Journal of Mountain Science Vol **1** No 3 (2004): 239-249
http://www.imde.ac.cn/journal

Article ID: 1672-6316 (2004) 03-0239-11

Anthropogenic Impacts on the Sediment Flux in the Dry-hot Valleys of Southwest China—an Example of the Longchuan River

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Abstract The sediment flux data, measured from a dry-hot valley of the Longchuan River, a tributary of the lower Jinsha River, were analyzed with Mann-Kendall test, Seasonal Mann-Kendall test and Sen's test. In both the upper reaches (Xiaohekou) and the lower reaches (Xiaohuangguayuan), the sediment fluxes showed a significant increase from 1970 to 2001, despite the fact that the water discharge did not change significantly during the period and numerous reservoir constructions which contribute to the trap of sediment. This can be attributed to the intensification of human activities, especially the activities related to land surface disturbances such as deforestation and afforestation, expansion of agriculture land, and road constructions. This increase is more significant in the lower reaches of the river observed at the place of Xiaohuangguayuan due to the dry-hot climate. The profound increase in sediment flux has significant implications for effective management of the sedimentation problems of the on-going Three Gorges Reservoir.

Keywords: Sediment flux; dry-hot valley; deforestation; afforestation; reservoir; road construction

Received: 15 June 2004
Accepted: 1 September 2004

Introduction

There is a growing concern about the potential impact of human activities on soil erosion and sediment flux in rivers, which can exacerbate the process of land degradation, aggravate the problem of water pollution, and shorten the life span of reservoirs. Previous researches showed that human activities, like hydrological facilities construction and land use alteration (including afforestation and deforestation, intensification of agriculture, draining of wetlands and urbanization), would alter such basic components of hydrological and physical processes such as interception, evapotranspiration, infiltration, soil erosion, sediment transportation, and finally affect the sediment flux in rivers. However, the relationship between land use change and sediment concentration in a river is complex. There are many progresses, which contribute positively or negatively to the sediment production. Afforestation, for example, may increase or reduce erosion through several mechanisms (Calder 1993). The ultimate response depends on the interaction and intensity of these processes (Vanacker 2003).

The profound disturbances of land surface such as land use changes, reservoir and road constructions have been superimposed during the past five decades in China due to population pressure and socio-economic policies. Forest cover in southwest China, for example, was decreased by about 10% between the 1950s and the 1980s (Yu *et al*. 1991), and such a large reduction might be expected to lead to increasing water discharge and sediment flux (Chen 1999). Lu *et al*'s (2003) research suggested that most of the changes in sediment load in the upper Yangtze River be caused by human activities. Reservoir constructions also had a consequence on the changes in sediment flux. The studies, examining sediment the yields within the upper Yangtze (Gu and Douglas 1989, Dai and Tan 1996), indicated that, when soil erosion in the same areas got more serious, there was no apparent increase in sediment output at Yichang. The reason is suggested that the local reservoirs trap considerable proportion of eroded sediment and prevent its transfer to the river. It's estimated that the total reservoir storage capacity by the mid-1980s exceeded 16 billion m^3 in the upper Yangtze River (Gu *et al.* 1987).

Dry-hot valley is a special environmental type in southwest China. They are widely found along the main rivers and their tributaries in this region, notably along the upper Yangtze (Jinsha), Dadu, Yalong, Min, Lancang (Mekong), Nu (Salween), and Yuan (Red) rivers and their tributaries. They usually refer to the valleys under the elevation of 1300 m (northern slope of the mountain)~1600 m (southern slope) and are characterized by a hotter and dryer climate, compared with their neighboring areas. For example, the annual mean temperature in the dry-hot valleys along the Jinsha River (upper reaches of the Yangtze River) is 20~27ºC, the annual total precipitation is only 600~800 mm, and the annual evaporation is 3~6 times of the precipitation. Furthermore, the precipitation in dry season (from December to next May) only accounts for 10% to 22.2% of the total annual precipitation, which results in a arid index as high as 10~20 in the dry season. Despite their fragile ecosystem, the dry-hot valleys are usually highly populated because of the relatively flat landform, and the abundant solar radiation and heat for agriculture. Due to the harsh natural environment and the increasing pressure from human activities, most of the dry-hot valleys in southwest China have the problem of degradation. Soil erosion is found very common there. For example, the dry-hot valleys along the lower Jinsha River are the main source of the sediment in the river. The sediment yield of the dry-hot valleys between Panzhihua and Pingshan along the Jinsha River is 2412 t/km^2.a and the annual sediment load is 1.9 billion t, which contribute to 35.5% of the sediment in the upper Yangtze River, while the annual water discharge only accounts for 8.9% (Ji 2003).

