

The United Nations World Water Assessment Programme

Scientific Paper

# The Impact of Global Change on Erosion and Sediment Transport by Rivers: Current Progress and Future Challenges

Desmond E. Walling for the International Sediment Initiative of UNESCO-IHP



SCIENTIFIC PAPER

Side publications series

World Water Assessment Programme



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Published by the United Nations Educational,  
Scientific and Cultural Organization,  
7 place de Fontenoy, 75352 Paris  
07 SP, France

© UNESCO 2009

ISBN 978-92-3-104135-8

Design and typesetting by Pica Publishing  
publish@picapublish.com

Cover graphics by Peter Grundy,  
www.grundini.com

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### Acknowledgement

The content of this paper draws on information and data provided by many different individuals and organizations, whose input is gratefully acknowledged. It also draws on recent papers published by the author.

# The Impact of Global Change on Erosion and Sediment Transport by Rivers:

## Current Progress and Future Challenges

Desmond E. Walling

### 1. Introduction

The processes of erosion, sediment delivery and sediment transport are key components and measures of the functioning of the Earth system. Erosion and sediment redistribution processes are the primary drivers of landscape development and play an important role in soil development. Equally, the sediment load of a river provides an important measure of its morphodynamics, the hydrology of its drainage basin, and the erosion and sediment delivery processes operating within that basin. The magnitudes of the sediment loads transported by rivers have important implications for the functioning of the system; for example through their influence on material fluxes, geochemical cycling, water quality, channel morphology, delta development, and the aquatic ecosystems and habitats supported by the river.

In addition to their key role in the functioning of the natural Earth system, erosion and sediment dynamics have important implications for human exploitation of that system and the sustainable use of natural resources. They must therefore be seen as having a highly significant socio-economic dimension. Soil erosion is integrally linked to land degradation, and excessive soil loss resulting from poor land management has important implications for crop productivity and food security – and thus for the sustainable use of the global soil resource (Montgomery, 2007).

Similarly, the sediment loads of rivers can exert an important control on the use of a river for water supply, transport and related purposes. High sediment loads can, in particular, result in major problems for water resource development, through reservoir sedimentation and the siltation of water diversion and irrigation schemes, as well as increasing the cost of treating water abstracted from a river. High sediment inputs into lakes and coastal seas can result in sedimentation and changes in nutrient cycling. Furthermore, high sediment loads can result in pollution and habitat degradation in river systems.

Against this background, changes in erosion rates and in sediment transport by the world's rivers can have important repercussions at a range of levels. From a global perspective, changes in erosion rates have important implications for the global soil resource and its sustainable use for food production. Changes in land–ocean sediment transfer will result in changes in global biogeochemical cycles, particularly in the carbon cycle, since sediment plays an important role in the

flux of many key elements and nutrients, including carbon. At the regional and local levels, changes in erosion rates can have important implications for the sustainability of agricultural production and for food security. Equally, changes in the sediment load of a river can give rise to numerous problems. For example, increased sediment loads can result in accelerated rates of sedimentation in reservoirs, river channels and water conveyance systems, causing problems for water resource development, and adverse impacts on aquatic habitats and ecosystems. Conversely, reduced sediment loads can result in the scouring of river channels and the erosion of delta shorelines as well as causing reduced nutrient inputs into aquatic and riparian ecosystems – particularly lakes, deltas and coastal seas.

Because of their close links to land cover, land use and the hydrology of a river basin, erosion and sediment transport processes are sensitive to changes in climate and land cover and to a wide range of human activities. These include forest cutting and land-clearance, the expansion of agriculture, land use practices, mineral extraction, urbanization and infrastructural development, sand mining, dam and reservoir construction, and programmes for soil conservation and sediment control (Walling, 2005).

Although recent concern about the impact of global change on the Earth system has emphasized the impact of climate change resulting from the increased emission of greenhouse gases and associated global warming, it is important to consider other measures of the functioning of the system. Soil erosion rates and the sediment loads transported by the world's rivers provide an important and sensitive indicator of changes in the operation of the Earth system and, as indicated above, widespread changes in erosion rates and sediment flux can have important repercussions and give rise to significant socio-economic and environmental problems.

This contribution attempts to give a brief review of existing knowledge regarding the impact of global change on erosion and sediment dynamics and to identify key uncertainties and future research needs. Emphasis is placed on a global perspective and on changes in the erosion rates and the sediment loads of the world's rivers.

Although this contribution focuses on how the world's rivers respond to global change, both in terms of erosion rates and sediment loads, it is important to recognize that, to date, less attention has been directed towards global erosion rates than to sediment yields and sediment loads. This situation largely reflects the spatially integrated nature of measurements of sediment transport, such that a single measuring point on a river can provide representative information on the upstream drainage basin. In contrast, soil erosion rates are more difficult to quantify and are site-specific. They are characterized by high spatial variability and must therefore be documented over very small areas. As a result, it is

difficult to produce global generalizations regarding erosion rates and their changes through time, and most attention will therefore be directed to sediment loads. However, since the sediment export from a river basin will reflect the intensity of erosion in the upstream basin, the two are closely linked.

The distinction between erosion rates and sediment yields must, nevertheless, be emphasized. The sediment yield from a river basin reflects only that part of the sediment eroded from within the basin that reaches the basin outlet. Existing understanding of sediment delivery ratios (as outlined by Walling, 1983 and De Vente et al., 2007), suggests that these can be relatively low in larger river basins. The high spatial variability commonly associated with erosion rates means that erosion rates in some areas of the basin with a high erosion risk could be several orders of magnitude higher than suggested by the specific sediment yield.

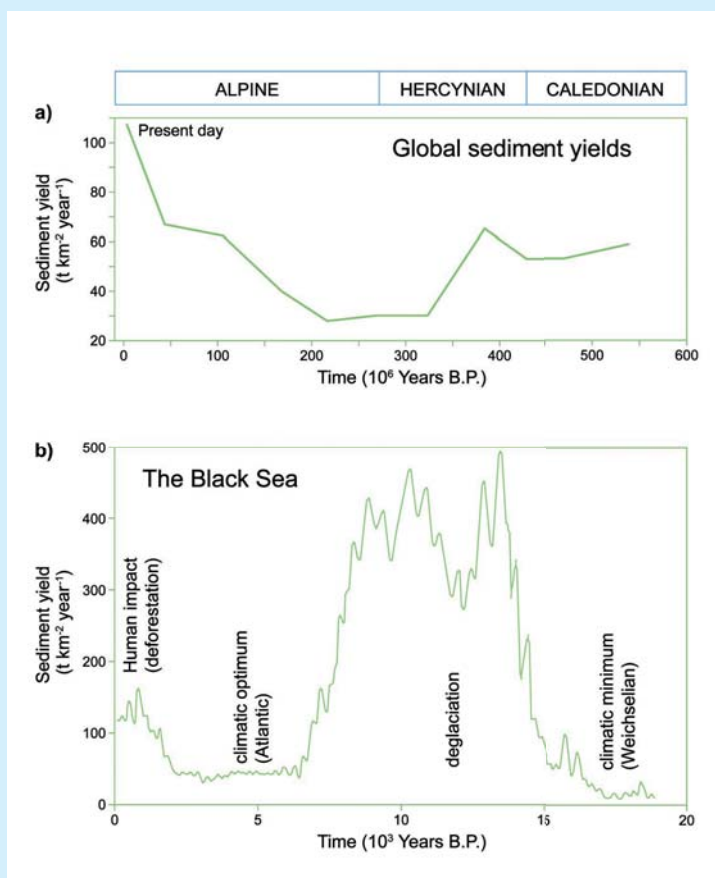
## 2. Existing understanding of the impact of global change on the global erosion rates and sediment loads of the world's rivers

### 2.1 The longer-term perspective

When considering the sensitivity of global erosion rates and sediment fluxes to global change, it is useful to begin by considering the evidence for past, longer-term changes – to provide some indication of the physical bounds of the potential variability. And by considering longer-term changes, it is possible to consider recent human impact in the context of the natural variability of the system in response to past 'natural' changes. The Earth's surface and the hydroclimatic conditions experienced by that surface have evidenced many important changes over geological time. The cycles of erosion, sedimentation and orogeny that have produced the current land surface are closely linked to the magnitude of past land–ocean fluvial sediment transfer.

Andrey Panin, in his 2004 paper on land–ocean sediment transfer in palaeotimes, used available information on the volumes of clastic sedimentary rocks associated with different geological epochs to estimate the land–ocean sediment flux since the late Jurassic. This was found to range between 3 Gt per year and 5 Gt per year during the period extending from the late Jurassic to the end of the Cretaceous. During the Cenozoic, the land–ocean sediment flux increased, reaching 9.6 Gt per year in the Pliocene as a result of the Alpine orogeny. It increased still further, to around 15 Gt per year, during the Pleistocene and Holocene, in response to further increases in the intensity of erosion. A similar analysis undertaken by Tardy et al. in 1989 covered a longer period, extending back over more than 500 million years. This can be used to provide estimates of sediment yield from the land surface of the globe ranging from approximately 30–120 t per km<sup>2</sup> per year in the Holocene (Figure 1a). Both of these studies suggest that global land–ocean sediment fluxes

Figure 1 **Orogenic cycles**



Tentative reconstructions of (a) the variation of sediment yield from the land surface of the globe during the past 500 million years (based on Tardy et al., 1989), and (b) sediment yield from the land draining into the Black Sea over the past 20,000 years (based on Degens et al., 1976 and 1991).

have varied over a four- to five-fold range through geological time.

Information on past sediment inputs to lakes and enclosed seas (such as the Black Sea) derived from sediment cores can provide further important evidence of more recent changes in sediment flux over the millennial timescale. Figure 1(b) presents a tentative reconstruction of the changes in sediment yield in the 2.3 million square kilometre ( $2.3 \times 10^6 \text{ km}^2$ ) catchment of the Black Sea over the past 20,000 years, based on evidence from sediment cores reported in Degens et al., 1976 and Degens et al., 1991.

The record indicates that sediment inputs into the Black Sea were relatively low during the Weichselian glaciation, when much of its catchment area was ice-covered. The sediment input increased dramatically during the subsequent period of deglaciation in response to the increased runoff, the abundant sediment supply exposed by the retreating ice, and the lack of vegetation cover. However as vegetation subsequently colonized the area and forests expanded during the Atlantic climatic optimum, sediment yields declined markedly and reached a low of 30-40 t per  $\text{km}^2$  about 3,000 to 5,000 years ago. The subsequent increase in sediment yield

towards the present can be linked to human activity, and more particularly, to forest clearance and the development of agriculture.

Overall, the records from the Black Sea indicate that sediment yields from its catchment have varied by more than 1,000% over the past 20,000 years in response to both climate change and human impact. Over this timescale, it would seem that climate change has proved more important than human impact in driving changes in sediment yield.

### 2.2 Recent changes in the sediment loads of the world's rivers: the evidence

The above long-term reconstructions of past variations in sediment fluxes at the global and regional levels clearly involve many uncertainties and can provide only a general assessment of the likely magnitude of the variations involved. Many opportunities undoubtedly exist to exploit the potential of sediment cores collected from lakes and other sediment sinks, including river deltas, to provide evidence of changes in sediment fluxes over a range of time scales (Dearing and Jones, 2003 and Ta et al., 2002). However, records of sediment load obtained from long-term monitoring programmes clearly provide a key source of evidence for assessing recent changes in the sediment loads of the world's rivers.

Such records rarely extend back more than about fifty years, so they are unable to document all the key changes in the erosion and sediment dynamics of a drainage basin that may have occurred in the recent past, particularly where significant human impact has extended over millennia.

In many areas of the 'Old World' the major phase of forest clearance and land disturbance by agriculture will occurred several millennia ago. Furthermore, use of such records necessarily depends heavily on the availability of data and the quality of those data. In the absence of information on bed-load transport for most world rivers, emphasis is commonly placed on suspended sediment loads. Reliable suspended sediment load data are unavailable for many of the world's rivers and, for those rivers where data are available, the short period of record or the temporally lumped nature of the data frequently preclude analysis of the nature and extent of recent changes. It is something of a paradox that although many areas of the developing world have seen major changes in land cover and land use as well as rapid growth of population and infrastructure in recent years, and could therefore be expected to provide evidence of significant changes in sediment load, it is these areas where sediment records are frequently lacking. However, the available data provide a useful basis for assessing the likely nature of recent changes in the sediment loads of the world's rivers.

Figure 2 provides evidence of the potential magnitude and nature of recent changes in the suspended sediment loads of the world's rivers, by presenting information from three rivers that provide evidence of marked changes in their sediment loads in recent years and are also characterized by contrasting trends in their records of annual water discharge and sediment load. The data available for the measuring station at Lijin on the lower Yellow River in China, which has a catchment area of 752,500 km<sup>2</sup> (Figure 2a), provides clear evidence of a major decrease in both the annual sediment load and the annual water discharge since the late 1970s. The mean annual suspended sediment load for this station, based on the record available through to the 1970s, is commonly reported as 1.08 Gt per year. However, the annual load has shown a significant reduction in recent years, falling to around 0.8 Gt per year in the 1980s, and to around 0.4 Gt per year in the 1990s.

