Human Impact on Erosion and Sedimentation (Proceedings of Rabat Symposium S6, April 1997).
IAHS Publ. no. 245, 1997

The response of sediment yields to environmental change

D. E. WALLING
Department of Geography, University of Exeter, Exeter EX4 4RJ, UK

Abstract Increased sediment yields from river basins resulting from catchment disturbance and land use change have been increasingly recognized as a major problem in many areas of the world. Available evidence clearly demonstrates the potential magnitude of such increases, but it important to recognize that there are also cases where sediment yields have remained essentially constant despite significant catchment disturbance and where sediment loads have been substantially reduced due to reservoir construction. Against this background, there is need to synthesize the available evidence and to produce a general assessment of the impact of environmental change on the global sediment flux from the land to the oceans. The available sources of evidence are reviewed in this contribution. Long-term records of river sediment load are limited in both number and duration, but they, nevertheless, provide invaluable evidence of the changes involved. Such evidence can be supplemented by information obtained from marine and lake sediments, which can frequently provide evidence extending over longer periods, from catchment experiments and from contemporary measurement programmes by space-time substitution. Scope now exists to synthesize these various sources of evidence to produce a general assessment of the impact of environmental change on the sediment loads of world rivers.

INTRODUCTION

Increased sediment yields from river basins consequent upon accelerated erosion caused by vegetation clearance, land use change, and other forms of catchment disturbance have been increasingly recognized as a major environmental problem in many areas of the world. Thus Eckholm (1976) contended that "excess sediment is the major form of human-induced water pollution in the world today". The resulting increased sediment loads in rivers can also give rise to important practical and economic problems in terms of sedimentation of reservoirs and navigation channels and impairment of irrigation schemes and water treatment facilities (cf. Clark *et al.*, 1985). Mahmood (1987), for example, has estimated that the major reservoirs of the world are currently losing storage at the rate of 1% of gross capacity or 50 km^3 per year through sedimentation. Viewed in terms of replacement costs, this loss is equivalent to an annual economic loss of more than $6 billion. Furthermore, changes, and more particularly increases, in the flux of sediment from the land surface of the earth to the oceans must be seen as representing a significant perturbation of the global geochemical cycle, since sediment-associated fluvial transport accounts for a major proportion of the land-ocean flux of many elements. At the global scale, the potential for changes in the overall flux of sediment from the land to the oceans is clearly evident from basic statistics on the expansion of agriculture and the increasing problem of land degradation. Thus Buringh & Dudal (1987) indicate that over the past 200 years the area of the earth's surface given over to crop production and livestock grazing has increased by more than five-fold and the recent International Soil Reference and Information Centre/UNEP global survey of human-induced soil degradation (Oldeman *et al.*, 1991) has shown that nearly 10% of the total land surface of the globe is currently adversely affected by water erosion. Recent interest in the broader context of global environmental change promoted by the International Geosphere Biosphere Programme (IGBP) and related international scientific activities has also directed attention to the potential impact of climatic change on land erosion and sediment fluxes.

Against this background, there is a need to consider the degree to which the sediment loads of the world's rivers have changed within the recent past in response to the impact of both human activity and other aspects of environmental change. Some of the available evidence emphasizes the potential magnitude of such changes. For example, data assembled by Abernethy (1990) for a number of small reservoir catchments in Southeast Asia indicate that the sediment yields of such catchments may have increased by up to an order of magnitude over the past 60-70 years. Based on these trends, Abernethy suggests that the annual sediment yields of many rivers in developing countries can be expected to double over a period of 20 years in response to population growth and associated land use change. Similarly, in a longer-term assessment of the changes in the sediment load of the Yellow River in China, Milliman *et al.* (1987) conclude that the recent sediment input from this river basin to the Yellow and East China Seas is approaching an order of magnitude greater than that existing in the Early and Middle Holocene, as a result of land clearance and agricultural development in the loess region of the Middle Yellow River Basin. Taking account of the major contribution of Asian rivers to the total annual sediment flux from the land to the oceans (cf. Milliman & Meade, 1983), the fact that the Yellow River itself contributes of the order of 10% of this flux, and evidence that human activity has increased sediment yields in many other areas of the world, it is tempting to speculate that the global suspended sediment flux from the land to the oceans, which is estimated by Milliman & Syvitski (1992) to be currently *ca.* 20×10^9 t year^{-1}, may have doubled within the historical period. However, any such speculation must be tempered with caution. There are, for example, instances reported in the literature where sediment yields have not evidenced significant increases in response to land disturbance. Thus 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. Equally, there are many situations where human activity has caused a *reduction* rather than an *increase* in sediment yield. More particularly, the construction of reservoirs will commonly trap the majority of the sediment load formerly transported by the river. The closure of the Aswan Dam on the River Nile has, for example, reduced the annual suspended sediment load of that river from *ca.* 100×10^6 t year^{-1} to almost zero and Meade & Parker (1985) cite the case of the Mississippi River in the USA where the construction of five major dams on the Missouri River, one of its major tributaries, reduced the sediment load at its mouth by more than 50% between the 1950s and the

1980s. It therefore 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 fluxes may be little different from those existing prior to the onset of widespread land disturbance by human activity. Furthermore, there is a need to recognize that changes in sediment mobilization within a river basin may not always be closely reflected in the sediment yield at the basin outlet, due to storage within the sediment delivery system (cf. Walling, 1983, 1995) and that in some situations it may be necessary to distinguish the impact of human activity from that of climate change.

