The changing sediment loads of the world's rivers

D. E. WALLING
Department of Geography, University of Exeter, Amory Building, Rennes Drive, Exeter EX4 4RJ, Devon, UK
d.e.walling@exeter.ac.uk

Abstract Recent anthropogenic pressures on the Earth's surface, including population growth, wide ranging disturbance of the land surface by land use activities, infrastructure development and mineral exploitation, and modification of the hydrological cycle caused by water resource exploitation, have resulted in significant changes to the sediment loads of some of the world's rivers. In some cases loads have increased, whereas in others loads have reduced. Examples of such changes are provided and an attempt is made to identify the key drivers of changing sediment loads at the global scale. Situations that can lead to blurred signals of upstream changes in sediment flux at the catchment outlet are also considered. Recent changes in the sediment loads of the world's rivers, as demonstrated by existing short-term records, may represent only the recent phase of longer-term changes and there is therefore a need to place recent changes into a longer-term context. The implications of changing sediment fluxes, and particularly sediment trapping by dams, for land–ocean sediment transfer and the global sediment budget are assessed.

Key words world rivers; erosion; sediment yield; sediment load; human impact; reservoir sedimentation; land disturbance; global sediment budget

INTRODUCTION

The International Geosphere Biosphere Programme (IGBP) initiated by ICSU in 1987 (see Steffen *et al.*, 2004), as well as a number of related initiatives, have focused increasing attention on the changes in the functioning of the Earth system caused by human activity and on the problems and challenges associated with the sustainable management of this changing system over the coming centuries. The increased emission of greenhouse gases, leading to climate change, has provided a focus for many of the resulting research programmes. However, as recognized by the IGBP, anthropogenic pressure must be seen as the cause of many other facets of global change. These include major changes in vegetation cover across the Earth's surface, wide ranging disturbance of that surface by land use activities, infrastructure development and mineral exploitation, and modification of the hydrological cycle caused by water resource exploitation. The accelerating pace of such changes is emphasized when it is recognised that since 1900 and thus over just the past 100 years, world population has increased 6-fold, the world's cropland has almost doubled, the area of pasture has increased by about 75% and the area of the globe covered by tropical forests has decreased by about 25%. Similarly, almost all of the world's major reservoirs were constructed during the past 60 years.

These changes in the condition of the land surface of the Earth, as well as ongoing climate change, can be expected to have exerted a significant influence on global erosion rates and the sediment loads of the world's rivers. Erosion rates are particularly sensitive to changes in vegetation cover and land use activities and sediment loads will closely reflect both increases and decreases in land erosion caused by human activity, as well as changes in river flows and sediment transport caused by water resource exploitation, construction of dams and other human uses of river systems. The temporal trajectories of these anthropogenic impacts will have varied across the land surface of the globe in response to the history of human exploitation of the landscape. In some areas of the "old world", for example, forest clearance and the expansion of agriculture can be expected to have initiated increased erosion and sediment loads as far back as several millennia, whereas in areas of the "new world" equivalent changes may have occurred within the last two centuries. Furthermore, as successful large-scale erosion control programmes are introduced in some areas of the world, erosion rates and sediment loads may be declining, whereas in other areas of the world erosion may still be increasing due to forest clearance, expansion of cultivation and widespread catchment disturbance.

The significance of potential changes in erosion and sediment transport is wide ranging. Increased soil erosion will have implications in terms of reduced soil productivity, food security and sustainable use of the soil resource. Furthermore, the impact of increased soil loss extends to off-site, as well as on-site effects, and increased sediment delivery to watercourses and river systems can cause further problems. Changes in sediment load again have many important implications. From a global perspective, changes in land–ocean sediment transfer will result in changes in global biogeochemical cycles, since sediment is important in the flux of many key elements and nutrients, including carbon. At the regional and local scales, changes in the sediment load of a river can give rise to a range of problems. Excessive sediment loads can result in accelerated rates of sedimentation in reservoirs, river channels and water conveyance systems, causing problems for water resource development, as well as in adverse impacts on aquatic habitats and ecosystems. Conversely, reduced sediment loads can result in the scouring of river channels and erosion of delta shorelines, as well as reduced nutrient inputs to aquatic ecosystems, particularly lakes, deltas and coastal seas. Erosion rates and river sediment loads must therefore be seen as important components of the Earth system. This contribution reviews existing evidence for recent changes in the sediment loads of the world's rivers, in response to the increasing pace of global change and identifies a number of important uncertainties in attempting to establish both the recent and the longer-term impact of global change on the global sediment budget