Available information suggests that the load at Lijin has reduced still further in the early years of the current century and may now be as low as 0.15 Gt per year (Wang et al., 2007). Based on these data, the current sediment load at Lijin is approaching an order of magnitude lower than that documented for the period up to about 1980. Simple trend analysis applied to the records of annual water and suspended sediment discharge for the Yellow River at Lijin presented in Figure 2a, using linear regression to establish trend lines, provides clear evidence of a statistically significant ( $P > 99.9\%$ ) reduction in both

the annual runoff and sediment load over the past fifty years. The lack of any clear break in the double mass plot (Figure 2a, lower), a tool frequently used to identify changes in the sediment response of a river (Walling 1997), suggests that both the runoff and sediment response have responded to similar controls.

The progressive reduction in both the water discharge and suspended sediment load of the Yellow River has been partly accounted for as a response to climate change and, more particularly, reduced precipitation over the central region of the catchment. However, it is primarily the result of more direct human impact – increasing water abstraction (as evidenced by the greatly reduced flows shown in Figure 2a); sediment trapping by an increasing number of (large and small) reservoirs; and an extensive programme of soil and water conservation, aimed at both improving agricultural productivity and reducing sediment inputs to the river where siltation poses major problems for effective flood control and water use in its lower reaches.

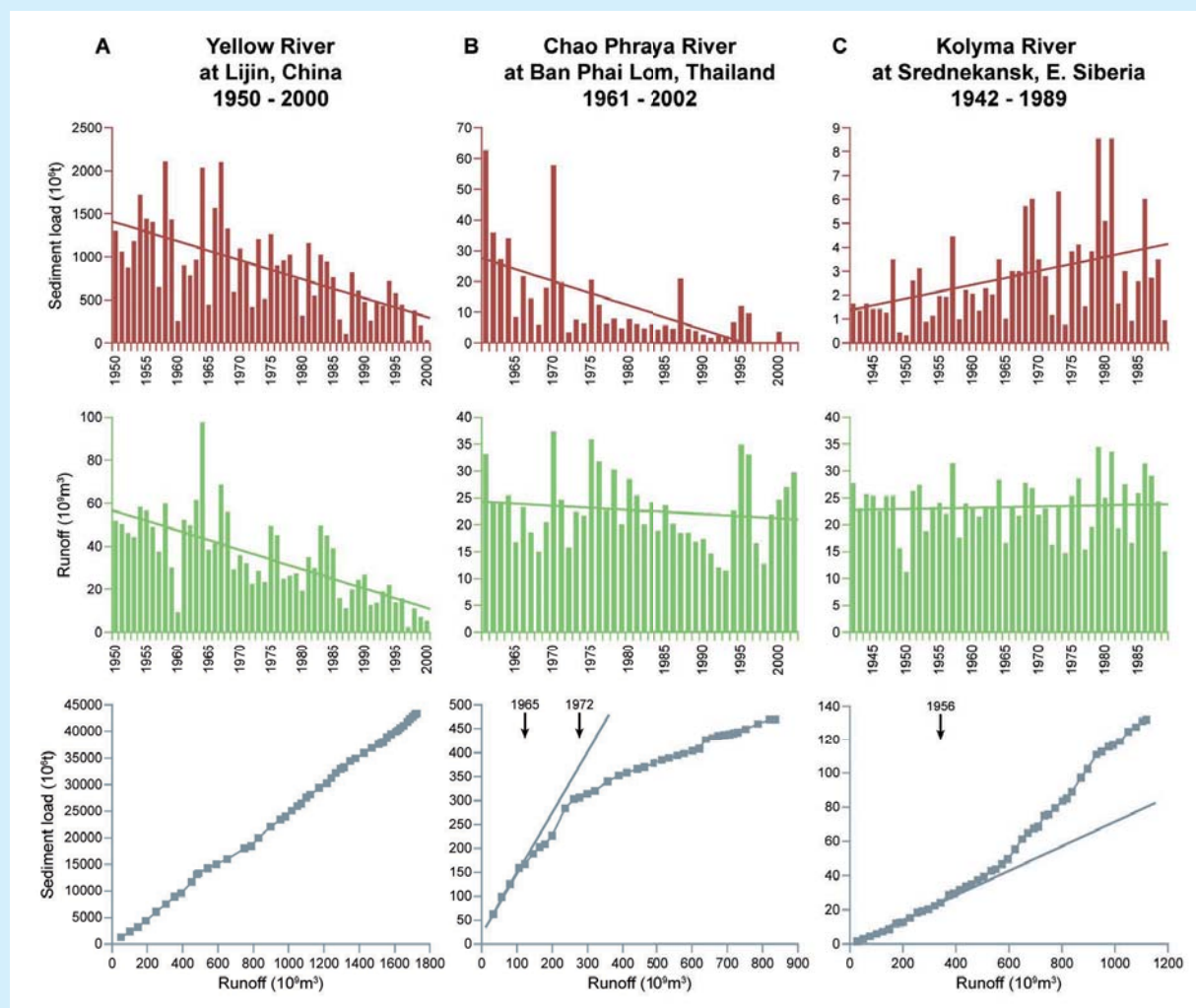
A recent attempt to attribute the reduction in annual sediment load to specific causes, reported by Wang et al. in 2007, suggested that 30% of the decrease in the sediment load of the lower Yellow River could be attributed to decreased annual precipitation over the basin, with the remaining 70% being attributable to human activities. The successful soil conservation programmes established within the loess region of the middle Yellow River basin were estimated to account for 40% of the overall reduction, while sediment trapping by reservoirs accounted for 30% of the reduction.

In the case of the Chao Phraya River in Thailand (Figure 2B), the annual sediment load of the river, which drains a catchment of 110,569 km<sup>2</sup>, again provides clear evidence of a statistically significant ( $P > 99\%$ ) reduction over the period of record, declining from around 28 Mt per year in the 1960s and early 1970s to around 6 Mt per year in the 1990s. However, in this case, the reduction in sediment load has occurred without a significant decrease in annual runoff and primarily reflects the trapping of sediment by a large number of small dams and irrigation structures and also by the larger Bhumibol and Sirikit hydroelectric power stations, commissioned in 1965 and 1972 respectively, and situated on major headwater tributaries. The change in the sediment response of the river caused by the construction of these dams is clearly demonstrated by the double mass plot.

The final example, relating to the 99,400 km<sup>2</sup> basin of the upper Kolyma River in eastern Siberia, Russia shown in Figure 2C, contrasts with the other two examples in that it documents a river where the annual sediment load evidences a significant ( $P > 99\%$ ) increase over the period of record. In this case, there is no evidence of a significant trend in the annual runoff, but the double mass plot suggests that the sediment load has increased by 1.5 times since the late 1950s. However, unlike the Yellow

## 2. Existing understanding of the impact of global change on the global erosion rates and sediment loads of the world's rivers

Figure 2 Recent trends in the annual suspended sediment loads and annual runoff



(A) the Yellow River at Lijin, China (B) the Chao Phraya River at Ban Phai Lom, Thailand and (C) the Kolyma River at Srednekansk, E. Siberia, Russia, as shown by the time series of annual sediment loads and annual runoff and the double mass plots of annual sediment load versus annual runoff.

River and the Chao Phraya River basins, where the population density is relatively high, the basin of the Kolyma River is largely undeveloped and has a population density of less than one person per square kilometre. The increased sediment loads have been attributed by Bobrovitskaya (personal communication) to gold mining and associated disturbance within the catchment. There is, however, a need to explore whether the increased sediment load of the Kolyma River might in some part reflect changes in the permafrost regime linked to climate change.

The results presented above provide clear evidence of recent changes in the sediment loads transported by the world's rivers. These include both increases and decreases. Further consideration of their wider significance can usefully consider the key drivers of the changes and their likely importance at the global level.

### 2.3 Recent changes in the sediment loads of the world's rivers: the key drivers

The trends for the three rivers discussed above provide evidence of two primary drivers causing changes in the sediment loads of the world's rivers. Firstly, there's catchment disturbance, which is linked to human activities such as deforestation, land clearance for agriculture, mining, mineral exploitation, construction, and infrastructural development, and results in *increased* sediment loads. Second, there's dam construction, which results in sediment trapping and *reduced* sediment loads. These and other important drivers can be briefly reviewed.

#### 2.3.1 Land clearance and catchment disturbance

Because many of the rivers that are likely to be characterized by increasing sediment loads as a result of disturbance of their catchments are located in developing countries – where long-term sediment

monitoring programmes are absent – there are fewer well-documented examples of the resulting increased sediment loads than there are for rivers where the sediment load has declined as a result of dam construction. Furthermore, dam construction is a relatively recent phenomenon and its impact can be documented by existing sediment load records extending back over forty or fifty years, but for many rivers, the main impact of catchment disturbance by, for example, forest clearance, would have occurred further back in the past and cannot be documented by such records.

However, the available evidence again emphasizes the importance of this driver. Walling (2005) cites the example of the Rio Magdalena River in Colombia, which drains a catchment of around 250,000 km<sup>2</sup> and accounts for about 9% of the total sediment flux from the eastern seaboard of South America. Data assembled by Restrepo and his team in 2006, indicate that sediment yields from large areas of the basin have increased substantially over the past ten to twenty years and that, as a result, the sediment load at the basin outlet has increased by possibly as much as 40% to 45% between 1975 and 1995 in response to forest clearance, land use intensification and gold mining (Figure 3).

The precise magnitude of the increase in sediment load caused by land clearance and disturbance will clearly depend on the nature of the disturbance, the proportion of the catchment affected and the degree

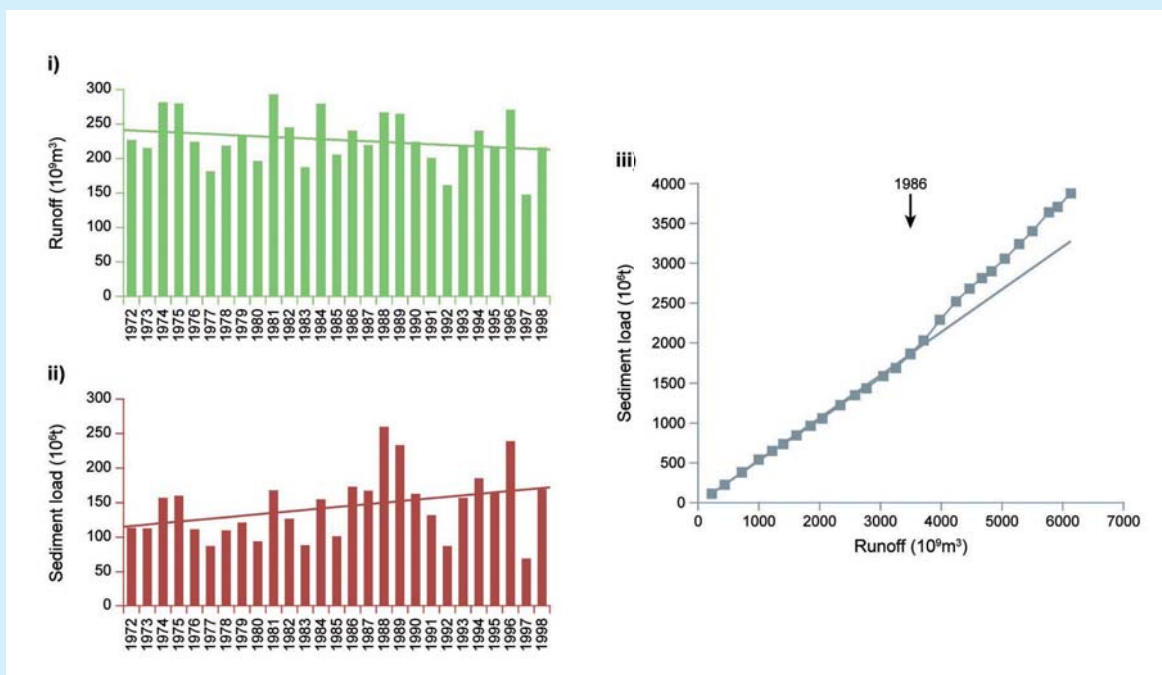
of development of the river basin, the catchment characteristics, and the climatic conditions.

A useful example of the potential magnitude of the increase in response to such factors is provided by the Bei-Nan River in Taiwan. This 1,584 km<sup>2</sup> mountainous river basin is characterized by steep, unstable slopes, tectonic instability and frequent typhoons generating heavy rainfall (Kao et al., 2005). Here, land clearance and road construction caused the annual sediment load to increase by almost an order of magnitude after the early 1960s (Figure 5). The trend shown by this river is likely to be mirrored by many rivers in the Pacific Rim region draining small mountainous basins, where forest clearance and surface disturbance have been widespread in recent decades. This has important implications for land–ocean sediment fluxes, as Milliman and Syvitski (1992) have shown that this region accounts for a substantial proportion of the global land–ocean sediment flux.

