Erosion and sediment yield: a global overview

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Abstract The classic monograph *Climat et Erosion* published by Fournier in 1960 provided a valuable demonstration of the potential for using information on the sediment loads of the world's rivers to study the global denudation system. Such early work was hampered by lack of data for many areas of the world, but recent improvements in data availability now afford a meaningful basis for estimating the total suspended sediment flux from the land to the oceans and for establishing the global pattern of sediment yield and its major controls. The lack of long-term records for most rivers precludes detailed assessment of the role of anthropogenic activity in modifying the global denudation system but there is now a wide range of evidence to demonstrate the importance of such changes, in terms of both increases and decreases in sediment flux. Analysis of available longer-term records provides an important means of assessing the sensitivity of sediment yields to environmental change, which in turn requires consideration of the impact of both human activity and climate change.

INTRODUCTION

It was 35 years ago that Frédéric Fournier published his classic monograph entitled *Climat et Erosion*, which attempted to review existing information on the sediment yields of world rivers and to establish the primary controls on the global pattern of denudation (Fournier, 1960). Fournier's monograph represents an important milestone in the development of our understanding of the global denudation system, since it emphasized the potential for using river load data to assess global patterns of erosion and land denudation. Subsequent increases in data availability have inevitably caused some of Fournier's assumptions and conclusions to be questioned and revised, but his study has provided the foundation for a wide range of subsequent work aimed at developing an improved understanding of the global denudation system (cf. Jansson, 1982, 1988; Milliman & Meade, 1983; Walling, 1985; Walling & Webb, 1983). This contribution attempts to provide an overview of our current knowledge of global sediment yields and to identify outstanding uncertainties and research needs.

MAGNITUDE CONSIDERATIONS

Data availability

Working in the 1950s, Fournier had access to only limited information regarding the suspended sediment loads of world rivers, and his data-base extended to only 96 rivers.

Most of these were from North America, no data were available for Africa, South America or Australasia and the data for Asia were biased by the inclusion of several rivers from the Yellow River basin with very high sediment loads. Subsequent workers have benefited from the more recent expansion in sediment monitoring activity throughout the world and have been able to base their analysis on data-bases an order of magnitude or more greater in size. Walling & Webb (1983), for example, considered data from nearly 2000 river monitoring stations, and Dedkov & Mozzherin (1984) assembled data from more than 3000 stations. Recent work coordinated by Milliman within the framework of the IGBP LOICZ programme (Milliman *et al.*, 1995) has focused on river inputs to the oceans and the associated GLORI data-base currently provides information on suspended sediment fluxes for more than 400 rivers representing 66% of the land surface of the earth draining to the oceans. Despite this major expansion, the existing global data-base still possesses many limitations in terms of providing a comprehensive and reliable basis for investigating the global denudation system. Many regions of the world remain unrepresented or poorly represented. In other cases, whilst information on total sediment flux may be available for the outlets of large river basins, little is known about the variation of specific sediment yield within those basins. Even where data are available, important uncertainties may exist because of lack of information regarding the source of the information, short record lengths, differing periods of record, non-stationary river behaviour, and data reliability. The latter must be recognized as a major problem, since the measurement programmes employed in many areas of the world are inadequate for generating accurate assessments of sediment loads. Where only infrequent sediment samples are available, the application of different load calculation procedures can result in significantly different estimates of sediment yield (cf. Walling, 1984; Walling & Webb, 1981, 1985, 1988).

Sediment flux to the oceans

Early attempts to generate estimates of the total flux of suspended sediment from the land to the oceans faced major problems in terms of lack of data for many major rivers and for extensive areas of the globe. Faced with this paucity of data, it was necessary to extrapolate existing information to ungauged areas. In the case of the work of Fournier (1960) referred to above, the over-representation of Chinese and other rivers with relatively high suspended sediment yields in his limited data-base resulted in a value of 51.1×10^9 t which was undoubtedly an overestimate. Subsequent workers have been able to take advantage of the increasing number of gauged rivers and the improved representation of different areas of the world, and values closer to $15\text{-}20 \times 10^9$ t year^{-1} have been most frequently cited (cf. Table 1). However, although data are now available for an increasing number of the major rivers of the world, which in turn account for a substantial proportion of the land surface, important uncertainties still exist regarding the sediment flux from the smaller river basins draining to the oceans. Milliman & Syvitski (1992) have, for example, estimated that whereas the world's 100 largest rivers drain *c.* 60% of the land surface draining to the ocean, data from more than 10 000 smaller rivers would be required to produce a definitive value for the total flux. Any attempt to extrapolate existing data from large rivers to these smaller river basins faces substantial problems, since the specific sediment yields of small river basins are

Table 1 Existing estimates of total suspended sediment transport to the oceans.

Author	Estimated mean annual load (10^9 t)
Fournier (1960)	51.1
Kuenen (1950)	32.5
Gilluly (1955)	31.7
Jansen & Painter (1974)	26.7
Pechinov (1959)	24.2
Schumm (1963)	20.5
Milliman & Syvitski (1992)	20.0
Holeman (1968)	18.3
Goldberg (1976)	18.0
USSR National Committee for the IHD (1974)	15.7
Sundborg (1973), Walling & Webb (1983)	15.0
Milliman & Meade (1983)	13.5
Lopatin (1952)	12.7
Mackenzie & Garrels (1966)	8.3

typically much greater than those of large basins. Furthermore, many small rivers drain areas of high relief which are not only characterized by high specific sediment yields but also by marked spatial variability of sediment response.