The Longchuan River flows through one of the most famous dry-hot valleys, Yuanmou, in southwest China. The river basin has experienced a wide range of common human activities in China, such as deforestation starting from the 1950s to the 1980s, afforestation from the late 1980s, constructions of reservoirs and canals, and expansion of the irrigated land. In this paper we used the Longchuan River as an example to examine the spatial variability and temporal changes of the sediment fluxes in the lower Jinsha River in 1970~2001 and investigate the possible impact of human activities such as land use changes, road and reservoir constructions, on the sediment flux in dry-hot valleys.

1 Study Area

The Longchuan River, is located between 24º45'~26º15' N and 100º56'~102º02' E, in southwest China. It is a tributary of the Jinsha River. The location of the river is shown in Figure 1. The Longchuan River is the first order tributary of the Jinsha River. It originates in Tianzimiao, Nanhua County, and flows for 231.2 km east to north through Chuxiong, Mouding, Lufeng and Yuanmou counties till it reaches the Jinsha River at Jiangbian, Yuanmou County. There are two gauging stations along its main channel, Xiaohekou in the upper stream and Xiaohuangguayuan in the down stream. The drainage sizes of Xiaohekou and Xiaohuangguayuan are 1788 km^2 and 5560 km^2 respectively.

Most of the basin has a subtropical monsoon climate with an annual average rainfall of 800-1000 mm and temperature of 14~18ºC, except the river valleys around Yuanmou County which has a dry-hot climate due to its terrain that is surrounded by higher mountains. The dry-hot climate is characterized by a lower rainfall (620 mm) and a higher temperature (21.9 °C) and thus a higher potential evaporation and high arid index (Table 1). The dry-hot valley in the Yuanmou County consists of around 60% of its total land area. Under the monsoon climate, more than 80% of the annual precipitation and the annual water discharge occur in the wet season, from May to November, and mainly concentrated in summer (July, August and September).

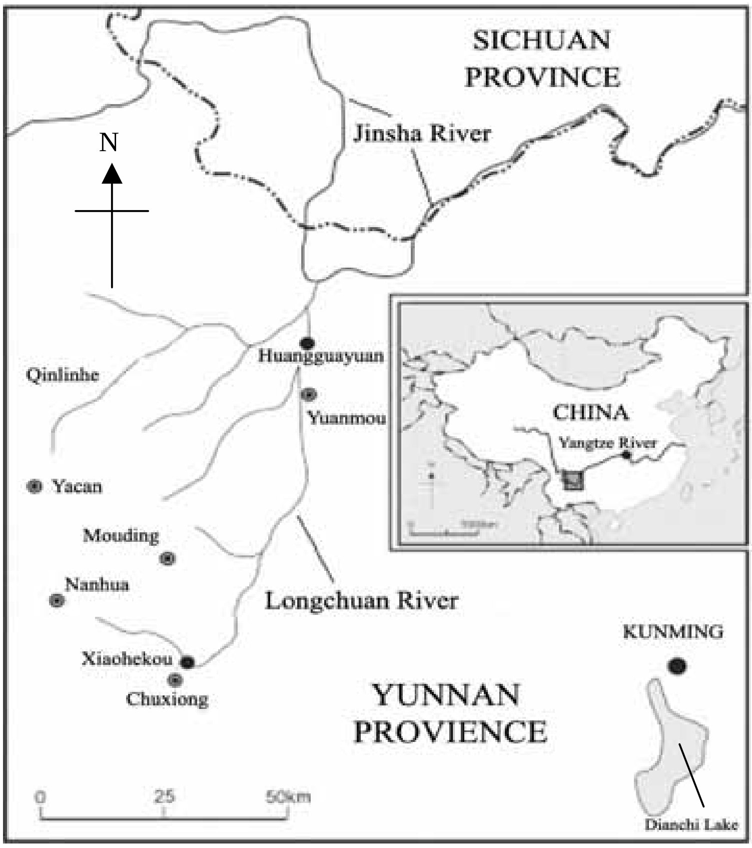


Figure 1 The lower Jinsha River and its tributary, the Longchuan River

Table 1 Summary of some climate indicators in the Longchuan River basin

County	Annual temperature (°C)	Annual rainfall (mm)	Percentage of rainfall in wet season (%)	Annual evaporation (mm)	Arid index
Nanhua	14.9	837.1	89%	1933.7	2.31
Mouding	15.7	862.2	91%	2140.3	2.48
Chuxiong	15.6	824.6	89%	2019.4	2.45
Yuanmou	21.9	619.8	92%	3823.4	6.17