CHANGING SEDIMENT LOADS

Figure 1 provides evidence of the potential magnitude and nature of recent changes in the suspended sediment loads of the world's river by presenting information from three rivers that provide evidence of marked changes in their sediment load 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 Lijn on the Lower Yellow River in China (catchment area 752 500 km^2) provides clear evidence of a major decrease in both the annual sediment load and the annual water discharge, since the late 1970s. In the literature, the mean annual suspended sediment load of the Yellow River is frequently cited as 1.6 Gt year^{-1} (e.g. Shi *et al.*, 2002) and as representing the largest sediment load of all world rivers. This value is, however, based on the available records extending through to the 1980s for the long-term monitoring station at Sanmenxia, which is located some 800 km from the delta, where the river flows out of the loess region and enters the North China Plain. The equivalent value for the downstream monitoring station at Lijin, which is located about 40 km from the delta and which provides a more meaningful estimate of sediment delivery to the ocean is 1.08 Gt year^{-1}. Recent years have, however, seen a significant reduction in the load measured at Lijin, with this falling to approx. 0.8 Gt year^{-1} in the 1980s, and to approx. 0.4 Gt year^{-1} in the 1990s (see Fig. 1(a)) Available information suggest 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 year^{-1} (see Yang *et al.*, 2007). Based on these data, the current sediment load at Lijin can be seen as being almost an order of magnitude lower than that documented for the period prior to about 1980. Simple trend analysis applied to the records of water and suspended sediment discharge for the Yellow River at Lijin in Fig. 1(a), using linear regression to establish trend lines, provides clear evidence of a statistically significant (P > 99.9%) reduction in both water and sediment load over the past 50 years. The lack of any clear break in the double mass plot (Fig. 1(a) lower), a tool frequently used to identify changes in the sediment response of a river (see 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, demonstrated by Fig. 1(a), has been accounted for as being in part a response to climate change, and, more particularly, reduced precipitation over the central region of the catchment, but it is primarily the result of more direct human impact and, more particularly, increasing water abstraction (as evidenced by the greatly reduced flows in Fig. 1(a)), sediment

