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Seasonal Water Discharge and Sediment Load Changes in the Upper Yangtze, China

Analysis of seasonal water discharge and sediment load data for major tributaries of the Upper Yangtze indicates significant changes from 1957 to 1987. Discrimination between land use–induced and climatic variation–induced changes was attempted using the systematic shift in the seasonal sediment load relative to the seasonal water flow. Available evidence suggests that most of these changes were caused by human activities such as deforestation, water use, and construction of reservoirs rather than by decadal climatic variations. The changes identified in water flow and sediment flux in both wet and dry seasons for some tributaries had significant implications with respect to flooding and water shortages.

Keywords: *Water discharge; sediment transport; land use change; Upper Yangtze; China.*

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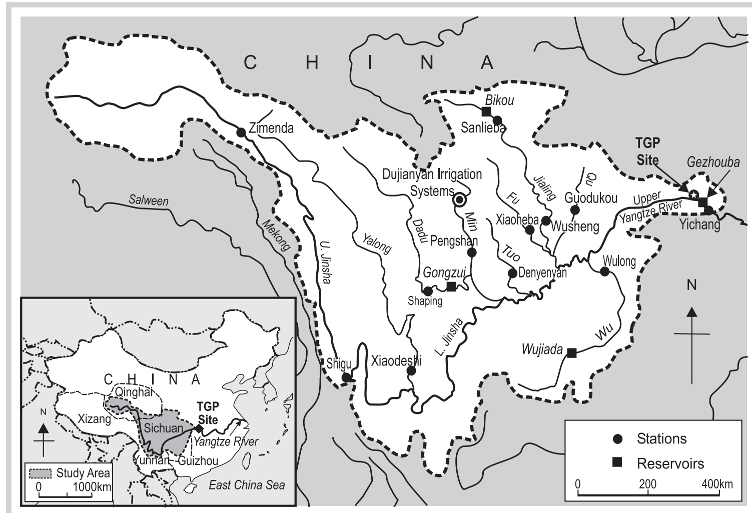


FIGURE 1 The Upper Yangtze and its main tributaries. (Map by authors)

Introduction

There is growing concern about the potential effect of landscape degradation in mountain areas on hydrological processes and catastrophic events such as floods and droughts. Deforestation in the region of headwaters, for example, is assumed to result in changes in the flow regimens of rivers downstream. The scope and magnitude of such changes have been investigated extensively (Gentry and Lopez-Parodi 1980; Bosch and Hewlett 1982; Clark 1987; Sahin and Hall 1996). A recent review by Bruijnzeel (1996) revealed that most results indicate that deforestation causes increased water and sediment yield. Whereas the results obtained from small catchment studies show clearly how hydrology responds to land use changes and human activity, uncertainty remains about water discharge (WD) and sediment load for large mountain river basins (Walling 1999). In particular, the effects of deforestation on flood and flow regimens in dry seasons are still arguable (Bruijnzeel 1996). Hewlett (1982), for example, demonstrated that there was no cause and effect relationship between deforestation in the upper streams and floods that occurred downstream. Identification and interpretation of hydrological changes can be much more difficult for large basins because of a variety of land surface conditions, spatial climatic variations, and, more importantly, various human activities and hydrological time lag in relation to activities during the investigation period. Attempts to analyze precipitation, streamflow, and sediment transfer data from the Himalayan region, for example, are inconclusive (Carson 1985; Hamilton 1987; Ives and Messerli 1989; Hofer 1993). Carson (1985) demonstrated that flooding and sedimentation problems in India and Bangladesh were caused by the geomorphic character of the rivers and river management schemes and that deforestation likely played a minor role in these problems. Hamilton (1987) also concluded that afforestation will not prevent flooding or sedimentation in the lower reaches of major rivers or significantly reduce flooding during major storm events.