In order to obtain a clearer understanding of the sensitivity of sediment yields to environmental change, particularly at the global scale, there is a need to undertake a comprehensive review and synthesis of the available evidence relating to the impact of human activity and other aspects of environmental change The lack of reliable long-term records of sediment transport for most areas of the world and the limited period covered by such records as do exist, mean that other sources of information must also be exploited. This contribution aims to identify the key sources of information and to assess their potential and limitations and likely consistency. These sources reflect a variety of time scales ranging from the evidence afforded by lake sediments and other sedimentary deposits which extends back over 10^2 to 10^4 years, through available long-term records, to recent catchment experiments and attempts to use contemporary data to provide a longer term perspective by means of space-time substitution. They are considered in more detail below.

SOURCES OF EVIDENCE

Long-term records

Reliable long-term records of river sediment loads are limited in both number and duration in most areas of the world. Most available long-term records extend back only to the 1920s and 1930s and the reliability of early measurements is frequently open to question due to the many problems associated with obtaining accurate estimates of annual sediment loads (cf. Walling & Webb, 1981). Furthermore, changes in sampling techniques and the location of sampling sites can introduce additional uncertainties into the temporal consistency of such data. However, long-term records of suspended sediment load must represent a very important source of evidence in any attempt to establish trends in the sediment yields of world rivers and such evidence should clearly be exploited. Figure 1 presents examples of such records for four rivers kindly made available by Dr F. H. Weiss of the Bayer Landesamt für Wasserwirtschaft, Munich, Germany (Rivers Lech and Isar), and by Professor N. Bobrovitskaya of the State Hydrological Institute in St Petersburg, Russia (Kolyma and Dnestr Rivers). These examples usefully illustrate several different trends. In the case of the 1422 km^2 catchment of the River Lech above Fussen in Bavaria, Germany (Fig. 1(a)), the record spans more than 60 years and, since the river has been essentially unaffected by impoundment and regulation, it provides a valuable example of the response of an Alpine river to recent environmental change. The annual runoff record shows evidence of a small reduction

