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Patterns of sediment yield in the Upper Yangtze basin, China

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Abstract Long term sediment yield data from more than 250 stations in the Upper Yangtze basin have been analysed to examine the temporal and spatial patterns of sediment yield. The potential sedimentation problem at the Three Gorges dam site is compounded by evidence of the increasing magnitude and extent of soil erosion in the basin. Spatially, the sediment supply is dominated by the agricultural areas of the Sichuan basin. The evidence of increasing soil erosion is not clearly matched by a increase in sediment yield over time and the role of water conservancy projects in trapping and storing sediment requires further attention.

INTRODUCTION

The proposal to build the world's largest dam, the Sanxia (Three Gorges Project; TGP), has generated widespread commentary. Formally approved by China's National People's Congress in 1992, the political leadership were convinced that the potential benefits of power generation and flood control would outweigh any environmental costs. International opinion has been less favourable (e.g. Edmonds, 1992). One of the many environmental issues at stake is the impact of sedimentation on the operational life of the reservoir. Proponents of the project have argued that the flow regulation procedures will permit the maintenance of reservoir capacity by discharging sediment laden waters through sluices. Much of the debate has focused on the assumptions of hydraulic models of reservoir sedimentation (Qian *et al.*, 1993; Williams, 1993) but relatively little attention has been paid to the controls on the source of sediment in the Upper Yangtze basin and the linkages between soil erosion and sediment delivery. Analysis of regional patterns of sediment yield is complicated by the basin size- and time-dependency of the data. Stations operating over different years cannot be compared directly because of the high variability of discharge from year to year. Similarly, as sediment yield is partly a function of the drainage basin area, correction for the attenuation of sediment delivery is required.

Several attempts have been made to explain global and regional patterns of sediment yield in terms of climate (Langbein & Schumm, 1958; Douglas, 1967; Jansen & Painter, 1974; Jansson, 1988) and topography (Milliman & Syvitski, 1992; Summerfield & Hulton, 1994). The Langbein and Schumm model has been used by Xu (1994) to explain spatial variation in sediment yield across China, but within the Upper Yangtze basin patterns are more complex, reflecting the combination of climatic, topographic, lithological and land-use controls. Simple models of sediment yield will be of limited value in predicting the evolution of the sedimentation problem at the dam site.

THE DATA ARCHIVE

The current programme involves a field based investigation of soil erosion and sediment delivery in small catchments within the Three Gorges area, as well as analysis of the sediment load data for the entire upper basin. This paper focuses on the latter component, but the link between erosion and sediment transport in rivers is a key theme in geomorphology and some of its implications are discussed in the final section. The data available for the analysis comprise monthly and annual mean sediment discharges (kg s^{-1}) for 255 hydrographic stations upstream of Yichang, Hubei Province, covering the period 1956-1987. The original records of sediment load were recorded in units of 10^6 or 10^4 t depending on the station basin area and it is apparent that the compilation of records into yearbooks has led to some confusion of units. Recalculation of annual load from monthly load data has enabled several transcription errors to be corrected. The measurements refer to suspended sediment yield and were collected in line with standard procedures. Error is introduced through the use of daily measurements rather than continuous monitoring and by the underestimation of the bed load contribution. Limited data are available for bed load transport in the Upper Yangtze. Consulting engineers for the TGP estimated bed load as of 0.05% of sediment load but measurements at Yichang suggest a bed load contribution of 1.5-2%. This may be particularly significant in the Three Gorges area where landslides can supply sediment to the channel directly.

Drainage basin areas range from 109 to just over 1 million km^2. The principal tributaries are indicated in Fig. 1 and the sediment load database has been grouped into tributary basin units. The main channel of the Yangtze (Chang Jiang) is referred to as the Jinsha above Yibin. There is some spatial bias in the station network, with limited coverage in the headwaters of the Jinsha, which is largely uninhabited. There has been

