*<sub>sediment</sub> are Spearman rank-order coefficients for water discharge and sediment respectively. If  $|r| > c$ , the variation trend is obvious (O), or it is not obvious (U)

of Jinsha river, there were slight increases in both sediment and water discharge after late 1970s, but since 2000, there has been an evident decrease of sediment and water discharge. Unlike Yichang and Pingshan, both water discharge and sediment load at Beibei station decreased with a notably sharper decrease in sediment load. The water discharge variations and sediment load of the three stations were tested by Spearman's Rank Correlation. The test (Table 1) shows the same results for trend variation of water discharge and sediment as indicated in Fig. 3. The double accumulative curve of sediment yield-to-water discharge of Yichang station drew by Zhang and Wen (2004) clearly shows a turning point in 1991, indicating that the sediment concentration and yield became lower than that before 1991. At the Beibei station, sediment yield fell after 1985. However, the curve of Pingshan station demonstrates two turning points during 1995 and 2000. That is, between 1995 and 2000, the sediment increased than before 1995. After 2000, the sediment decreased again.

Based on the formulas (1)–(3), annual rainfall erosivity for each station was calculated and then the spatial distribution map of mean annual rainfall erosivity in the Upper Yangtze basin was interpolated by the Inverse Distance Weight method (Fig. 4). Rainfall erosivity for the study area had a minimum value of 119 (Qumalai) and a maximum value of 11,349 (Yaan) MJ mm ha<sup>-1</sup> h<sup>-1</sup> a<sup>-1</sup>. The distribution map shows several rainy centers (Fig. 4), such as Yaan and Huili cities. Generally, R values in the eastern part of the Upper Yangtze basin were greater than those of the western region, which followed a close relation to the step-wise topography. From 1954 to 2006, the R value of the whole basin had a maximum annual mean value of 3,803 MJ mm ha<sup>-1</sup> h<sup>-1</sup> a<sup>-1</sup> in 1998 and a minimum value of 2,235 MJ mm ha<sup>-1</sup> h<sup>-1</sup> a<sup>-1</sup> in 1997, which were induced by a severe flood and drought, respectively. The line parallel to the calendar year axis is a trend line fit by linear regression (Fig. 5a). The trend line with a slight increment demonstrates that the rainfall erosivity along with the calendar year increased but the variation was not significant. The annual rainfall erosivity fluctuates around ca. 3,000 MJ mm ha<sup>-1</sup> h<sup>-1</sup> a<sup>-1</sup> except for some special years of flood or drought (Fig. 5a).

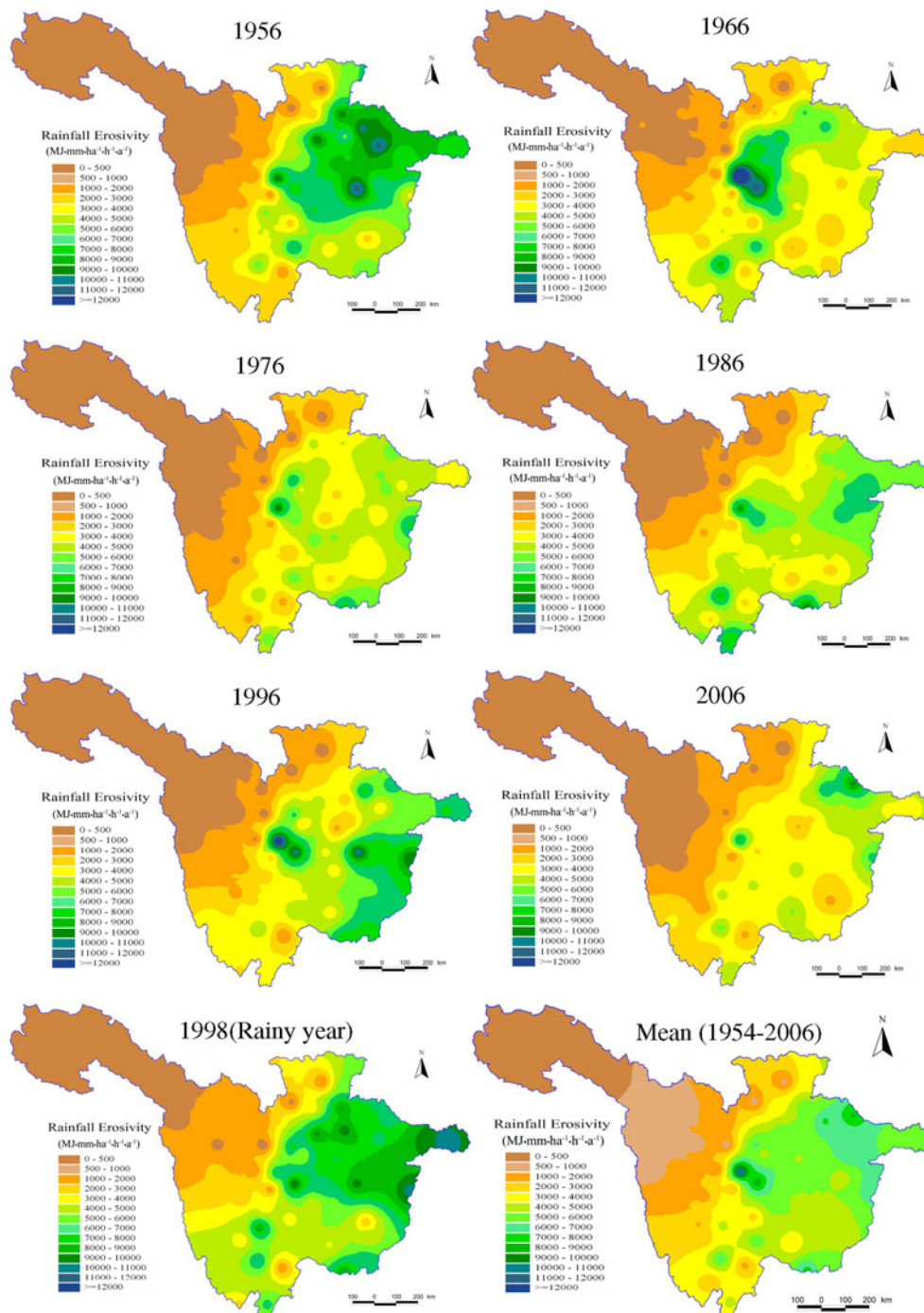
Impacts of human activities on sediment load indicated by the sediment load/rainfall erosivity