The basin with the highest elevation of 3000 m and the lowest 700 m is dominated by Triassic shales and sandstone with small proportion of granite, limestone and Quaternary deposits. Purple shales weather rapidly under the subtropical climatic conditions, yielding the soils (purple soils in Chinese classification, see Photo 1) particularly susceptible to erosion and coarsening through the loss of fine particles. The soils along the hot-dry valleys are very unique (dry red soil in Chinese classification) due to the hot-dry climate. The lowland and valleys are in generally developed as paddy fields, while the slopes are occupied by sparse trees or exposed as barren land which is normally dissected by erosion features such as gullies (Photo 1+2). The basin is also well known for its 'soil forest', one of the fluvial landforms curved by severe weathering and soil erosion (Photo 3+4).


Photo 1+2 Gullies in the Longchuan River: showing the purple soils and serious soil erosion


Photo 3+4 "Soil forest" formed through severe weathering and soil erosion

2 Methodology and Data

Monthly and extreme daily sediment flux data are obtained from the two hydrological stations—Xiaohekou in Chuxiong County, and Xiaohuangguayuan in Yuanmou County (Figure 1). The data span over 32 years from 1970 to 2001. However, the sediment flux is only measured during wet season from May to November, because in dry season the water discharge is low, thus, the sediment flux is low.

The temporal change in sediment flux was analyzed. The trends of 3 variables, annual sediment yield, annual maximum monthly sediment flux and annual maximum daily sediment flux, were studied with Mann-Kendall test. Kendall's correlation of coefficient (Kendall's tau), an effective and general measurement of correlation between two variables (Kendall 1938, Mann 1945), was extensively used for testing the trend in hydrological data (Helsel & Hirsch 1992, Burn and Hag Elnur 2002, Xiong and Guo 2004, Yue and Pilon 2004). The trends of monthly sediment flux are tested with Seasonal Kendall test. Seasonal Kendall Trend Test (SKTT) is a modified version of the standard Kendall test to assess the trend of data in which there is a significant seasonal component (Hirsch *et al.* 1993). The slope of the changing trend is tested by Sen's method. Sen's method is a nonparametric method used to estimate the value and confidence interval for the slope of an existing trend. It is widely used in hydrological data analysis because of its characteristics such as allowing missing data, making no assumptions on distribution of data and not being affected by gross data errors and outliers.

Furthermore, multi-years average of sediment fluxes will be compared for the two stations to elucidate the spatial variability.

3 Results and Analysis

3.1 Annual sediment flux changes

Time series of annual mean sediment fluxes, their five-year moving average, the long term means and the trend lines (regression) at the two stations are plotted in Figure 2. The long term annual mean sediment fluxes at Xiaohekou and Xiaohuangguayuan are 0.47 million ton (equivalent to a sediment yield of 255 t km^{-2} yr^{-1}) and 5.55 million ton (equivalent to 947 t km^{-2} yr^{-1}), respectively (Table 2). At Xiaohekou the annual sediment flux increased from 1982. At Xiaohuangguayuan, the sediment flux had a sharp increase from 1990. During the 12 years from 1990 to 2001, only two years, 1991 and 1992, had sediment flux lower than the long term mean. As to the overall trend, both stations showed a trend of increase by linear regression (Figure 2).

The maximum monthly and daily sediment fluxes at Xiaohekou and Xiaohuangguayuan are plotted in Figure 3. The daily extremes presumably reflect single events and are inherently more variables.

According to the results of Mann-Kendall test (Table 3), all three variables, annual sediment yield, maximum monthly and daily sediment fluxes at Xiaohekou, had a positive trend with a 0.05, 0.05, 0.1 significant level, respectively. As for Xiaohuanguayuan, the increasing trends of these variables were significant at 0.01, 0.01 and 0.1 level.