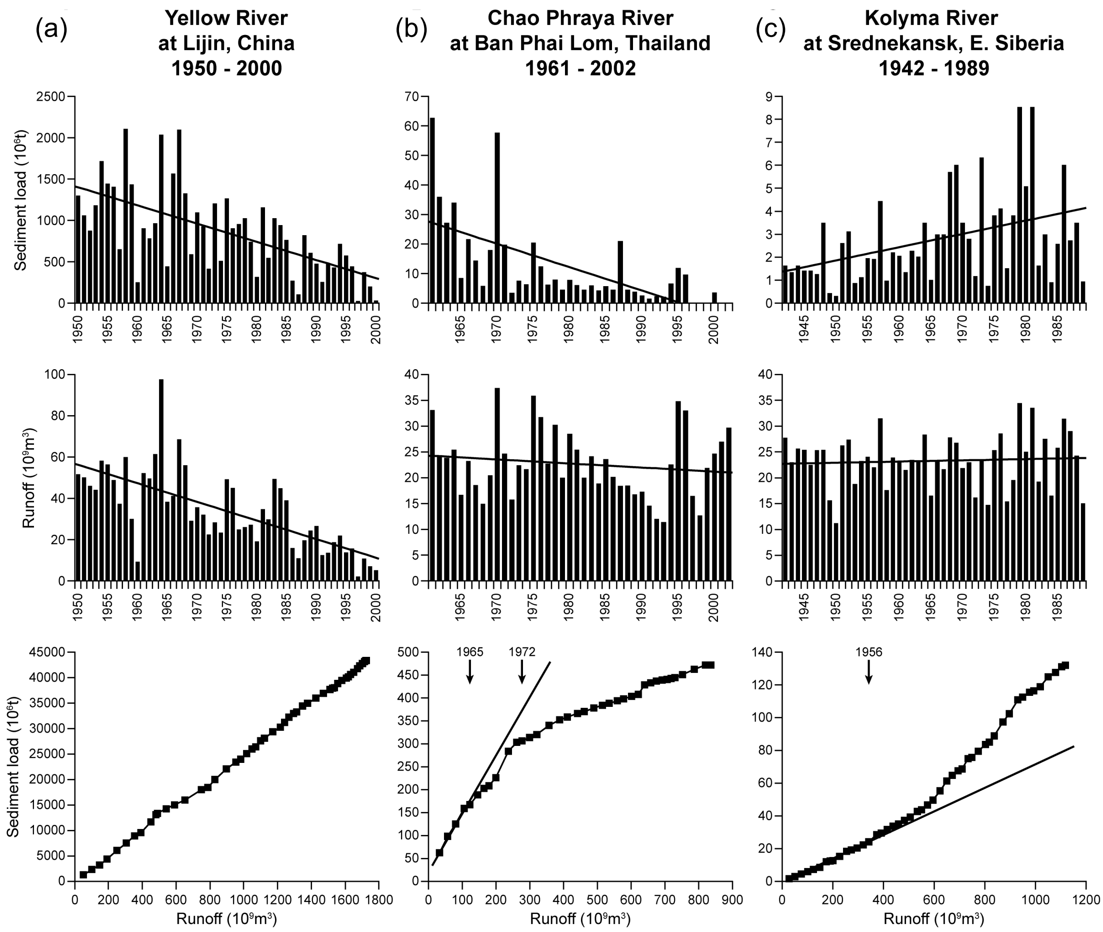

Fig. 1 Recent trends in the annual suspended sediment loads and annual runoff of: (a) the Yellow River at Lijin, China; (b) the Chao Phraya River at Ban Phai Lom, Thailand; and (c) the Kolyma River at Srednekansk, East Siberia, Russia, as shown by the time series of annual sediment loads and annual runoff and the double mass plots of annual sediment load *vs* annual runoff.

trapping by an increasing number of both 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 the lower reaches of the river system. A recent attempt to attribute the reduction in annual sediment load to specific causes, reported by Wang *et al.* (2007a) 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, whilst sediment trapping by reservoirs accounted for 30% of the reduction.

In the case of the Chao Phraya River in Thailand, shown in Fig. 1(b), the annual sediment load of the river, which drains a catchment of 110 569 km^2, again provides clear evidence of a statistically significant ($P > 99\%$) reduction over the period of record, declining from approx. 28 Mt year^{-1} in the 1960s and early 1970s to approx. 6 Mt year^{-1} 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 Sirkit hydropower and water supply dams on major headwater tributaries commissioned in 1965 and 1972, respectively. 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^2 basin of the upper Kolyma River in Eastern Siberia, Russia, contrasts with the two examples presented above, 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 and the double mass plot suggests that the sediment load has increased by 1.5 times since the late 1950s. However, unlike the Yellow 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 <1 person per km^2. The increased sediment loads have been attributed by Bobrovitskaya (personal communication) to gold mining activity and associated disturbance within the catchment.

KEY DRIVERS

The trends exhibited by the records for the three rivers presented above provide evidence of two key drivers of changes in the sediment loads of the worlds rivers, namely catchment disturbance, linked to such human activities as deforestation, land clearance for agriculture, mining and mineral exploitation, and building construction and infrastructure development, resulting in *increased* sediment loads, and dam construction, resulting in sediment trapping and *reduced* sediment loads. These and other important drivers will be briefly reviewed.

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 to the Mediterranean Sea of approx. 100 Mt year^{-1} 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 construction of a dam will depend on a number of factors, including the location of the 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 due to 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 current annual water discharge of these two rivers is only approx. 0.5% and 4% of the pre-dam value and the sediment loads have been reduced by 100% and 96%, respectively (see Vorosmarty *et al.*, 2003). In the case of the lower Indus River, the annual runoff is now less than approx. 20% of that prior to the development of the extensive irrigation systems that commenced in the 1940s and the current annual sediment load has similarly declined to approx. 20% of its previous value (see Milliman *et al.*, 1984; Walling, 2007) Dam construction has caused a major reduction in the sediment loads transported by the Mississippi and Danube rivers, where annual sediment loads have declined to about 30% of those transported in the early 1950s (see Walling, 2006). However, for these rivers there has been no significant reduction in the annual runoff.