The fluctuation of the S/R indicator during the calendar year is helpful to identify human impacts on sediment yield. In drought-ridden years, such as 1959–1961, rainfall infiltrated into the subsurface soil and rock, with less runoff and less soil loss. A similar situation was found in 1967 and 1995. On the contrary, in 1974 and 1998, floods damaged soil and water conservancy works, and washed out previous slopeland deposits into the gullies; therefore, the anomalous large amount of sediment yield can be ascribed to the rainfall factor.

In the early 1950s, China was undergoing the First Five Year Economic Development Plan. The aggressive output target of the plan led to intensive disturbance of land cover and surface soil, which led to severe soil erosion. In 1958, steel production exploded during the Mass Steel campaign. Sixty million people are said to have participated in ore and coal mining, and in the smelting of iron and steel (Hsia 1961). At that time, forests and grasslands were harvested to meet the tremendous demand for fuel. Large-scale deforestation induced long-term erosion, especially in the Jinsha river where debris flow and landslides have been a constant factor in the landscape. During the “Cultural Revolution” from 1966 to 1976, the “Learning Agriculture from Dazhai” campaign was organized by Chairman Mao. This Upper Yangtze campaign focused on basic construction in the fields with a large number of terrace field structures being built. In addition, traditional soil conservation practices of “Tiaoshamiantu” and “Biangoubeigou” were employed to control soil loss and ensure soil fertility (He et al. 2007). The first 3 years of the Cultural Revolution was an active agricultural change phase, during which sediment load reached a highest level (Fig. 5b) due to lack of rational land management and sediment control measures (Wei et al. 2006).

Since the late 1970s, the central government has applied a number of policies to encourage economic growth in rural areas. One significant reform was the household responsibility system, which de-collectivized agriculture and gave farmers greater autonomy in managing their

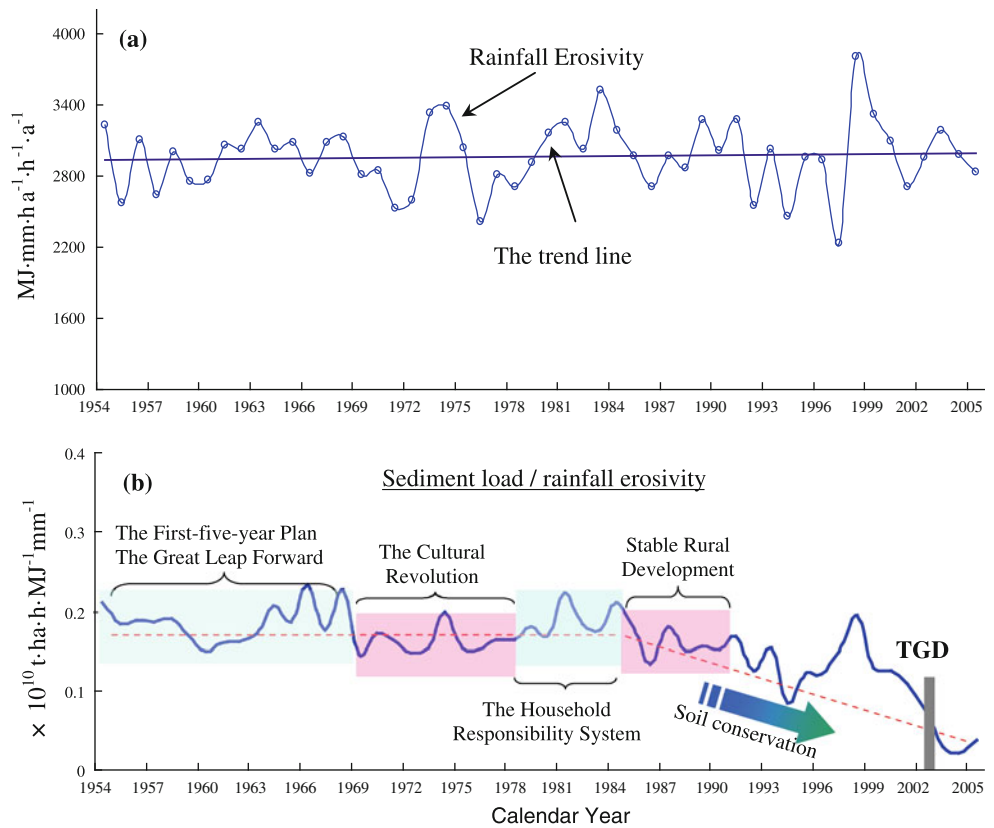
**Fig. 4** Spatial distribution of mean annual rainfall erosivity in the Upper Yangtze river