Profound changes in land use, including widespread deforestation and extension of agricultural land, have taken place during the past 4 decades in China because of population pressure and socioeconomic policies. Three historical events, in particular—the Great Leap Forward, the Cultural Revolution, and the Land Responsibility Reforms—have had profound effects on land use and hence on soil erosion and sediment transport (ST) potential (Lu and Higgitt 1998). The result was a significant decrease in forest cover in China. This is particularly acute in the Upper Yangtze Basin. For example, forest cover in Sichuan decreased from 19% to 12% between the 1950s and the 1980s, whereas in Guizhou, it declined from 23% to 13% between the 1960s and the 1980s (Yu et al 1991). Such a great reduction in forestland cover might be expected to lead to increasing WD and sediment loads, but studies examining sediment yields within the Upper Yangtze (Gu and Douglas 1989; Dai and Tan 1996) have noted the lack of a trend in sediment output at Yichang despite apparent increases in soil erosion within the basin. This is mainly caused by the increasing storage capacity of water conservancy projects, in gener-

TABLE 1 Hydrological regimens for the stations examined. Figures in brackets indicate the lowest and highest water and sediment yields. (Source: own data)

No	Stations	Tributary	Drainage area (km^2)	Measurement years	Average water yields (mm/y)	Average sediment yields (tons/km^2/y)
1	Zimenda	Jinsha	137,704	1957–1987	90 (51–132)	68 (9–139)
6	Shigu	Jinsha	232,651	1957–1987	175 (129–233)	91 (30–182)
67	Xiaodeshi	Yalong	118,294	1958–1987	418 (324–622)	249 (107–544)
116	Shaping	Dadu	75,016	1966–1987	576 (477–681)	420 (189–732)
94	Pengshan	Min	30,661	1957–1987	443 (310–584)	337 (131–721)
128	Denyenyan	Tuo	14,484	1957–1987	655 (370–984)	617 (73–1571)
197	Xiaoheba	Fu	29,420	1957–1987	508 (283–806)	650 (59–3121)
154	Sanleiba	Jialing	29,247	1957–1987	355 (232–535)	563 (110–1381)
164	Wusheng	Jialing	79,714	1957–1987	342 (197–558)	928 (123–2542)
180	Guodukou	Qu	31,626	1957–1987	624 (295–1246)	630 (102–1517)
207	Wulong	Wu	83,035	1957–1983	605 (384–824)	390 (134–730)
250	Yichang	Main river	1,005,501	1957–1987	431 (355–518)	524 (361–725)

al, and by large reservoirs, in particular, which trap considerable portions of eroded sediment and prevent its transfer to the river (Luk and Whitney 1993; Lu and Higgitt 1998). It is estimated that by the mid 1980s the total storage capacity of the reservoir exceeded 16 billion m^3 in the Upper Yangtze Basin (Gu et al 1987).

By examining annual sediment load data in subcatchments, Lu and Higgitt (1998), however, have identified parts of the basin that increased or decreased in importance as suppliers of sediment from the 1950s to the 1980s. In regions with monsoon climates, such as the Upper Yangtze, water and sediment discharge are highly concentrated in summer, from July to September. The annual values dominated by these months may conceal significant differences between wet and dry seasons. This article examines the seasonal differences in stream flow and sediment load responses in relation to land use changes and human activity. Its aims are to:

1. Examine seasonal differences in hydrological trends in the monsoon climate.
2. Investigate possible shifts in the sediment load relative to the water flow due to human activity.
3. Attempt to discriminate between these human effects and the effect of climatic variations.