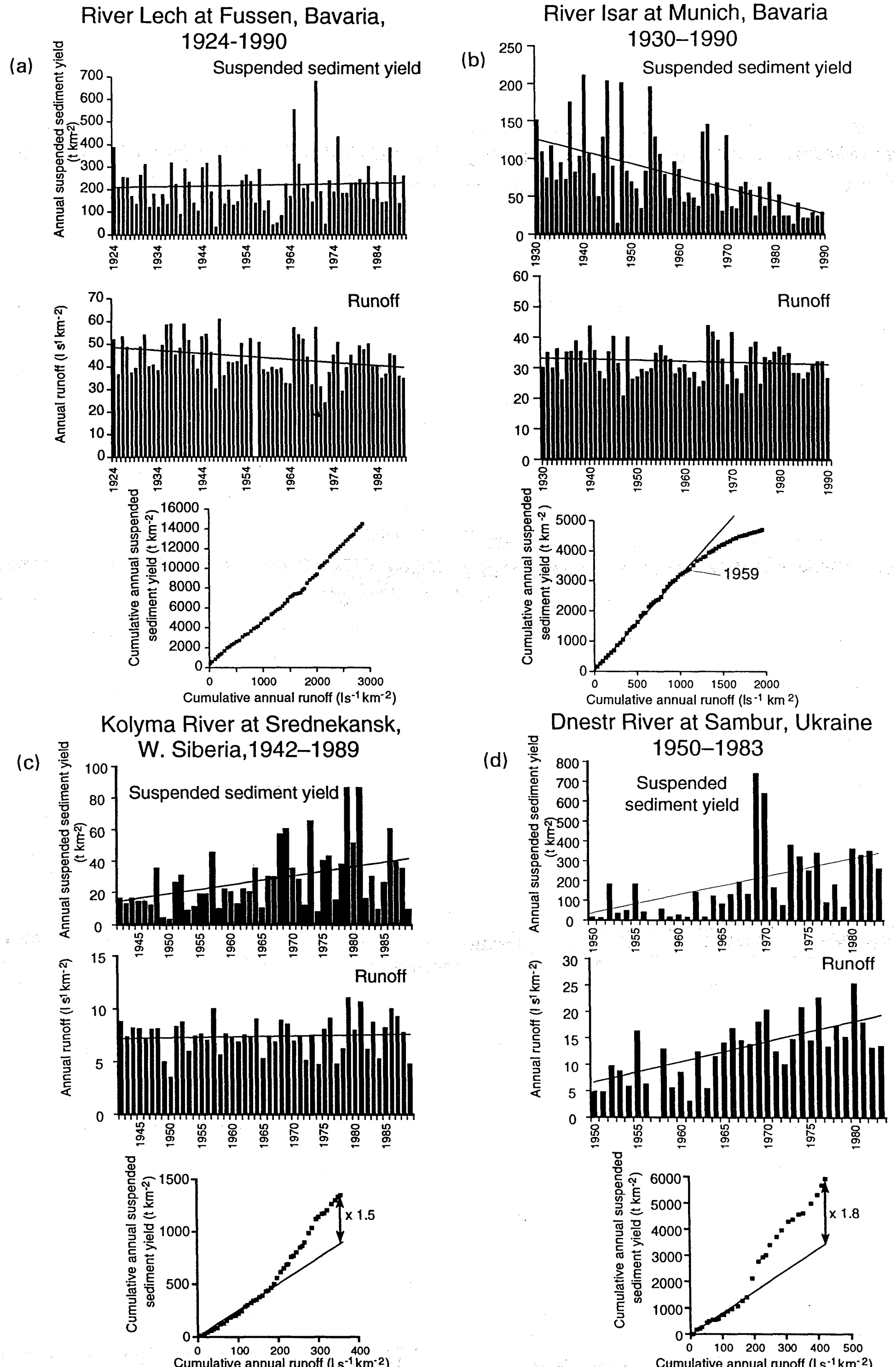

Fig. 1 Longer-term trends in suspended sediment transport and runoff for the River Lech at Fussen, Bavaria (a), the River Isar at Munchen, Bavaria (b), the Kolyma River at Srednekansk in western Siberia (c) and the Dnestr River at Sambur, Ukraine (d). (Based on data supplied by Dr F. H. Weiss (a and b) and Professor N. Bobrovitskaya (c and d).)

over the period of record and this trend is statistically significant at the 95% level. Despite the apparent reduction in annual runoff over the period of record, there is some evidence of an increase in sediment yield during this period. The overall upward trend is not statistically significant, but the plot of annual sediment yields includes several years with markedly higher annual sediment yields during the period since 1965, even though these years were not associated with significantly greater annual runoff totals. This feature may reflect an increased frequency of high magnitude storm events or an increased susceptibility of the landscape to erosion during high magnitude events. The double mass plot presented in Fig. 1(a) also shows some evidence of increasing sediment yields since the early 1960s, but this trend is again not well defined. In this case, therefore, there is no definitive evidence of a change in the sediment regime, despite the likelihood of significant changes in land use within the catchment (cf. Summer *et al.*, 1996), but there are some signs of a small increase in sediment yields. In contrast, the records of annual suspended sediment yield for the River Isar at Munchen, Germany (2855 km^2) for the period 1930-1990 (Fig. 1(b)), show a significant reduction that in turn reflects the development of hydropower stations and associated storage reservoirs on this river and, more particularly, the commissioning of the Sylvenstein dam in 1959 (cf. Weiss, 1996). There is no significant trend in the annual runoff totals during the period of record, but sediment yields have decreased to only about 20% of their former level over this period and the trend of the double mass plot suggests that the reduction has intensified in recent years.

The record for the 99 400 km^2 basin of the Kolyma River above Srednekansk in western Siberia presented in Fig. 1(c) shows a clear trend of increasing suspended sediment yields during the period of record, which extends from 1941-1988. 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 Bobrovitskaya (personal communication) has indicated that the increased sediment loads reflect the impact of gold mining activity within the drainage basin. The final example relates to the Dnestr River at Sambur, which drains an 850 km^2 catchment in the Ukraine (Fig. 1(d)). Here the trend line fitted to the annual sediment yields suggests that these have increased by as much as five-fold since the early 1950s. This increase undoubtedly reflects the impact of forest clearance within the upstream catchment (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 suggests that the impact of forest clearance was particularly felt after 1968 and that this itself accounts for a 1.8 fold increase in the sediment load of the river.

Compilation and analysis of similar records from other rivers in different areas of the globe could afford valuable evidence in any attempt to produce a more general assessment of the sensitivity of sediment yields to environmental change and the interaction 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 change was as important, if not more important, than land-use change in causing increased sediment yields. Recent analyses of the changing sediment loads of the Middle Yellow River in China have also stressed the importance of considering the interaction of human impact and climate change. Mou (1996) reports that the mean annual suspended sediment yield of the 667 948 km^2 catchment of the Middle Yellow River above Sanmenxia in the 1980s was 799×10^6 t $year^{-1}$. This compares with a long-term average for the same measuring station of 1606×10^6 t $year^{-1}$. Part of this reduction can be ascribed to the successful implementation of soil conservation measures aimed specifically at reducing the sediment load of the river. However, the reduced runoff of the 1980s, which was only 87% of the long-term mean, must also be taken into account. In this case, *ca.* 40% of the reduction in sediment yield from the loess region was ascribed to the conservation measures, whereas *ca.* 60% of the reduction resulted from the reduced runoff.