production (Krusekopf 2002). During the first several years of the reform, farmers challenged the new policy by converting forests into short-term money driven. After the mid-1980s, farmers' attitudes toward farming changed to favor sustainable land production. Subsequently, the re-adoption of traditional farming practices and the development of land preservation techniques have resulted in obvious decreases of river sediment load. With the implementation of China's reform policies, a large

percentage of farmers have migrated to cities for work. In the cities, the farmer's incomes and living conditions are much improved, and coal and electric are the main source of energy rather than forests and grasslands, which has reduced the energy burden in the countryside. All of these anthropogenic factors have positively reduced erosion and sediment transport in the Upper Yangtze. This is indicated by a dramatic decline of the S/R from 0.21 to 0.03 ( $\times 10^{10} \text{ t ha h MJ}^{-1} \cdot \text{mm}^{-1}$ ) since the mid-1980s.

**Fig. 5 a** Time series of regional rainfall erosivity; **b** impacts of human activities on sediment load variation judging from the indicator S/R. TGD is the Three Gorges dam



Since the 1980s, the central government has invested in socio-economic reforms including soil conservation, food security, and watershed management have been launched both nationwide and in the Upper Yangtze basin. These campaigns and programs have led to re-vegetation, conservation tillage, terrace farming, food production, and sediment control improvements. However, the impoundment of water behind the Three Gorges Dam in June 2003, has influenced the sediment dynamics of the Upper Yangtze river (Yang et al. 2006a; Dai et al. 2008).

