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Determining variations in sediment yield in large river basins: an example of the Upper Yangtze

DAVID L. HIGGITT

Department of Geography, University of Durham, Science Laboratories, South Road, Durham DH1 3LE, UK

e-mail: d.l.higgitt@durham.ac.uk

XIXI LU

Department of Geography, University of Western Ontario, London, Ontario N6A 5C2, Canada

Abstract Numerous attempts have been made to explain global and regional patterns of sediment yield in terms of climate and topography. Extending analysis to include human impact via land use and to examine patterns of sediment sources *within* large basins has been limited. This has mainly been due to the difficulty of obtaining detailed land-use information for large areas and of isolating land-use effects from other controls. Examination of temporal and spatial variability of sediment yields in relation to controlling variables, including land cover, has been undertaken in the Upper Yangtze, China, in an attempt to predict future sedimentation impacts. Long-term sediment yield measurements from Yichang do not indicate any trend despite widespread evidence for increased soil erosion (Gu & Douglas, 1989; Wen, 1993). This apparent paradox is investigated by attempting to discriminate parts of the basin where there is evidence for trending sediment yield, by examining sediment delivery characteristics of tributaries and by developing a simulation model of sediment yield response to disturbance. Although the controls on sediment yield remain complex and only partly explained by multivariate analysis, the detailed examination of the temporal and spatial patterns of sediment yield provide a basis for modelling future changes in sediment delivery.

INTRODUCTION

Is it possible to develop predictive models of sediment delivery for very large basins? The construction of the Three Gorges Dam on the Yangtze River in China will impound a reservoir with a basin area about 1 million km^2. In the eastern part of the basin area there has been much concern about the escalating extent and magnitude of soil erosion. Clearly, the delivery of sediment to the reservoir is one of a number of environmental problems that requires attention, but, in general, there has been limited research on elucidating the controls on sediment yields within large basins. This paper discusses attempts to determine the factors that control spatial and temporal patterns of sediment yield in the Upper Yangtze. Analysis is based on combining a data archive of suspended sediment measurements from 250 gauging stations with variables derived from a number of geodatabases. In particular, it is noted that the evidence for increased soil erosion within the basin is not reflected in the long-term record of sediment yield at Yichang, the gauging station which is just downstream of the dam site. Exploratory analysis of trends in sediment yield variability within the basin may assist in explaining the overall basin response.

THE UPPER YANGTZE: CHARACTERISTICS AND DATA SOURCES

The Upper Yangtze refers to the basin upstream of Yichang, Hubei Province (Fig. 1). It includes a diverse range of environments, rising on the arid Qinghai-Xizang Plateau at an elevation above 4000 m and descending into the Sichuan basin. The majority of the basin, with the exception of the extreme west, experiences a subtropical monsoon climate. Of the major tributaries, the Upper Jinsha, Yalong, Dadu and Min principally drain the mountainous areas to the west of the basin. The Tuo, Fu, Jialing and Qu flow through areas of high population density and agricultural activity. The Wu, the only significant right-bank tributary, is largely agricultural but drains the karst uplands of Guizhou Province.

Profound changes affecting land use and resource exploitation in rural China during the last four decades have been particularly significant to the five "eastern" tributaries noted above. It is estimated, from land-use inventories carried out in the 1950s and 1980s, that forest cover reduced from 19% to 12% in Sichuan and from 23% to 13% in Guizhou (Yu *et al.*, 1991). Land affected by erosion increased from 16% to 67% in Sichuan and from 11% to 31% in Guizhou. It might be expected that an increase in the extent of land degradation might be reflected in increased sediment load in the Upper Yangtze, but the period also witnessed rapid development of local water conservancy projects comprising ponds, check dams, ditches and small headwater reservoirs. These activities may account for the trapping and temporary storage of a proportion of the eroded sediment (Luk & Whitney, 1993). Together with more recent large hydro-electric power (HEP) schemes it has been estimated