Marine and lake sediments

In the absence of long-term records of river sediment loads, the sediments preserved in marine and lake basins can frequently provide valuable evidence regarding past changes in sediment fluxes over periods as long as 10^4 years. Detailed analysis and dating of sediment cores can be used to reconstruct variations in past sediment inputs, and, although it may not be possible to express the results in terms of actual sediment yields, the relative magnitude of the changes can be evaluated. Thus, for example, Degens *et al.* (1976, 1991) demonstrate how they were able to use information obtained from sediment cores to reconstruct the record of sediment input to the Black Sea from its *ca.* 2.3×10^6 km^2 catchment area over the past 20 000 years (cf. Fig. 2(a)). The evidence obtained from the sediment cores indicated that the sediment input to the Black Sea, and therefore sediment yields from its catchment area, were relatively low during the Weichselian glaciation. The sediment input increased dramatically during the subsequent period of deglaciation in response to the increased runoff, abundant supplies of readily mobilized sediment exposed by the retreating ice and the lack of vegetation cover, but later slowly declined towards the Atlantic climatic optimum, when a relatively dense vegetation cover would have existed. The significant increase in sediment inputs during the past 2000 years can be directly related to the impact of human activity, and more particularly deforestation and expansion of agriculture within the catchment area, which have caused sediment yields to increase by a factor of about 3. The data presented in Fig. 2(a) afford a useful means of evaluating the impact of human activity on sediment yields in this region, but they also emphasize that natural variations associated with periods of glaciation and deglaciation may cause greater changes in sediment fluxes.

Where the sedimentary record preserved in smaller lakes can be analysed, it is frequently possible to provide more detailed information on the magnitude and timing of changes in sediment input from the lake catchment over periods of 10^2 to 10^3 years. Furthermore, where the catchment draining to the lake is relatively small, it may be possible to relate the reconstructed record of sediment yield to documentary evidence regarding the precise nature of changes in land use and other human impacts. Use of accurate core dating techniques in association with core correlation procedures can also permit the establishment of accurate estimates of changing sediment yields. An example of the application of this approach, which has enabled the record of sediment yield from a small lake catchment in southern Skane, Sweden,

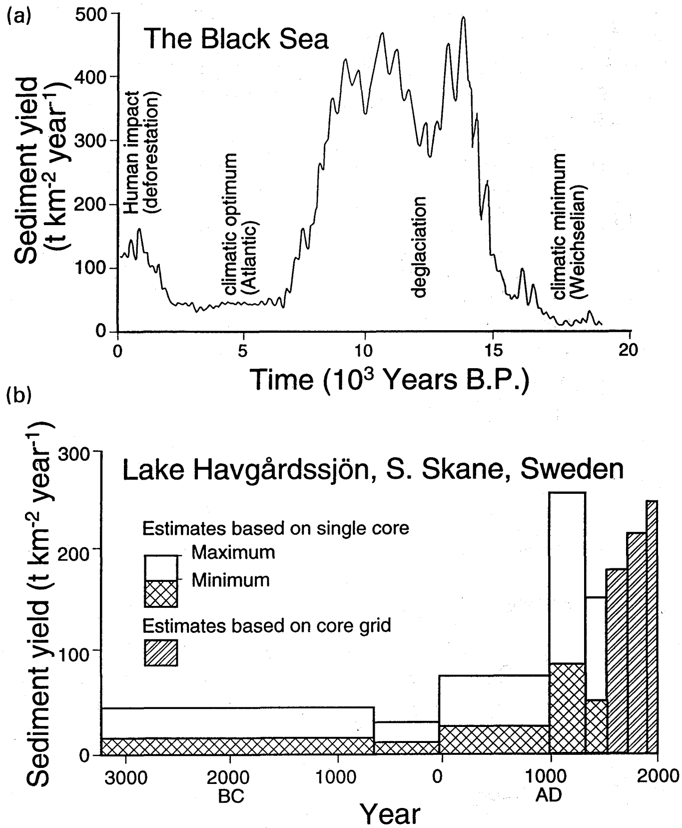

Fig. 2 Long-term variations in the sediment inflow to the Black Sea reconstructed by Degens *et al.* (1991) (a), and the historical trend of sediment yield in the catchment of Lake Havgardssjon reconstructed by Dearing *et al.* (1987) (b).

to be reconstructed, is provided by Fig. 2(b). In this study, Dearing *et al.* (1987) used a grid of 47 cores to reconstruct the record of sediment yield to Lake Havgardssjon for the period post-1550, and information from a single 4 m core was used to extend the record back to 3050 BC on a more tentative basis. Based on this evidence it can be seen that the sediment yield from the lake catchment began to increase from about 50 BC with the onset of forest clearance and the expansion of agriculture and reached a peak during the period AD 950-1300. The subsequent decrease in sediment yield from AD 1300-1550 coincides with the agrarian depression documented in many areas of northwest Europe and the climatic deterioration associated with the early part of the "Little Ice Age". More recent increases in sediment yield post 1550 correspond closely with available records which document an expansion of the cultivated area.