2.3.2 Dam construction

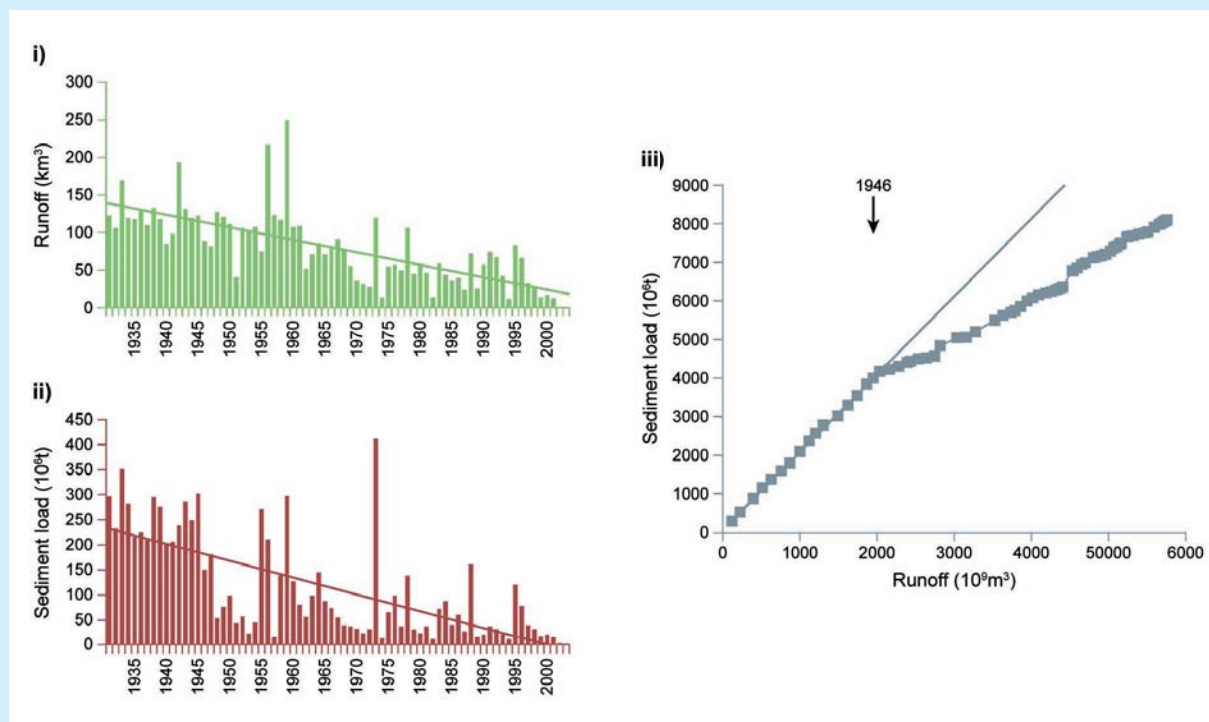
Many of the world’s rivers provide evidence of reduced sediment loads resulting from dam construction. For example, the River Nile has been widely cited as a river where the pre-dam sediment load discharged into the Mediterranean Sea of circa 100 Mt per year has been effectively reduced to zero by the construction of the Aswan dam. The magnitude of the reduction in the sediment load of a river caused by the construction of a dam will depend on a number of factors including the location of the

Figure 3 Rio Magdalena River, Colombia 1972–1988



Recent changes in the suspended sediment load of the Rio Magdalena River, Colombia, as demonstrated by the time series of the annual suspended sediment load (i) and annual water discharge (ii) and the associated double mass plot (iii).

Figure 4 River Indus at Kotri, Pakistan 1931–2003



Recent changes in the annual suspended sediment load of the River Indus, Pakistan as demonstrated by the time series of annual water discharge (i) and annual suspended sediment load (ii) and the associated double mass plots (iii). (Data compiled by Professor John Milliman, Virginia Institute of Marine Science, USA.)

dam within the river basin, the trap efficiency of the associated reservoir, and the proportion of the flow withdrawn for use and the nature of that use. In general, the greatest reductions in sediment loads occur where the annual runoff passing through the river system is also reduced because of water abstraction for irrigation and other uses.

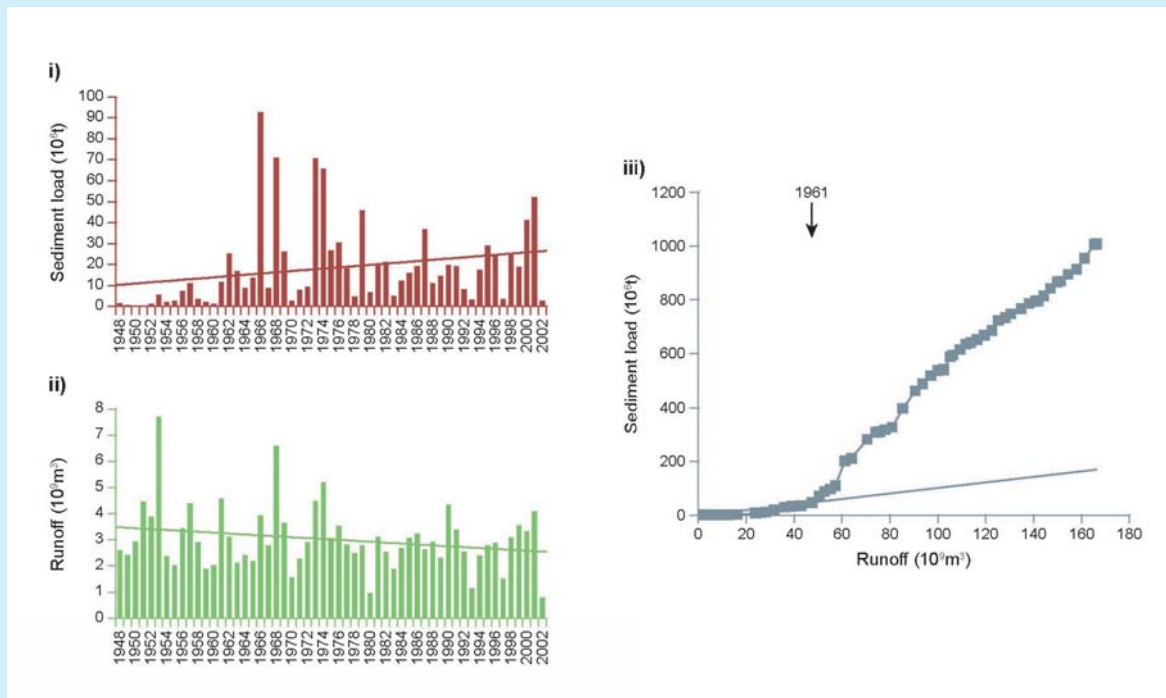
The Colorado River and the Rio Grande in the southwest USA provide good examples of this situation. The annual water discharges of these two rivers are currently only around 0.5% and 4% of their pre-dam values and the sediment loads have been reduced by 100% and 96% respectively. The changes in the sediment load of the lower Indus resulting from the progressive development since the 1940s of extensive irrigation systems, supplied by dams and barrages constructed on the river, are shown in Figure 4. Here large volumes of water are again abstracted and the annual runoff is now less than ca. 20% of that prior to the development of the irrigation systems and the current annual sediment load has similarly declined to ca 20% of its previous value. Dam construction has caused a major reduction in the sediment loads transported by the Mississippi and Danube Rivers, where annual sediment loads have been reduced by about 30% from those transported in the early 1950s (Walling, 2005). However, for these rivers there has been no significant reduction in the annual runoff.

### 2.3.3 Sand mining

Although the trapping of sediment by dams and the loss of sediment caused by the diversion of flow for irrigation and other large-scale water uses must be seen as the major cause of reduction in the amount of sediment transported to the outlet of a river basin, there is increasing recognition that in many areas of the world, and particularly in developing countries, the extraction of sand from river channels for use in the construction industry may represent a significant loss from the system. For example, Marchetti (2002) suggests that as much as two megatonnes of sediment are extracted each year from the central area of the River Po basin in Northern Italy. However, it is necessary to recognize that in some locations the sediment removed may be coarser than that represented by the measured suspended sediment load of the river or may not have been in active transport if, for example, it was extracted from the alluvial fill of a valley floor. It is difficult to obtain reliable information on the quantities of sediment involved, since much of the material may be being removed illegally.

A useful indication of the potential importance of this driver is nevertheless, provided by the available data for the middle and lower Yangtze basin in China, where Chen et al. (2006) report that in-channel sand extraction has developed as an important industry since the late 1980s, with individual

Figure 5 Bei-Nan River, Taiwan 1948–2002



Recent changes in the suspended sediment load of the Bei-Nan River, Taiwan, as demonstrated by the time series of the annual suspended sediment load (i) annual water discharge (ii) and the associated double mass plot (iii). (Based on data provided by Dr Shuh-Ji Kao)

dredgers being capable of removing up to 10,000 t per day. They estimate that the total quantity of sediment extracted could have been as high as 80 Mt per year in the late 1990s, while Wang et al. (2007) suggest that as much as 110 Mt per year is currently being extracted from the entire Yangtze system. Chen et al. (2004) indicate that, along with soil conservation and sediment control programmes and sediment trapping by dams, sand mining represents an important cause of the progressive reduction of the suspended sediment load of the Yangtze River at the downstream measuring station at Datong, where the mean annual suspended sediment load has progressively reduced from around 500 Mt per year during the 1960s and 1970s to around 350 Mt per year in the 1990s and around 200 Mt per year at the beginning of the current century.

### 2.3.4 Soil conservation and sediment control programmes

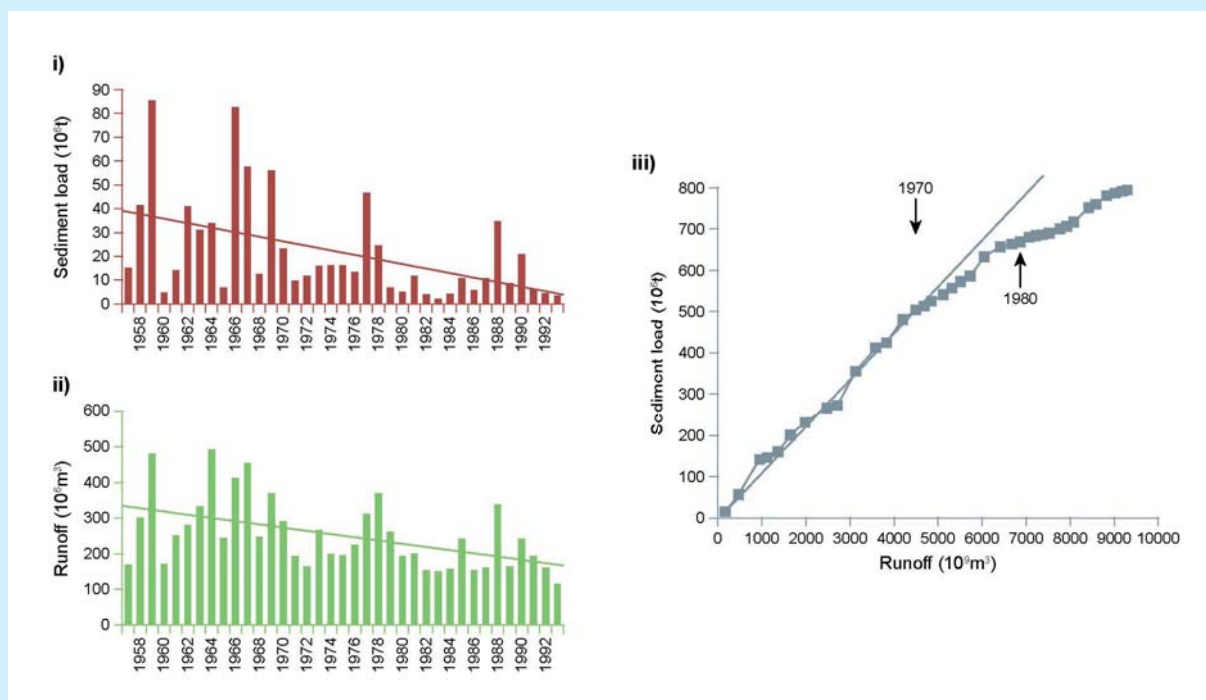
Land use impacts on sediment loads are commonly seen as resulting in increased sediment loads and therefore as an inadvertent consequence of human activity. However, the active implementation of soil and water conservation and sediment control programmes in river basins can have the reverse effect and result in reduced sediment loads – or at least reduce the increases associated with land clearance and surface disturbance. Since soil and water conservation and sediment control programmes are being increasingly adopted in many areas of the

world, this component of human impact on the sediment loads of the world's rivers must be assuming increasing importance.

Uri and Lewis (1999) for example indicate that as a result of the widespread implementation of soil conservation measures and other financial incentives introduced by the Food Security Act of 1985, the total erosion from U.S. cropland was reduced from 3.4 Gt per year in the early 1980s to 2.0 Gt per year in the latter half of the 1990s. Equally, Lal et al. (2004) estimate that no-till practices aimed at reducing erosion have currently been implemented on about 5% of the world's cropland. And recent estimates indicate that in Brazil, the proportion of cropland under no-till could be as high as 50%.