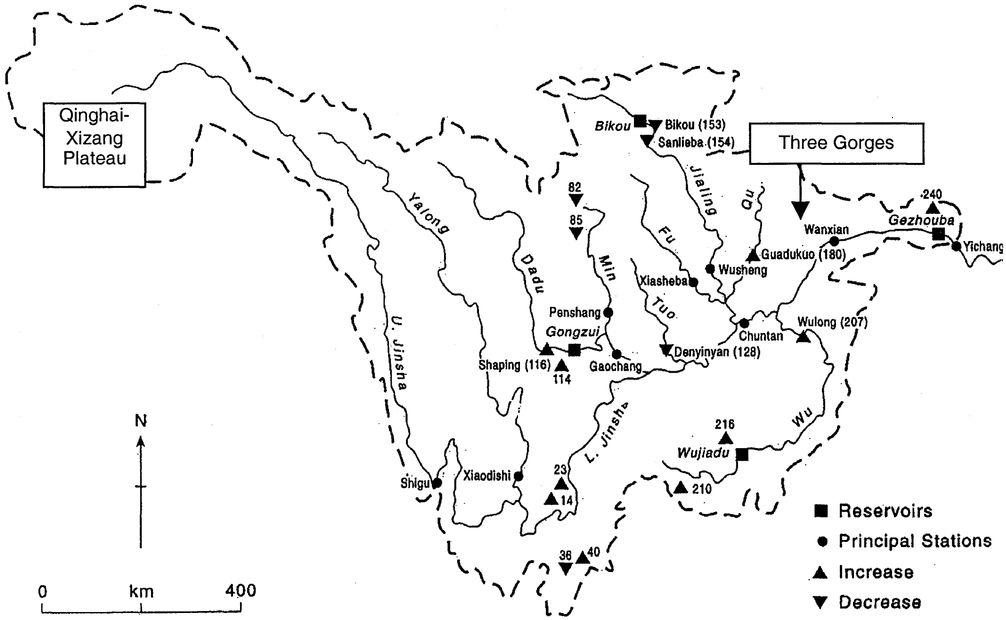

Fig. 1 The Upper Yangtze basin indicating the distribution of major tributaries and some gauging stations exhibiting trending sediment yields (modified from Lu & Higgitt, 1998).

that total reservoir capacity in the Upper Yangtze basin upstream of the Three Gorges Project exceeds 16 billion m^3.

The sediment yield and runoff data have been extracted from the China Hydrological Books, which summarize measurements from a network of hydrographic stations throughout the Upper Yangtze (Higgitt & Lu, 1996). Sediment-load data were extracted from 250 stations in the Upper Yangtze for the period from 1956 to 1987 (after which records are not in the public domain). There are large variations in the spatial distribution, length and period of operation and the basin area of gauging stations, which have implications for statistical analysis. There are 56 stations with records of 25 years or more. Together with six stations from the Wu tributary (which is otherwise under-represented), these 62 sub-basins are used in a more detailed analysis of sediment yield variability (Lu & Higgitt, 1999).

SPATIO-TEMPORAL VARIABILITY IN SEDIMENT YIELDS

The GIS environment enables values for basin characteristics to be obtained for both individual pixels (approximately 1 km^2) and for delineated sub-basins. Multivariate

Table 1 Definition and source of variables used in multivariate analysis of sediment yield.