Study area

The Upper Yangtze, traditionally referring to the catchment upstream of Yichang, consists of a number of major tributaries: the Upper Jinsha, Yalong, Dadu, Min, Tuo, Fu, Jialing, Qu, and Wu (Figure 1). The climate is mainly influenced by elevation because atmospheric circulation is affected by the Qinghai-Tibet Plateau (Ruddiman et al 1989). Most of the basin has a subtropical climate, with precipitation greater than 1000 mm, whereas the western plateau and mountainous areas have a temperate or arid climate, with precipitation less than 400 mm (Lu and Higgitt 1999). Under the influence of the monsoon climate, 70% of the annual precipitation falls in summer (June, July, and August) and 50% of the annual WD occurs in the period July–September. Population densities are inversely related to elevation, with values ranging from less than 10 people per km^2 in the Tibet Plateau to more than 500 people per km^2 in the eastern part of the basin (ie, the Sichuan Basin), an area with one of the highest population densities in China. Deforestation is very common across these large basins, whereas reservoir construction is mainly concentrated in the Sichuan Basin. The Yalong tributary, for example, used to be covered by natural forest but at present there are only few trees left along the river valley. It was reported that during flooding of the Yangzte in 1998, the 300-m-wide river was blocked by tens of thousands of logs, making navigation impossible.

Hydrological data

The available WD and sediment load data cover the period from 1957 to 1987. Data after 1987 are no longer publicly available; therefore, recent trends cannot be determined. The study examines monthly and extreme daily WD and ST for the 12 stations, 11 covering all major tributaries plus the Yichang station that covers the entire Upper Yangtze Basin (Figure 1). ST refers to suspended sediment and was collected in line with standard procedures (Lu and Higgitt 1999). Error crept into sediment measurements through the use of daily or weekly measurements (no measurements in dry season for some stations), rather than through continuous monitoring, which is likely to underestimate sediment load during peak hours. The basic information for the 12 stations is summarized in Table 1. The Jinsha tributary had the lowest water and sediment yields, Tuo had the highest water yields, and Jialing in Wusheng station had the highest sediment yields. Whereas the effects of land use changes are an important issue, analysis of the temporal trends in hydrology is problematic. There are problems in obtaining annual climatic records; therefore, it is difficult to relate hydrological changes to a climatic signal and segregate the possible land use effects. In addition, land use changes vary substantially across these large basins; the relevant information is greatly generalized and the size of the basin

TABLE 2 Water discharge (WD) and sediment transport (ST) changes for each month in the measurement years shown in Table 1 at 95% significance level (Spearman correlation); —: no data; ○: no change; △: significant increase; ▽: significant decrease. (Source: own data)

Group	No	Station	Hydrological variables	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean (Lu and Higgitt 1998)
I	1	Zimenda	WD	○	○	○	○	○	○	○	○	○	○	○	○	○
			ST	○	○	○	○	○	○	○	○	○	○	○	○	○
I	6	Shigu	WD	○	○	○	○	○	○	○	▽	○	○	○	○	○
			ST	△	○	○	○	○	○	○	○	○	○	○	○	○
II	67	Xiaodeshi	WD	○	○	○	○	○	○	○	○	○	○	○	○	○
			ST	—	—	—	—	○	○	○	○	○	○	—	—	○
II	116	Shaping	WD	○	▽	○	○	○	○	○	○	○	○	○	○	○
			ST	△	△	△	○	○	○	△	○	△	○	△	△	△
II	180	Guodukou	WD	○	○	○	○	○	○	○	○	○	○	○	○	○
			ST	—	—	—	○	○	○	△	○	○	○	—	—	△
II	207	Wulong	WD	○	○	○	○	○	○	○	○	○	○	○	○	○
			ST	○	○	○	○	○	○	△	○	○	○	○	○	△
III	94	Pengshan	WD	○	○	○	○	▽	○	○	▽	○	▽	▽	○	○
			ST	○	○	○	○	○	○	○	○	○	○	○	○	○
III	128	Denyenyan	WD	○	○	○	○	○	○	○	○	○	○	○	○	○
			ST	—	—	—	▽	○	○	○	▽	○	▽	—	—	▽
III	197	Xiaoheba	WD	○	○	○	○	○	○	○	▽	○	▽	▽	○	○
			ST	—	—	—	○	○	○	○	○	○	▽	—	—	○
III	154	Sanleiba	WD	○	△	△	○	○	○	○	○	○	▽	○	○	○
			ST	—	—	—	▽	▽	○	○	▽	▽	▽	—	—	▽
III	164	Wusheng	WD	○	○	○	○	○	○	○	○	○	▽	○	○	○
			ST	—	—	—	▽	○	○	○	○	○	▽	▽	○	○
IV	250	Yichang	WD	○	○	○	○	○	○	○	○	○	○	○	○	○
			ST	▽	▽	▽	○	○	○	○	○	○	○	▽	▽	○

causes potentially long time lags between land use changes and their effects on downstream hydrology.