The most rigorous attempt to estimate the global suspended sediment flux to the oceans available to date is probably the work of Milliman & Meade (1983), which was further refined by Milliman & Syvitski (1992). Based on their analysis of available river load data and extrapolation of this information to ungauged areas, Milliman & Meade (1983) produced an estimate for the total suspended sediment flux to the oceans of 13.5×10^9 t year^{-1}. This value excludes sediment deposited in major reservoirs which would previously have reached the oceans, and Milliman & Meade indicated that it should be increased to *c.* 14×10^9 t year^{-1} to represent the "natural" flux. A provisional reassessment of the values used by Milliman & Meade (1983) when extrapolating to ungauged areas led Milliman & Syvitski (1992) to suggest that the yields from many areas had been underestimated and that the total flux is in fact likely to be *c.* 20×10^9 t year^{-1}.

It is interesting to compare this value of 20×10^9 t year^{-1} with current estimates of global rates of soil erosion or soil loss. The recent GLASOD (Global Assessment of Soil Degradation) survey (Oldeman *et al.*, 1991) has indicated that more than 10^9 ha of the land surface of the earth are currently experiencing serious soil degradation as a result of water erosion, and if it is assumed that the mean rate of soil loss from these areas is *c.* 50 t ha^{-1} year^{-1}, the total annual soil loss would be of the order of 50×10^9 t year^{-1}. Pimental *et al.* (1995) also provide a similar estimate of the current global rate of annual soil loss of 75×10^9 t year^{-1}. If it is further assumed that *c.* 50% of the contemporary sediment flux to the oceans represents essentially "natural" erosion, whilst the remaining

50% represents this accelerated or human-induced erosion, it can be suggested that *c.* 13-20% of the eroded soil is delivered to the oceans. A sediment delivery ratio (SDR) of 13-20% is in turn consistent with existing information on the magnitude of SDRs (cf. Walling, 1983).

SPATIAL VARIABILITY

The global range of sediment yields

The current availability of sediment yield data for the world's rivers provides a reasonable basis for establishing the global range of specific sediment yields. Taking basins >100 km^2 in size in order to avoid local anomalies, global minima for mean annual specific suspended sediment yield lie below 1 t km^{-2} year^{-1}. Branski (1975), for example, reports values of <1.0 t km^{-2} year^{-1} for several rivers in Poland, and Dedkov & Mozzherin (1984) cite similar low values <1.0 t km^{-2} year^{-1} for several rivers of the former Soviet Union on the Kola Peninsula, in the Yenesei and Dneiper basins and in the drainage area of the Sea of Azov. In most cases these basins are characterized by very low relief, good vegetation cover and surface materials which are either relatively resistant to erosion or which afford only a limited source of fine particulates for transport as suspended sediment.

Maximum reported mean annual specific suspended sediment yields exceed 10 000 t km^{-2} year^{-1}, and Table 2 lists a number of rivers for which such extreme values have been reported. The highest value included in Table 2 is a mean annual specific suspended sediment yield of 53 500 t km^{-2} year^{-1} for the Huangfuachan River (3199 km^{-2}) in the People's Republic of China. This river is a tributary of the middle reaches of the Yellow River which drain the gullied loess region. Any attempt to account for the very high values of specific suspended sediment yield cited in Table 2 must take account of several important controls related to the erodibility of the terrain, the erosivity of the hydrometeorological regime, tectonic instability, and the impact of human activity. In the case of the tributaries of the Yellow River, the highly erodible loess soils, the lack of vegetation cover and the semiarid climate with intense storm rainfall are major controlling factors. The semiarid climate is again an important causal factor in the Kenyan example, but here severe disturbance of the catchment by overgrazing must also be invoked. For Taiwan, Java, and New Guinea, the steep mountainous relief, tectonic activity, high rainfall totals and intense agricultural activity are important, and in South Island, New Zealand the steep relief, tectonic uplift and very high rainfall (up to 9000 mm year^{-1}) may again be cited.

The global pattern and its controls

The literature provides examples of a number of attempts to generate maps of the global pattern of suspended sediment yield. Such attempts have inevitably faced a number of important problems, including lack of data for many areas of the world, inadequate extrapolation procedures, and the scale dependent nature of sediment yield data. In the latter context, whilst information on sediment yields at the outlets of major river basins

Table 2 Maximum reported values of mean annual specific suspended sediment yield for world rivers.

Country	River	Drainage area (km^2)	Mean annual sediment yield ($t\ km^{-2}\ year^{-1}$)	Source
China	Huangfuchuan	3 199	53 500	Yellow River Conservancy Commission (personal communication)
	Dali	187	21 700	Mou & Meng (1980)
China (Taiwan)	Erjenhsi	350	28 911	Hwang (1980)
	Tsengwen	1 000	28 000	Milliman & Meade (1983)
Kenya	Perkerra	1 310	19 520	Dunne (1975)
Java	Cilutung	600	12 000	Hardjowitjitro (1981)
	Cikeruh	250	11 200	Hardjowitjitro (1981)
New Guinea	Aure	4 360	11 126	Pickup *et al.* (1981)
North Island New Zealand	Waiapu	1 378	19 970	Griffiths (1982)
	Waingaromia	175	17 340	Griffiths (1982)
	Hikuwai	307	13 890	Griffiths (1982)
South Island New Zealand	Hokitika	352	17 070	Griffiths (1981)
	Cleddau	155	13 300	Griffiths (1981)
	Haast	1 020	12 736	Griffiths (1981)

may be invaluable for assessing sediment flux to the oceans, the associated values of specific sediment yield provide no information on the spatial variability of sediment yield within the upstream basin and may indeed serve to mask such variability. Furthermore, it is well known that specific suspended sediment yields are influenced by drainage area (cf. Walling, 1983; Milliman & Syvitski, 1992) and a map which attempted to depict the sediment yields of drainage basins of one scale (e.g. 10^3 km^2) would present a different range of values from a map based on the sediment yields of basins of contrasting scale (e.g. 10^5 km^2).