Variable	Definition	Source
Specific sediment yield	Annual sediment load per unit area (t km^{-2} $year^{-1}$)	China Hydrological Yearbooks
Mean elevation	Mean of elevation of all cells within delineated catchment boundary (m)	30 arcsecond DEM (pixel size approx. 1 × 1 km, height accuracy ±30 m)
(Sub-)catchment area	Catchment above gauging station (km^2)	China Hydrological Yearbooks—boundaries derived from DEM or digitized from various map sources
Basin length	Maximum straight line distance between watershed and gauging station (km)	Arc/Info utility
Basin relief	Difference between maximum and minimum cell elevation within catchment boundary (m)	From statistical file after clipping DEM using delineated catchment boundary
Relative relief	Basin relief/basin length (m km^{-1})	Derived index
Mean slope	Mean of slope of all cells within delineated boundary (degrees)	Arc/Info slope grid generation (maximum elevation changes within nine neighbouring cells)
Population density	Number of persons (km^{-2})	Asian Population database, derived from 1992 census
Precipitation	Mean annual precipitation from 0.5 × 0.5 degree resolution (mm)	Global Ecosystems Database (Version 1.0, 1992)
Runoff	Mean annual runoff (mm)	China Hydrological Yearbooks
Land-cover class – Unvegetated – Alpine meadow or steppe – Grass/shrub – Shrub/woodland – Woodland – Cropland (mosaic <50%) – Cropland (mosaic >50%) – Paddy field	Regrouped land-cover classifications	China Land Cover Database, EROS Data Center (based on AVHRR data)

techniques can then be employed to examine the extent to which variation in sediment yields can be explained by basin controls (defined in Table 1). Initially, the influence of the following six controlling variables was considered: mean elevation, basin relief, slope, population density, precipitation and runoff. Interpretation of spatial variability is complicated by the interaction of several controlling factors and the data are highly scattered. Following previous studies of global sediment yields (Jansson, 1988; Summerfield & Hulton, 1994; Ludwig & Probst, 1996), a strategy of grouping data was employed. Based on tributary groupings clear patterns in sediment yield become evident in the Jinsha-Yalong and Dadu-Min basins. Multiple regression suggests that up to 95% of the variability in sediment yields in the west of the Upper Yangtze can be explained in terms of "natural" basin characteristics, but these provide a relatively poor explanation (33%) of sediment yields in the more populated east of the basin. In order to investigate whether land use provides the additional explanation, land-cover information has been obtained from the China land-cover database, a part of the global land-cover project of EROS (Earth Resources Observation System) Data Center. The database is derived from 1 × 1 km Advanced Very High Resolution Radiometer (AVHRR) data. The 157 different land-cover types have been regrouped into eight land-cover classes (Higgitt & Lu, 1999). However, the relationship between specific sediment yield and any measure of agricultural land for the 62 sub-basins is not significant. Incorporating land cover into the multiple regression equations also fails to improve the degree of explanation. Factor analysis suggests that the basins with the highest sediment yields are highly scattered in factor space, such that they have few common characteristics. It is often individual basin characteristics, such as the presence of an erodible substrate (e.g. loess) which is the dominant control on sediment yield. There is also a tendency towards some clustering of intermediate sediment-yield rates in association with a high proportion of agricultural land.

The use of geodatabases for deriving spatially-distributed environmental variables is now suitable for examining controls on sediment dynamics within large basins. However, the reliability of some variables remains problematic. Mean slope for each basin is derived by averaging the slope for each pixel, which in turn is calculated from maximum elevation change within nine neighbouring pixels, using an Arc Info utility. Clearly this is a crude measure of the effect that gradient might exert on soil erosion processes. Recent examination of scale effects on digitized elevation model (DEM) construction (Zhang *et al.*, 1999) have indicated that a fractal model may be suitable for representing slopes from relatively coarse (e.g. 1 km^2) grids. The increasing availability and resolution of environmental data sets will enable more sophisticated modelling to be attempted. Concerning the incorporation of land-use information, the planned acquisition strategy of Landsat 7, which was launched in April 1999, should provide a much more reliable stream of data in the near future.