Similar reconstructions of changing sediment yields from small lake catchments have been undertaken in several other studies and the results of a number of these are summarized in Table 1. Such data again emphasize the sensitivity of catchment sediment yields to land use change and they provide a valuable complement to the available longer-term records by extending the time scales to cover periods of

Table 1 Some examples of lake-sediment-based evidence of increases in sediment yield due to catchment disturbance by human activity.

Lake	Location	Documented increase in sediment yield	Source
Frains Lake	Michigan, USA	×10*	Davis (1976)
Llyn Peris	North Wales, UK	×8	Dearing *et al.* (1981)
Lake Patzcuaro	Mexico	×7	O'Hara *et al.* (1993)
Lake Sacnao	Mexico	×35	Deevey *et al.* (1979)
Lake Ipea	Papua New Guinea	×10	Oldfield *et al.* (1980)
Lac Azigza	Morocco	×5	Flower *et al.* (1989)

* This value refers to the sustained increase, the short-term increase was up to ×70.

catchment disturbance which occurred well before the establishment of river monitoring programmes.

Catchment experiments

Most catchment experiments are, by design, concerned with relatively small areas and with the application of specific treatments or land use changes to the entire catchment area in order to document the magnitude of the changes involved (cf. Ward, 1971; Walling, 1979). Both the heterogeneity of larger catchments and problems of relating the response of small headwater catchments to downstream changes in sediment yield mean that the results obtained from catchment experiments cannot readily be scaled up to assess regional changes in sediment yield consequent upon land use change. Nevertheless, the results available from catchment experiments afford useful information on the potential magnitude of changes in sediment response associated with particular types of catchment disturbance or land use practices. Table 2 lists a small selection of such results, which serve to emphasize the high sensitivity of sediment yields to catchment disturbance at this scale. In these examples, increases in sediment yield of more than two orders of magnitude have been documented.

Although most catchment experiments have focused on documenting the magnitude of *increases* in sediment yield caused by land use change or catchment disturbance, it is also important to consider the results of those studies which have assessed the impact of soil conservation and related management practices aimed at

Table 2 Examples of results from experimental catchment studies of the impact of land use change on suspended sediment yields.

Location	Land use change	Increase in sediment yield	Source
Westland, New Zealand	Clearfelling	×8	O'Loughlin *et al.* (1980)
Oregon, USA	Clearfelling	×39	Fredriksen (1970)
Northern England	Afforestation (ditching and ploughing)	×100	Painter *et al.* (1974)
Texas, USA	Forest clearance and cultivation	×310	Chang *et al.* (1982)
Maryland, USA	Building construction	×126-375	Wolman & Schick (1967)

reducing suspended sediment yields. Such results provide a valuable perspective on the potential for reversing the detrimental effects of land use change and land management practices. Table 3 presents the results obtained from studies of four small catchments in the highly eroded loess region of the Middle Yellow River aimed at evaluating the success of soil conservation measures such as tree planting and construction of terraces and check dams in reducing sediment yields. In these cases sediment yields have been reduced by *ca.* 90% or more. Again, uncertainties exist in attempting to scale up such findings to larger river basins, but the results nevertheless serve to emphasize further that any attempt to consider the impact of human activity on sediment fluxes must also take account of the potential for reducing sediment fluxes by soil conservation and other catchment management strategies.

Table 3 The impact of soil and water conservation measures on catchment sediment yields in the Loess region of the Middle Yellow River, China.

Catchment	Area (km^2)	Area controlled	Sediment yield reduction (%)	Source
Wangmao Gully	5.97	68	89	Mou (1991)
Wangjia Gully	9.1	71	91	Mou (1991)
Nanxiaohe Gully	36.3	58	97	Mou (1991)
Yangjiagou Gully	0.87	40	93	Li (1992)