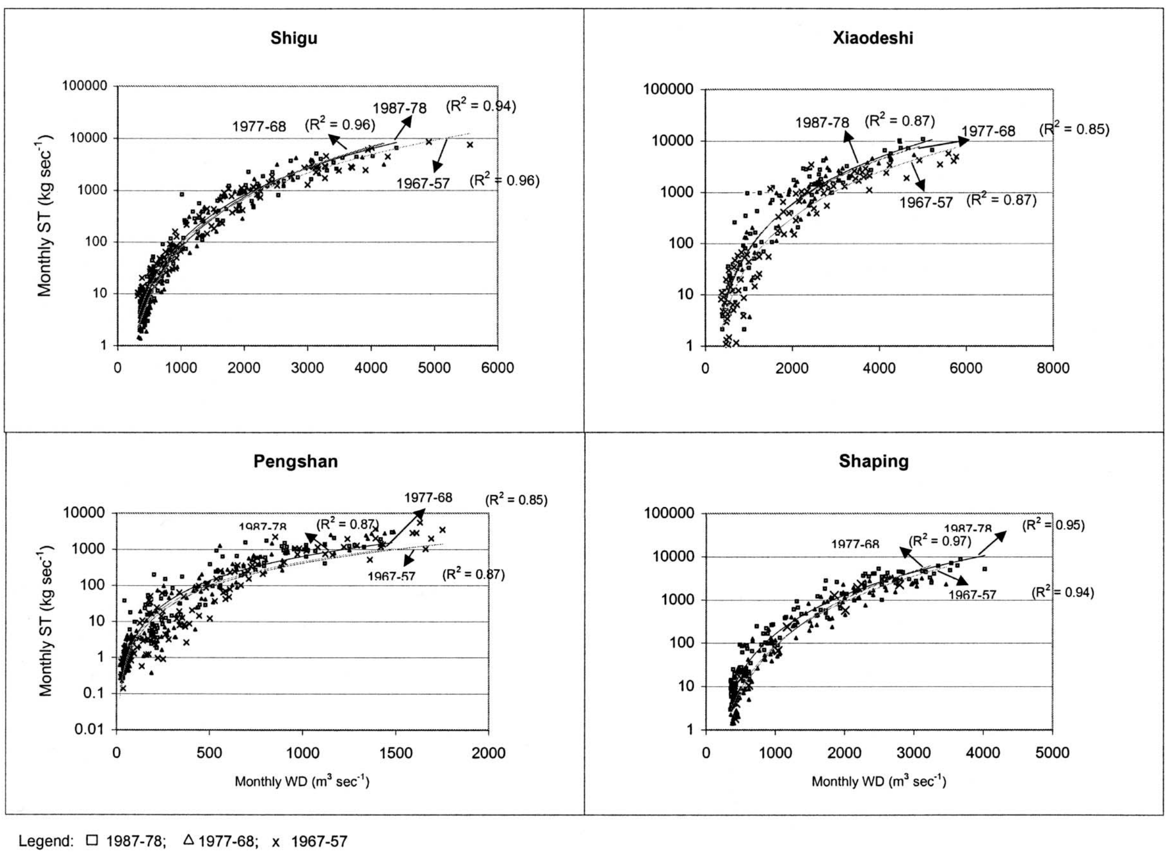
Methods

The Spearman test, a nonparametric tool, was used to measure the association between the seasonal hydrological variables (monthly or extreme daily WD and sediment load) and the year in which they occurred. A statistically significant association between these variables indicates a trend. The Spearman test has been used in a similar manner for investigating trends in annual rainfall and runoff (Keim et al 1995) because this test accepts ordinal data and data assumptions are more relaxed when compared with the parametric Pearson method of correlation. Interpretation of the determined trends must be done prudently because of both the varied record lengths (Keim 1997) and the cyclicity of climatic and hydrological data during the test periods. This is particularly problematic if records are less than about 20 years old (Ives and Messerli 1989). In our study, most of the hydrological stations have records for a 31-year period, 1957–1987 (Table 1).

TABLE 3 Maximum and minimum monthly and daily water discharge (WD) and sediment transport (ST) changes in the measurement years shown in Table 1 at 95% significance level (Spearman correlation). —: no data; ○: no change; △: significant increase; ▽: significant decrease. (Source: own data)

Group	No	Station	Hydrological variables	Maximum monthly	Minimum monthly	Maximum daily	Minimum daily	Annual mean (Lu and Higgitt 1998)
I	1	Zimenda	WD ST	○ ○	○ ○	○ ○	○ —	○ ○
I	6	Shigu	WD ST	○ ○	○ ○	○ ○	○ —	○ ○
II	67	Xiaodeshi	WD ST	○ △	○ —	○ ○	○ —	○ ○
II	116	Shaping	WD ST	△ △	▽ △	○ △	▽ —	○ △
II	180	Guodukou	WD ST	○ ○	○ —	△ ○	○ —	○ △
II	207	Wulong	WD ST	○ △	○ ○	○ △	○ —	○ △
III	94	Pengshan	WD ST	▽ ○	○ ○	○ ○	○ —	○ ○
III	128	Denyenyan	WD ST	○ ○	○ —	○ ○	▽ —	○ ▽
III	197	Xiaoheba	WD ST	○ ▽	○ —	○ ○	○ —	○ ○
III	154	Sanleiba	WD ST	○ ▽	△ —	○ ○	▽ —	○ ▽
III	164	Wusheng	WD ST	○ ○	○ —	○ ○	○ —	○ ○
IV	250	Yichang	WD ST	○ ○	○ ▽	○ △	○ —	○ ○

FIGURE 2 Monthly ST against monthly WD for the 4 stations less affected by reservoirs in western mountain areas. (Source: own data)