A fundamental problem of the approach outlined above is that, in relating time-averaged sediment yields to spatially distributed basin characteristics, significant changes in the distribution of controlling factors are ignored. Variables such as population density and land cover are not time-constant. The major changes in resource exploitation and agricultural activity experienced within the basin may be evident in temporal patterns of sediment yield. There is evidence for both increasing and decreasing sediment yields in different parts of the basin over different periods (Lu & Higgitt, 1998). A statistically significant linear regression model of sediment yield against year of measurement ($\alpha = 0.05$) could be fitted to 16 of the stations, of which 10 (7.9% of basin area) displayed increasing trends and six (2.8%) displayed decreasing trends (Fig. 1). The sharpest rates of increasing sediment yield for large stations is experienced on the Dadu, Qu and Wu, and for decreasing sediment yield is experienced on the Tuo and Jialing tributaries. The latter reflect the impact of large reservoir projects. Seasonal data (monthly and daily maximum and minimum sediment load and water discharge) analysis supports the findings from annual sediment loads. The tributaries of the Yalong, Dadu and Min, located in the transition area between the Qinghai-Xizang Plateau and the Sichuan basin, together with the Qu and Wu, witnessed significant increases in seasonal and daily sediment load over the last 40 years.

Two hypotheses can be advanced to examine the apparent paradox of increasing soil erosion but no change in net sediment yield in the Upper Yangtze. First, it might be considered that increased sediment production on hillslopes is counteracted by impoundment in reservoir storage on some of the major tributaries. Evidence for changes in the transmission of sediments down tributaries may be reflected in sediment delivery characteristics. Second, the impact of episodic disturbance across the basin as manifest by land-use change, can be simulated to investigate probable changes in sediment yield.

SEDIMENT DELIVERY CHARACTERISTICS

The spatial distribution of gauging stations within the Upper Yangtze enables the sediment delivery characteristics of each tributary to be examined. Following De Boer & Crosby (1996), regression relationships between sediment load (SL) and basin area (DA), taking the form $SL = aDA^b$, have been obtained. The value of exponent b indicates the extent to which sediment yield increases in the downstream direction. Where $b < 1$, basin area is increasing more rapidly than sediment load. This situation has been reported in many agricultural environments as a consequence of sediment storage (Walling, 1983). Counter-examples are generally found in

Table 2 Sediment delivery exponents for major tributaries of the Upper Yangtze, for all station years and for the last year in the time series.

Tributary	Coefficient a	Exponent b	Standard error of exponent	n	R^2	b, end of time series	R^2
Jinsha	697.9	0.916	0.088	39	0.744	1.149	0.647
Yalong	5219.7	0.686	0.156	12	0.659	0.622	0.584
Min	1843.3	0.827	0.077	16	0.892	1.083	0.933
Dadu	1835.0	0.816	0.129	21	0.676	0.937	0.733
Jialing	378.5	1.082	0.086	30	0.849	1.097	0.781
Qu	623.2	1.014	0.083	13	0.931	1.005	0.955
Fu	76.8	1.250	0.138	12	0.891	1.112	0.901
Wu	66.0	1.179	0.122	23	0.817	0.721	0.382
Main	751.9	0.973	0.033	18	0.982		

mountainous regions where sediment load increases more rapidly than basin area ($b > 1$) as a consequence of channel processes and/or reworking of Quaternary sediments (Church *et al.*, 1989; Dedkov & Mozzherin, 1992). Examining the sediment delivery characteristics for the 187 basins with at least 5 years data, the exponents for each tributary are contrary to expectation, where the predominantly agricultural areas have values of $b > 1$, and the western tributaries have $b < 1$ (Table 2). Few studies of sediment delivery ratios have been undertaken for such a