The percentage of Sen's slope estimator to the median for annual mean was 2.49 at Xiaohekou and 3.95 at Xiaohuangguayuan (Figure 4)

Table 2 Annual water and sediment flux at the two stations averaged from 1970 to 2001

Station	Drainage size (km^2)	Annual water flux (million m^3)	Water yield (mm yr^{-1})	Annual sediment fluxes (million t)	Sediment yield (t yr^{-2} yr^{-1})
Xiaohekou	1,788	317.8	177.0	0.4	255
Xiaohuangguayuan	5,560	817.0	147.0	5.3	947

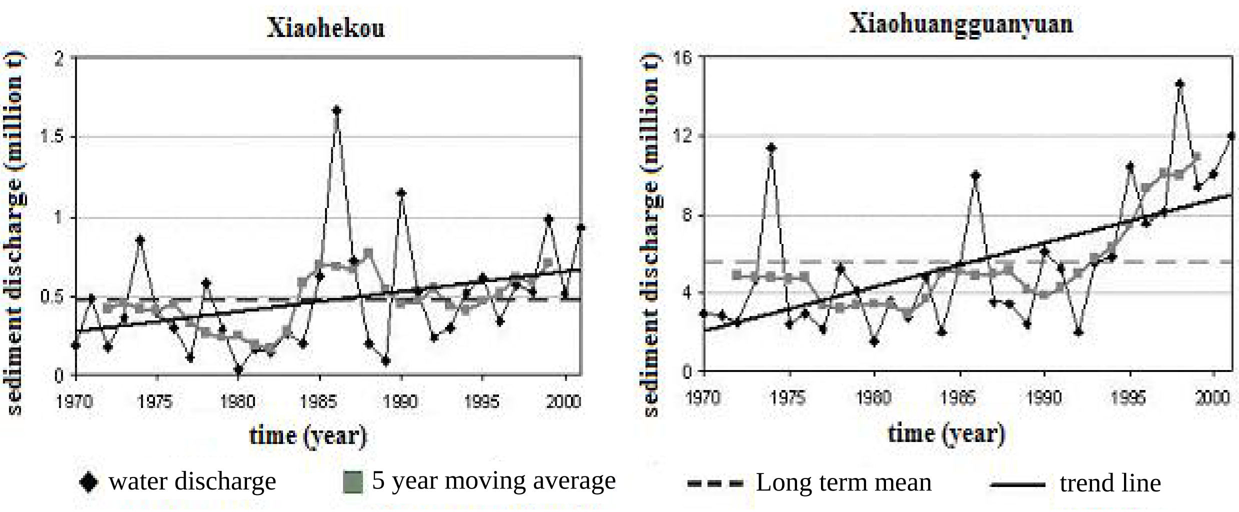


Figure 2 Annual sediment discharges at Xiaohekou and Xiaohuangugayuan

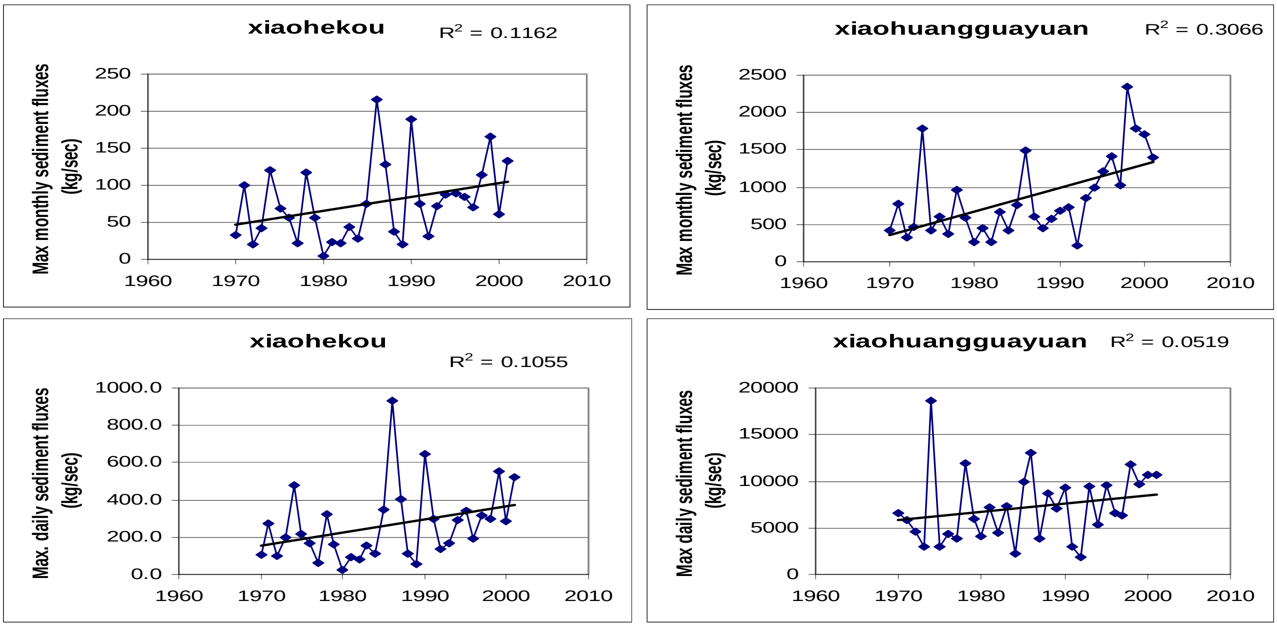


Figure 3 Maximum monthly/daily sediment fluxes (1970 ~2001)

Table 3 Results of sediment flux trend analysis with Mann-Kendall test

Station	Dataset	n*	Mann-Kendall test statistics			Sen's slope estimator	
			Z	Trend	α**	Q	Q (%)
Xiaohekou	Annual total flux (million t)	32	1.99	+	0.05	0.012	2.49
	Maximum monthly flux (kg/s)	32	2.04	+	0.05	1.952	2.59
	Maximum daily flux (kg/s)	32	1.95	+	0.1	14.976	2.12
Xiaohuang-guayuan	Annual total flux (million t)	32	3.45	+	0.01	0.219	3.95
	Maximum monthly flux (kg/s)	32	3.32	+	0.01	31.160	3.69
	Maximum daily flux (kg/s)	32	1.87	+	0.1	139.722	1.95

*:Number of year, from 1970 to 2001 **: Significant level