Although the early maps of the global pattern of sediment yield produced by Fournier (1960) and by the Soviet scientist Lopatin (cf. Strakhov, 1967) have been frequently cited in attempts to describe the global denudation system, they were based on very limited data (96 rivers in the case of Fournier and 60 rivers for Lopatin) and inadequate extrapolation procedures, and must therefore be viewed as unreliable. Walling & Webb (1987) have, for example, emphasized that the sediment yields shown on Fournier's map are frequently an order of magnitude greater than those depicted by Strakhov and that there are significant contrasts in the overall patterns evidenced by the two maps. More recent improvements in data availability have permitted the production of more meaningful and reliable maps. Those concerned primarily with fluxes to the oceans (e.g. Milliman & Meade, 1983) are, as noted above, of limited value for establishing the details of the global pattern involved and in some cases only areas for which sediment yield data were available have been mapped (e.g. Jansson, 1988). However, more explicit attempts to map these patterns have been documented by

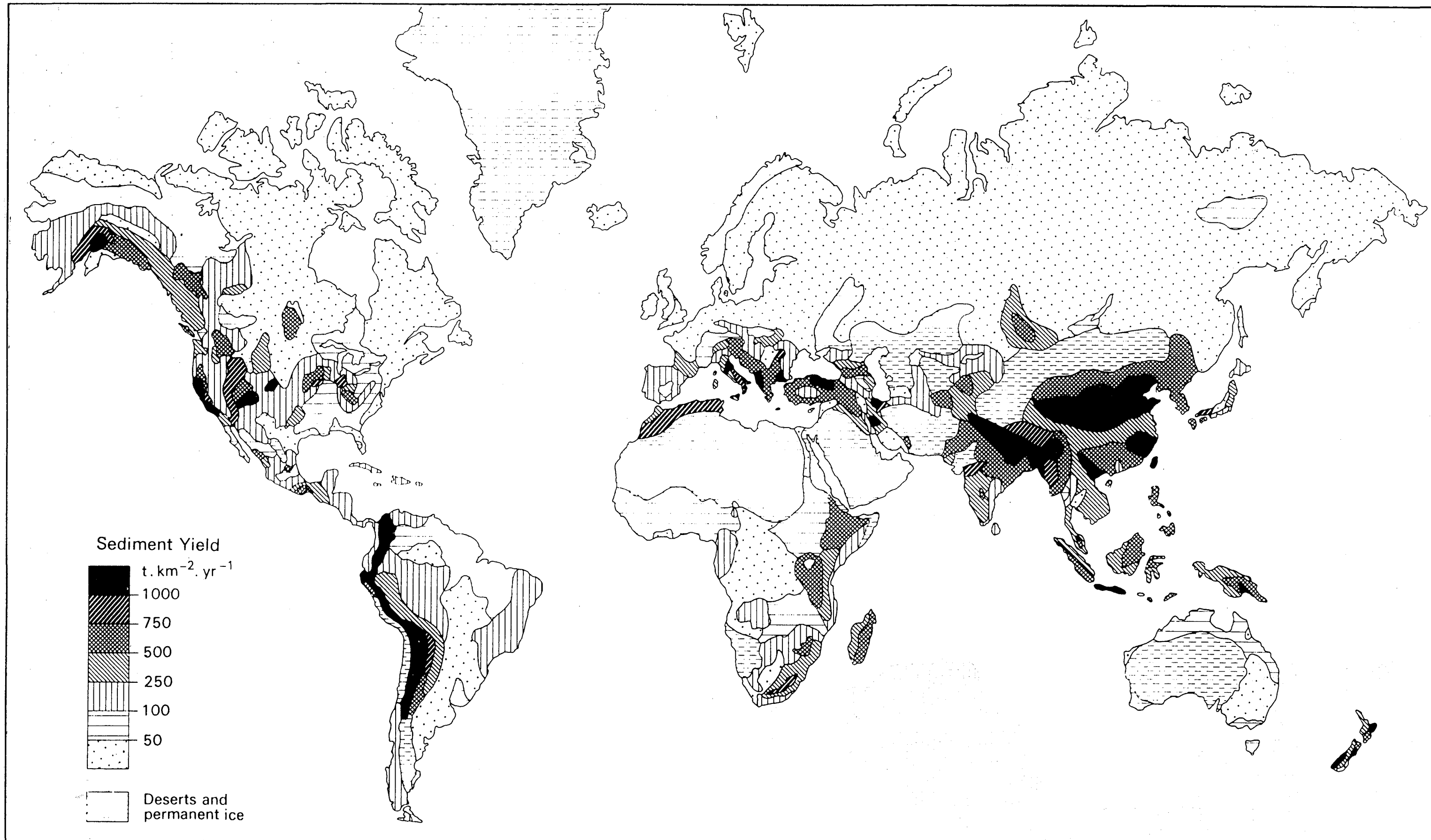

Fig. 1 The global pattern of suspended sediment yield according to Walling & Webb (1983).