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 the catchment by deforestation, land clearance for agriculture, intensification of agriculture, mining, infrastructure development and related activities, 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 for rivers where the sediment load has declined as a result of dam construction. Furthermore, whereas dam construction is a relatively recent phenomenon and its impact can therefore be documented by sediment load records extending back over say 40 or 50 years, for many rivers the main impact of surface 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 emphasises the importance of this driver. Walling (2006) cites the example of the Rio Magdalena River in Columbia, which drains a catchment of approx. 250 000 km^2 and accounts for about 9% of the total sediment flux from the eastern seaboard of South America. Data assembled by Restrepo and his co-workers (e.g. Restrepo *et al.*, 2006), indicate that sediment yields from large areas of the basin have increased substantially over the past 10–20 years and that, as a result, the sediment load at the basin outlet has increased by possibly as much as 40–45% over the period 1975–1995, in response to forest clearance, land use intensification and gold mining activity within the river basin. An assessment of recent changes in the sediment load of another major South American river, the São Francisco River, in Brazil, reported by Carvalho *et al.* (2007), similarly suggests that the sediment load of this river increased about 3-fold between the late 1970s and the mid 1980s, as a result of land clearance, agricultural development and mining activity. Walling (2006) also cites the case of the Upper Mekong or Lancang River in China, which drains a catchment of 140 933 m^2. Here, land clearance and land use change in the 1970s and 1980s, associated with rapid population growth, has resulted in a significant ($P > 95\%$) trend of increasing annual sediment loads over the period 1963–1990, with loads increasing by the order of 40%, although the record of annual runoff showed no significant trend. You (1999) demonstrated the link to population growth by establishing a significant multivariate linear relationship ($R = 0.83$) between annual sediment yield and annual runoff and the size of the population, for the Lancang Basin for the period 1965–1987.

In the case of the Rio Magdalena and the Lancang River considered above, the annual sediment loads evidenced an increase of approx. 40% over the study period in response to catchment disturbance. The precise magnitude of any such increases 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 1584 km^2 mountainous river basin is characterised by steep unstable slopes, tectonic instability and frequent typhoons generating heavy rainfall (see 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 (see Fig. 2). The trend shown by this river in Taiwan 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, since Milliman & Syvitski (1992) have shown that this region accounts for a major proportion of the global land–ocean sediment flux.

The importance of mining activity in causing increased sediment loads is well demonstrated by the available data for the Fly River in Papua, New Guinea, whose "natural" sediment load of approx. 10 Mt year^{-1} has shown a marked increase. Much of the basin of the Fly River remains pristine, but, beginning in 1985, approx. 90 Mt year^{-1} of rock waste and tailings were discharged from the major Ok Tedi gold and copper mine to the Ok Tedi River, a tributary of the Fly River. Much of this sediment was deposited within the Ok Tedi catchment and within the channel and flood plain of the Fly River, downstream of its confluence with the Ok Tedi River. Approximately 30% of the mine-derived sediment was transported by the Fly River to its confluence with the Strickland River, thereby increasing the downstream sediment load of the Fly River by approx. 2.5 times to approx. 35 Mt year^{-1}. The total sediment load discharged to the sea by the combined Fly–Strickland River system under natural conditions has been estimated to be approx. 85 Mt year^{-1}, and this was increased by about 40% to 120 Mt year^{-1}, as a result of the waste discharge from the Ok Tedi mine.