Although the literature provides many examples of plot and small catchment experiments that clearly demonstrate the success of soil and water conservation measures and improved management practices in reducing local soil loss, there is currently limited quantitative evidence of the impact of such measures in reducing the sediment fluxes from larger river basins. Such evidence is now available for the loess region of the middle Yellow River basin in China, where extensive soil and water conservation and sediment control programmes have been implemented over the past thirty years. In this region, attention has been directed to both reducing downstream sediment loads and to on-site soil

Figure 6 Sanchuan River at Xiadacheng, China 1957–1993



Recent changes in the suspended sediment load of the Sanchuan River, China, as demonstrated by the time series of the annual suspended sediment load (i) and annual water discharge (ii) and the associated double mass plot (iii).

and water conservation in order to reduce reservoir sedimentation and to alleviate siltation problems which cause serious problems for flood control along the course of the lower Yellow River.

In the case of the 4,161 km<sup>2</sup> basin of the Sanchuan River (Figure 6), a tributary of the middle Yellow River and the focus of extensive soil and water conservation works and sediment control measures in the 1980s, Zhao et al. reported in 1992 that by the end of the 1980s, the soil conservation and sediment control programme implemented in this river basin had resulted in active control of erosion and sediment delivery over nearly 30% of its basin. A comparison of the mean annual sediment loads for the periods 1957 to 1969 and 1980 to 1993 indicates that sediment yields in the latter period decreased to only about 25% of those for the former period.

As with the reduction in the sediment load of the Yellow River, discussed previously, part of this decrease is likely to reflect the onset of drier conditions in the 1980s, although Zhao et al. (1992) estimate that the implementation of soil conservation and sediment control measures after 1970 was responsible for reducing the sediment load of the Sanchuanhe basin by between 36% and 41%. The results of applying soil conservation and sediment control measures over an even wider area are shown in Figure 2a, which presents data for the entire 752,500 km<sup>2</sup> basin of the Yellow River, for which

about 40% of the reduction in sediment load has been attributed to the implementation of soil conservation and sediment control measures.

### 2.3.5 Climate change

Most of the examples of recent changes in the annual sediment loads of the world's rivers introduced above relate to specific anthropogenic impacts such as catchment disturbance and dam construction. However, the example of the lower Yellow River documented in Figure 2a, highlights the need to recognize that climate change can also interact with these more specific anthropogenic impacts in causing changing sediment loads. In most rivers, it is likely to prove difficult to disentangle the impact of climate change or variability from changes resulting from other human impacts and existing evidence suggests that, in most cases, these human impacts are at present likely to be more significant. Equally, the clarity of the signal reflecting the impact of human activity could be reduced by climatic variability, for example where it is superimposed on changes associated with variation of the Southern Oscillation Index and associated shifts between El Niño and La Niña conditions.

Lawler et al. (2003) were, nevertheless, able to report a clear example of the impact of recent changes in atmospheric circulation on the suspended sediment fluxes from two glacierized river basins in Iceland. In this case, there was negligible anthropogenic disturbance of the basins and any trends were

attributed to climate variability. Analysis focussed on trends during the period from 1973 to 1992 and involved values of instantaneous load rather than estimates of annual load. However, the available data suggested that the sediment loads transported by the two rivers had decreased by around 48% and 75% respectively over the study period as a result of the spring cooling and a decrease in the incidence of heavy precipitation in the autumn.

Notwithstanding the problems of disentangling the impacts of climate change from those associated with human impacts on a river basin and the lack of long-term records of sediment load for many areas of the globe, there is a small but growing body of evidence that climate change is having a significant impact on the sediment loads of the world's rivers. Amsler and Drago (2009), for example, direct attention to recent changes in the sediment loads of the Parana-Paraguay Rivers in South America. A comparison of data collected in the 1970s with those collected in the 1990s provides clear evidence of changes in the sediment loads transported by this large river system. Recent increases in precipitation and runoff across parts of the Parana-Paraguay system have caused increased erosion and sediment mobilization, but in some rivers this has been offset by sediment trapping by dams, resulting in reduced sediment loads. The impact of climate change and increased climate variability on sediment loads may require more detailed studies of the Upper Parana, where by the 1990s the sediment load was found to have decreased by 60% due to sediment trapping by dams, including the Itaipú and Yaciretá dams. However, the sediment load of the Bermejo River, a major tributary of the Paraguay River, was estimated to have increased by 85% over the same period, resulting in an overall increase in the sediment load of the Middle Parana River, below the confluence of the Upper Parana and Paraguay Rivers, by 35%. In the 1970s, the Bermejo River contributed 60% of the sediment load of the Middle Parana, but in the 1990s this increased to 90%.

Recent concern about changes in the flow regimes of major glacier-fed rivers flowing from the Himalayas and the Andes in South America, resulting from glacier retreat, also directs attention to potential changes in their sediment loads, (glacierized river basins are frequently characterized by high sediment loads.) Reduction in glacier meltwater could reduce sediment inputs and sediment transport, but equally, exposure of large areas recently covered by ice could provide important new source areas.

Further investigation and assessment of the impact of climate change and increased climate variability on the sediment loads of the world's rivers will also require more detailed studies of their sediment load and runoff records, involving, for example, the intra-annual distribution, as well as the annual totals. Changes may also manifest themselves in the magnitude and frequency of extreme events, rather than in average conditions.

### 2.4 Implications for the global sediment budget

It is important to consider the implications that changing sediment loads have for the global sediment budget. This budget represents a key component of the Earth system, and changes in the budget provide an important measure of global change. In its simplest form, the budget can be defined in terms of the mean, annual, global, land-ocean sediment flux. There have been numerous estimates of the magnitude of this flux (see Walling, 2005 and Panin, 2004) and significant uncertainties exist in terms of the precise interpretation of delivery to the 'ocean' and whether the total explicitly includes or excludes the recent impact of dams in reducing the flux. Furthermore, the examples of recent changes in the sediment flux of several major world rivers presented above emphasises that attempting to establish the magnitude of the global land-ocean sediment flux is dealing with a 'moving target'. For example, a sediment load of 1.08 Gt per year was widely cited for the Yellow River in the 1980s and the early 1990s, but an estimate of the current value is likely to be around 0.15 Gt per year. This reduction of approximately 0.9 Gt per year is equivalent to 5% to 7% of the likely total land-ocean sediment flux.

The lack of reliable records of sediment load makes it difficult to extrapolate the findings presented above to obtain an indication of the likely magnitude of changes in the global land-ocean sediment flux. In the first place, the lack of sediment load data for many areas of the world makes it difficult to establish the overall magnitude of that flux. Secondly, the lack of detailed longer-term records for many, if not most, of those rivers for which data exist precludes a detailed assessment of the likely magnitude of recent changes in that flux. In 2003, Walling and Fang presented a study of the longer-term records of annual sediment load for 145 rivers. They reported that approximately 48% were essentially stationary, while the remaining 52% provided evidence of statistically significant trends – approximately 5% increasing and 47% decreasing. However, the sample of rivers involved was not really representative of the world's rivers, as it was drawn exclusively from the northern hemisphere and included no rivers in Africa or South America.

In a similar exercise, Bobrovitskaya et al. (2003) analyzed the trend of the longer-term records of annual sediment load available for a number of the rivers of the former Soviet Union and found more widespread evidence of changing sediment loads. In this case, nineteen of the twenty rivers provided evidence of either an increasing or a decreasing trend, with twelve showing a decrease and seven showing an increase.

The likely dominance of decreasing loads at the global level, where trends exist, is emphasized by a recent study of the longer-term records of sediment load for ten major rivers in China reported separately in 2008 by Liu et al. and Hu et al. In the study, all ten rivers were characterized by ratios of the mean

## 2. Existing understanding of the impact of global change on the global erosion rates and sediment loads of the world's rivers

**Table 1 Recent changes in the sediment loads of ten major Chinese rivers**

Rivers	Station	Catchment area (km <sup>2</sup> )	Period of record	Ratio of mean annual sediment load for 1996–2005 to longer-term mean
Songhua	Harbin	38,9769	1955–2005	0.74
Liaohe	Tieling	12,0764	1954–2005	0.23
Yongding	Yanchi	4,3674	1963–2005	0
Huaihe	Bengbu	121,330	1950–2005	0.57
Yangtze	Datong	1,705,383	1950–2005	0.68
Qiantang	Lanxi	18,233	1977–2005	0.81
Minjiang	Zhuqi	54,500	1950–2005	0.39
Dongjiang	Boluo	25,325	1954–2005	0.59
Xijiang	Gaoyao	351,535	1957–2005	0.69

Based on Liu et al. (2008) and Hu et al. (2008)

annual sediment load for the past ten years (1996–2005) to the longer-term mean annual load, based on the available period of record of < 1.0 and with the highest value reaching only 0.81 (Table 1).

At one time these Chinese rivers together probably accounted for more than 10% of the global land–ocean sediment flux, and their declining loads clearly have important implications for changes in the overall land–ocean flux. However, sediment loads are likely to have increased in other rivers. Such increases could, at least in part, offset decreases elsewhere, with the result that there may have been little change in the overall global land–ocean sediment flux over the past twenty-five to fifty years, despite the changes described above. Interestingly, the various attempts to derive estimates of the global land–ocean sediment flux over the past twenty-five years have generally produced values of around 15 Gt per year, which could reflect such a balancing effect. It is nevertheless important to explore this issue further.

The lack of longer-term records of sediment load for many world rivers, and particularly those in developing countries that are likely to have been influenced by land clearance and related catchment disturbance in the recent past, makes it difficult to estimate the magnitude of the increase in sediment load for those rivers that might be expected to be characterized by increasing loads. However, available information on the amount of sediment deposited in the world's

reservoirs provides some basis for estimating the potential magnitude of the overall decrease in flux associated with dam construction. There is currently considerable uncertainty associated with existing estimates of the amount of sediment sequestered behind dams on the world's rivers.

Vörösmarty et al. (2003) estimate that more than 40% of the global river discharge is currently intercepted by large ( $\geq 0.5$  km<sup>3</sup> maximum storage capacity) reservoirs. By coupling this information with estimates of reservoir-trap efficiency, they estimate that reservoirs are currently sequestering approximately 4 Gt per year to 5 Gt per year of sediment, with the potential for this value to be considerably higher if the large number of smaller reservoirs are also taken into account. This value is very significantly lower than that suggested by a recent study involving in the region of 33,000 dams included in the International Commission on Large Dams (ICOLD) World Register of Dams (2006), undertaken by the ICOLD Reservoir Sedimentation Committee and reported by Basson in 2008. This study suggests that sedimentation behind the world's major dams is currently equivalent to a reduction in total storage by 0.8% per year. Based on an estimate of the current storage capacity of the world's major dams of 6,000 km<sup>3</sup>, this is equivalent to an annual loss of storage of approximately 48 km<sup>3</sup> per year. Assuming a dry bulk density for the deposited sediment of roughly 1.2 t per m<sup>3</sup>, this is equivalent

to annual sequestration of approximately 60 Gt per year – a value more than ten times greater than that proposed by Vörösmarty et al. in 2003. This value is also about four times the likely annual land–ocean sediment flux, estimated at approximately 15 Gt per year. The value of approximately 60 Gt per year could, in fact, be an underestimate, as the ICOLD register may not include all the dams that should be included and there are many other smaller dams that may sequester sediment.

It is, however, important to recognize that the estimate of the current rate of sediment sequestration in the world's reservoirs of roughly 60 Gt per year presented above represents the mass of sediment sequestered behind dams and does not represent the reduction in the land–ocean sediment flux. Much of this sediment would previously not have reached the oceans, as a result of deposition and storage within the river system and particularly on river floodplains. In the case of the lower River Ob in Russia, the reduction in load or conveyance loss associated with sediment transfer through the lower reaches of the river system is of the order of 40% (Bobrovitskya et al., 1996). This value is likely to be much higher if the whole river system is considered.

Similar conveyance losses of the order of 40% to 60% have been cited for floodplains bordering the main channel systems of the Rivers Ouse, Tweed and Culm in the UK, by Walling et al. (1999) and Sweet et al. (2003), and for the Amazon Floodplain by Mertes (1994). A conveyance loss of 60% has also been cited by Phillips (1996) for the sediment delivered to the channel systems of several larger (more than 1,000 km<sup>2</sup>) river basins draining the Piedmont region of North Carolina, USA. The conveyance loss associated with sediment movement through a river system can clearly be expected to vary according to the magnitude of the

sediment flux, the sediment transport and flood regime of the river, and the morphology of the channel system. And it is likely to decrease in heavily managed channels, where the flow is constricted and flood inundation is restricted.

It is therefore difficult to propose a typical value for the conveyance loss likely to be associated with the estimated 60 Gt per year of sediment currently being sequestered behind dams constructed on the world's rivers. However, Walling (2008) has suggested a value of 60% as a first order estimate. Use of this value would mean that 40% of the total 60 Gt per year might be expected to have previously reached the oceans and that dam construction is currently reducing the global land–ocean sediment flux by about 24 Gt per year, a value that is considerably in excess of the likely contemporary global land–ocean sediment flux. This value of 24 Gt per year is approaching an order of magnitude greater than the values of 3 Gt per year to 5 Gt per year suggested by Vörösmarty et al. in 2003 and Syvitski et al. in 2005 as representing the reduction in the contemporary global, annual, land–ocean flux resulting from sediment trapping by reservoirs.