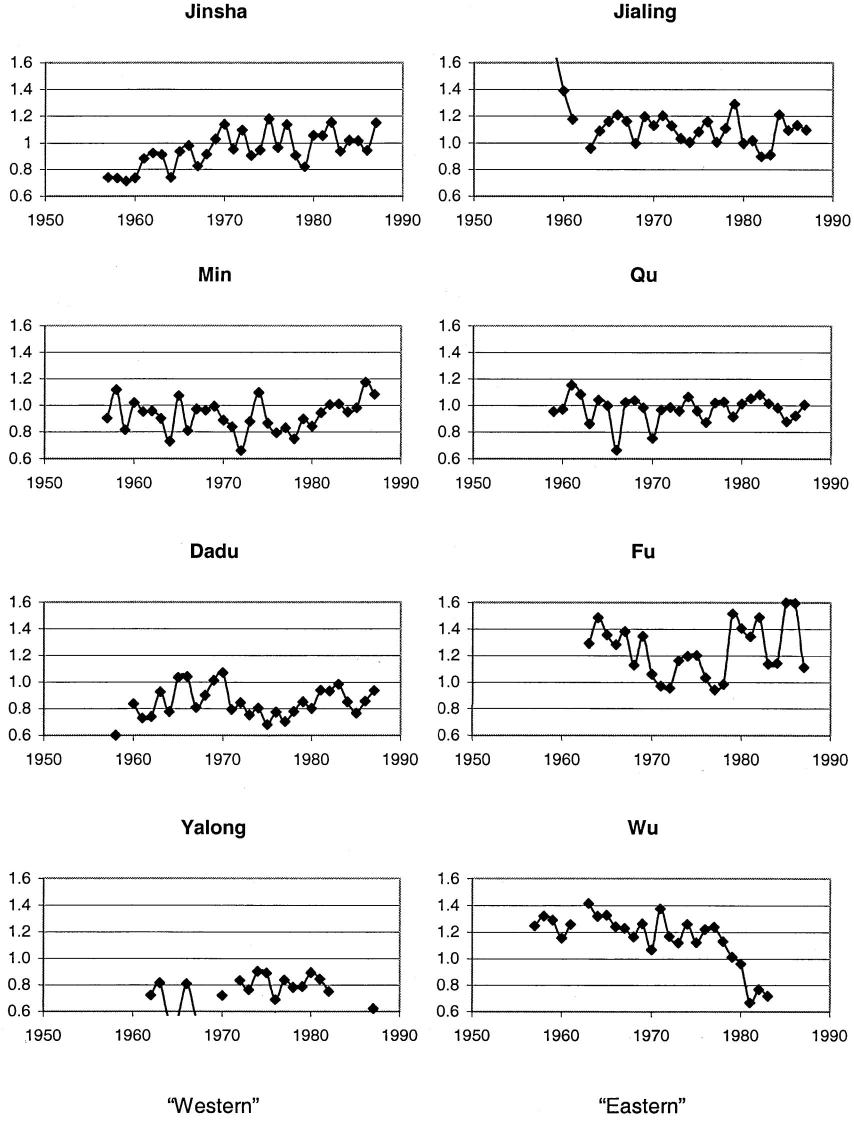

Fig. 2 Time series of sediment delivery exponents for the major tributaries of the Upper Yangtze. Only exponents from regression equations that are significant ($\alpha = 0.05$) are plotted.

selection of large basins and the results may in part be an artefact caused by the geographic spacing of gauging stations. However, the year-to-year variation in sediment delivery characteristics can also be examined (Fig. 2). Plotting exponent b for each year where a significant regression relationship between SL and DA can be defined, indicates that there is some evidence for declining transmission of sediments in the eastern tributaries. The decline is strongest in the Wu, but also evident in the Jialing and Qu. This does not indicate an absolute decline in sediment yield, but rather a decrease in the transmission of sediment, which is consistent with the hypothesis that sediment is being intercepted by large dam schemes on these tributaries. By contrast, there is some evidence that transmission of sediments is increasing on the Jinsha.