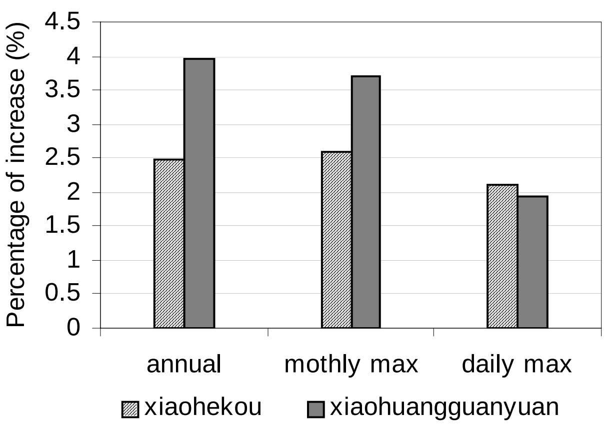


Figure 4 Sen's estimator of slope (%) of sediment flux

3.2 Seasonal sediment flux changes

The mean monthly sediment fluxes during wet season and their standard deviation are plotted in Figure 5. The sediment flux is highest in August and the amount of sediment load in the three months, July, August and September, accounts for more than 80% of the total annual load for the both stations. The standard deviation is very high compared to the long term mean. Apart from August, it is higher than the long term mean for the rest months.

The results of SMK test are listed in Table 4. Except for November, the monthly sediment flux in wet season had a positive trend. At Xiaohekou, the sediment flux had a significant increase (at 0.05 level) in September. At Xiaohuangguayuan, the increasing trend was significant at 0.05 level in July, August and October, and was significant at 0.01 level in September.

As to the percentage of the Sen's slope estimator to long term mean, the sediment fluxes at both stations increased greatly in June, July, August, September and October. Generally, the flux at Xiaohuangguayuan had a greater and more significant change than that at Xiaohekou.