Contemporary measurements

In view of both the paucity of longer-term records capable of documenting the impact of environmental change on sediment yields and the greatly increased availability of shorter-term contemporary measurements of sediment transport by the world's rivers, space-time substitution or the ergodic hypothesis can afford an effective means of assessing the potential magnitude of the changes involved. In essence this approach involves assembling information on the spatial variation in sediment yield associated with factors such as land use and using these variations to assess the likely magnitude of changes in sediment yield associated with known temporal changes in catchment condition. A classic example of the potential of this approach is provided by the work of Wolman (1967) and Wolman & Schick (1967) in reconstructing the changes in sediment yield that have occurred and were likely to occur in the Piedmont region of Maryland, USA. In this case data such as those shown in Fig. 3(a) were combined with a generalized representation of land use change in the region to synthesize the record of temporal changes in sediment yield presented in Fig. 3(b). In this region, sediment yields can be seen to have increased by an order of magnitude as a result of forest clearance by European settlers and the expansion of agriculture, reaching a maximum around 1900. After this date, sediment yields declined in response to the introduction of soil conservation measures and a decline in the area under cultivation. Construction activities associated with rapid and extensive urban and suburban development caused a major increase in sediment yields during the 1960s, but levels subsequently declined to values approaching those associated with the natural forest land use as a result of the protection afforded by the extensive areas covered by urban development. Potential clearly exists to apply a similar approach in other regions of the world where the necessary data exist.

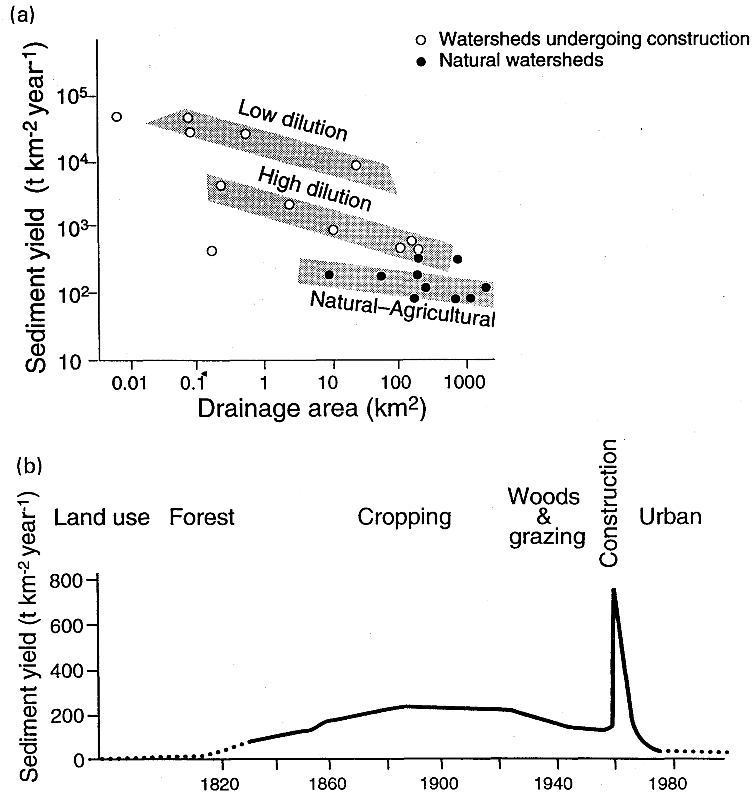

Fig. 3 Spatial variation of suspended sediment yields in the Piedmont Region of the Eastern USA (a) and a reconstruction of the record of suspended sediment yields in the region based on space-time substitution. (Based (a) on Wolman & Schick (1967) and (b) on Wolman (1967).)

A further example of the potential of this approach, which attempts to apply the ergodic hypothesis at the global scale, is provided by the work of Dedkov & Mozzherin (1984). These authors assembled suspended sediment yield data from more than 3600 rivers in different areas of the world. The river basins were classified into mountain or lowland types and were further grouped into large (>5000 km^2) and small (<5000 km^2) basins. The resulting data set was further stratified into three classes in terms of the degree of disturbance by agricultural activity. Category I basins were largely undisturbed and were characterized by either a >70% forest cover or a cultivated area <30%. Category II basins were associated with an average degree of disturbance and were characterized by an area under forest or cultivation of between 30% and 70%. The degree of disturbance by land use activities increased further in category III basins where the area under forest was <30% or the cultivated area >70%. By comparing the average sediment yield of category III river basins with those of category I an approximate measure of the magnitude of the increase in sediment yield associated with land disturbance by human activity was obtained (cf. Table 4). In the lowland regions of the world the average increases were 8.1 and 13.0 for large and small river basins respectively, whereas in mountain regions the equivalent values were 3.8 and 2.2. The reliability

Table 4 Increases in the sediment yields of world rivers resulting from catchment disturbance by land use activities, based on data assembled by Dedkov & Mozzherin (1984).

Group	Small basins	Large basins	All basins
Lowland rivers (n = 1854)	×13.0	×8.1	×10.0
Mountain rivers (n = 1811)	×2.2	×3.8	×2.8

of these values is necessarily constrained by the fact that they represent simple comparisons of mean values of sediment yield for drainage basins in different categories and are therefore heavily dependent on the representativeness of the sample of river basins comprising the database. Furthermore, some assessment of the areal extent of each category would be required to derive an assessment of the likely change in the global sediment flux from the land to the oceans. Nevertheless, the results obtained provide a useful indication of the possible magnitude of the increase in the sediment yields of world rivers resulting from catchment disturbance by land use activities and scope undoubtedly exists to refine the approach further at this global scale.