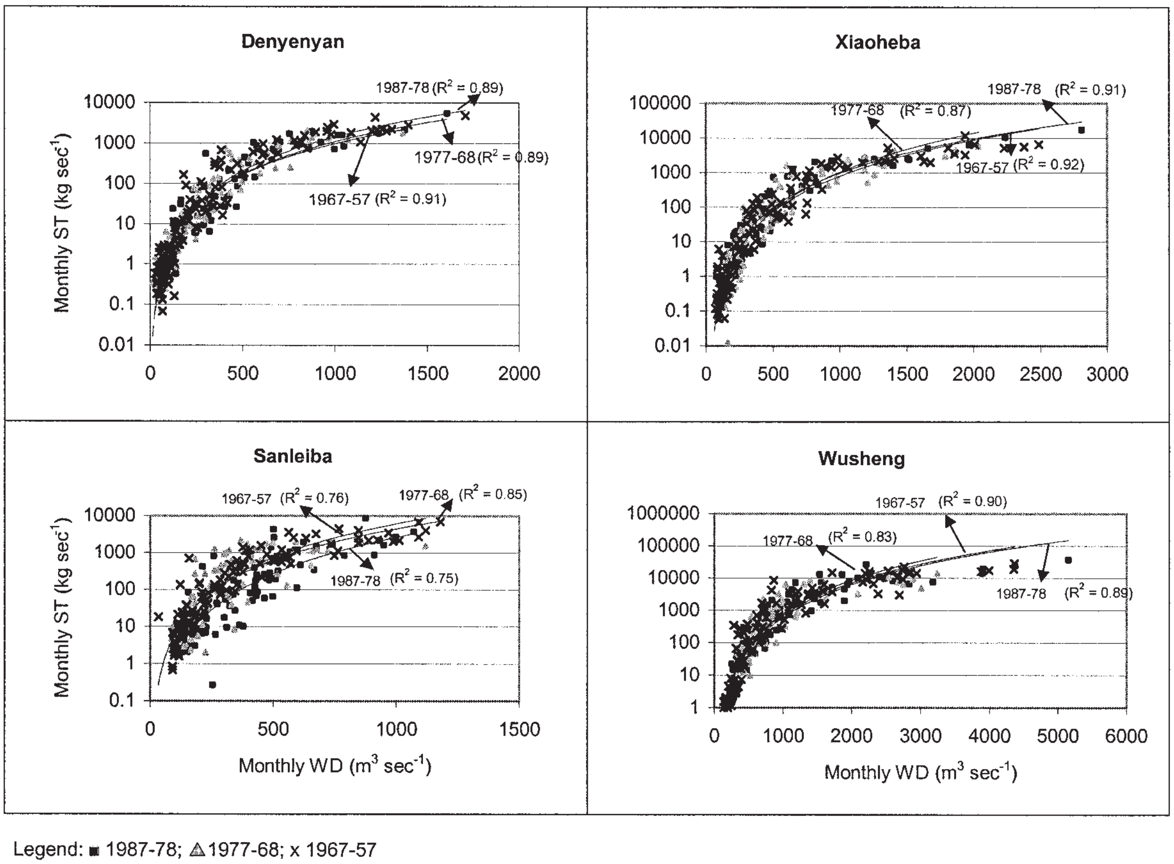
Results

Monthly changes

A marked feature of the monthly changes (Table 2) is that the Yichang station experienced significant decreases in ST from November to March, with no substantial change in flows, and typically, the tributaries show much greater variability in the changes in flow and sediment load. Only 2 of the 12 stations had no changes at all in monthly WD and ST: Zimenda and Xiaodeshi, possibly because both stations are located in sparsely populated areas. The remaining stations showed significant changes in WD or ST for at least 1 month, but the months in which changes occur and the direction of change are not consistent across the basin. Although there is a tendency for changes to occur more commonly between October and March, changes are also detectable in the summer months in many cases, which does not match the observed seasonal timing of changes at Yichang.

Some of the monthly changes are reflected by changes in the annual mean. Stations with significant changes in annual sediment delivery are also those that show significant changes in mean monthly values (Table 2). Yet, there are also stations (Guodukou and Wulong) in which the apparent changes in annual ST are the result of significant changes during only 1 (wet season) month and other stations (eg, Wusheng) in which significant monthly changes (normally dry season) do not produce a significant change in the annual mean ST. There are 2 stations with changes in WD and ST during 8 months of the year: Shaping and Sanleiba. The remaining basins show changes during 4 or fewer months. The most notable changes are