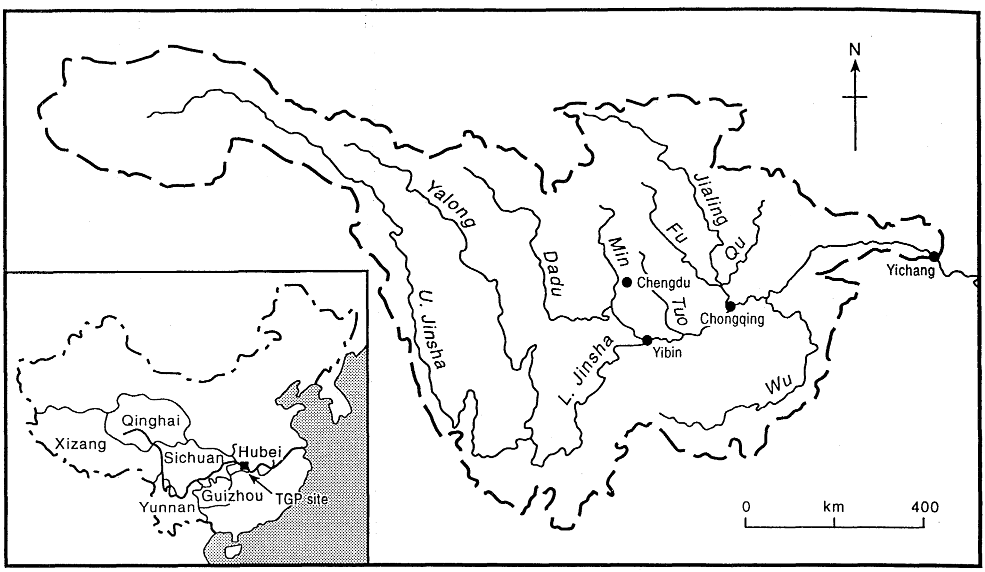

Fig. 1 The Upper Yangtze basin.

a steady increase in the distribution of hydrographic stations over time, but a number of stations have operated for short periods only. The dataset comprises a total of 3820 station-years with 187 stations having five or more years of sediment yield data and 135 more than 15 years. Direct comparison of the sediment yield data is not straightforward, as the limited period of individual station operation may have coincided with particularly wet or dry years, or with phases of erosive activity (such as deforestation) or with conservation initiatives. Temporal bias can be accommodated by filtering the data to extract comparisons between stations operating over the same time period.

SEDIMENT YIELD-BASIN AREA RELATIONSHIPS

Sediment yields from basins of widely varying size cannot be compared directly because of the likely relation between specific sediment yield (load per unit area per unit time) and drainage basin area. The conventional model of sediment delivery suggests that there is an inverse relation between specific sediment yield and basin area (Walling, 1983) as opportunities for sediment storage increase downstream and gradient decreases. Recent research has suggested that such a relation does not hold for mountainous areas, particularly those which were affected by Quaternary glaciation where large quantities of glacially-derived sediment are being eroded from storage in lowland valleys (Church *et al.*, 1989; Dedkov & Moszherin, 1992). A similar scenario is found in agricultural areas where a past period of disturbance has delivered sediment into downstream storage where it is undergoing remobilization (Trimble, 1993). However, few studies of the specific sediment yield-basin area relationship have considered catchments as large as the Upper Yangtze.

In order to examine yield-area relationships over consistent measurement periods and to investigate the changing nature of the relationship over time, the data have been divided into three time periods; 1956-1965; 1966-1976 and 1977-1987. These represent near equal divisions of the record period but also coincide with profound changes in agricultural practice within China (Higgitt & Rowan, 1995). The first period encompasses the Great Leap Forward from 1958, during which time widespread deforestation occurred to produce charcoal for the steel furnaces. Many small scale water conservancy projects were initiated in the late 1950s becoming widespread in the second time division, which coincides with the Cultural Revolution. During the final period, land responsibility reform in 1978 is believed to have given rise to widespread soil erosion, particularly on steeper slopes.

Regression relationships for the three time periods are indicated in Fig. 2(a). In each case only stations with a complete record of sediment yield for the time period were included, except for the 1956-1965 period when fewer stations were operating. In this case stations with at least 8 out of 10 years of data are included. The regression relationships are compared with published relations for 51 basins in the Missouri, USA (Glymph, 1951) and an average relationship for 250 stations on four continents (Fleming, 1969). The Yangtze curves are considerably higher than the four continent average and lie just within the upper envelope of the US data. In each case an inverse relation is indicated, although the degree of explanation afforded by basin area is small. The equations for each relation are indicated in Fig. 2(a) where it can be seen that the exponent decreases in each time period, suggesting an increasing sediment delivery