Typical anthropogenic drivers of riverine sediment load variations

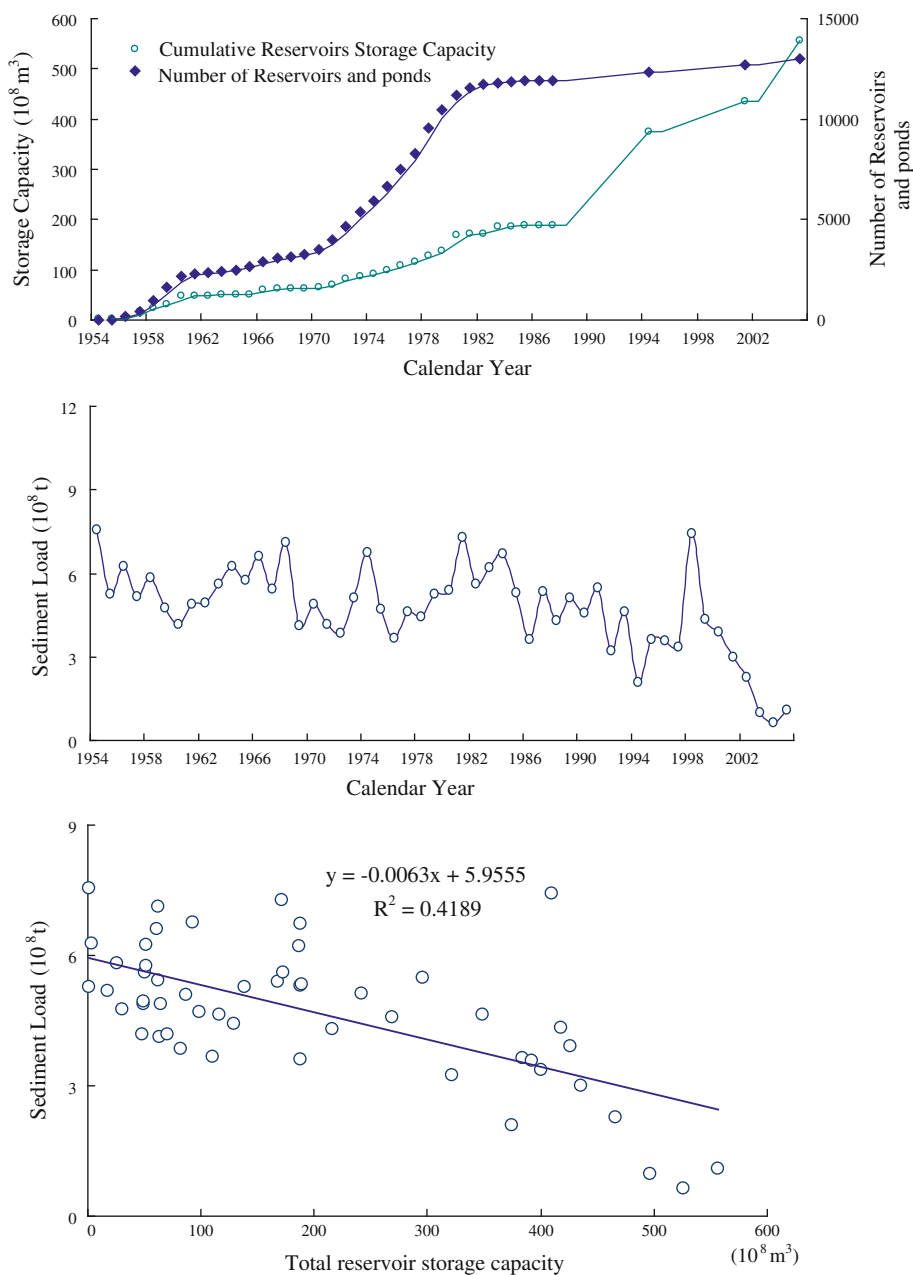
*Reservoir and dam construction*

Reservoir and dam construction has played an important role in sediment reduction in the Upper Yangtze basin (Walling and Fang 2003; Zhang and Wen 2004; Chen and Huang 2005; Yang et al. 2006b). In 1950, there was one 60 million m<sup>3</sup> reservoir, but during the 1960s–1980s, a rapid increase in reservoirs occurred. In the late 1990s, in response to the “Go West” Development Campaign and West-to-East Power Transmission Project, hydropower developments and water diversions in the Upper Yangtze and Southwest China boomed, with 2,441 completed or under construction hydropower stations in 2005. Reservoirs

along the Yangtze totaled 12,996 in 2005 with a total storage capacity of  $556.9 \times 10^8$  m<sup>3</sup>. Figure 6 suggests a negative relationship between the total reservoir storage capacity in the Upper Yangtze river basin and the sediment load of the Yichang station. With the increment of reservoirs and dams, the surface runoff and stream flow slowed down markedly and much more sediments deposit in the bottomland on the land surface, ponds, or reservoirs in front of the dams. Sixty-seven ponds and 4 reservoirs in the central Sichuan hilly areas within the basin were investigated in the year 2004–2005. Soil erosion and sediment deposition traced by <sup>137</sup>Cs indicated that annual sediment trapped proportion by reservoir is about 0.27% and sedimentation rate was 632–1,489 t km<sup>-2</sup> a<sup>-1</sup>, but by ponds 0.49–0.57% and sedimentation rate of 79–1,568 t km<sup>-2</sup> a<sup>-1</sup>. Annual trapped sediment in the reservoirs was estimated to be approximately 140 million tons, with an uneven distribution of water conservancy projects along the rivers. Table 2 shows the storage capacity of various scale reservoirs and annual sediment retention. The number and storage capacity of the reservoirs along the rivers of Jialing, Wu, Min, and Tuo rivers were greater than those in the Jinsha river and tributaries. Therefore, building reservoirs and dams may be able to reduce sediment load in the Jinsha river.

The construction of the Three Gorges Dam on the mainstream of Yangtze river started in 1993 and was

**Fig. 6** Relationship between the total reservoir storage capacity in the Upper Yangtze river basin and the sediment load of the Yichang station



completed in 2009. The reservoir began to store water in June of 2003 and since then sediment load has been reduced dramatically (see Fig. 5b). The mean annual sediment concentration of  $0.17 \text{ kg m}^{-3}$  in 2003–2006 is far less than that of  $1.1 \text{ kg m}^{-3}$  in 1954–2002. The mean annual sediment loads of  $0.70 \times 10^8 \text{ t}$  for post-2003 and  $4.97 \times 10^8 \text{ t}$  for pre-2003 happens distinct discount of 86%. So far, it is sound to consider reservoir and dam construction as a significant anthropogenic drivers of sediment load variations in the Upper Yangtze. With gradual implementation of the cascade power station planning, the total reservoir storage capacity of Upper Yangtze river will reach 61% of the total river discharge. If a greater number

of small-scale reservoirs are considered, the surface runoff controlled by reservoirs will exceed more than 70% of annual water discharge. In the future, joint operation of the reservoirs and dams would trap more sediment load coming from the Upper Yangtze.

#### *Soil conservation and sediment control programs*

The Upper Yangtze river was listed as a National Key Soil Conservation Project (NKSCP) by the State, and has been financially supported since 1989 to guarantee the safety of water quality and the Three Gorges Project (TGP). By the end of 2005, small catchments with soil conservation



**Table 2** Various scales reservoirs in Upper Yangtze river

River	Large scale			Medium scale			Small scale			Total		
	N <sup>a</sup>	SC <sup>b</sup> 10 <sup>8</sup> m <sup>3</sup>	SR <sup>c</sup> 10 <sup>6</sup> m <sup>3</sup>	N	SC 10 <sup>8</sup> m <sup>3</sup>	SR 10 <sup>6</sup> m <sup>3</sup>	N	SC 10 <sup>8</sup> m <sup>3</sup>	SR 10 <sup>6</sup> m <sup>3</sup>	N	SC 10 <sup>8</sup> m <sup>3</sup>	SR 10 <sup>6</sup> m <sup>3</sup>
Jinsha R.	3	71.52	1.41	56	12.71	4.17	2,009	13.81	11.80	2,068	98.04	17.38
Min & tuo Rs.	4	12.05	15.37	58	11.95	2.72	2,425	17.6	9.65	2,487	41.6	27.74
Jialing R.	11	61.56	16.83	63	19.49	6.68	4,915	24.68	24.61	4,989	105.73	48.12
Wujiang R.	7	100.52	12.88	42	9.7	1.16	1,764	10.76	6.41	1,813	120.98	20.45
Other tributaries	4	172.15	16.90	32	8.43	0.82	1,603	10.06	8.46	1,639	190.64	26.18
Upper Yangtze	29	417.8	63.39	251	62.28	15.55	12,716	76.91	60.93	12,996	556.99	139.87