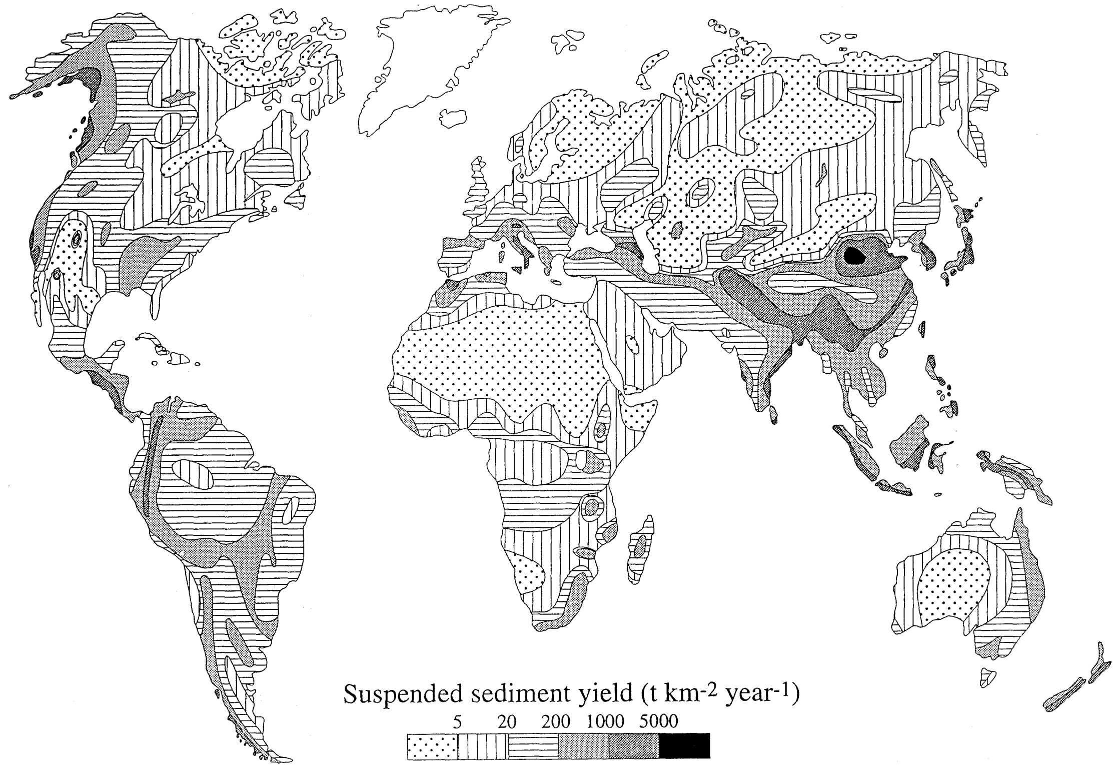

Fig. 2 The global pattern of suspended sediment yield according to Lvovich *et al.* (1991).

Walling & Webb (1983, 1987), Walling (1987), Dedkov & Mozzherin (1984) and Lvovich *et al.* (1991). The maps produced by Walling & Webb (1983) and by Lvovich *et al.* (1991) are presented here as Figs 1 and 2. Both relate to intermediate-sized drainage basins (i.e. 1000-10 000 km^2) and whilst somewhat different procedures were used to derive the maps, the patterns depicted evidence close similarities. Maximum sediment yields are associated with the loess area of China and the Cenozoic mountain areas around the Pacific margin. High values are also to be found in other mountain areas and in regions with mediterranean and semi arid climates and in the seasonally humid tropics. Low values are associated with desert regions and with the low relief, glaciated regions of the Canadian Shield and northern Eurasia. In both cases, these maps must be seen as only tentative representations of the detailed global patterns involved, and further work is needed both to extend the sediment load databases used and to refine the extrapolation procedures employed in areas where data are deficient. Recent advances in the development of detailed global databases for land surface and climate characteristics coupled with GIS techniques clearly offer considerable potential for such refinement.

Attempts to account for the broad trends encompassed by maps such as Fig. 1 and Fig. 2 and the data used for their development have frequently focused on climatic controls and, more particularly, the relationship between specific sediment yield on the one hand and mean annual precipitation and runoff and measures of precipitation seasonality on the other (cf. Langbein & Schumm, 1958; Fournier, 1960; Douglas, 1967; Wilson, 1969; Walling & Webb, 1983; Jansson, 1988). Jansson (1988) also reported a more detailed attempt to relate global variations in sediment yield to climate based on differentiation of 13 climatic groups. More recently, Pinet & Souriau (1988), Milliman & Syvitski (1992) and Summerfield & Hulton (1994) have emphasized the importance of relief in accounting for global variations in sediment yield. Summerfield & Hulton (1994), for example, analysed specific sediment yield data from 33 major world rivers and found that the greatest degree of statistical explanation was provided by variables reflecting catchment relief as represented by the basin relief and the relief ratio. Whereas basin relief accounted for 64% of the total variance of the dataset, mean annual runoff accounted for only 20% of the variance. It should, however, be recognized that the dataset used by Summerfield & Hulton (1994) to establish these relationships was very limited in size (33 rivers) and, furthermore, relief indices and values of mean annual runoff calculated for very large river basins will be spatially averaged to the extent of providing only very limited capacity for representing key contrasts between individual river basins. In their attempt to decipher the primary controls on global variations in sediment yield, Dedkov & Mozzherin (1984) recognized the importance of relief by distinguishing "mountain" and "plains" rivers, with specific sediment yields from the former being on average three times greater than the latter. Within these two groups, however, sediment yields were shown to vary between individual morphoclimatic zones. Similarly, in their attempts to generalize global variations in sediment yield, Lvovich *et al.* (1991) focused primarily on regional variations in the relationship between specific sediment yield and mean annual runoff. More work is clearly required to clarify the relative importance of relief and climatic factors in influencing the global pattern of sediment yield. Recent increases in data availability will undoubtedly facilitate such work, but there is also a need to develop more meaningful indices of relief and climate to assist in establishing the key relationships involved.