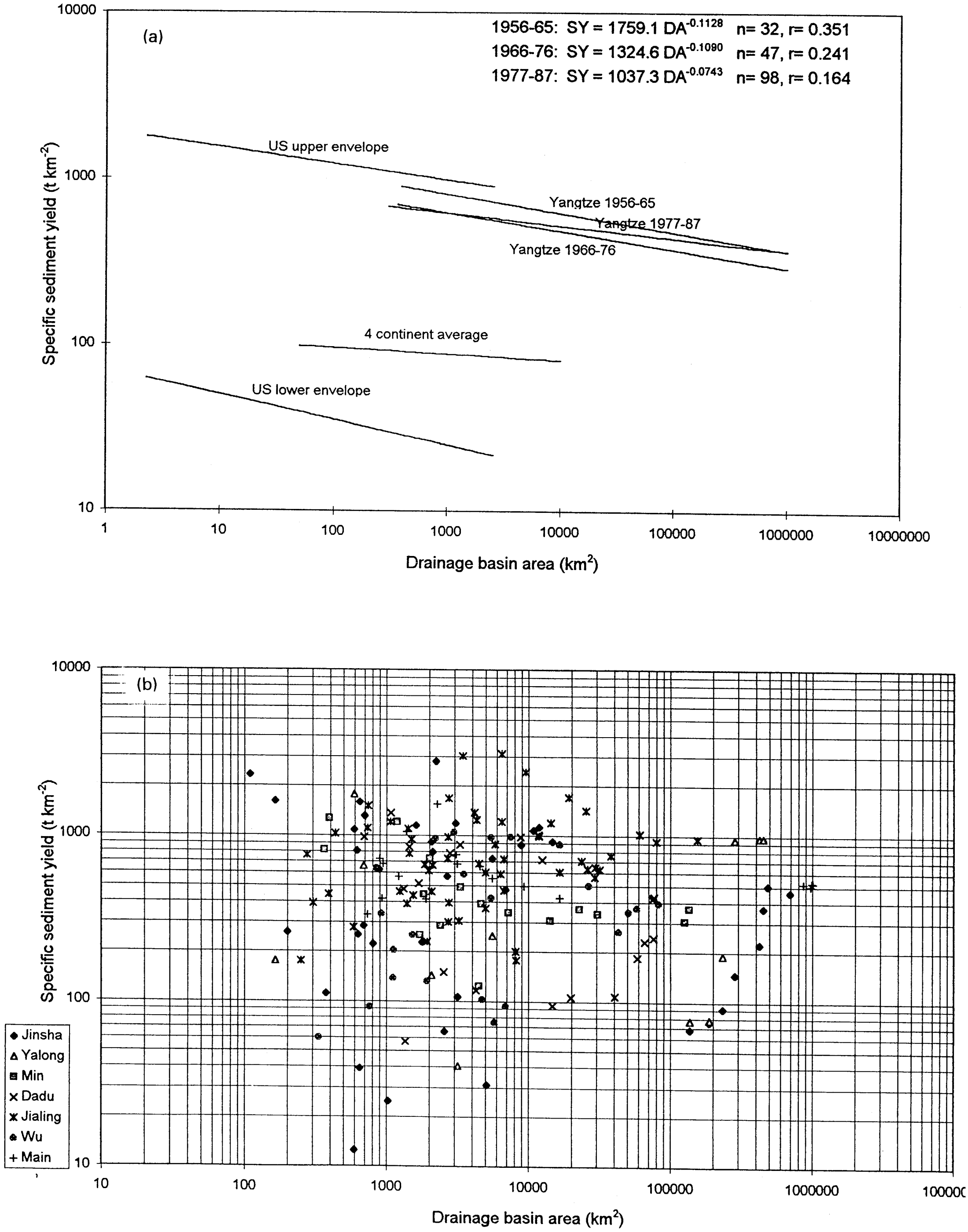

Fig. 2 Relationships between specific sediment yield and drainage basin area. (a) Comparison of Yangtze data for different time periods with US and global curves (based on Glymph, 1951; Fleming, 1969; via Church *et al.*, 1989). (b) Mean specific sediment yield for all stations with $\geq$ 5 years data.