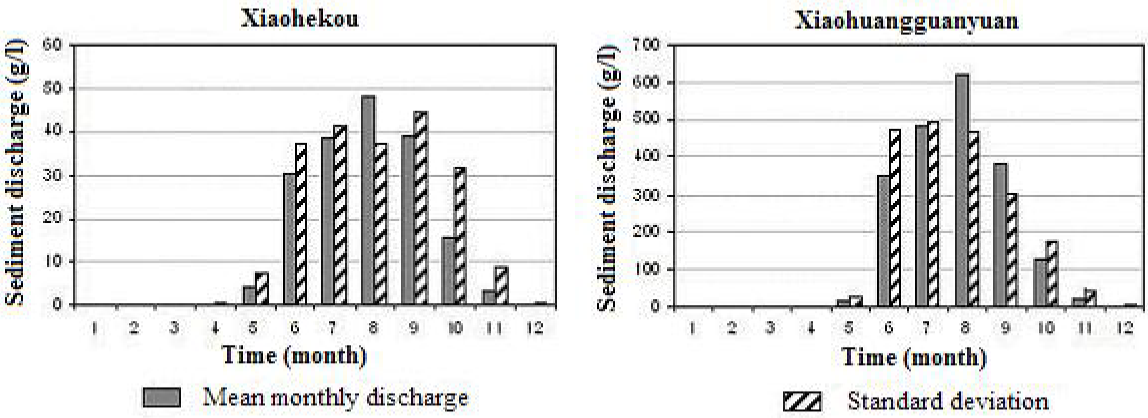


Figure 5 Long term monthly mean sediment flux and standard deviation

Table 4 Results of sediment flux trend analysis with Seasonal Mann-Kendal test

Station	Dataset	n*	Mann-Kendall test statistics			Sen's slope estimator	
			Z	Trend	α**	Q	Q (%)
Xiaohekou	May	32	0.03	+		0.012	0.29
	June	32	1.09	+		0.347	1.14
	July	32	1.54	+		0.706	1.84
	Aug.	32	1.64	+		1.135	2.35
	Sep.	32	2.11	+	0.05	1.088	2.79
	Oct.	32	1.18	+		0.171	1.12
	Nov.	32	-0.62	-		-0.001	-0.02
Xiaohuangguayuan	May	32	0.46	+		0.010	0.06
	June	32	1.51	+		7.993	2.08
	July	32	2.59	+	0.01	16.130	3.06
	Aug.	32	2.5	+	0.05	14.867	2.32
	Sep.	32	2.92	+	0.01	15.341	3.85
	Oct.	32	2.24	+	0.05	3.904	3.19
	Nov.	32	-1.17	-		-0.040	-0.19

*: Number of year, from 1970 to 2001 **: Significant level

4 Discussion

The sediment flux is highly correlated with water discharge. However, the sediment and water discharge do not increase at the same rate. Figure 6 is the double plots of cumulative annual water discharge and sediment discharge from 1970 to 2001. The trend lines were based on the data from 1970 to 1979. It is obvious from the plots that the sediment fluxes increased at a higher speed than that of water discharge. Besides, the lower reaches of the river basin (Huangguayuan) generated much higher sediment flux to the Jinsha River as a result of the hot-dry climate and the dissected terrain along the lower reaches of the river.

Nevertheless, both stations had lower sediment yield than expected, giving the severe soil erosion as we observed in the field (Photo 1 & 2). Annual sediment at Xiaohekou was within the band of 0~500 t km^{-2} yr^{-1}, while Xiaohuangguayua lied in the band of 500~1000 t km^{-2} yr^{-1}. Both classes are within lower bands of the sediment yield normally used in China. The changes of sediment fluxes in the river basin can be explored from the following aspects.

4.1 Climate factors

Sediment flux is closely related with precipitation intensity. The annual sediment flux and annual precipitation at Xiaohekou in Chuxiong and Xiaohuangguayuan in Yuanmou had almost the same trend. The correlations between the annual sediment fluxes at these two stations were significant at 0.01 level. However, precipitation was not the only factor that influences the sediment flux. Sen's slope (%) of temperature, precipitation, water discharge and sediment flux changes from 1970 to 2001 are plotted in Figure 7. The annual water discharge, annual sediment flux and annual precipitation all had a positive trend, but the trend for water discharge was not significant for the both stations. Annual increases of precipitation (0.84% and 0.63%) and water discharge (2.0% and 1.95%) were much slower than that of sediment (2.48% and 3.94%). This suggests that the climate variation have a very limited impact on sediment flux in this basin.

4.2 Afforestation and deforestation

The forest cover in the Longchuan River has changed significantly since the 1950s. It decreased from 55% to 24.1% from the 1950s to the 1980s due