The role of drainage basin area

An inverse relationship between specific suspended sediment yield and drainage basin area has been widely reported in the literature (e.g. Walling, 1983, Milliman & Syvitski, 1992). The inverse trend of the relationship is commonly accounted for in terms of the increased opportunity for deposition of transported sediment as it moves through the fluvial system and into areas with reduced slope gradients and well-developed flood plains. Thus, the probability that a sediment particle eroded from the upstream catchment will be deposited increases with increasing transport distance and thus catchment area. This effect is frequently paralleled by a general decrease in sediment yield in downstream areas, due to reduced relief and precipitation / runoff, such that the average sediment yield per unit area also decreases as basin area increases. This simple relationship has, however, been questioned by a number of recent studies. Church & Slaymaker (1989), for example, suggest that in British Columbia, Canada, specific sediment yields frequently increase downstream up to catchment areas of *c.* 3×10^4 km^2 as a result of remobilization of Quaternary sediments stored in the valley and channel systems. It is also relatively easy to conceive of situations where deviations from the "standard" inverse relationship could be accounted for by specific local conditions. Sediment yields in headwater areas characterized by resistant rocks and good vegetation cover could thus be much lower than in downstream areas developed on softer, more erodible rocks, and in such circumstances specific sediment yield would therefore increase downstream.

A more fundamental questioning of the traditional view is, however, provided by Dedkov & Moszherin (1992) who have suggested that river systems will be characterized by either positive or negative relationships between specific sediment yield and catchment area according to the relative importance of channel and slope erosion (e.g. Fig. 3). Where channel erosion is dominant, as for example in forested areas with a dense vegetation cover, erosion rates will increase downstream in response to greater entrainment and transport of sediment. Specific sediment yield will therefore increase downstream, resulting in a positive relationship between specific sediment yield and basin area. Where slope erosion (i.e. sheet and gully erosion) constitutes the dominant sediment source, most of the erosion will be concentrated in the headwater areas and a proportion of the mobilized sediment will be deposited during transport through the system, resulting in an inverse relationship between specific sediment yield and basin area. Dedkov & Mozzherin (1992) based their proposal on a study of sediment yield data

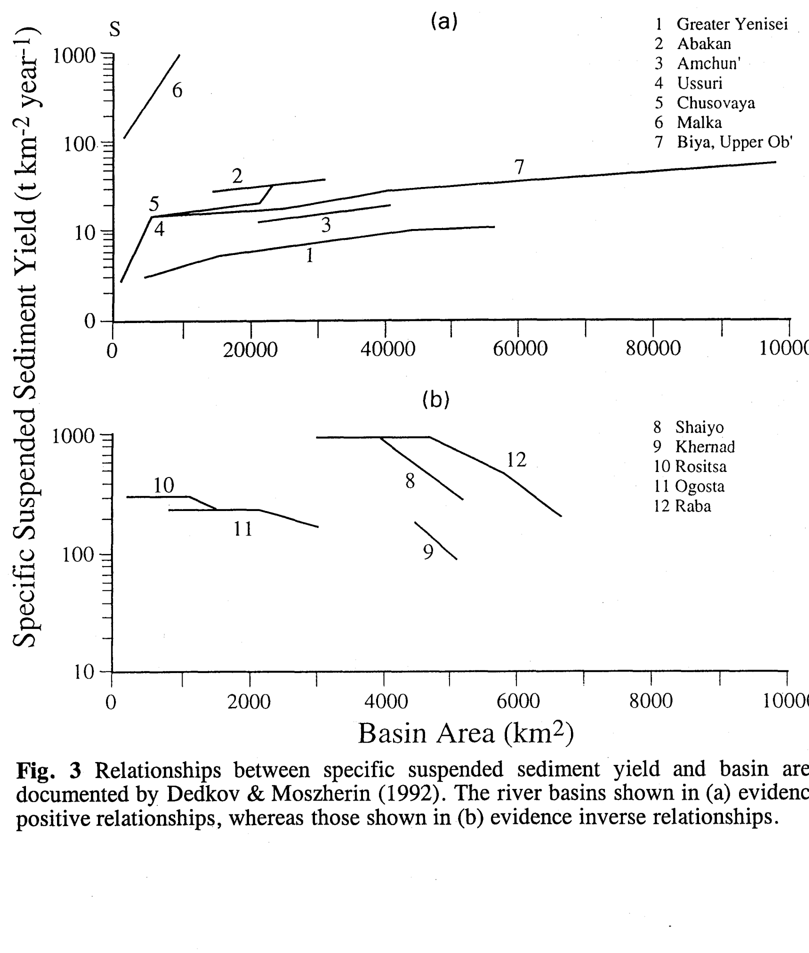

Fig. 3 Relationships between specific suspended sediment yield and basin area documented by Dedkov & Moszherin (1992). The river basins shown in (a) evidence positive relationships, whereas those shown in (b) evidence inverse relationships.

from a range of morphoclimatic zones and suggested that the positive relationship indicative of the dominance of channel erosion was typical of forested areas with an undisturbed vegetation cover, whereas the inverse relationship is characteristic of natural zones with poor vegetation cover and strong surface erosion (e.g. glacial, subnival and semiarid zones) and of areas disturbed by human activity (e.g. agriculture). It is thus important to question whether some of our commonly-accepted assumptions reflect the preponderance of studies based on regions such as the USA which are heavily impacted by human activity, rather than a more general feature of the global system. More detailed analysis of sediment yield data from different regions of the world and from different environments is clearly required to explore this question, but it is nevertheless tempting to suggest that the inverse relationship between specific sediment yield and basin area which has been widely cited in the literature is to a large extent a reflection of human impact on the fluvial system, rather than a basic precept.