Following Walling (2008) and taking the above information on the potential impact of sediment trapping by dams on the global land–ocean sediment flux, it is possible to combine it with recent estimates of other components of the global sediment budget provided by Syvitski et al. (2005) in order to speculate further on the possible nature of the global sediment budget and the extent to which it has been perturbed by human activity. Syvitski et al. estimate that the contemporary land–ocean sediment flux is 12.6 Gt per year, and that the contemporary flux in the absence of reservoir trapping would be 16.2 Gt per year. They also provide an estimate of the pristine flux for the

**Table 2 A comparison of the estimates of the major components of the global sediment budget and their modification by human activity provided by Syvitski et al. (2005) with those generated by Walling (2008) using a different estimate of the reduction in the contemporary sediment flux by sediment trapping**

Component	Syvitski et al. (2005)	Walling (2008)
Pre-human land–ocean flux (Gt per year)	14.0	14.0
Contemporary land–ocean sediment Flux (Gt per year)	12.6	12.6
Reduction in flux associated with reservoir trapping (Gt per year)	3.6	24.0
Contemporary flux in the absence of reservoir trapping (Gt per year)	16.2	36.6
Increase in pre-human flux due to human activity (%)	16.0	160.0
Reduction in contemporary gross flux due to reservoir trapping (%)	22.0	66.0

pre-human period of 14 Gt per year. Using these values, they estimated that human activity has increased the global land–ocean sediment flux by about 16% from the pre-human value of 14 Gt per year to 16.2 Gt per year, with sediment trapping by dams reducing this by around 22% to 12.6 Gt per year (Table 2).

If, following Syvitski et al., it is assumed that the contemporary land–ocean sediment flux is around 12.6 Gt per year, the estimate of 24 Gt per year introduced above for the reduction associated with reservoir trapping would mean that the total flux in the absence of reservoir trapping would be approximately 36.6 Gt per year. Using again the estimate of the pre-human flux provided by Syvitski et al. of 14 Gt per year it would now suggest that human activity has increased this by 160% to 36.6 Gt per year and that reservoir trapping has reduced this total by approximately 66% to 12.6 Gt per year.

Despite using common estimates for the contemporary land–ocean sediment flux and the pre-human flux, the two sets of estimates of the potential magnitude of human impact on the global sediment budget shown in Table 2 differ substantially. The revised estimates must be viewed as speculative, but they emphasise the need for further investigation of the global sediment budget and the extent to which it has been perturbed by human activity.

### 3. Key challenges

The review of existing knowledge of the sensitivity of erosion and sediment dynamics to global change presented above emphasises a number of important areas highlights the existence of many areas of uncertainty that represent key challenges for future work require further work. These are briefly reviewed below.

The following ten areas have been identified as key challenges for future work:

- Assessment of changing erosion dynamics
- Linking changes in erosion rates and sediment yields
- The availability of sediment data
- Sediment quality
- The importance of buffering and storage
- Evaluating the drivers
- Adding the temporal dimension
- Refining the global sediment budget
- Improved prediction
- The need for new tools

Each of these is considered further below.

#### 3.1 Erosion dynamics

To date, there have been few meaningful attempts to develop existing empirical information on soil erosion rates to provide global and regional assessments of past and recent impacts of global change on erosion rates. The results obtained from the vast number of plot and small watershed experiments that have been undertaken provide valuable information on the potential impact of changes in vegetation cover and land use activities on erosion rates, but this information needs to be coupled with information on changing patterns of vegetation and land use through time and expanded to provide an assessment of the overall impact of the changes on the magnitude of soil erosion and soil loss.

One valuable attempt to apply such an approach is the work of Sidorchuk and Golosov (2003) who report an attempt to assess the impact of agriculture on soil erosion across the Russian Plain. They reconstructed the spread of agriculture across the Russian Plain after 1696 and calculated that 99 billion cubic metres ( $99 \times 10^9 \text{ m}^3$ ) of soil have been lost from the slopes since 1696 CE, with rates of soil loss being relatively low prior to this date. Across the whole area of the Russian Plain, the expansion and development of intensive agriculture caused the loss of more than 10 cm of soil from 82% of the cultivated land, with the loss increasing to 10 cm to 12 cm over 11% of the cultivated area and to more than 40 cm over 1% of the area. Interestingly, they also estimated that about 97% of the eroded soil has been re-deposited locally, rather than being transported out of the region by rivers.

The work of Yang et al. (2003) provides an example of the potential to broaden the evidence base for the global level. In this case, emphasis was put on the use of a model to synthesize existing understanding of the key controls on rates of soil loss and the Revised Universal Soil Loss Equation (RUSLE) model was coupled with a Geographic Information System (GIS) model to produce a global assessment of soil loss over a  $0.5^\circ$  grid. By manipulating the data sets representing land use and vegetation cover and the climate drivers that were input to the model, estimates of past erosion rates from the 1900s to the 1980s, present erosion rates (1980s) and future erosion rates (2090s), reflecting both climate change (doubling of  $\text{CO}_2$ ) and land use change, were obtained.

The results indicated a present global rate of soil loss of 10.2 t per hectare per year, with rates of soil loss having increased by circa 1.5 t per hectare per year (i.e. by around 17%) during the twentieth century. Looking to the future and the 2090s, the study estimated that soil erosion rates would increase by a further 13.9%, with about 65% of this increase being the result of climate change and increased erosivity, and about 35% the result of population growth and changes in land use. Although both land use and climate change caused increased erosion rates in most areas of the globe, reductions were predicted for North America and Europe as a

result of land use changes and for North America due to climate change, resulting in a net reduction on both these continents.

Although interest in changing erosion rates is likely to focus on the impact of increasing erosion rates in many areas of the developing world, there is also a requirement to consider the large-scale impact of soil conservation programmes and improved land-management programmes, involving minimum-till or no-till practices, on soil erosion rates. There is again a need to broaden available evidence to estimate the larger-scale impact of such programmes. As indicated above, Uri and Lewis (1999) have estimated that as a result of the widespread implementation of soil conservation measures and other financial incentives introduced by the Food Security Act of 1985, the total erosion from US cropland was reduced by about 40% from 3.4 Gt per year in the early 1980s to 2.0 Gt per year in the latter half of the 1990s. There is clearly a need to assess the wider impact of such trends and, more particularly, the rapid growth in the implementation of minimum-till and no-till practices on soil loss at the global level. Recent reports suggest, for example, that such practices have now been adopted on approximately half of the cultivated land in Brazil.

Most attempts to date to establish the impact of recent climate change on soil erosion rates over larger areas have been model-based. The work of Yang et al. (2003) described above applied the RUSLE model to a 0.5° grid representation of the land surface of the globe and the results therefore depend heavily on the global applicability and veracity of the model. Clearly there are many uncertainties associated with applying a model founded on data collected in the USA across many different environments. However, where such models are applied within the region for which they were developed, greater reliance can be placed on the results. A 2003 report by the US Soil and Water Conservation Society, for example, used information on the changes in precipitation regimes over the past century to estimate the likely magnitude of the associated changes in rates of annual soil loss in different areas of the USA. The results indicated increases in erosion rates across the country ranging from 4% to 95%.

Further work is needed to collate and synthesize the available empirical information on soil erosion rates for different areas of the world and to use this information for assessing the impact of land use change and recent climate change on global and regional soil erosion rates. Available soil erosion models, calibrated against the empirical data and coupled with large-scale environmental databases, such as the new FAO soils database, could provide an effective basis for spatial extrapolation, in order to provide global and regional predictions of the likely magnitude of the changes involved, and to link such predictions to the available empirical evidence.

### 3.2 Linking changes in erosion rates and sediment yields

Although, as indicated above, there have been few attempts to collate and broaden existing empirical information on changing erosion rates and apply it at the regional and global levels, model-based studies, such as that reported by Yang et al. in 2003, provide some basis for identifying the temporal trends and spatial patterns involved. There is a need to explore further the links between changing erosion rates and changing sediment yields, which will frequently involve common drivers.

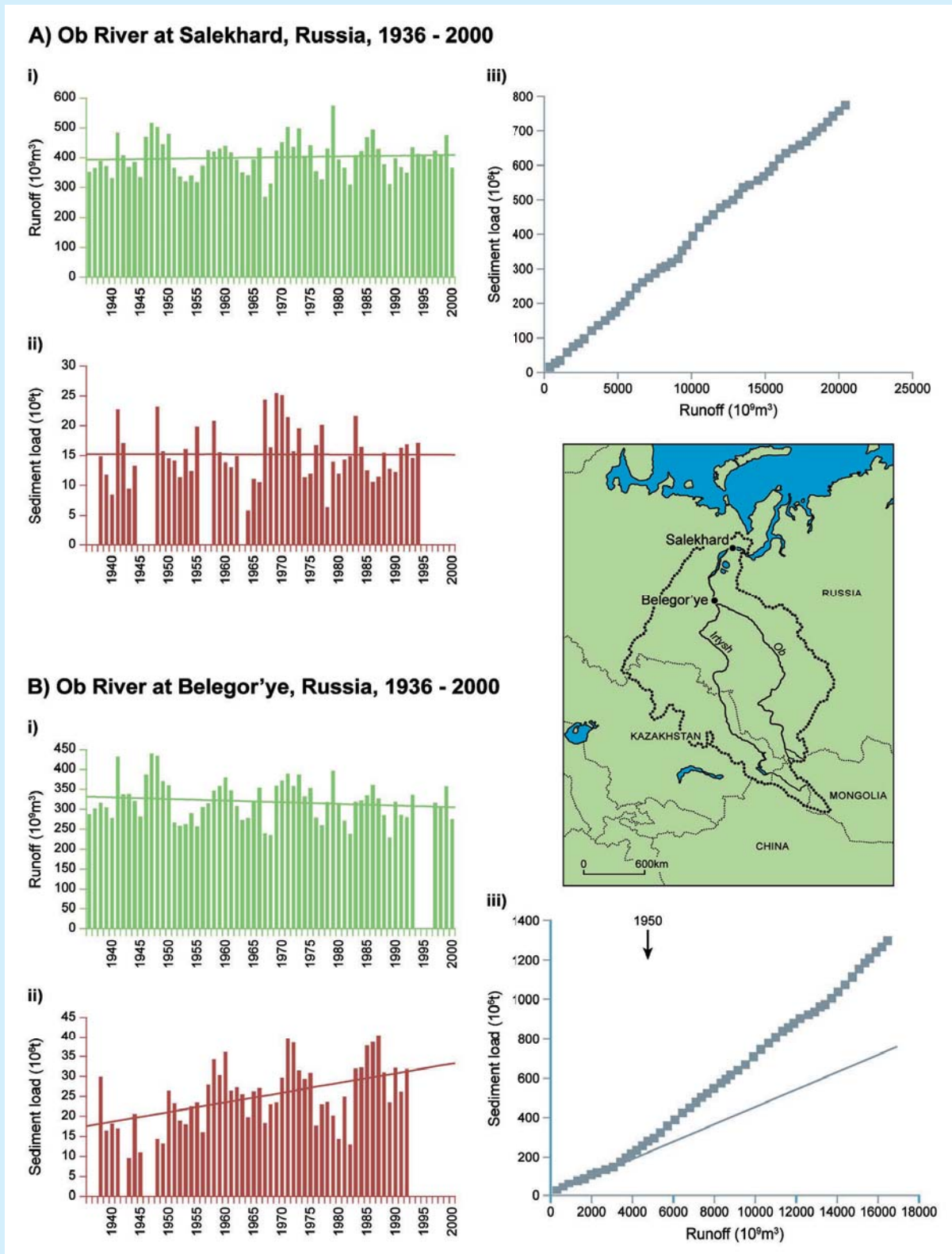
The precise relationship between the two will reflect the complexities of sediment delivery and the possible effects of buffering and storage. Some indication of the likely relationship between the magnitude of gross soil erosion from the land surface of the continents and the land–ocean sediment flux is provided by comparing an estimate of the former based on the global predictions presented by Yang et al. with the estimate of the current land–ocean sediment flux provided in Table 2. This indicates that the current gross soil loss from the land surface of circa 200 Gt per year is more than an order of magnitude greater than the current land–ocean sediment flux of 12.6 Gt per year.

Because the soil loss estimate is based on the Modified Universal Soil Loss Equation (MUSLE) model, it effectively represents on-site soil loss and much of the eroded soil would be deposited before reaching the stream network. If conveyance losses associated with the stream and river networks are also considered, an overall sediment delivery ratio representing the relationship between gross erosion and sediment input to the oceans of around 6% is not unreasonable. Since Yang et al. suggest that the global mean erosion rate has increased by some 17% between the 1900s and the present, it is interesting to speculate what impact that increase would have had on the land–ocean sediment flux over the same period.

### 3.3 The availability of sediment data

Existing understanding and assessment of the impact of global change on the sediment loads of the world's rivers relies heavily on the existence and accessibility of reliable long-term records of sediment flux for those rivers. As indicated above, such data are lacking for many rivers, particularly those in areas of the developing world, where changes in land cover and land use are likely to be greatest. Further effort could usefully be directed to assembling available datasets. This could involve seeking out new sources or securing the release of previously restricted data. In some cases, such data will already be compiled, whereas in others there may be a need to collate and process the basic data in order to provide estimates of sediment flux. To date, most investigations of changing sediment loads have focussed on annual fluxes. Further work is undoubtedly required to explore other parameters of sediment flux records, involving sub-annual time-frames and including the magnitude and frequency of extreme events.