an increase in sediment load during the winter dry season at Shaping, contrasting with decreasing loads in the summer at Sanleiba. In both cases, there is no significant trend in WD in most of the corresponding months. The most consistent pattern is the decrease in monthly WD in October and November at several stations, often accompanied by a decrease in ST. But changes in monthly WD are not always associated with a change in ST (eg, at Pengshan).

FIGURE 3 Monthly ST against monthly WD for the 4 stations heavily affected by reservoirs in the Sichuan Basin. (Source: own data)



Maximum and minimum monthly changes

Apparent changes in monthly WD or ST may be caused by shifts from year to year in the onset of wet and dry seasons as well as by long-term spatial shifts in precipitation patterns. The effect of annual differences in timing of wet and dry seasons can be circumvented by looking only at the extreme monthly discharge and load, independent of the calendar month (Table 3). Although there are changes in the monthly extremes at many of the stations, only at Shaping are there changes in both WD and ST extremes; here it is notable that minimum monthly ST increased, whereas minimum WD decreased. Monthly maximum ST decreases in 3 stations (Denyenyan, Xiaoheba, and Sanleiba) and increases in 3 stations (Xiaodeshi, Shaping, and Wulong). Minimum monthly loads change only at Shaping and Yiching, but data are missing for several other stations. The changes in monthly maximum ST at most stations are consistent with the changes in mean monthly ST. But in some stations, the trends in mean and maximum differ (eg, Xiaodeshi).