ratio. Tests for the coincidence of each regression relationship, using the procedure of Kleinbaum *et al.* (1988), indicate no significant difference between intercepts, but a significant difference between the 1956-1965 and 1977-1987 exponents. It should, however, be noted that the mean and median basin area of the sample for 1956-1965 were considerably larger than those in subsequent periods, and this may introduce bias into the analysis. Combining the data from each of the three periods, the following regression equation, which is significant at $\alpha = 0.01$, can be derived:

$$SY = 1126.2\ DA^{-0.0826} \quad r = 0.197 \tag{1}$$

where SY = specific sediment yield (t km^{-2}) and DA = drainage basin area (km^2). Equation (1) is subsequently used to compare actual and predicted sediment yields in order to identify the relative contribution of different sized basins to the sediment load. Although noting considerable variation, Walling (1983) reported a typical world-wide exponent value of -0.125. The yield-area relationships for the Yangtze suggest that the proportion of eroded material transferred downstream is somewhat higher than the global average. The considerable scatter of the sediment yield-basin area relationship is indicated in Fig. 2(b), where all stations with at least 5 years of sediment yield measurements are plotted. The scatter is not unexpected given the climatic, topographic and land-use diversity of the basin. None of the individual tributaries provide statistically significant yield-area relationships.

VARIABILITY IN SEDIMENT DELIVERY AND YIELD

Management of the sedimentation problem requires an effective understanding of the source and transmission of material from diverse parts of the basin and of the trend in sediment supply and delivery. Evidence for a widespread increase in the area being affected by soil erosion since the mid 1950s (CAS, 1988) is not clearly mirrored by the sediment yield data. Year to year variations have been compensated by using a five year running mean. As some stations have individual years where measurements have not been returned, qualification for the running mean required at least 3 out of the 5 years of measurement. Using records of all stations larger than 25 000 km^2 with sufficient operational coverage, the mean sediment yields at the end of the measurement period (1983-1987) were 17.7% up on the initial period (1956-1960). However, compared to the period 1961-1965, the most recent measurements were, on average, down 3.3%. Most stations record a slight increase in yields until the mid-late 1960s, followed by a decade of lower yields and a sharp increase in the late 1970s (Fig. 3(a)).

In order to illustrate general patterns, stations on the larger tributaries were selected and two methods of standardization were employed. None of these stations have overlapping catchment areas and a statistical summary of their sediment yield records is shown in Table 1. The first standardization method employed the regression relationship (equation (1)) to predict the sediment yield from the tributary basin area. Actual yield was then divided by predicted yield to derive a standardized proportional contribution which has been plotted against time (Fig. 3(b)). The Jialing can be seen to have a substantial relative contribution to the sediment load throughout the time period with a similar, though less exaggerated pattern for the Fu and Qu Rivers (which are