Figure 7 **Contrasts in recent trends in the suspended sediment load of the lower Ob River at Salekhard (downstream), and Belegor'ye (upstream) as demonstrated by: (i) the time series of the annual suspended sediment load; (ii) the annual water discharge; and (iii) the associated double mass plot**



### 3.4 Sediment quality

Studies of changing sediment dynamics have traditionally focussed on changes in the magnitude and timing of sediment fluxes, both because these are relatively easy to document and because they are directly linked to many key sediment-related problems. Increasing recognition of the importance of the quality dimension of sediment fluxes and of the important role of sediment-associated nutrients and contaminants in generating environmental problems, does, however, emphasise the need to also consider the impact of global change on *sediment quality*.

Changes in sediment quality will reflect changing sediment sources (Minella et al., 2008), the increasing pollution of soil and river systems, as highlighted by the EU Sednet initiative ([www.sednet.org](http://www.sednet.org)), and the potential for climate change to cause changes in river and floodplain behaviour, which could in turn remobilize contaminated sediment stored in long-term fluvial sinks (Dennis et al., 2003).

In the latter context, it is important to recognize that the surface sediment of many floodplain systems is contaminated with polluted sediment released by mining and industrial activity prior to the introduction of environmental legislation aimed at controlling the release of sediment-associated pollutants. Such deposits have frequently been referred to as 'chemical time bombs' awaiting detonation. Again there has been relatively little work undertaken to assess changes in sediment quality at the regional and global levels.

The pioneering work of Martin and Meybeck in 1979 has identified the key controls on the geochemistry of fluvial sediment at the global level, but their work requires further extension to gain a full understanding of the spatial and temporal variability of the geochemistry of fluvial sediment and the land–ocean fluxes involved, prior to further investigations of longer-term and more recent changes in sediment chemistry. Recent work led by Norwegian scientists within the framework of a global survey of the trace metal and contaminant content of fluvial sediment in large river basins has highlighted the potential for using floodplain deposits to characterize recent and 'pre-industrial' sediment and to thus provide a means of establishing the magnitude of recent changes in sediment quality.<sup>1</sup> Such changes clearly have important implications for changes in global geochemical cycling, since land–ocean sediment transfer must be seen as a key pathway in such global cycling.

<sup>1</sup> Global Geochemical Mapping and Sediment-Associated Flux of Major World Rivers A project, developed by the Norwegian Water Resources and Energy Directorate (NVE) and the Norwegian Geological Survey (NGU) in association with the International Commission on Continental Erosion.

### 3.5 The importance of buffering and storage

There is increasing evidence of the ability of some rivers to buffer changes in upstream sediment flux. The very large basin of the River Ob in Siberia provides a useful example of how appreciable increases in the annual sediment flux, clearly evident at an upstream station, were not apparent at the downstream station and appeared to have been buffered by overbank deposition on the extensive river floodplains between the two stations (Figure 7). This river drains a large, 2,950,000 km<sup>2</sup> catchment in Siberia to the Arctic Ocean. Over the period 1936 to 2000, the records of annual water discharge and suspended sediment load for the River Ob at Salekhard, the lowest monitoring station on this river, for the period 1936 to 2000, show no evidence of statistically significant trends and the double mass plot provides further evidence of a stable system.

However, Bobrovitskaya et al. (1996) report that in this river basin the period from 1957 to 1970 was characterized by significant human impact, both on the river channel and within the basin more generally. They cite an increase in the mean annual sediment load at Belegor'ye, some 700 km upstream of Salekhard, from approximately 19.2 Mt per year between 1938 and 1956 – which was seen as representing the 'natural' regime – to 28.4 Mt per year between 1957 and 1990. This represents an increase of almost 50%.

The lack of evidence of an increase in annual sediment load over the period of record at Salekhard can be attributed to overbank deposition on the 15,000 km<sup>2</sup> of well-developed floodplains that border the 870 km reach of the Ob River between Belegor'ye and Salekhard. The significance of this deposition is clearly demonstrated by a comparison of the annual suspended sediment loads at Belegor'ye and Salekhard, with those of Salekhard (downstream) currently being only about 50% of those of Belegor'ye (upstream). This is despite an increase in catchment area of almost 10% and an increase in annual runoff of about 25% between the two monitoring sites. Bobrovitskaya et al. suggest that the amounts of sediment deposited on the floodplain between Belegor'ye and Salekhard have increased more than threefold in recent years and it would seem that the increased deposition rates have effectively blurred the signal of increasing sediment loads, which is clearly apparent at Belegor'ye.

Available data from the two main sediment measuring stations on the Yangtze River in China again highlight the importance of storage in regulating the sediment flux at the outlet of the basin. Here there are measuring stations at Yichang, located in the upper part of the middle reaches (1,005,501 km<sup>2</sup>) of the basin, and at Datong, located near the basin outlet (1,705,383 km<sup>2</sup>). Although the catchment area increases by almost 70% between Yichang and Datong and the total annual runoff approximately doubles, there is very little change in the annual sediment load between the two sites. In most years,

the sediment load at Datong is slightly less than that at Yichang, The expected increase in total load associated with sediment inputs from the substantial increment in catchment area downstream of Yichang is apparently balanced by depositional losses on the floodplain and within the many lakes along the lower reaches of the Yangtze, such as the Dongting and Poyang Lakes.

Buffering can also operate in the reverse direction, whereby upstream reductions in sediment flux could be offset by increased channel and floodplain erosion downstream. Phillips et al. (2004), for example, cite the case of the 46,100 km<sup>2</sup> drainage basin of the Trinity River in Eastern Texas, USA, which provides an example of this effect. Here, much of the reduction in sediment load caused by sedimentation behind the Livingston Dam is offset by remobilization of sediment from alluvial storage downstream. The upper basin is effectively decoupled from the basin outlet by virtue of sediment storage in the extensive alluvial floodplain in the lower reaches of the basin. As a result, there is no evidence that the sediment input to Trinity Bay has been reduced as a result of the construction of the Livingston Dam in 1968. Equally, the earlier discussion of the need to take account of sediment storage within river systems when attempting to link estimates of sediment sequestration in reservoirs to the associated downstream reduction in sediment flux further emphasises the important role of storage in the functioning of large river basins.

An improved understanding of the storage component of river basin sediment budgets is therefore clearly an important requirement for assessing and predicting the impact of global change on the sediment loads of the world's rivers. The assembling of detailed information on sediment storage frequently depends on the availability of reliable records of sediment flux for key stations within a river network. Often there is only one station, located at the outlet of a river basin and if upstream measuring stations exist, they are frequently not located at the points that would be required in order to assess conveyance losses through key reaches of the system. The location of the two stations on the middle and lower Ob, which provide clear evidence of storage of sediment within the floodplain system, must be seen as fortuitous. Strategically located measurement stations that are capable of providing high quality records are undoubtedly a key requirement for work of this nature and should be incorporated in sediment flux measuring networks.

### 3.6 Evaluating the drivers

Although the above review of the primary causes of change in the sediment loads of the world's rivers has identified the key drivers, further work is required to explore the influence of other, perhaps secondary, drivers and to provide more definitive assessments of the relative importance of different drivers. In many river basins, several drivers will interact to cause the observed changes. To date, few

studies have provided definitive evidence of the impact of recent climate change in causing changes in the sediment loads of the world's rivers, and there is clearly a need to establish the importance of this driver in both absolute terms and in relation to other, more direct, impacts of human activity.

In many areas it may prove difficult to separate the impacts of climate change from the inherent variability of the system and, as indicated above, there may be a need to consider different measures of the sediment record, involving sub-annual timeframes and the magnitude and frequency of extreme events, in addition to time series of annual loads. Equally, further work is undoubtedly required to assess the impact of soil conservation and sediment control programmes in reducing both soil erosion and fluvial sediment loads, and thus to establish the relative importance of poor management in increasing, and pro-active management improvements in reducing, erosion rates and sediment loads.

Although recent work on Chinese rivers, such as that presented above, has provided clear evidence of the impact of soil conservation and sediment control programmes in reducing erosion and sediment loads in the loess region, there is little direct evidence of the impacts of improved land management in many other areas of the world. Improved land management and associated control of diffuse source pollution, will undoubtedly assume increasing importance in the future, as evidenced by the current implementation of the Water Framework Directive ([www.euwfd.com](http://www.euwfd.com)) in the countries of the European Union, and it is important to develop an improved understanding of the likely impact of such strategies on sediment mobilization and sediment fluxes. Overall, there is a need to place greater emphasis on *quantitative assessment* and *attribution* of changes associated with specific drivers, as distinct from simply identifying changes and linking these to likely causes.

### 3.7 Adding the temporal dimension

In this overview, attention has focussed on recent changes in erosion rates and river sediment loads in response to global change. The need to place such changes within a longer-term context has, however, been emphasized in section 2.1. The relatively short duration of contemporary records further strengthens the need to consider other sources of information, which provide a longer-term context for recent change.

Figure 8 provides an example of the potential for exploring the temporal dimension. In this case, the information on changes in the sediment load of the lower Yellow River over the past fifty years or so, provided by the instrumental record, has been coupled with evidence of longer-term changes in the sediment load of the river derived from investigations of the sedimentary record reported by Milliman et al. (1987), Saito et al. (2001) and Xu (1998), to produce a tentative reconstruction of changes in the sediment load of the river over the past 4,000 years.

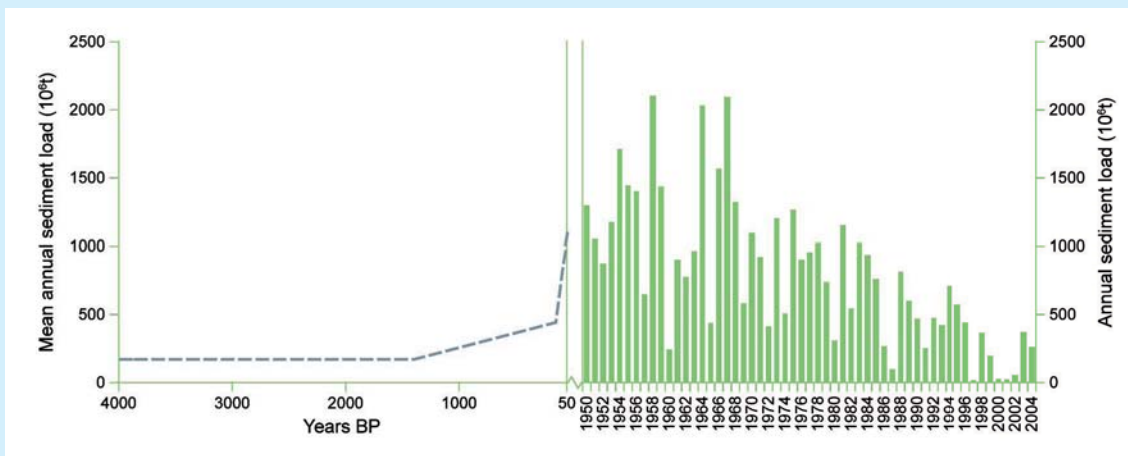
The availability of dated sediment cores from both a wide area of the North China Plain and the Yellow River delta and from offshore sediment deposits provides a basis for documenting the magnitude of the longer-term sediment flux of the lower Yellow River and the variation in that flux over time.

This evidence suggests that prior to around 600 CE, the sediment load of the lower Yellow River was only about 10% to 20% of that associated with the period of maximum sediment load in the middle of the twentieth century. The subsequent increase, which intensified about 150 years ago, can be linked to the effects of forest clearance and the expansion of agriculture in increasing erosion. It can also be linked to the progressive stabilization and control of the course of the lower Yellow River by levees, which restricted the widespread deposition

relationship between recent changes and longer-term changes will clearly depend on the history of anthropogenic impact on the sediment load of the river and the nature and intensity of recent impacts. In some rivers, such as those in Taiwan exemplified by the Bei-Nan River shown in Figure 5, the recent increase in sediment load shown by the available records probably represents the first major perturbation of the 'natural' sediment flux.

For most rivers, however, human impact on erosion and sediment yield is likely to extend back well beyond the instrumental record and there is therefore a need to explore other sources of information, such as sedimentary evidence, to provide the temporal dimension. Where rivers discharge into a lake, sediment cores collected from the lake can provide valuable information on past changes in sediment

**Figure 8 A tentative reconstruction of the longer-term trend in the suspended sediment load of the lower Yellow River over the past 6,000 years, based on information presented by Milliman et al., Saito et al., and Xu**



associated with natural changes in the course of the river, and thereby increased the proportion of the sediment load entering the lower Yellow River that reached the basin outlet. Interestingly, Figure 8 suggests that the reduction in the sediment load of the river that commenced in the latter part of the twentieth century, and which has continued to the present (see also Figure 2a), has restored the load to a magnitude similar to that existing several millennia ago, prior to major human impact, when it has been suggested that the Yellow River was a 'clear river' (Shi et al., 2002).