A MODEL OF BASIN DISTURBANCE

As mentioned above, the last 40 years have witnessed marked land-use change in the Upper Yangtze, which has resulted in a large increase in the area considered to be affected by erosion. However, it has been demonstrated in a variety of fluvial environments that when a system is disturbed, sediment yield increases rapidly but will decrease over time if the disturbance is not sustained (Schumm & Rea, 1995). The idea has been tested using a simple simulation model consisting of a representation of a basin as a series of 100 grid cells. The impact of a disturbance, which might be deforestation or extension of agricultural land, on any cell can be represented by the exponential decay function:

$$SY = m\,\mathrm{e}^{-nT} + k \tag{1}$$

where m, n, k are constants and T = time (years). The curve indicates that, following a disturbance at time $T = 0$, the sediment yield gradually returns towards the pre-disturbance constant, k. The amount of sediment exported from each cell that reaches the basin outlet is a function of the travel distance and represented by:

$$SY_i = SD^p \tag{2}$$

where SY_i, SD and p are sediment yield from cell i that is exported to the basin outlet, sediment delivery per cell length and travel distance in cell lengths, respectively. Values for the constants were chosen to represent a five-fold increase in soil erosion following disturbance which declined to 50% after 3 years and 10% after 10 years ($m = 4$, $n = 0.25$, $k = 1$). Sediment yields are in arbitrary units where the pre-disturbance conditions would produce an output of 100 units if the sediment delivery ratio was 1. Values for sediment delivery per cell length, rate and direction of disturbance were varied in the simulation. The direction of disturbance is important because a larger proportion of sediment contributes to basin yield when cells close to the basin outlet are affected. For most simulations, sediment yield increases over the time period (of 20 years) but the rate of increase begins to slow after 5–10 years (Fig. 3). In the case of upstream propagation of disturbance (i.e. from the outlet towards the watershed) sediment yield reaches a constant value after a short period and even falls in one simulation, despite the total area being disturbed increasing from 0 to 80% over the simulation. As the direction of land-use