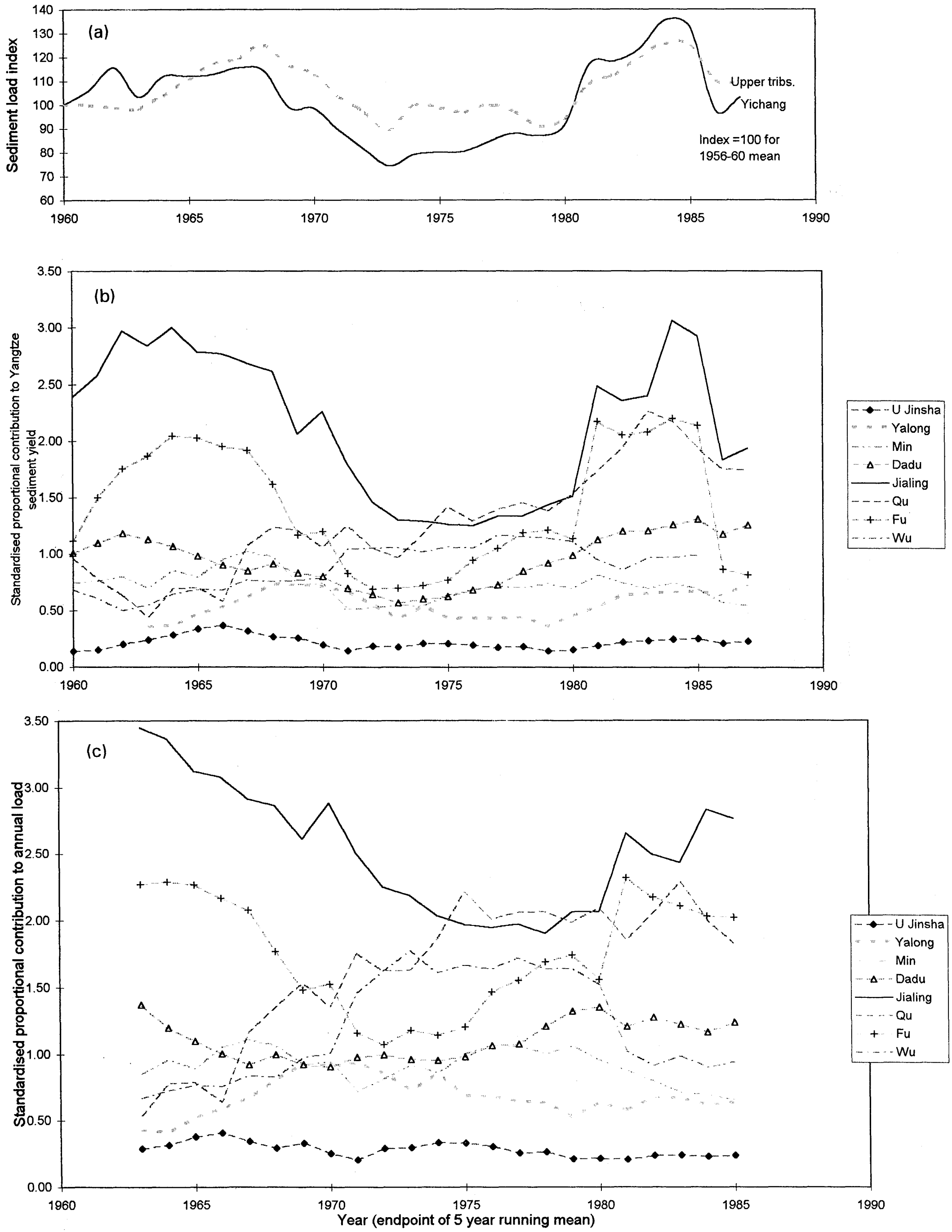

Fig. 3 Contribution of Upper Yangtze tributaries to sediment load expressed as (a) Five year running mean of sediment load index compared with Yichang; (b) standardized proportional contribution (actual yield/predicted yield from sediment yield-basin area regression) and; (c) standardized proportional contribution to annual load, corrected for basin area. See text for further explanation of standardization techniques.

Table 1 Sediment yields and relative contribution of Upper Yangtze tributaries.

River	Station	DA (km^2)	Mean load (Mt $year^{-1}$)	±sd (Mt $year^{-1}$)	Max (Mt $year^{-1}$)	Min (Mt $year^{-1}$)	DA (%)	DA_{adj} (%)	Mean concentration (%)
U Jinsha	Shigu	232 651	21.22	9.80	42.29	6.97	34.19	32.04	8.89
Yalong	Xiaodeshi	118 294	29.42	13.47	64.38	12.69	17.39	17.23	12.11
Min	Pengshan	30 661	10.32	4.82	22.12	4.01	4.51	4.99	4.58
Dadu[a]	Shaping	75 016	32.22	10.49	54.91	14.17	11.03	11.34	13.62
Jialing	Wusheng	79 714	73.97	44.77	202.60	9.78	11.72	11.99	31.96
Fu	Guodukou	31 626	19.93	10.87	47.97	3.22	4.65	5.14	8.40
Qu	Xiaoheba	29 420	19.11	16.64	91.83	1.74	4.32	4.81	8.34
Wu	Wulong	83 035	32.42	12.31	60.59	11.14	12.20	12.45	14.42
Σ tribs		680 417					100.00	100.00	100.00
Main	Yichang	1 005 501	527.22	98.83	728.98	362.91			

[a] Gauging station relocated from Tunjianzhi (DA = 77 202 km^2) in 1967. Mean loads and contribution corrected for change in DA.