There are, however, important differences between the situation several millennia ago and the current situation, particularly in terms of the water discharge of the river. The present water discharge of the river has been greatly reduced by abstraction and soil conservation measures (Figure 2a) to the extent that the river has been reported to 'dry up' for extended periods. For other rivers, the precise

flux. Dearing et al. (1987) were, for example, able to reconstruct the record of sediment output from the small catchment draining to Lake Havgardsson in southern Skane, Sweden, extending back more than 5,000 years to 3050 BCE. In this catchment, sediment yields prior to circa 50 BCE were relatively low and of the order of 25 t per km<sup>2</sup> per year, a value which is consistent with the existence of an essentially undisturbed forest cover. Post 50 BCE, sediment yields reached a maximum of around 250 t per km<sup>2</sup> per year during the period extending from 950 to 1300, which was characterized by extensive forest clearance, village development and the expansion of agricultural activity. A subsequent decrease in sediment yield between 1300 and 1550 to around 100 t per km<sup>2</sup> per year was linked to the deteriorating climate in the early part of the Little Ice Age and to the agrarian depression. More recently, sediment yields increased again to around 250 t per km<sup>2</sup> per year, in response to an expansion of the area under cultivation.

Again involving lake sediment deposits, a recent study by Zhang et al. (2009) focussed on longer-term changes in erosion and sediment yield from a small (0.1 km<sup>2</sup>) catchment in the loess region of China. In this case, a landslide in 1569 had caused a temporary dam across the outlet of the catchment and the annual laminations in the remnants of the deposits associated with thirty years of deposition of all the sediment entering the landslide-dammed lake prior to the breaching of the dam were used to estimate the annual sediment yield of the catchment during the period after the landslide. The value of approximately 12,500 t per km<sup>2</sup> per year obtained was within the range of the estimated current specific sediment yields for the local area of 10,000 t per km<sup>2</sup> to 15,000 t per km<sup>2</sup> per year – suggesting that erosion rates in this area were already high in the mid-sixteenth century as a result of agricultural activity. More detailed analysis of the estimates of annual sediment yield provided by the laminated sediments, in conjunction with information on the pollen content of the sediment, emphasised the importance of land use in controlling erosion and sediment yield, in that the sediment yield from the catchment showed clear evidence of a sharp decline in the years immediately after the landslide, when agricultural activity was reduced.

Working at a somewhat larger scale, and coupling proxy information for the catchment with a distributed soil erosion and sediment delivery model, researchers from the Netherlands and Belgium (Thodsen et al., 2008; Zhu et al., 2008) were able to reconstruct the suspended sediment yield from the 33000 km<sup>2</sup> basin of the River Meuse over several millennia and to explore the relative importance of changes in land use and climate on the suspended sediment yield from the basin. The model was used to estimate the sediment yield from the basin during three periods. The first was the period 2000–1000 BCE, when the catchment was assumed to be completely forested, the second was the period 1000–2000 CE, when major land use change occurred, and the third involved an attempt to forecast the likely impact of climate change as predicted by IPCC scenarios, for the twenty-first century.

These estimates indicated that the annual suspended sediment load of the river increased more than three fold from ca. 92000 t in 2000–1000 BCE to ca. 306,000 t in 1000–2000 CE primarily as a result of land use change. Maximum mean annual sediment loads, in the region of 388,000 t were predicted to have occurred in the nineteenth century as a result of deforestation, and loads declined through the twentieth century to ca. 281,000 t, due to reforestation and the expansion of urban areas. Overall these trends were primarily the product of land use change. The results for the twenty-first century indicated that the sediment load could increase by 8% to 12%, as a result of climate change, but these increases were offset by reductions in the range 26% to 46% associated with likely changes in land use. Overall the results emphasised the overriding

important of land use change in causing changes in the sediment load of this river and therefore provide a valuable perspective on the wider issue of attribution within the wider context of global change.

The many uncertainties associated with the reconstruction and forecasting of longer-term changes in river sediment loads, such as that presented above, necessarily makes the results tentative. Nevertheless, such work can provide a valuable longer-term perspective on recent evidence for global change. In the case of the River Meuse, for example, the results emphasise the overriding importance of land use change in causing changes in erosion and sediment yields. To date, however, many palaeo studies have frequently failed to link closely with information on current erosion rates and sediment fluxes and closer collaboration between those involved in palaeo and contemporary studies is arguably required. Scope undoubtedly exists to both develop new work to exploit this potential and to collate existing information from palaeoenvironmental and more recent historical investigations based on sediment deposits.

The IGBP PAGES LUCIFS project aims to explore further the evidence for past changes in sediment budgets in response to climate and land use change and could usefully link more closely with those researching the contemporary evidence.

### 3.8 Refining the global sediment budget

A number of uncertainties regarding the global sediment budget and, more particularly, the impact of human activity on that budget were highlighted in section 2.4. Although the magnitude of the overall land–ocean sediment flux is supposedly now known with a reasonable level of confidence, recent changes in the sediment loads of many of the world's major rivers introduce difficulties when trying to integrate and reconcile existing studies. Furthermore, there are still substantial areas of the world for which little or no data are available and for which reliable data extrapolation exercises are required. There is arguably a need for an updated review and synthesis of the available data, taking account of existing knowledge of recent changes.

Further work is also required to resolve the current uncertainty regarding the magnitude of contemporary sediment sequestration behind dams and to thereby provide a more definitive assessment of the relative importance of human impact in reducing and increasing land–ocean sediment fluxes. The lack of sediment load data for many world rivers, particularly those in developing countries, where increased sediment loads are most likely to be found, necessarily represents an important problem for any such assessment.

There is also a need to incorporate a temporal dimension into any attempt to establish a baseline or 'pre-human' land–ocean flux for the Earth system and to then assess the extent to which this has been increased by human activity such as forest clearance,

the establishment of agriculture, and other land use activities; and the extent to which it has been reduced as a result of sediment trapping by dams and by programmes aimed at reducing sediment mobilization and transport.

Whereas sediment trapping by dams is likely only to have had a substantial impact on land–ocean sediment fluxes over the past fifty years, and most extensive soil conservation and sediment control programmes are likely to be even more recent, the impact of land clearance and land use change will have influenced sediment loads over several millennia. In simple terms, changes in sediment loads are likely to have been dominated by a progressive increase above the baseline flux, over a period stretching back several millennia, but reductions in sediment load as a result of sediment trapping by dams would only have begun to be significant about fifty years ago. Further work is required to decipher the likely trend of the net change in the land–ocean sediment flux. Table 2 suggests that the current flux has now fallen below the natural baseline flux, but a more detailed integration of the spatial and temporal trends of human impact on the sediment flux is required if the impact of human activity on the global sediment budget is to be defined reliably.

### 3.9 Improved prediction

This overview has focussed on current understanding of the impact of global change on erosion and sediment dynamics, with the emphasis on a global perspective. This understanding is important both for understanding the changing Earth system and for informing the sustainable management and development of land and water resources globally. In the latter context, there is clearly a need to use existing understanding of the impact of global change in order to develop improved approaches and techniques for predicting future changes. The many uncertainties associated with current understanding, particularly at the global level, necessarily impact on our ability to predict future change, but progress is being made. To date, most of such studies have been at local and regional level rather than at the global level. Furthermore, much of this work has focussed on changes in erosion rates – somewhat paradoxically in view of the more limited scope of existing work on assessing the impact of global change on global erosion rates as compared to sediment loads. This situation doubtless reflects the closer links between land use and climate change and erosion rates, because the prediction of changing sediment loads necessitates consideration of sediment delivery and transfer, and thus the overall functioning of a river basin, as distinct from on-site changes in sediment mobilization.

The work of O’Neal et al. (2005), which deals with the Midwest United States, provides a useful example of the potential of such studies. In this case, attention was directed to changes in the key hydroclimatic drivers as well as to changes in crop

growth rates caused by increased carbon-dioxide, and changes in crops and crop management as farmers adapted both their crops and their management practices to the new climate. In their study, the Water Erosion Prediction Project (WEPP) model is used coupled with a CO<sub>2</sub> submodel to take account of carbon dioxide – plant growth relationships (WEPP-CO<sub>2</sub>) was used for erosion modelling and the changing hydrometeorological drivers were derived from the Hadley Centre, HadCM3-GGal climate-change scenarios. The results suggest that from 2040 to 2059, soil erosion rates could increase by between 33% and 274% on figures for the period from 1990 to 1999 over the different regions of the Midwest. This emphasizes the potential importance of climate change as a driver of future changes in erosion rates. The study also highlights the need to take account of changes in crops and crop management and not only the hydrometeorological drivers when predicting the likely impact of climate change.

At the global level, the work of Yang et al. (2003), using a simpler erosion model, a greatly reduced spatial resolution (0.5°), and focussing on changes in annual precipitation and mean temperature in response to global warming, predicted that by the 2090s global soil erosion rates would have increased by 9%. Interestingly, the same work estimated that increases in cropland, associated with increased population, would cause an additional increase in erosion rates of some 5%. Further work is clearly required to refine global predictions by broadening the more comprehensive approaches now being developed for smaller regions, such as the Midwest described above, to make them usable at the global level. However, such work will clearly be hampered by the lack of well-calibrated erosion models in many areas of the world and the lack of sufficient background information to successfully transfer existing models to different environments.

As with the prediction of future erosion rates, most work on river sediment fluxes has focussed on individual river basins and has attempted to predict the impact of potential future climate-change scenarios. The simplest approaches have involved calibrating models to reproduce the existing sediment response and running those models with inputs reflecting climate-change scenarios. In this way Thodsen et al. (2008) predicted that increases in mean temperature and mean annual precipitation would cause increases in mean annual suspended sediment load of 17% and 27% in two Danish rivers over the next 60 to 90 years – although when an increased growing season was factored into the model, the increases were reduced to 9% and 24% respectively.

Similarly, Zhu et al. (2008) used artificial neural networks (ANNs) calibrated using sediment records for the period from 1960 to 1990 to explore the potential impact of increased temperatures and changing annual precipitation on the sediment load of the Longchuanjiang River, a tributary of the upper Yangtze River. In this case, changes in

the annual sediment load ranging between a small reduction of 0.7% and a maximum increase of 13.7% were predicted for various current projected climate-change scenarios.

As with erosion, it is important to consider the many potential interactions between climate change and land use and other human activity, and thus the likelihood of non-stationary behaviour – all of which could limit the reliability of models calibrated using current records. Furthermore, both the magnitude of changes in erosion and sediment yield and the direction of these changes could vary across a large river basin. In this context a physically-based, distributed modelling approach may be required to generate meaningful predictions. Such an approach is used well in the work of Asselman et al. (2003) when attempting to predict the potential effects of changes in climate and land use on the sediment load of the lower reaches of the River Rhine in the Netherlands. A suite of GIS-embedded models involving an erosion model, a sediment transport model, and a floodplain deposition model were used for the predictions. Using UK Hadley Centre climate-change scenarios for 2050 in combination with projected land use changes, the study indicated that erosion rates would increase in the Alps and reduce in the German part of the basin, producing an overall increase of about 12% in the average erosion rate. However, as a result of conveyance losses associated with the river system, the increased soil loss in the Alps was found to have little effect on sediment loads further downstream and a 13% decrease in the annual sediment load of the lower reaches of the River Rhine was predicted.

### 3.10 The need for new tools

As further attention is directed to developing an improved understanding of the impact of global change on erosion and sediment dynamics and to predicting future impacts, there is a need to consider the requirement for new or improved tools to support such studies. Data availability will inevitably remain a key constraint as the lack of reliable long-term records is difficult to address in the absence of existing measurement programmes. However, as indicated above, surrogate data can provide a valuable complement to available records and there is a need to direct attention to the development and improvement of methods for extracting such information from sediment cores collected from lakes and estuaries.

In the case of erosion, the site-specific nature of most measurements also presents scope to apply an ergodic approach, involving space-time substitution. However, if this is to be pursued effectively, there's a need to assemble further data from sites representative of different conditions. In this context, recent progress in the application of the fallout radionuclides, caesium-137 (<sup>137</sup>Cs), excess lead-210 (<sup>210</sup>Pb<sub>ex</sub>) and beryllium-7 (<sup>7</sup>Be), would appear to offer considerable potential for assembling new data on recent erosion rates.

The procedures for using these radionuclides for documenting erosion rates have the advantage of being able to generate retrospective estimates of medium-term erosion rates on the basis of a single site visit.<sup>2</sup> The results obtained relate primarily to rill and inter-rill erosion, rather than to gully erosion but the former is generally the most difficult to document using traditional approaches because of the difficulty of quantifying the loss or gain of small volumes of sediment from the soil surface.

Information on gully erosion is frequently available from sequential remote sensing imagery and aerial photographs, which permit the rates of gully extension to be estimated. However such techniques are unable to provide equivalent information on the rates of surface lowering by sheet and rill erosion. The scope for developing fallout radionuclide techniques to assemble information that can be used to assess the impact of global change on soil erosion rates merits further investigation.