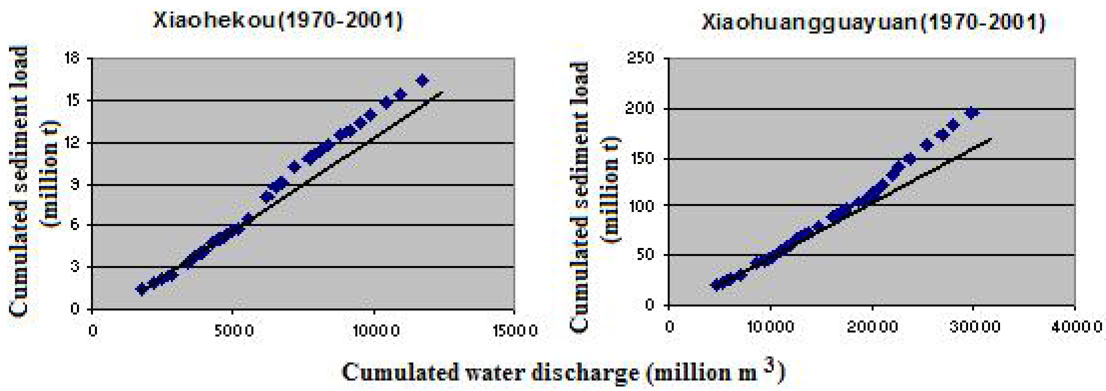
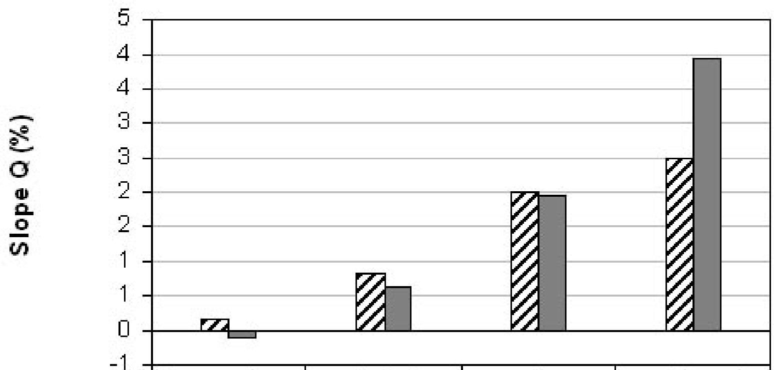


Figure 6 Relationship between cumulated water discharge and sediment flux



	temperature	precipitation	water	sediment
xiaohekou	0.179	0.838	2.005	2.487
xiaohuangugayuan	-0.115	0.627	1.957	3.947

Figure 7 Sen's slope (%) of temperature, precipitation, water discharge, and sediment flux changes

to the pressure of population and unsustainable decision making on socio-economic development. Since the late 1980s, many ecological engineering projects aiming at coordinating the economic development and environmental protection have been carried out in the basin by national and local governments. Most of these ecological engineering projects took reforestation as a measure and thus led to the increase in forested area. In 1999, the overall forest cover percentage of the basin was 39.5%. But at some places under harsh environmental condition as in the dry-hot valleys, once the vegetation was destroyed, it would be very difficult to recover. In basin areas of the dry-hot valleys in Yuanmou County, the forest cover was only 0.06% (in 1999). The slight increase might have an effective control of water discharge and sediment flux, but the opposite arguments seemed to be more convictive, because land surface disturbance during the process of reforestation occurred intensively and widely before the forests could grow up. It was observed that after deforestation, the transpiration and the water storage capacity of the soil would decrease thus lead to the increasing of the water in the river (Calder 1993). Besides, the destruction of plant cover, together with other developing activities, would usually intensify the problem of soil erosion and finally result in the increasing sediment discharge in the river.

4.3 Engineering projects

Many engineering projects, such as road construction, mining and urban construction, also have effect on the soil erosion in the basin. The natural surface of the slope is cut and the vegetation on the land will be cleared when building a road. The earth and stones dug out are usually thrown into the river or heaped up along the road. When storm comes, most of the earth flows into the river and increases the suspended sediment concentration of the water. Furthermore, in the area between Xiaohekou and Xiaohuangguayuan, which are suffered from mud-rock flows, many canals were built to lead the mud-rock flow into Longchuan River for the safe of the roads. The length of road in Chuxiong has increased from 506 km in 1952 to 14081 km in 2003. It is estimated that the sediment yield from the road construction is 100 t km^{-2} yr^{-1} and the increase of the sediment discharge in Xiaohuangguayuan Gauging Station since 1989 is partially due to the road construction (Chuxiong Hydraulics Bureau 2003). Sand collection from riverbed along the Longchan River is another contribution factor. During the past five years, the collection of sand as building material nearly became a moderate industry. It produced a huge amount of sediment in the water.