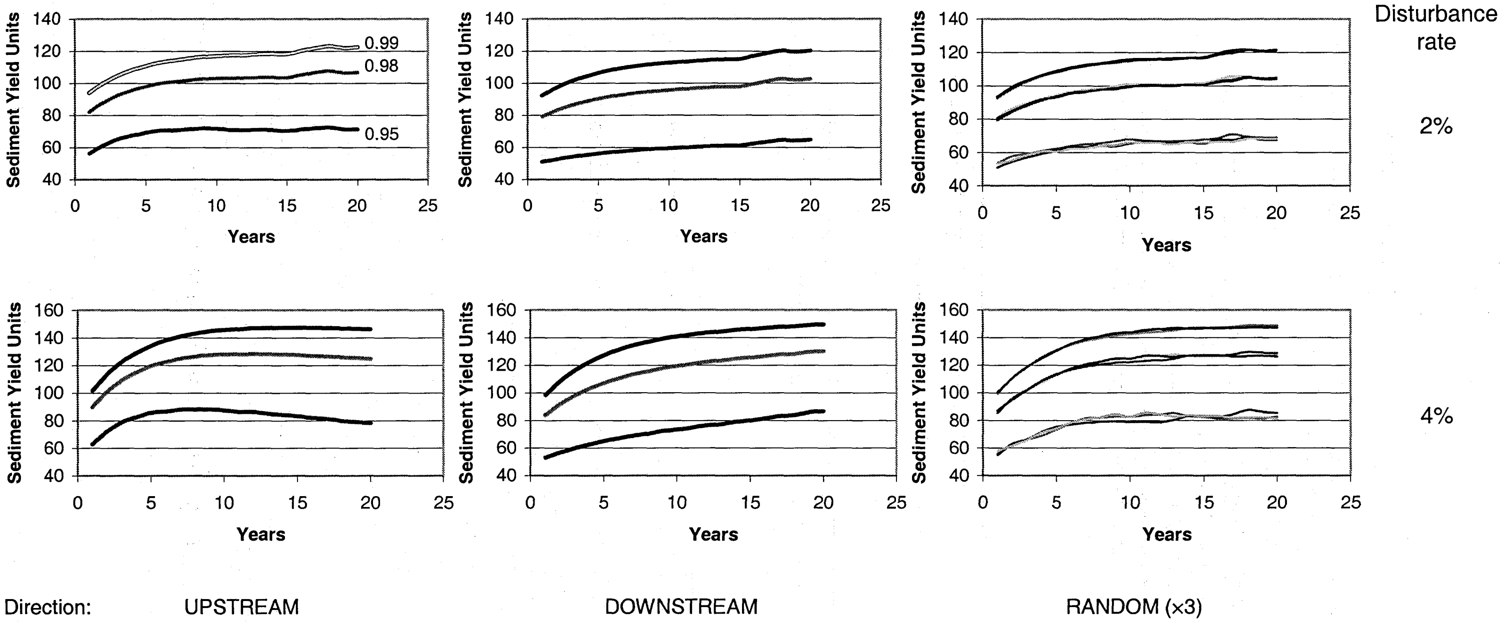

Fig. 3 Changes in predicted sediment yield following a wave of disturbance through a hypothetical basin. The disturbance rate is 2% of basin area per year (upper panel) and 4% per year (lower panel) for sediment delivery ratios (per cell length) of 0.99, 0.98 and 0.95. The direction of disturbance is upstream (from outlet), downstream (from watershed), or random.

change in China has tended to spread upbasin both in terms of disturbance by extension of agricultural land and by deforestation, the results of the "upstream" simulation are interesting. Despite the large increase in the areas which have been deforested or encroached by visible soil erosion during the period since the 1950s, the net impact on sediment yield may not have been so dramatic. The simulation model does not allow for any variation in erosion sensitivity in any of the cells, nor distinguish between grades of disturbance. Similarly, the parameter values describing recovery rate are chosen arbitrarily. Nevertheless, the simulation demonstrates that sediment delivery characteristics relating to the timing and location of disturbance can have a marked effect on the output of sediment reaching the next gauging station or basin outlet. Work is now in progress to reconstruct the spatio-temporal pattern of agricultural extensification and deforestation across central and southern China to test the model further.

SUMMARY

Novel approaches using GIS techniques to extract spatially-distributed data for the analysis of within-basin variability of sediment yields have been demonstrated. The high degree of scatter that is present in the data set has been overcome to some extent by grouping strategies, but the incorporation of land-use information does not markedly improve the level of explanation of sediment yields, particularly in the agricultural portion of the basin. Individual gauging stations reporting extremely high sediment yields can be attributed to a specific condition such as the presence of loess cover or frequency of landsliding. There are several reasons why the relationship between land use and sediment yields is unclear, which in turn indicate requirements for improvements in analytical and data-capture techniques. First, past land-cover information is not available at appropriate resolutions for incorporation into GIS modelling, but generalized reconstruction of the spatial pattern of deforestation may be feasible from a combination of archive sources. Second, Chinese landscapes are frequently mosaics and the distinction between arable land, forest and paddy fields at a resolution of about 1 km causes difficulties. Third, the grouping of hierarchical basin areas presents some difficulties for statistical mapping analysis.

Modelling spatial variability is sensitive to the synchronism of the sediment yield records and the basin variables. This is a problem for measures of population density and land cover which have fluctuated during the period. Time-series analysis of individual gauging station records has demonstrated that some parts of the basin are experiencing increasing sediment yields while a few stations have measured decreasing yields. The latter appear to be explained by the construction of large reservoir schemes on the major tributaries. This pattern is also confirmed by analysis of sediment delivery characteristics in the tributaries. Several of the eastern tributaries indicate declining transmission of sediments as indicated by the exponent of the sediment load–basin area regression. Western tributaries, by contrast have experienced an increase in transmission. Though there has been widespread deforestation and a large increase in the area affected by soil erosion between the 1950s and 1980s, a simulation model of sediment yields reacting to disturbance demonstrates that the sediment-yield output may not necessarily continue to increase with the area of disturbed land. Controls on the spatio-temporal expression of sediment yields in a large basin such as the Upper Yangtze are complex. One point is clear—that reliance on sediment yield measurements from the basin outlet masks considerable variation within the basin.

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