<sup>a</sup> N is the number of the reservoirs in the mainstream and tributaries of the Upper Yangtze basin

<sup>b</sup> SC is the storage capacity of the existing reservoirs and the data is up to 2005

<sup>c</sup> SR is the annual sediment retention by the reservoirs and the data is up to end of 1980s

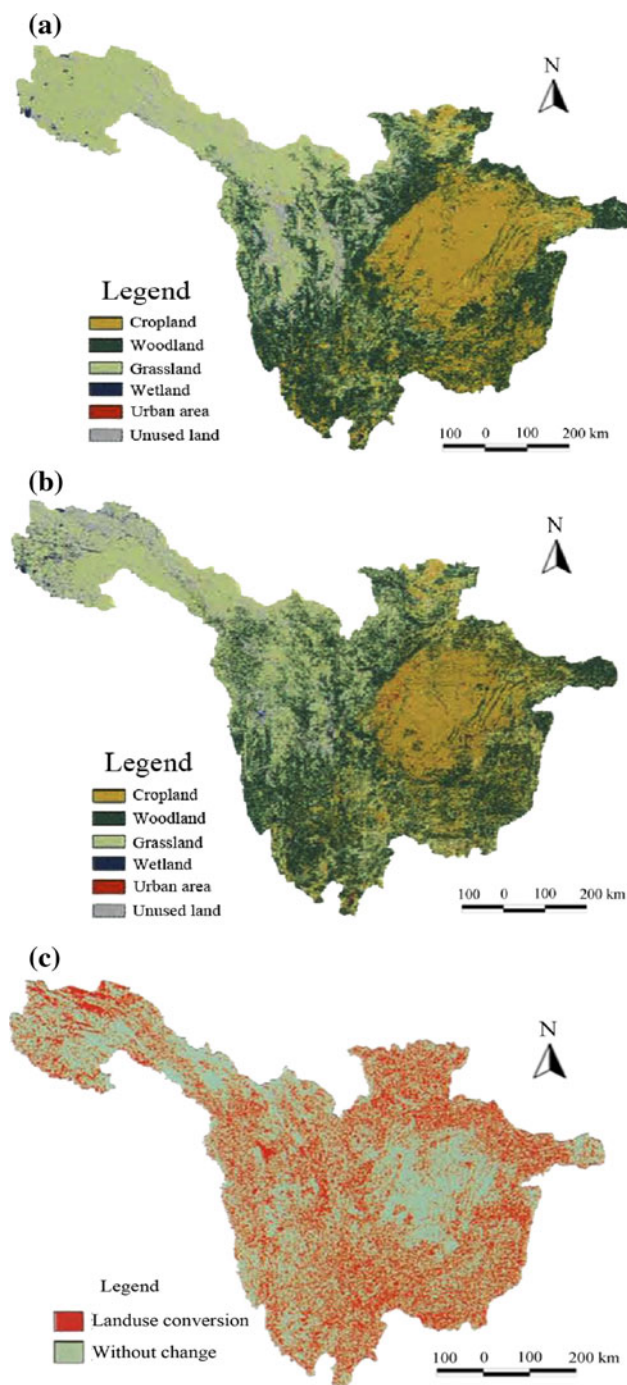
projects along the river totaled 3,531, with a coverage area of  $7.46 \times 10^4$  km<sup>2</sup>. Within the first 6 periods (from 1989 to 2005), the project had converted 6,000 km<sup>2</sup> of slopeland to terraced farming, planted 210,000 km<sup>2</sup> of forests and 8,000 km<sup>2</sup> of fruit orchards for soil–water conservation, and cultivated 2,900 km<sup>2</sup> of grassland. The 22,000 km<sup>2</sup> of land was designated as non-grazing conservation land, and, 135 km<sup>2</sup> of farmlands were converted to conservative tillage. In addition, a great number of ponds, pools, methane tanks, and irrigation ditches were built. The NKSCP has improved the agricultural production conditions and ecological environment in the seriously-eroded areas of the Upper Yangtze basin. Forest coverage changed from 33.8 to 56.2% and the sediment trapping capacity increased to  $5.1 \times 10^8$  tons in these areas. The erosion rate declined from 3,832 to 1,900 t km<sup>-2</sup> a<sup>-1</sup> by a 51.4% reduction (CIECC 2007). In conclusion, the project has contributed significant benefits in reducing water and soil loss.

Besides the NKSCP, several soil–water conservation programs have been launched, including conserving natural forest projects, closing the mountains to nurture forests, and protecting forests in the middle and upper reaches of the Yangtze river. These projects have increased forest cover and managed soil and water resources, which in turn have reduced sediment yield and soil loss. Traditional indigenous small-scale agro-ecosystem management systems have received increasing attention during the past few decades for their high potential for sustainable land use value. For example, traditional cultivation measures return deposited sediments from ponds and trenches back to the sloped cultivation land in the Central Sichuan region, which reduced sediment delivery into the river systems (Zhang and Wen 2004; He et al. 2007). The soil erosion–deposition assessment by the <sup>137</sup>Cs technique indicated that net soil erosion rate in the fields with applied conservation measures was half the amount of fields with no conservation measures (He et al. 2007).