PERSPECTIVE

In reviewing the various sources of evidence concerning the impact of environmental change, and particularly land use activities, on the suspended sediment yields of world rivers, this contribution has emphasized the general lack of longer-term records of sediment yield which can be used to assess the magnitude of the changes involved. However, it has also highlighted the potential for exploiting complementary information from other sources, including marine and lake sediments, catchment experiments and contemporary measurement programmes. It has not attempted to synthesize and interpret this information, but it has rather sought to demonstrate that sediment yields are frequently highly sensitive to environmental change and to suggest that scope now exists to undertake a comprehensive synthesis and assessment of the available evidence. Such synthesis and assessment could aim to produce estimates of the magnitude of changes in sediment transport by world rivers at a variety of temporal and spatial scales, whilst taking account of changes associated with both human activity and climatic variability or change.

Acknowledgement The assistance of Dr F. H. Weiss of the Bayer Landesamt für Wasserwirtschaft, Munich, Germany and Professor N. Bobrovitskaya of the State Hydrological Institute, St Petersburg, Russia, in generously making available data for the Lech, Isar, Kolyma and Dnestr Rivers, and of Dr Phil Owens in processing these records, is gratefully acknowledged.

REFERENCES

Abernethy, C. (1990) The use of river and reservoir sediment data for the study of regional soil erosion rates and trends. Paper presented at the International Symposium on Water Erosion, Sedimentation and Resource Conservation (Dehradun, India, October 1990).

Alford, D. (1992) Streamflow and sediment transport from mountain watersheds of the Chao Phraya basin, northern Thailand: a reconnaissance study. *Mountain Research and Development* **12**, 257-268.

Buringh, P. & Dudal, R. (1987) Agricultural land use in space and time. In: *Land Transformation in Agriculture* (ed. by M. G. Wolman & F. G. A. Fournier), 9-43. SCOPE Report no. 32, Wiley, Chichester.

Chang, M., Roth, F. A. & Hunt, E. V. (1982) Sediment production under various forest-site conditions. In: *Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield* (ed. by D. E. Walling) (Proc. Exeter Symp., July 1982), 13-22. IAHS Publ. no. 137.

Clark, E. H., Haverkamp, J. A. & Chapman, W. (1985) *Eroding Soils: The Off-Farm Impacts*. The Conservation Foundation, Washington DC.

Davis, M. B. (1976) Erosion rates and land use history in southern Michigan. *Environ. Conservation* **3**, 139-148.

Dearing, J. A., Elner, J. K & Happey-Wood, C. M. (1981) Recent sediment flux and erosional processes in a Welsh upland lake catchment based on magnetic susceptibility measurements. *Quatern. Res.* **16**, 356-372.

Dearing, J. A., Hakansson, H., Liedberg-Johnsson, B., Persson, A., Skansjo, S., Widholm, D., & El Daoushy, F. (1987) Lake sediment used to quantify the erosional response to land use change in southern Sweden. *Oikos* **50**, 60-78.

Dedkov, A. P. & Mozzherin, V. T. (1984) *Eroziya i Stock Nanosov na Zemle*. Izdatelstvo Kazanskogo Universiteta.

Deevey, E. S., Rice, D. S., Rice, P. M., Vaughan, H. H., Brenner, M. & Flannery, M. S. (1979) Mayan urbanism: Impact on a tropical karst environment. *Science* **206**, 298-306.

Degens, E. T., Paluska, A. & Eriksson, E. (1976) Rates of soil erosion. In: *Nitrogen, Phosphorus and Sulphur-Global Cycles* (ed. by B. H. Svensson & R. Soderlund), 185-191. SCOPE Report no. 7, Stockholm.

Degens, E. T., Kempe, S. & Richey, J. E. (1991) Summary: Biogeochemistry of major world rivers. In: *Biogeochemistry of Major World Rivers* (ed. by E. T. Degens, S. Kempe & J. E. Richey), 323-347. Wiley, Chichester, UK.

Eckholm, E. P. (1976) *Losing Ground*. Norton, New York.

Flower, R. J., Stevenson, A. C., Dearing, J. A., Foster, I. D. L., Airey, A., Rippey, B., Wilson, J. P. F.& Appleby, P. G. (1989) Catchment disturbance inferred from palaeolimnological studies of three contrasted sub-humid environments in Morocco. *J. Palaeolimnology* **1**, 293-322.

Fredriksen, R. L. (1970) Erosion and sedimentation following road construction and timber harvest on unstable soils in three small western Oregon watersheds. *US Forest Service Res. Pap. PNW 104*.

Li, Z. (1992) The effects of forest in controlling gully erosion. In: *Erosion, Debris Flows and Environment in Mountain Regions* (ed. by D. E. Walling, T. R. Davies & B. Hasholt) (Proc. Chengdu Symp., July 1992), 429-437, IAHS Publ. no. 209.