TEMPORAL VARIABILITY

The anthropogenic impact

In assessing current estimates of the total suspended sediment flux from the land surface of the earth to the oceans and the associated global patterns of sediment yield (cf. Figs 1 and 2), it is important to consider the extent to which the natural denudation system has been perturbed by human activity (cf. Douglas, 1967; Meade, 1969; Walling, 1995). It is well known that soil erosion rates can increase by an order of magnitude or more under cultivation and other agricultural activity, and when it is recognized that the area of the earth's surface given over to crop production and livestock grazing has increased by more than 5-fold over the past 200 years (cf. Buringh & Dudal, 1987) it is clear than such changes must have produced increases in the sediment loads transported by the world's rivers. In the absence of long-term records of sediment transport spanning the period of such changes for most areas of the world, it is necessary to look to other sources of evidence of the magnitude of the changes involved. Thus, for example, Milliman *et al.* (1987) were able to use evidence drawn from long-term rates of Holocene sedimentation in the Yellow and East China Seas, which receive sediment from the Yellow River, to estimate that, as a result of land clearance and agricultural development in the loess region of the Middle Yellow River Basin, the recent river input was approaching an order of magnitude greater than that existing in the early and Middle Holocene. A similar approach was used by Degens *et al.* (1991) to reconstruct the changing sediment inputs to the Black Sea over the past 20 000 years. This reconstruction suggested that the sediment loads of the tributary rivers had increased by a factor of about three over the past 2 000 years as a result of deforestation and agricultural development. Other workers have employed detailed analysis of sediment deposits from small lakes to reconstruct more recent changes in sediment inputs consequent upon disturbance of the catchment area by human activity, and again increases in the range of five to ten times have been widely documented (e.g. Dearing *et al.*, 1987; Oldfield *et al.*, 1980). A similar range of increases was documented by Abernethy (1990) based on analysis of reservoir sedimentation data for a number of reservoir catchments in Southeast Asia which had been impacted by land use change

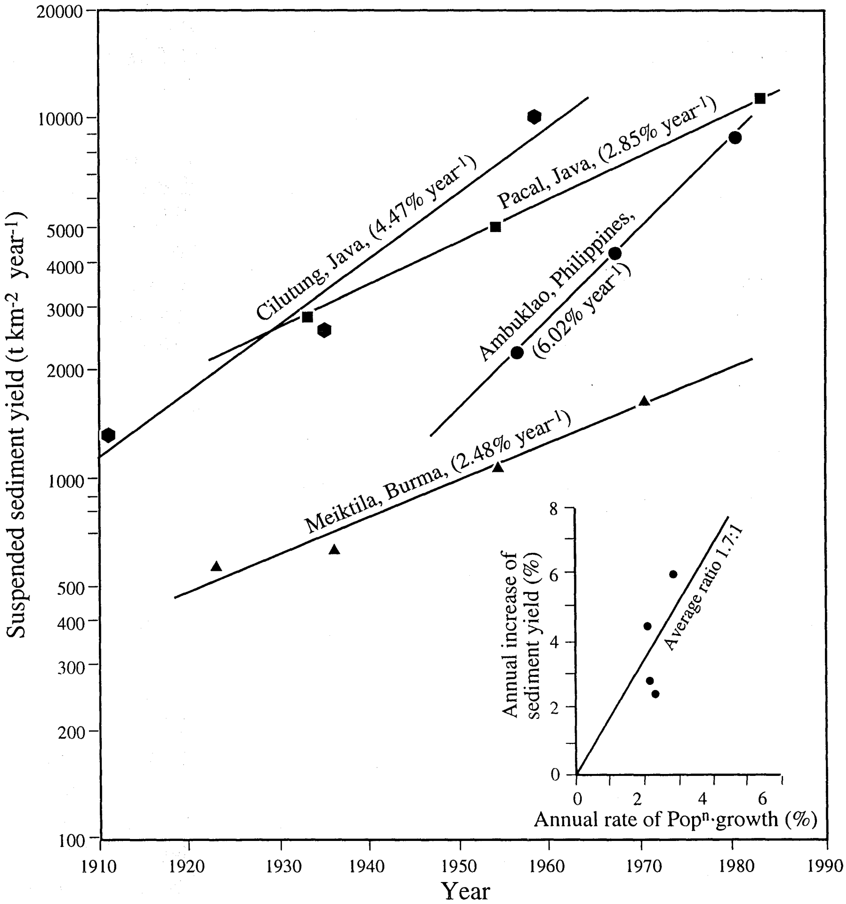

Fig. 4 Trends of increasing sediment yield during the present century in selected reservoir catchments in Southeast Asia (based on Abernethy, 1990).

during the twentieth century (Fig. 4). In this case, annual rates of sediment yield increase were within the range 2.48-6.02% year^{-1} and Abernethy (1990) suggested that these increases closely paralleled the rate of population growth in the areas concerned, although the ratio of the rate of increase of sediment yield to that for the population was greater than unity (Fig. 4). Based on this evidence, he suggested that annual suspended sediment yields in many developing countries were currently increasing at a rate equivalent to 1.6 times the rate of population increase and could therefore be expected to double in about 20 years. There is clearly scope to use information on recent and projected population increases to estimate likely changes in sediment yield, although caution should be exercised in extrapolating this simple relationship outside the area to which it relates. Furthermore, it should be recognized that although the reservoir catchments cited by Abernethy (1990) showed clear evidence of increasing sediment yields in response to land-use change, Alford (1992) reports a study of the 14 028 km^2 Chao Phraya river basin draining the highlands of northern Thailand which showed no evidence of a significant increase in sediment yield during the period extending from the late 1950s to the mid 1980s, despite substantial deforestation and extensive swidden agriculture within the basin.