*Land use change and rural socio-economic development*

Unlike reservoirs and dams, which trap sediment, land use change controls the generation of sediment which directly reduces sediment load to the rivers. During the past decades, land use in the study area changed dramatically (Fig. 7) by soil–water conservation projects and rural industrial realignment. The terracing slopeland project reduced slope steepness and decreased soil erosion in areas. The high implementation cost, however, limited its application in more difficult areas. The sloping land conversion program, initially started as a pilot program in Sichuan, Gansu and Shaanxi provinces in 1999, and further expanded nationwide in 2001. The program compensates participating farmers with cash subsidies, grain subsidies, and free saplings for reforestation. Hence, agricultural cropland with a gradient over 25° was easily converted or restored to forestland or grassland. Consequently, the area of the forest increased from  $33.47 \times 10^4$  km<sup>2</sup> in the 1970s, covering 33.92% of the total basin, to  $33.63 \times 10^4$  km<sup>2</sup>, covering 34.09% of the total. The grassland area changed from  $34.33 \times 10^4$  km<sup>2</sup> (34.80%) to  $35.64 \times 10^4$  km<sup>2</sup> (36.12%), the unused land from  $5.35 \times 10^4$  km<sup>2</sup> (5.42%) to  $5.54 \times 10^4$  km<sup>2</sup> (5.62%), the wetland from  $0.37 \times 10^4$  km<sup>2</sup> (0.38%) to  $1.41 \times 10^4$  km<sup>2</sup> (1.43%), and the urban area from  $0.06 \times 10^4$  km<sup>2</sup> (0.06%) to  $0.52 \times 10^4$  km<sup>2</sup> (0.52%). Sediment yield reports null or little in these types of area because of high coverage and less exposure to soil erosion. However, the sloping farmland, which is supposed to be the main sediment source in the Upper Yangtze, decreased from  $25.08 \times 10^4$  km<sup>2</sup> (25.42%) to  $21.92 \times 10^4$  km<sup>2</sup> (22.22%).

It is no doubt that the above land use conversion is beneficial for soil erosion control. The correlation between land use and erosion responses in the Upper Yangtze river has been studied for cost-benefits reporting (e.g., Wen et al. 2002; Zhang et al. 2003). The soil erosion rates of the cultivated land was determined by using <sup>137</sup>Cs tracing, and



**Fig. 7** **a** Land use in the Upper Yangtze river basin in year 1970; **b** Land use in the Upper Yangtze river basin in year 2000; **c** Land use change in the Upper Yangtze river basin between 1970 and 2000

ranged from 758 to 9,854 t km<sup>-2</sup> a<sup>-1</sup> (Wen et al. 2002; Zhang et al. 2003). Slopeland with a gradient above 10° suffered serious erosion, but terraces with the same or greater gradient approximated no erosion. Erosion rates in non-cultivated land were mainly determined by the type of vegetation cover, and a negative correlation was found between vegetation coverage density and erosion. Wen

et al. (2002) and Zhang et al. (2003) showed erosion rates of non-cultivated land in the Upper Yangtze ranging from 310 to 4,435 t km<sup>-2</sup> a<sup>-1</sup>. Where forest coverage was greater than 80%, erosion rates were between 0 and 300 t km<sup>-2</sup> a<sup>-1</sup>; 700–900 t km<sup>-2</sup> a<sup>-1</sup> with forest coverage of 60%; and more than 4,000 t km<sup>-2</sup> a<sup>-1</sup> with a coverage of less than 30%.

In addition, road construction has played an important role in the amount of sediment load in the Upper Yangtze river. In the first several years of extensive road construction, top soil removal, native vegetation destruction, and topography alterations resulted in severe surface runoff and water erosion (Xu et al. 2006). However, from a long-term perspective, road construction has reduced sediment significantly by channeling runoff through drains and eliminating washout of young gully sediments (Zhang and Fu 1999). Without gully erosion, trees and shrubs populated the areas quickly, which lead to “gully vanishment”. Despite the observation of positive sediment reduction by road construction, there is no formal study providing data to quantify the soil conservation benefits. It should also be noted that sediment dredging had great impacts on the sediment load at the Yichang station outlet. In 2002 alone, more than 3.57 million tons of sediment was dredged from a 114 km reach in the lower Jialing river to fulfill booming construction needs (Lin et al. 2005).

## Conclusions

In Southern China, rainfall erosivity is determined by the amount of rainfall received rather than rainfall intensity; and is estimated by the simple R-precipitation equation. The mean annual R in the Upper Yangtze basin was distributed unevenly, with a minimum 119 MJ mm ha<sup>-1</sup> h<sup>-1</sup> a<sup>-1</sup> received at Qumalai station and a maximum of 11,349 MJ mm ha<sup>-1</sup> h<sup>-1</sup> a<sup>-1</sup> at the Yaan station. Due to the stepwise topography, R values in eastern part of the Upper Yangtze basin were greater than those of the western region. In terms of a time series, the R varied around about 3,000 MJ mm ha<sup>-1</sup> h<sup>-1</sup> a<sup>-1</sup> and there was a slight increase in the general trend. The maximum annual mean value of 3,803 MJ mm ha<sup>-1</sup> h<sup>-1</sup> a<sup>-1</sup> occurred during the flood of 1998 and the minimum value of 2,235 MJ mm ha<sup>-1</sup> h<sup>-1</sup> a<sup>-1</sup> occurred during the drought of 1997.