The need to disentangle the impacts of several drivers when assessing the impact of global change on erosion and sediment dynamics and to apportion changes to specific drivers, has introduced a need for new and more powerful statistical techniques that are also able to take account of uncertainties associated with the available data. Equally, evidence of the existence of thresholds and non-linear responses provided by investigations of longer-term global change also needs to be taken into account when analyzing changes in erosion and sediment dynamics (see the IGBP Past Global Changes [PAGES] Land Use and Climate Impacts on Fluvial Systems [LUCIFS] project). Closer contact should be encouraged with hydrologists working on other aspects of global change and who are also facing similar problems.

As understanding of the impact of global change increases, our predictive capabilities should also increase. From a global and regional perspective, the need to consider very large areas of the Earth's surface inevitably introduces the need to establish an effective compromise between the use of simple models with limited data requirements and the use of more sophisticated models that are better able to take account of the complexities of the system – including internal interactions – but which require considerably more data. The embedding of models within a distributed GIS framework capable of exploiting the growing number of global bases clearly offers considerable scope for the generation of improved predictions. However, there remains a need to ensure that the models used are able to adequately model a non-stationary system and not rely heavily on existing data for calibration purposes. Similarly, recognition of the likely importance of thresholds and a non-linear response when attempting to predict the impact of global change places further demands on predictive models.

2 See Zapata, 2002; Walling, 2006; Walling et al., 2003; Schuller et al., 2004; and Golosov, 2003.

### Conclusion

#### 4.1 Wider implications

This brief overview of current evidence for global scale changes in erosion rates and sediment transport by rivers has emphasised that such changes must be seen as a key component of global change and its impact on the Earth system. While emphasis has been placed on the physical processes involved and changes in sediment fluxes and the global sediment budget, it is important to recognize that the changes described have many wider implications and also a social and economic dimension.

As indicated previously, changing erosion rates have important implications for land degradation, the sustainability of the global soil resource and food security. Attention commonly focuses on the detrimental impact of increased erosion rates, with their direct link to reduced soil productivity and a reduction in the global stock of productive agricultural land. However, it is also important to assess the effectiveness of recent improvements in land management, including the introduction of no-till and minimum-till management practices and the implementation of large-scale soil conservation programmes, and their implications for the sustainability of the soil resource and future food security. The removal of nutrients by soil erosion frequently necessitates the increased application of fertiliser, which in turn has important implications for the cost of food production, diffuse source pollution and the degradation of aquatic ecosystems caused by eutrophication.

An increase in the sediment load of a river will also frequently have important environmental implications linked to the degradation of aquatic ecosystems and habitats, including fish spawning gravels as well as implications for water use. As indicated above, it has been estimated that sedimentation is currently reducing the storage capacity of the world's major reservoirs by about 0.8% per year. At a time of rapidly increasing population in many regions of the world and an associated increase in demand for water for domestic, industrial and agricultural use, as well as for hydropower generation, such loss of storage is clearly an important problem in terms of sustainable water resource development and the means of replacing that storage through the construction of new dams.

Estimates produced by Basson (2008) suggest that by 2050, approximately 64% of the world's current reservoir storage capacity will have been filled with sediment. For many dams, the design incorporates a substantial volume of dead storage explicitly allocated to sedimentation, but existing evidence suggests that reservoir operation is likely to be seriously impacted by sediment once 70% to 80% of the original storage capacity is lost. In many cases, suitable replacement sites may not be readily available and, furthermore, the construction of new dams may meet with opposition.

Increased sediment loads will also frequently have important implications for river management for navigation and flood control. In many contexts, reduced sediment loads may be welcomed as resulting in improved water quality, improved aquatic habitats, improved navigation and reduced flood problems. However, reduced sediment loads can also bring problems, where, for example, reduced sediment input to a delta result in shoreline retreat, loss of land and increased coastal flooding. Much of Bangladesh lies within the estuary of the Ganges/Brahmaputra river system. Continued sediment accretion within the delta region is of critical importance for creating new land and reducing the threat of inundation associated with rising sea level.

More generally, reduced sediment deposition on fertile river floodplains could reduce nutrient inputs to such land and create a need for increased fertiliser application, with its potential to increase nutrient levels in groundwater.

#### 4.2 Whither ISI

The terms of reference of the International Sediment Initiative (ISI) and its associated programme ([www.irtces.org/isi](http://www.irtces.org/isi)) embrace many aspects of sediment and sediment-related problems linked to the sustainable management of rivers and river basins and their water resources. These include an information system, a global evaluation of sediment transport (the GEST project), an assembly of case studies of sediment problems and sediment management for river basins in different environments, a review of erosion and sedimentation research, and an initiative to promote education and capacity building in the sediment field. The theme of global change and its impact on erosion and sediment dynamics is central to most, if not all, of these aspects since it is now clear that change is a key feature of those dynamics and such change is in turn a key driver of sediment-related problems and has a fundamental influence on sustainable river and river basin management. It is therefore important that ISI should identify global change and the response of erosion and sediment dynamics to that change as a key area of interest. Furthermore, ISI has an important role to play in collaborating with other groups and bodies that are concerned with the current and future impact of global change on hydrological systems.

Global warming resulting from the increased emission of greenhouse gases has tended to dominate recent concern for global change and the associated research agenda. However, it is clear that the many other facets of global change, related to changes in the land surface of the globe resulting, for example, from population growth, land use change, mineral exploitation, infrastructural development and water resource development, also have important implications for the sustainable development of the Earth system.

ISI again has an important role to play in highlighting the wider context of global change and the importance of such change to erosion

and sediment dynamics, which impact directly on food security and sustainable water resources. There is a need to expand erosion and sediment monitoring programmes and ISI should play a central role in advocating the implementation of monitoring programmes in those many areas of the world where they are lacking – and in pressing for a reversal of the current trend of curtailing existing monitoring activities and closing long-term monitoring stations. The continuation of measurement programmes at long-term monitoring stations is of critical importance for assessing the magnitude of ongoing changes in sediment dynamics and for supporting the development of improved predictive capacity.

Taking account of the increasing concern for the impact of global change on the Earth system, both within the scientific community and by policy makers, governments and international agencies, and the many societal and economic implications of human dependence on a changing system, ISI should take a lead in emphasising the sensitivity of erosion and sediment dynamics to global change and the need to recognise the wide-ranging implications of changes in erosion and sediment dynamics.

Key issues to be communicated include:

- The need to recognise that global change involves more than climate change.
- The important changes to the earth's surface occurring as result of population growth, land clearance and land use change, infrastructure development and resource exploitation.
- The wide-ranging implications of changing erosion and sediment dynamics for food production, food security, water resource development and terrestrial and aquatic ecosystems.
- The need for improved sediment management in river basins, and the resulting need for capacity building and improved education in the sediment field.
- The need for improved sediment monitoring programmes in many areas of the world, and particularly in developing countries.
- The need for improved predictive capabilities for erosion and sediment dynamics, to take account of the complex relationship between erosion and sediment yield and the many feedbacks, both physical and socio-economic, involved.

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# World Water Assessment Programme side publications, 2009

During the consultation process for the third edition of the World Water Development Report, a general consensus emerged as to the need to make the forthcoming report more concise, while highlighting major future challenges associated with water availability in terms of quantity and quality.

This series of side publications has been developed to ensure that all issues and debates that might not benefit from sufficient coverage within the report would find space for publication.

The 21 side publications released so far represent the first of what will become an ongoing series of scientific papers, insight reports and dialogue papers that will continue to provide more in-depth or focused information on water-related topics and issues.

## Insights

Freshwater and International Law: The Interplay between Universal, Regional and Basin Perspectives — *by Laurence Boisson de Chazournes*

IWRM Implementation in Basins, Sub-Basins and Aquifers: State of the Art Review — *by Keith Kennedy, Slobodan Simonovic, Alberto Tejada-Guilbert, Miguel de França Doria and José Luis Martin for UNESCO-IHP*

Institutional Capacity Development in Transboundary Water Management — *by Ruth Vollmer, Reza Ardakanian, Matt Hare, Jan Leentvaar, Charlotte van der Schaaf and Lars Wirkus for UNW-DPC*

Global Trends in Water-Related Disasters: An Insight for Policymakers — *by Yoganath Adikari and Junichi Yoshitani at the Public Works Research Institute, Tsukuba, Japan, for the International Center for Water Hazard and Risk Management (ICHARM), under the auspices of UNESCO.*

Inland Waterborne Transport: Connecting Countries — *by Sobhanlal Bonnerjee, Anne Cann, Harald Koethe, David Lammie, Geerinck Lieven, Jasna Muskatirovic, Benjamin Ndala, Gernot Pauli and Ian White for PIANC/ICIWaRM*

Building a 2nd Generation of New World Water Scenarios — *by Joseph Alcamo and Gilberto Gallopin*

Seeing Traditional Technologies in a New Light: Using Traditional Approaches for Water Management in Drylands — *by Harriet Bigas, Zafar Adeel and Brigitte Schuster (eds), for the United Nations University International Network on Water, Environment and Health (UNU-INWEH)*

## Dialogue Series

Introduction to the IWRM Guidelines at River Basin Level — *by Toshihiro Sonoda for UNESCO-IHP, and the Network of Asian River Basin Organizations (NARBO)*

Water Adaptation in National Adaptation Programmes for Action: Freshwater in Climate Adaptation Planning & Climate Adaptation in Freshwater Planning — *by Gunilla Björklund, Håkan Tropp, Joakim Harlin, Alastair Morrison and Andrew Hudson for UNDP*

Integrated Water Resources Management in Action — *by Jan Hassing, Niels Ipsen, Torkil-Jønch Clausen, Henrik Larsen and Palle Lindgaard-Jørgensen for DHI Water Policy and the UNEP-DHI Centre for Water and Environment*

Confronting the Challenges of Climate Variability & Change through an Integrated Strategy for the Sustainable Management of the La Plata River Basin — *by Enrique Bello, Jorge Rucks and Cletus Springer for the Department of Sustainable Development, Organization of American States*

Water and Climate Change: Citizen Mobilization, a Source of Solutions — *by Marie-Joëlle Fluet, Luc Vescovi, and Amadou Idrissa Bokoye for the International Secretariat for Water and Ouranos*

Updating the International Water Events Database — *by Lucia De Stefano, Lynette de Silva, Paris Edwards and Aaron T. Wolf, Program for Water Conflict Management and Transformation, Oregon State University, for UNESCO PCCP*

Water Security and Ecosystems: The Critical Connection — *by Thomas Chiramba and Tim Kasten for UNEP*

## Scientific Papers

Freshwater Biodiversity versus Anthropogenic Climate Change — *by Luc Vescovi, Dominique Berteaux, David Bird and Sylvie de Blois*

The Impact of Global Change on Erosion and Sediment Transport by Rivers: Current Progress and Future Challenges — *by Desmond E. Walling, Department of Geography, University of Exeter, for the International Sediment Initiative of IHP UNESCO*

Climate Changes, Water Security and Possible Remedies for the Middle East — *by Jon Martin Trondalen for UNESCO PCCP*

A Multi-Model Experiment to Assess and Cope with Climate Change Impacts on the Châteauguay Watershed in Southern Quebec — *by Luc Vescovi, Ouranos; Ralf Ludwig, Department of Geography, University of Munich; Jean-François Cyr, Richard Turcotte and Louis-Guillaume Fortin, Centre d'Expertise Hydrique du Québec; Diane Chaumont, Ouranos; Marco Braun and Wolfram Mauser, Department of Geography, University of Munich*

Water and Climate Change in Quebec — *by Luc Vescovi, Ouranos; Pierre Baril, Ministry of Transport, Québec; Claude Desjarlais; André Musy; and René Roy, Hydro-Québec. All authors are members of the Ouranos Consortium*

Investing in Information, Knowledge and Monitoring — *by Jim Winpenny for the WWAP Secretariat*

Water Footprint Analysis (Hydrologic and Economic) of the Guadiana River Basin — *by Maite Martinez Aldaya, Twente Water Centre, University of Twente and Manuel Ramon Llamas, Department of Geodynamics, Complutense University of Madrid, Spain*



## **ISI: Linking Science with Policy & Management Needs**

The International Sediment Initiative (ISI) of the International Hydrological Programme (UNESCO-IHP) promotes sustainable sediment management at the global scale in an effort to contribute to sustainable water resources management.

The initiative assesses erosion and sediment transport by rivers to lakes, reservoirs and marine environments, with the objective of creating a holistic approach for the remediation and conservation of surface waters. ISI focuses on sediment quantity and quality, as well as the economic, social and ecological aspects related to erosion and sedimentation. It aims to develop a decision support framework for sediment management, in order to provide guidance on legislative and institutional solutions applicable to various socio-economic and physiographic settings in the context of global change.

ISI encourages international cooperation in managing regional sediment problems and in finding local solutions, such as better advice for policy development and implementation. It promotes the collection, analysis and interpretation of sediment data, as well as the exchange and use of appropriate methods and procedures for sediment management.

Within the framework of sustainable water resources management, ISI is a contribution to global sustainable sediment management. The initiative's outcomes contribute to the World Water Assessment Programme and its triennial World Water Development Reports and to other global efforts towards achieving the Millennium Development Goals.