Whilst most commonly cited examples of the impact of human activity on sediment yields relate to *increases*, it is important to recognize that instances of *reductions* also exist. More particularly, the construction of reservoirs will in most cases trap the majority of the sediment load transported by the river. In the case of the River Nile, for example, the annual sediment load transported by the river to its delta has decreased from *c.* 100×10^6 t $year^{-1}$ to almost zero as a result of the closure of the Aswan Dam. Similarly, Meade & Parker (1985) document the cases of the Missouri River where the construction of five major dams between 1953 and 1963 reduced its load entering the Mississippi to only about 25% of its former value. Since the Missouri River formerly represented the major supply of sediment to the Mississippi, the sediment load of that river has also declined and the load at its mouth in 1984 was less than one-half of the value before 1953. Data compiled by UNESCO (1978) relating to the major reservoirs of the world indicate that the associated impoundments now control around 10% of the total runoff from the land to the oceans. Although it seems reasonable to assume that the proportion of the total sediment flux from the land to the oceans which is trapped in these reservoirs will be similar, it is important to note that many of the major reservoirs of the world are located in arid and semiarid regions where sediment yields are relatively high. Furthermore, the important role of smaller dams and reservoirs in trapping sediment transported from upstream tributaries must also be considered, and the overall reduction in sediment yield caused by river impoundments is thus likely to be substantially greater than 10%. Indeed, it seems likely that in some areas of the globe increases in sediment transport caused by land clearance and land-use change will have been balanced by reductions caused by reservoir development, to the extent that current sediment yields may be fairly close to those existing prior to the onset of widespread land disturbance by human activity. Whilst there is clear evidence of the significance of human activity in influencing the sediment loads of the world's rivers, further work in evaluating and extrapolating the available evidence is required if a definitive assessment of the magnitude of this impact is to be produced.

Sensitivity to environmental change

Human activity represents only one facet of recent concern for the impact of global change on environmental systems, and, although the examples cited above provide clear evidence of the potential magnitude of changes in sediment yield associated with human activity, there is a need to place these within the broader context of environmental change, which also includes climate change. Although long records of sediment load and water discharge exist for relatively few measuring stations, it is possible to analyse available records to assess the sensitivity of sediment yields to environmental change. Examples of such analysis applied to the records from three rivers are presented in Fig. 5. These records were kindly supplied by Dr F. H. Weiss of the Bayer Landesamt fur Wasserwirtschaft, Munich, Germany (River Lech), and by Professor N. Bobrovitskaya of the State Hydrological Institute in St Petersburg, Russia (Kolyma and Dnestr Rivers). The record of suspended sediment transport for the River Lech at Fussen in Bavaria, Germany, spans more than 60 years and is