The proxy indicator S/R was proposed to distinguish anthropogenic impacts from climatic impacts on suspended sediment load in average rainfall years. High sediment load in the 1950s and 1960s was induced by large-scale deforestation driven by the high economic output targets of the First Five Year Plan, along with fuel demands to meet steel production. During the Cultural Revolution, and the campaign “Learning from Dazhai in Agriculture”, focus was

placed on field terrace construction as well as traditional soil conservation to control soil loss. In part due to these efforts, the sediment load decreased markedly. The higher S/R in the late 1970s and the early 1980s is ascribed to fierce deforestation during the household responsibility system implementation. Since the mid-1980s, a descending S/R can be attributed to stable rural development, joint operation of numerous reservoirs, and soil conservation measures.

Sediment yield process control and sediment translocation reduction are caused by human activities. The growth of reservoir capacity has decreased the sediment load tremendously, and the  $^{137}\text{Cs}$  soil erosion assessment study indicated that conservation measures reduced the erosion rate by half. Road construction must also be considered as a potential soil conservation function along with riverbed sediment dredging in order to elucidate all anthropogenic inputs to river sedimentation along the upper Yangtze river.

**Acknowledgments** The authors are grateful to Prof. Zhang Xinbao and Dr. Zeng Hongcheng for helpful suggestions and Ms. Heather Fair for careful language revisions. The daily precipitation data provided by the China Meteorological Data Sharing Service System and the financial supports from Major Science and Technology Program for Water Pollution Control and Treatment (No. 2009ZX07104), the National Natural Science Foundation of China (No. 41001168), Chongqing Education Committee (No. KJ100601) and the Doctoral Project fund by the Chongqing Normal University (No. 08XWB029), are gratefully acknowledged.

## References

- Chen J, Huang W (2005) Impacts of cascade power station reservoirs on the processes of runoff and sediment. *Resour Environ Yangtze Basin* 14:787–790 (In Chinese)
- CIECC (China International Engineering Consulting Corporation) (2007) Assessment report for national key soil conservation project in the Upper Yangtze River (In Chinese)
- Dai SB, Lu XX, Yang SL, Cai AM (2008) A preliminary estimate of human and natural contributions to the decline in sediment influx from the Yangtze River to the East China Sea. *Q Int* 186(1): 43–54
- Douglas I (1967) Man, vegetation and sediment yield of river. *Nature* 215:925–928
- Gu HY, Douglas I (1989) Spatial and temporal dynamics of land degradation and fluvial erosion in the middle and upper Yangtze River basin, China. *Land Degrad Rehabil* 1:217–235
- He XB, Zhou J, Zhang XB, Tang KL (2006) Soil erosion response to climatic change and human activity during the Quaternary on the Loess Plateau, China. *Reg Environ Change* 6:62–70
- He XB, Xu YB, Zhang XB (2007) Traditional farming system for soil conservation on slope farmland in southwestern China. *Soil Tillage Res* 94:193–200
- Higgitt DL, Lu XX (1999) Challenges in relating land use to sediment yield in the Upper Yangtze. *Hydrobiologia* 410:269–277
- Hsia R (1961) The development of mainland China's steel industry since 1958. *China Q* 7:112–120
- Kesel RH, Yodis EG, McCraw DJ (1992) An approximation of the sediment budget of the lower Mississippi river prior to major human modification. *Earth Surf Proc Land* 17:711–722
- Krusekopf CC (2002) Diversity in land-tenure arrangements under the household responsibility system in China. *China Econ Rev* 13:297–312
- Lane LJ, Hernandez M, Nichols M (1997) Processes controlling sediment yield from watersheds as functions of spatial scale. *Environ Model Softw* 12:355–369
- Lesschen JP, Kok K, Verburg PH, Cammeraat LH (2007) Identification of vulnerable areas for gully erosion under different scenarios of land abandonment in Southeast Spain. *CATENA* 71:110–121
- Lin BN, Zhang R, Dai DZ, Tan Y (2005) Sediment research for the three gorges project on the Yangtze river since 1993. *Int J Sed Res* 20:30–38
- Loureiro NS, Coutinho MA (2001) A new procedure to estimate the RUSLE EI30 index based on monthly rainfall data and applied to the Algarve region, Portugal. *J Hydrol* 250:12–18
- Lu XX (2005) Spatial variability and temporal changed of water discharge and sediment flux in the lower Jinsha tributary: impact of environmental changes. *River Res Appl* 21:229–243
- Lu XX, Higgitt DL (1998) Recent changes of sediment yield in the Upper Yangtze, China. *Environ Manage* 22:697–709
- Lu XX, Higgitt DL (1999) Sediment yields variability in the Upper Yangtze. *Earth Surf Proc Land* 24:1077–1093
- Meade RH, Parker R (1985) Sediments in rivers of the United States, in National Water Summary 1984. U.S. Geol Surv Water Supp Paper 2275:49–60
- Renard KG, Freimund JR (1994) Using monthly precipitation data to estimate the R-factor in the revised USLE. *J Hydrol* 157:287–306
- Renard KG, Foster GR, Weesies GA, McCool DK, Toder DC (1997) Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). USDA. Agricultural Handbook, vol 703. U.S. Government Printing Office, Washington, DC
- Silva AM (2004) Rainfall erosivity map for Brazil. *CATENA* 57:251–259
- Stanley DJ, Warne AG (1998) Nile delta in its destruction phase. *J Coastal Res* 14:794–825
- Syvitski JPM, Vörösmarty CJ, Kettner AJ, Green P (2005) Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science* 308:376–380
- Thiessen AH (1911) Precipitation averages for large areas. *Mon Weather Rev* 39:1082–1084
- Walling DE (2006) Human impact on land-ocean sediment transfer by the world's rivers. *Geomorphology* 79:192–216
- Walling DE, Fang X (2003) Recent trends in the suspended sediment loads of the world's rivers. *Global Planet Change* 39:111–126
- Wang HJ, Yang ZS, Saito Y, Liu JP, Sun XX, Wang Y (2007) Stepwise decrease of the Huanghe (Yellow river) sediment load (1950–2005): impacts of climate change and human activities. *Global Planet Change* 57:331–354
- Wei J, Zhou J, Tian JL, He XB, Tang KL (2006) Decoupling soil erosion and human activities on the Chinese Loess Plateau in the 20th century. *CATENA* 68:10–15
- Wen AB, Zhang XB, Wang YK, Feng MY, Zhang YY, Xu JY, Bai LX, He TR, Wang JW (2002) Study on soil erosion rates using  $^{137}\text{Cs}$  technique in upper Yangtze river. *J Soil Water Conserv* 16:1–3 (In Chinese)
- Wischmeier WH, Smith DD (1978) Predicting rainfall erosion losses: a guide to conservation planning. USDA. Agricultural handbook, vol 537. U.S. Government Printing Office, Washington, DC
- Xie Y, Liu BY, Zhang WB (2000) Study on standard of erosive rainfall. *J Soil Water Conserv* 14(4):6–11 (In Chinese)
- Xin ZB, Yu XX, Li QY, Lu XX (2010) Spatiotemporal variation in rainfall erosivity on the Chinese Loess Plateau during the period 1956–2008. *Reg Environ Change* 11:149–159