Maximum and minimum daily changes

The daily extremes (Table 3) show fewer changes than do the monthly data, presumably because they reflect single events and are inherently more variable. Shaping station had a significant increase in maximum daily ST and a decrease in minimum daily WD. Deyenyan and Sanleiba also had a decrease in minimum daily WD, whereas Guodukou experienced an increase in maximum daily WD and Wulong an increase in maximum daily ST. One interesting result is that at Yichang there was a significant increase in maximum daily ST, which is contrary to the monthly values showing no change. This maximum daily increase was a result of either the increases at the Shaping and Wulong stations (Table 3) or the regulation of the Gezhouba Dam immediately above Yichang (Figure 1). The increase in maximum daily WD implies an immediate runoff after rainfall and thus increased possibility of flooding in the rainy season. Zhao (1992), for example, reported that in West Sichuan the incidence of flooding increased from once in 15 years to once in 5 years. The evidence is consistent with the reports of Gentry and Lopez-Parodi (1980) and Clark (1987).

Discussion

Comparison of annual and seasonal changes

The changes in monthly or extreme daily WD and sediment load may or may not be related to changes in the annual mean. If the monthly changes are not in the same direction (eg, WD at Shaping), the annual mean would not reflect the monthly changes. This demonstrates that seasonal data are more useful than annual data in detecting hydrological changes under a monsoon climate. The water flow and sediment flux in the dry season contribute less to the annual value but can be used as a clue to detect certain signals responding to land surface disturbance. This is particularly true for the Shigu, Xiaodeshi, Pengshan, and Yichang stations, all of which had changes in seasonal data but not in the mean annual value (Tables 2, 3).

Spatial patterns of the changes

The stations studied can be categorized into 4 groups on the basis of the determined seasonal changes. The first group includes Zimenda and Shigu in the Jinsha tributary, where hydrological regimens were relatively stable (Tables 2, 3). This tributary, however, is ecologically fragile and vulnerable because of high elevation and hence requires more attention. The second group includes Xiaodeshi and Shaping, both located in the transition area between the Tibet Plateau and the Sichuan Basin, plus Guodukou and Wulong. This group witnessed significant increases in monthly or daily changes. The third group includes Pengshan, Denyenyan, Xiaoheba, Sanleiba, and Wusheng, located in the Sichuan Basin, where significant decreases in WD or ST have been observed during many months, most commonly in October and November (Table 2). The seasonal regimens at Yichang responded differently compared with the 11 stations, indicating that none of the above tributaries has major control over the station. The spatial pattern for the major tributaries was due to effects of different human activities, as discussed below.

Discrimination between the changes

The detected changes in WD and ST may be due to decadal climatic variations and land surface disturbance such as deforestation and reservoir constructions. Discrimination between the 2 induced changes is difficult without further information. It is, for example, difficult to relate the hydrological changes to climate signals and to segregate possible land use effects without annual climatic records throughout the basin. Walling and Webb (1996) suggested that plots of cumulative WD against cumulative ST are a useful graphic method of showing the changing relationship between ST and WD, whereas Helsel and Hirsch (1992) recommend examining the temporal trend in the residuals from sediment load and WD regression. This study attempts to use the systematic shift in the sediment load relative to the flow to deduce some of the reasons behind the detected seasonal changes. This is more informative than simply looking at the trends in WD and ST separately.