Mahmood, K. (1987) *Reservoir Sedimentation: Impact, Extent and Mitigation*. World Bank Technical Pap. no. 71.

Meade, R. H. & Parker, R. S. (1985) Sediment in rivers of the United States. In: *National Water Summary 1984, US Geol. Survey Wat. Supply Pap.* 2275, 49-60.

Milliman, J. D. & Meade, R. H. (1983) World-wide delivery of river sediment to the oceans. *J. Geol.* **91**, 1-21.

Milliman, J. D., Qin, Y.-S., Ren M.-E. & Saito, Y. (1987) Man's influence on the erosion and transport of sediment by Asian rivers: the Yellow River (Huanghe) example. *J. Geol.* **95**, 751-762.

Milliman, J. D. & Syvitski, J. P. M. (1992) Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *J. Geol.* **100**, 325-344.

Mou, J. (1991) The impact of environmental change and conservation measures on erosion and sediment loads in the Yellow River basin. In: *Sediment and Stream Water Quality in a Changing Environment* (ed. by N. Peters & D. E. Walling) (Proc. Vienna Symp., August 1991), 47-52. IAHS Publ. no. 203.

Mou, J. (1996) Recent studies of the role of soil conservation in reducing erosion and sediment yield in the loess plateau area of the Yellow River basin. In: *Erosion and Sediment Yield: Global and Regional Perspectives* (ed. by D. E. Walling & B. W. Webb) (Proc. Exeter Symp., July 1996), 541-548. IAHS Publ. no. 236.

O'Hara, S. L., Street-Perrott, F. A. & Burt, T. P. (1993) Accelerated soil erosion around a Mexican highland lake caused by prehispanic agriculture. *Nature* **362**, 48-51.

O'Loughlin, C. L., Rowe, L. K. & Pearce, A. J. (1980) Sediment yield and water quality responses to clearfelling of evergreen mixed forests in western New Zealand. In: *The Influence of Man on the Hydrological Regime, with Special Reference to Representative and Experimental Basins* (Proc. Helsinki Symp., June 1980), 285-292. IAHS Publ. no. 130.

Oldeman, L. R., Hakkeling, R. T. A. & Sombroek, W. G. (1991) *World Map of the Status of Human-Induced Soil Degradation: An Explanatory Note*. International Soil Reference and Information Centre, Wageningen.

Oldfield, F., Appleby, P. G. & Thompson, R. (1980) Palaeoecological studies of lakes in the Highlands of Papua New Guinea. I. The chronology of sedimentation. *J. Ecology* **68**, 457-477.

Painter, R. B., Blyth, K., Mosedale, J. C. & Kelly, M. (1974) The effect of afforestation on erosion processes and sediment yield. *In: Effects of Man on the Interface of the Hydrological Cycle with the Physical Environment* (Proc. Paris Symp., September 1974) , 150-157. IAHS Publ. no. 113.

Summer, W., Klaghofer, E. & Hintersteiner, K. (1996) Trends in soil erosion and sediment yield in the alpine basin of the Austrian Danube. In: *Erosion and Sediment Yield: Global and Regional Perspectives* (ed. by D. E. Walling & B. W. Webb) (Proc. Exeter Symp., July 1996), 473-479. IAHS Publ. no. 236.

Walling, D. E. (1979) Hydrological processes. In: *Man and Environmental Processes* (ed. by K. J. Gregory & D. E. Walling), 57-81. Dawson, Folkestone.

Walling, D. E. (1983) The sediment delivery problem. *J. Hydrol.* **65**, 209-237.

Walling, D. E. (1995) Suspended sediment yields in a changing environment. In: *Changing River Channels* (ed. by A. M. Gurnell & G. Petts), 149-176. Wiley, Chichester, UK.

Walling, D. E. & Webb, B. W. (1981) The reliability of suspended sediment load data. *In: Erosion and Sediment Transport Measurement* (Proc. Florence Symp., June 1981), 79-88. IAHS Publ. no. 133.

Ward, R. C. (1971) *Small Watershed Experiments: An Appraisal of Concepts and Research Developments*. University of Hull Occasional Papers in Geography no. 18.

Weiss, F. H. (1996) Sediment monitoring, long-term loads, balances and management strategies in southern Bavaria. In: *Erosion and Sediment Yield: Global and Regional Perspectives* (ed. by D. E. Walling & B. W. Webb) (Proc. Exeter Symp., July 1996), 575-582. IAHS Publ. no. 236.

Wolman, M. G. (1967) A cycle of erosion and sedimentation in urban river channels. *Geogr. Ann.* **49A**, 385-395.

Wolman, M. G. & Schick, A. P. (1967) Effects of construction on fluvial sediment: urban and suburban areas of Maryland. *Wat. Resour. Res.* **6**, 1312-1326.