- Xu JX, Cheng DS (2002) Relation between the erosion and sedimentation zones in the Yellow river, China. *Geomorphology* 48:365–382
- Xu XL, Zhang KL, Kong YP, Chen JD, Yu BF (2006) Effectiveness of erosion control measures along the Qinghai-Tibet highway, Tibetan plateau, China. *Trans Res Part D Trans Environ* 11:302–309
- Yang ZS, Milliman JD, Galler J, Liu JP, Sun X (1998) Yellow river's water and sediment discharge decreasing steadily. *EOS* 79:589–592
- Yang SL, Zhao QY, Belkin IM (2002) Temporal variation in the sediment load of the Yangtze river and the influences of human activities. *J Hydrol* 263:56–71
- Yang SL, Li M, Dai SB, Liu Z, Zhang J, Ding PX (2006a) Drastic decrease in sediment supply from the Yangtze river and its challenge to coastal wetland management. *Geophys Res Lett* 33:L06408. doi:10.1029/2005GL025507
- Yang Z, Wang H, Saito Y, Milliman JD, Xu K, Qiao S, Shi G (2006b) Dam impacts on the Changjiang (Yangtze River) sediment discharge to the sea: the past 55 years and after the Three Gorges Dam. *Water Resour Res* 42. doi:10.1029/2005WR003970
- Yin S, Xie Y, Nearing MA, Wang C (2007) Estimation of rainfall erosivity using 5- to 60-minute fixed-interval rainfall data from China. *CATENA* 70:306–312
- Yu B (1998) Rainfall erosivity and its estimation for Australia's tropics. *Aust J Soil Res* 36:143–165
- Yu B, Rosewell CJ (1996a) An assessment of a daily rainfall Erosivity model for New South Wales. *Aust J Soil Res* 34:139–152
- Yu B, Rosewell CJ (1996b) A robust estimator of the R-factor for the universal soil loss equation. *Trans ASAE* 39:559–561
- Yu B, Hashim GM, Eusof Z (2001) Estimating the r-factor with limited rainfall data: a case study from peninsular Malaysia. *J Soil Water Conserv* 56:101–105
- Zhang WB (2003) Tempo-spatial distribution of rainfall erosivity in the Chinese northern eco-tone. *Prog Nat Sci* 13:651–654 (In Chinese)
- Zhang XB, Fu SX (1999) A way for steep slopeland in the key erosion areas of the upper Yangtze river. *Soil Water Conserv China* 9:38–39 (In Chinese)
- Zhang XB, Wen AB (2004) Current changes of sediment yields in the upper Yangtze river and its two biggest tributaries, China. *Global Planet Change* 41:221–227
- Zhang XB, Zhang YY, Wen AB, Feng MY (2003) Assessment of soil losses on cultivated land by using the  $^{137}\text{Cs}$  technique in the upper Yangtze river basin of China. *Soil Till Res* 69:99–106