The maximum monthly increases in WD and ST, and minimum monthly decrease in WD but increase in ST at Shaping in the Dadu tributary, for example, could be a typical hydrological signal attributable to environmental deterioration caused by deforestation. Therefore, changes in the second group of stations studied provide preliminary evidence of the effect of deforestation. It was reported that over 50% reduction in forest cover took place in West Sichuan in only 40 years (Winkler 1996). This significant reduction in forest cover is responsible for gully generation and frequent slope failures in the tributary. For the Min tributary, the significant decreases of monthly WD during 4 months at Pengshan did not result in similar decreases in monthly ST (Table 2), suggesting an increase of sediment supply. In this tributary, forest cover was reduced from 32% in 1949 to only 14% in the 1990s. The WD decrease at Pengshan was due to water diversion through the Dujiangyan Irrigation Systems, with a history of over 2000 years, caused by a higher demand for irrigation in the Sichuan Basin. The arable land irrigated by the systems was 1920 km^2 in 1949 but increased to 6670 km^2 in the 1990s.

The above analysis of the systematic shift in the sediment load relative to water flow clearly points to the effect of land use changes for the 2 stations. However, if the changes in water flow and sediment flux are in the same direction, there may still be a change in an average sediment concentration. This will be further investigated using sediment-rating curves (Figures 2, 3). The data are divided into 3 periods: 1957–1967, 1968–1977, and 1978–1987, which not only give about 10 years' time span for each period but also coincide with the 3 historical events: the Great Leap Forward, the Cultural Revolution, and the Land Responsibility Reform. The latest period of 1978–1987 had consistently higher sediment concentration for the 4 selected stations in western mountain areas (Figure 2), even at Shigu, that did not show many changes in monthly and extreme monthly ST (Tables 2, 3). In other words, the higher monthly ST in the latest period was not due to the increase in monthly WD. If increases in ST are out of proportion with, or in the opposite direction to, changes in WD, this points to the effect of land surface changes rather than to annual or decadal climatic variation as the causative factor.

The period 1978–1987 had a lower sediment-rating curve than did the other 2 periods (1957–1967 and 1968–1977) for most of the 4 selected stations located in the Sichuan Basin (Figure 3). Numerous reservoirs and other water conservation projects have been developed within the Sichuan Basin, one of the areas with the highest population density in China. The Tou, Fu, and Qu tributaries have much higher ratios of reservoir capacity relative to catchment area than do the Jinsha and Yalong tributaries (Lu and Higgitt 1998). The construction of these water conservancy projects trapped significant amounts of sediment and reduced sediment concentrations and thus the sediment-rating curve, although massive deforestation also occurred in these tributaries over the past decades. The regulation of the reservoirs (ie, storing water in rainy season and releasing in dry season) resulted in a decrease in monthly ST in rainy seasons but an increase in monthly WD in dry seasons (Tables 2, 3).

Summary and conclusions

The Spearman test indicated that some of the major tributaries experienced significant changes in seasonal water flow and sediment load. The Jinsha tributary is relatively stable for seasonal hydrological regimens. The tributaries such as the Yalong, Dadu, Qu, and Wu witnessed significant monthly or extreme daily WD or ST increases. The tributaries of the Min, Tuo, Fu, and Jialin, located in the Sichuan basin, experienced monthly or extreme daily WD or ST decreases. The entire Upper Yangtze basin at Yichang experienced decreases in sediment load from November to March but significant increases in maximum daily ST without substantial changes in water flow.

This study demonstrates that seasonal data are more useful than aggregate annual values in a monsoon climate. The relation between seasonal water flow and sediment load changes can be used as an indicator of hydrological degradation if climate records are not available. By using this method, this study further discriminates between changes attributable to climate variation and those induced by human activity. Evidence suggests that the significant increases of sediment load in wet seasons and decreases of water flow in dry seasons (eg, Dadu tributary) were due to deforestation, and the inconsistency between water flow and sediment load changes (eg, Min tributary) was predominately due to water consumption.

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