4.4 Construction of reservoirs

By contrast, constructions of reservoirs and dams could reduce sediment discharge. Since the 1950's, 14 medium size reservoirs (drainage size larger than 60 km^2), 67 small size I reservoirs, 418 small size II reservoirs and 30060 ponds, have been built. These reservoirs and dams with a total capacity of more than 300 million m^3 can trap considerable amount of sediment. The information of deposition of nine medium size reservoirs in this river basin is listed in Table 5. Dahaibo was built on the main course of Longchuan River between Xiaokekou and Xiaohuangyuan in 1959. It is estimated

Table 5 Status of deposition in reservoirs

Reservoir	Year of construction	Reservoir storage ($10^6 m^3$)	Total deposition	
			($10^6 m^3$)	(%)
Maobanqiao	1957	19.4	6.8	35.1
Jiulongdian	1958	63	5.74	9.1
Dahaibo	1958	33	7.8	23.6
Qingfeng	1969	11.2	8.93	79.7
Menglian	1983	10.4	7.5	72.1
Bingjian	1982	17.8	2	11.2
Zhongtun	1991	11	1.1	10.0
Laochanghe	1992	15.7	3.83	24.4
Xijinhe	1999	11.2	5	44.6

that 90% of the sediment passed through Xiaohekou is trapped by the Dahaibo Reservoir (Chuxiong Hydraulics Bureau 2003).

Sediment yields measured at the plots, 10 small size (II) reservoirs and the two gauging stations in the river are plotted in Figure 8. The average sediment yields from the plots, reservoirs and river are 19,700 t km^{-2} yr^{-1}, 3536.7 t km^{-2} yr^{-1}, 601 t km^{-2} yr^{-1}, respectively. The sediment yield from the plots is much higher than that from reservoirs and the river, suggesting that these reservoirs might be an important control on sediment delivery to the main river (Lu and Higgitt 2001). However, the constructions of these reservoirs did not change the increasing trend of sediment discharge in the river. This contrasts the reports in other tributaries of the Upper Yangtze River (Dai and Tan 1996, Lu and Higgitt 1998). For example, Lu and Higgitt (1998) reported that the observed decreases in sediment yield were due to the large reservoir schemes on the river.

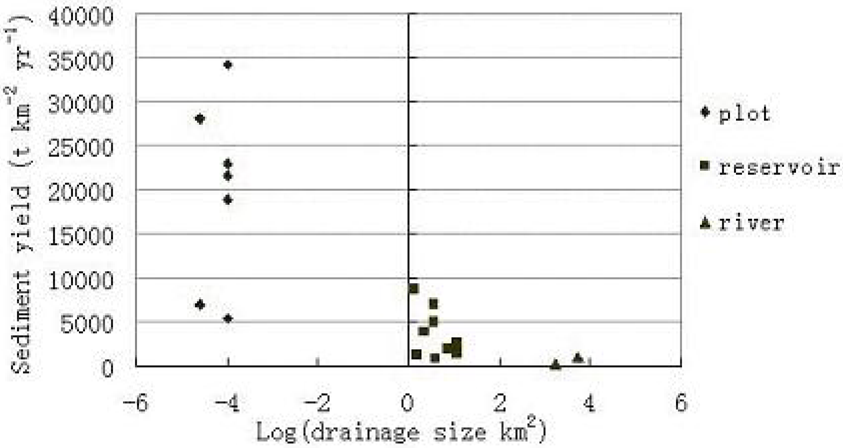


Figure 8 Sediment yield measured at plots, reservoirs and rivers

5 Conclusions

This study indicates that Longchuan River, a typical hot-dry valley in southwest China, has experienced a significant increase in sediment discharge in wet seasons at annual basis, notably in the lower part of the basin, as a result of human activities. Human activities related to land surface disturbance, such as deforestation and afforestation, agriculture land expansion and road construction, play an important role in this context. Though a significant amount of sediment is trapped by the reservoirs, which were constructed in the 1950s, the increase in sediment discharge is still obvious. This increase was more profound since the 1990s, though there has been a tremendous effort on reforestation within the river basin. The profound changes of the hydrological regimes resulting from such human activities have significant implications for effective management of soil erosion control.

This study provides an example of time series changes in sediment discharge in a dry-hot valley in the lower Jinsha River of the Upper Yangtze River over the past decades. Attempts have been made to evaluate the impacts of climate change and human activities on seasonal changes. While some of the changes can be explained, some other issues, such as climate variation and detailed land use changes, and their impacts on the water discharge and sediment flux, require further attention. A further quantitative analysis of contributions to sediment discharge from different factors is in process.

Acknowledgement

This project is funded by National Basic Research Program of China (also called 973 program) (project No. 2003CB415105-6) and National University of Singapore (NUS grant number R-109-000-034-112).

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