tributaries of the greater Jialing system). The latter has become an increasingly important source during the measurement period. These three rivers drain the agriculturally productive lands of the Sichuan basin. In contrast, the tributaries originating in the mountainous terrain of the far west of the basin (the Jinsha and Yalong Rivers) have substantially smaller contributions relative to their drainage area. The marked dip of most curves in the middle part of the time interval indicates the generally lower sediment yields recorded in the Upper Yangtze between the late-1960s to late-1970s. The standardization technique of Fig. 3(c) adjusts for this effect and permits the relative contribution of each tributary for each running mean period to be assessed, using a weighted basin area, DA_{adj}. The ratio produces broadly similar patterns to Fig. 3(b) but some features can be elaborated. Throughout the measurement period, the Jialing tributary contributes more than twice the sediment load than would be expected if sediment supply was spatially uniform, but its importance as a source area declined during the 1970s. The Fu and Dadu Rivers show similar trends, whilst the Wu reverses the pattern becoming a more important source in the 1970s. The Yalong and Jinsha have remained more or less constant and relatively unimportant, but the Qu has witnessed a dramatic rise in its importance as a sediment source throughout the period.

The above discussion concerns the trends at the outlets of the major tributaries but ignores the remainder of the dataset. Interrogation of more detailed patterns of sediment dynamics has been made possible using Arc/Info GIS. The drainage network of the upper Yangtze has been digitized from a variety of map sources and the point coverage of the gauging stations generated from their latitude-longitude coordinates. Work is currently in progress to interface the relational sediment database with topographic, climatic and ecological databases in order to examine the degree of explanation of sediment yields afforded by various factors, but is not reported here. In Fig. 4, the standardized residuals (a) for the regression of the data plotted in Fig. 2(b) and the coefficient of variation of the sediment yield (b) are mapped onto the station locations. The distribution confirms the largest relative contribution from the Sichuan basin while sediment yields from Guizhou, Yunnan and the mountainous west are lower. The largest degree of variability in annual sediment yields coincides with those areas which have experienced the greatest human influence, most notably the Sichuan basin.