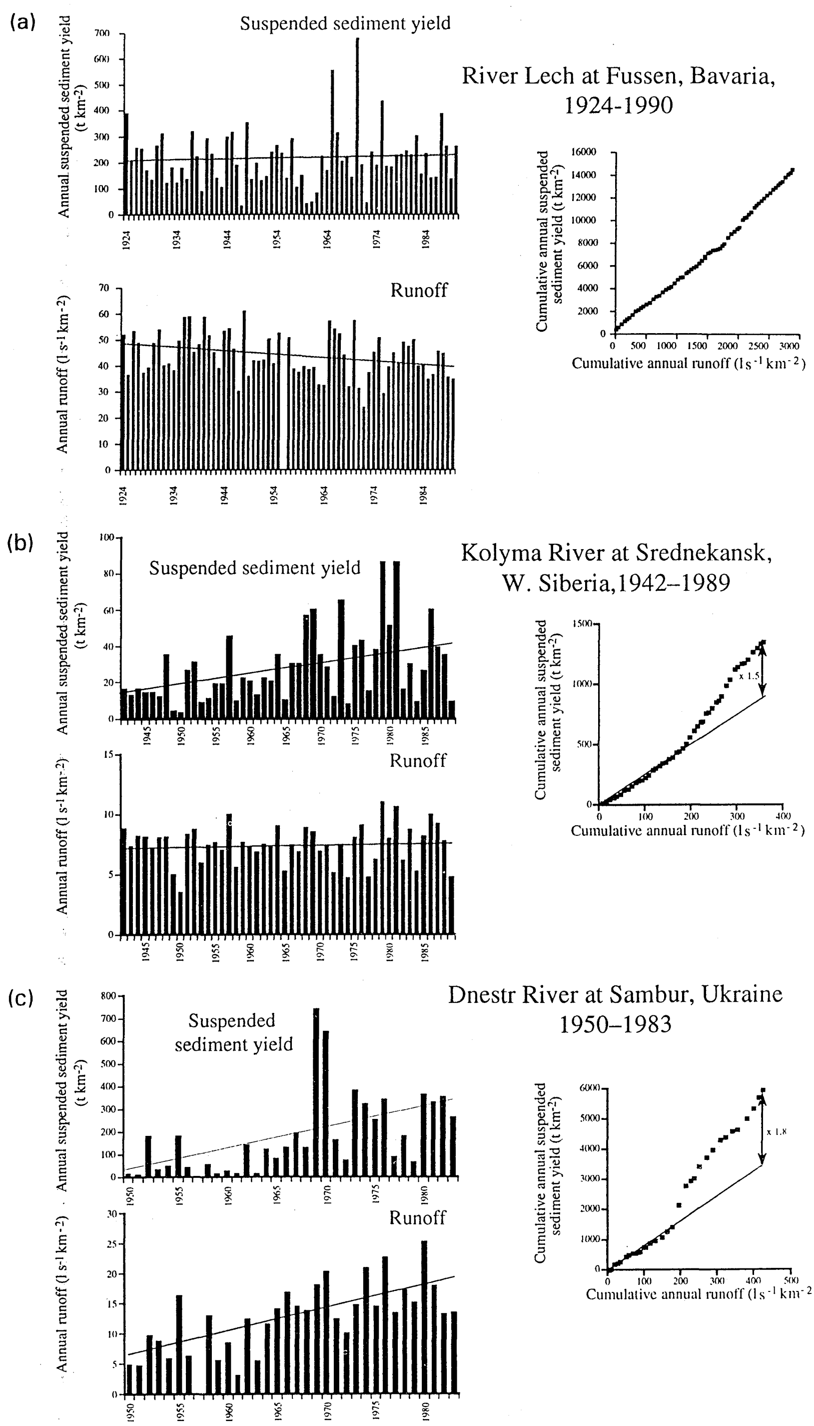

Fig. 5 Recent trends in suspended sediment yield for the Rivers Lech, Kolyma and Dnestr. (Based on data supplied by Dr F. H. Weiss, Bayer Landesamt fur Wasserwirtschaft, Munich, and Professor N. Bobrovitskaya, State Hydrological Institute, St Petersburg.)

depicted in Fig. 5(a). The river has been essentially unaffected by impoundment and regulation and it provides a valuable example of the response of an Alpine river to recent environmental change. In this case, there is some evidence of a reduction in runoff over the period of record and this trend is significant at the 95% level. Despite this trend of reduced annual runoff over the period of record, there is some evidence of an increase in sediment yield over the period. The overall upward trend is not statistically significant but the plot of annual sediment yield presented in Fig. 5(a) shows evidence of the occurrence of several years with markedly higher annual sediment yields during the period since 1965, even though these years show little or no evidence of higher annual runoff values. This feature may reflect an increased frequency of high magnitude storm events, the occurrence of which is not reflected in the values of annual runoff. The double mass plot presented in Fig. 5(a) also shows some evidence of increasing sediment yields since the early 1960s, but this trend is again not clearly defined. In this case, therefore, there is no definitive evidence of a change in the sediment regime, but there are some signs of a small increase.

The record for the 99 400 km^2 basin of the Kolyma River above Srednekansk in western Siberia presented in Fig. 5(b) shows clear evidence of increasing sediment yields during the period of record, which extends from 1941 to 1988. This upward trend of sediment yield is highly significant at the >99% level and the double mass plot suggests that sediment yields have increased by 1.5 times since about 1964. There is no significant change in annual runoff over the period of record and according to Bobrovitskaya (personal communication), the increased sediment yields can be accounted for by the impact of gold mining activity within the drainage basin. In the case of the Dnestr River at Sambur, which drains a catchment of 850 km^2 in the Ukraine, the trend line for the annual sediment yields presented in Fig. 5(c) suggests that these have increased by as much as five-fold since the early 1950s. This increase undoubtedly reflects the impact of forest clearance in the upstream catchment (cf. Bobrovitskaya, personal communication), but it is also a response to climatic change and the general increase in runoff amounts that has occurred over the period, and more particularly since the late 1960s. The double mass plot provides a means of establishing the timing of the changes involved and of tentatively distinguishing the effects of land-use and climate change. In this case, the break in the double mass plot around 1968 suggests that the impact of forest clearance was particularly felt after this date. Assuming that there is a linear relationship between annual runoff and sediment load, and that the effects of increased runoff will therefore not be reflected by a change in the slope of the double mass plot, disturbance by forest clearance can be estimated to have caused a 1.8 fold increase in the sediment load of the river.

Similar analysis of records from other rivers could provide a valuable means of developing a more general assessment of the sensitivity of sediment yields to environmental change and more particularly the relative importance of land-use change and climatic forcing. The need to take account of the latter is becoming increasingly apparent. The example from the Dnestr River cited above suggests that climatic forcing was more important than land-use change in causing increased sediment yields. Recent work undertaken in China aimed at assessing the efficacy of soil conservation and sediment control measures in reducing the sediment load of the Yellow River has also demonstrated that the reductions in sediment load documented in many tributary basins reflect both the impact of soil conservation and sediment control measures and the shift towards a drier climate. In their study of the Sanchuanhe River, which drains a 4161 km^2 basin in the gullied-hilly loess region of the Middle Yellow River basin, Zhao *et al.* (1992) demonstrated that sediment yields had declined by 74% over the period 1957-1989. However, only approximately 50% of this reduction could be ascribed to soil and water conservation measures, with the remaining 50% reflecting the shift to drier conditions. The need to couple consideration of the effects of human activity and land disturbance with those of climatic forcing could also prove particularly important in areas where the impact of land disturbance could be greatly increased by a shift towards a more erosive climatic regime.

PERSPECTIVE

As originally emphasized by Fournier (1960), sediment yield data for the world's rivers provide a valuable means of studying the global denudation system. The marked increase in data availability that has occurred in recent years now affords a meaningful basis for estimating the annual suspended sediment flux from the land to the oceans and for establishing the key features of the global variation of sediment yield across the land surface of the globe. Scope now exists to undertake more detailed analysis of the available data and of the patterns involved in order to establish the major controls on the magnitude and spatial variability of sediment yields. Such analysis could be greatly aided by the availability of a range of global environmental data bases and the use of GIS techniques. Assessment of the significance of anthropogenic activity in changing the sediment loads of the world's rivers affords a useful perspective on global change, but this should be coupled with more wide ranging analysis of the sensitivity of sediment yields to various facets of environmental change, including climate change. Sediment yields represent a key parameter in understanding the global system and assessing its sensitivity to change, but it must also be recognized that sediment transport by rivers has an important social and economic dimension related to problems of reservoir siltation and other aspects of water resource development as well as wide-ranging environmental implication, all of which further underscore the importance of its study.

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