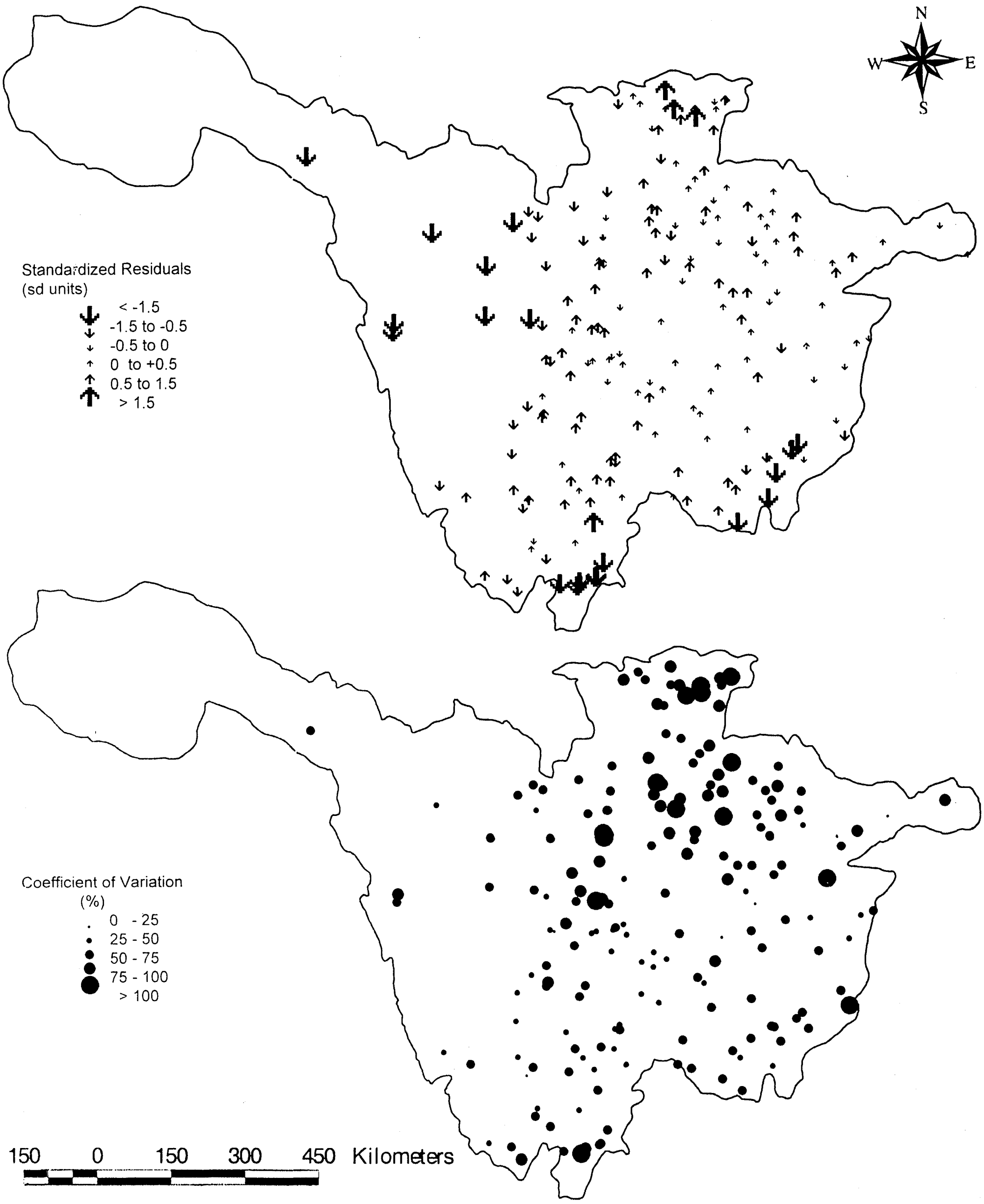

Fig. 4 Maps of (a) standardized residual and (b) coefficient of variation of annual sediment yield.

LINKING SEDIMENT SUPPLY WITH SEDIMENT YIELD: SOME CONSIDERATIONS

Earlier "laws" of sediment yield have generally proved difficult to apply because of the multitude of influential factors. The general importance of agricultural areas as the principal source is indicated, but further examination is required to consider the more detailed controls on soil erosion and the sensitivity of the coupling between erosion and fluvial sediment yield. A sediment budget study of a small reservoir catchment in the Three Gorges area is being conducted in conjunction with the current research project.

Although the temporal trend of the sediment yield data is ambiguous, data compiled from county based soil erosion inventories (CAS, 1988) suggest a doubling of the area affected by soil erosion in the whole Yangtze basin between 1957 and the mid 1980s. Within the upper basin, the affected area in Sichuan and Guizhou has risen from 16.1% and 11.3% to 67.3% and 31.2% respectively. These estimates are largely based on qualitative mapping and quantitative studies of headwater erosion dynamics are extremely limited. Although their accuracy may be disputed, the imbalance suggests considerable storage of sediment within the system. In the grain-producing areas of Sichuan, the distribution of valley floor paddy fields offer considerable potential for trapping the products of slope erosion. Furthermore, as the measurement period coincides with a concerted campaign of water conservancy projects throughout China, it is conceivable that much of the eroded sediment is trapped within reservoirs of varying size within the basin. The combined reservoir storage capacity above the Three Gorges dam site is 16 719.44 Mm^3 (Gu *et al.*, 1987). Assuming an average bulk density of reservoir sediments of 1.0 g m^{-3}, the total capacity is roughly equivalent to 30 years of basin sediment export. The rate at which individual reservoirs are infilling is a function of the intensity of the erosion in the contributing area and the reservoir trap efficiency. The transmission of sediment downstream towards the main channel will therefore increase as the trap efficiency of headwater reservoirs decreases. Forecasting the decline in trap efficiency and the implications for sediment yields is not possible without data on the configuration of small reservoirs to the catchment areas and annual runoff. As the ratio of capacity to runoff declines, sediment trapping may remain efficient for a considerable period before declining rapidly.

Although the dataset covers a relatively long period of 32 years, researchers in the US (e.g. Trimble, 1993; Phillips, 1993) have noted the long term legacy of historical land use changes on contemporary sediment loads. This is compounded by a consideration of the impact of resource exploitation such as deforestation during the measurement period. The impact of the increasing extent of erosion throughout the Upper Yangtze basin may result in pulsed rather than cumulative sediment supply (cf. Schumm & Rea, 1995). The present availability of information is therefore insufficient to evaluate with any certainty the likely trends of sediment yield to the main channel of the Yangtze. The potential for substantial increase in sediment load as artificial storage capacity is exhausted and sediment already in storage is remobilized should not be underestimated. Furthermore, the relocation of up to 1.2 million people, if it involves the extension of agriculture upslope, will result in enhanced erosion adjacent to the reservoir.

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