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

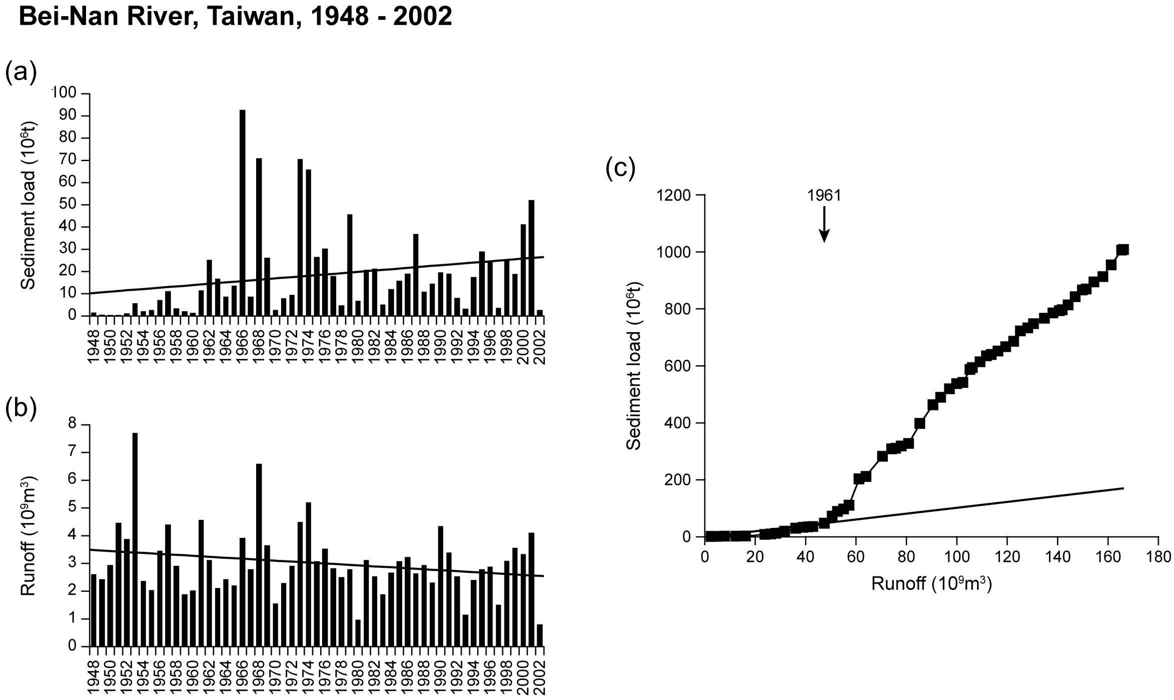

Fig. 2 Recent changes in the suspended sediment load of the Bei-Nan River, Taiwan, as demonstrated by the time series of the annual suspended sediment load (a); annual water discharge (b); and the associated double mass plot (c).

from river channels for use in the construction industry may represent a significant loss from the system. Marchetti (2002), for example, suggests that as much as 2 Mt of sediment are extracted each year from the central area of the River Po basin in northern Italy. However, it is necessary to recognise that in some locations the sediment removed may be coarser than that represented by the measured suspended sediment load 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 removed illegally without the required license. 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 dredgers being capable of removing up to 10 000 t day^{-1}. They estimate that the total quantity of sediment extracted could have been as high as 80 Mt year^{-1} in the late 1990s and Wang *et al.* (2007b) suggest that as much as 110 Mt year^{-1} are currently being extracted from the entire Yangtze system. Chen (2004) indicates 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 approx. 500 Mt year^{-1} during the 1960s and 1970s to approx. 350 Mt year^{-1} in the 1990s and approx. 200 Mt year^{-1} at the beginning of the current century.

Soil conservation and sediment control programmes

Land use impacts on sediment loads are commonly seen as resulting in increased sediment loads and as an inadvertent effect of human activity. However, the 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 & 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 US cropland was reduced from 3.4 Gt year^{-1} in the early 1980s to 2.0 Gt year^{-1} in the latter half of the 1990s. Equally, Lal *et al.* (2004) estimate that globally, no-till practices aimed at reducing erosion, have currently been implemented on approx. 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, which clearly demonstrate the success of soil and water conservation measures and improved management practices in reducing local soil loss, there is currently only limited quantitative evidence of the impact of such measures in reducing the sediment fluxes from larger river basins. Such evidence is, however, 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 30 years. In this region, attention has been direct to both reducing downstream sediment loads, as well as to on-site soil and water conservation, in order to reduce reservoir sedimentation and to alleviate siltation problems along the course of the Lower Yellow River, which cause serious problems for flood control.

Figure 3 presents information for the 4161 km^2 basin of the Sanchuan River, a tributary of the Middle Yellow River, which was the focus of extensive soil and water conservation works and sediment control measures in the 1980s. Zhao *et al.* (1992) reported that by the end of the 1980s, the soil conservation and sediment control programme implemented in this river basin had resulted in the construction of 267 km^2 of bench terraces and nine reservoirs and 703 km^2 of highly erodible land had been planted with forests and 46.7 km^2 with grass. Overall, nearly 30% of the basin area was actively controlled. The data presented in Fig. 3 provide evidence of a significant (P > 99%) decrease in both runoff and sediment load over the period of record. The double mass plot shows a well-defined departure from its initial trend around 1970, with this departure intensifying after 1980. A comparison of the mean annual sediment loads for the periods 1957–1969 and 1980–1993 indicates that sediment yields in the latter period have decreased to only

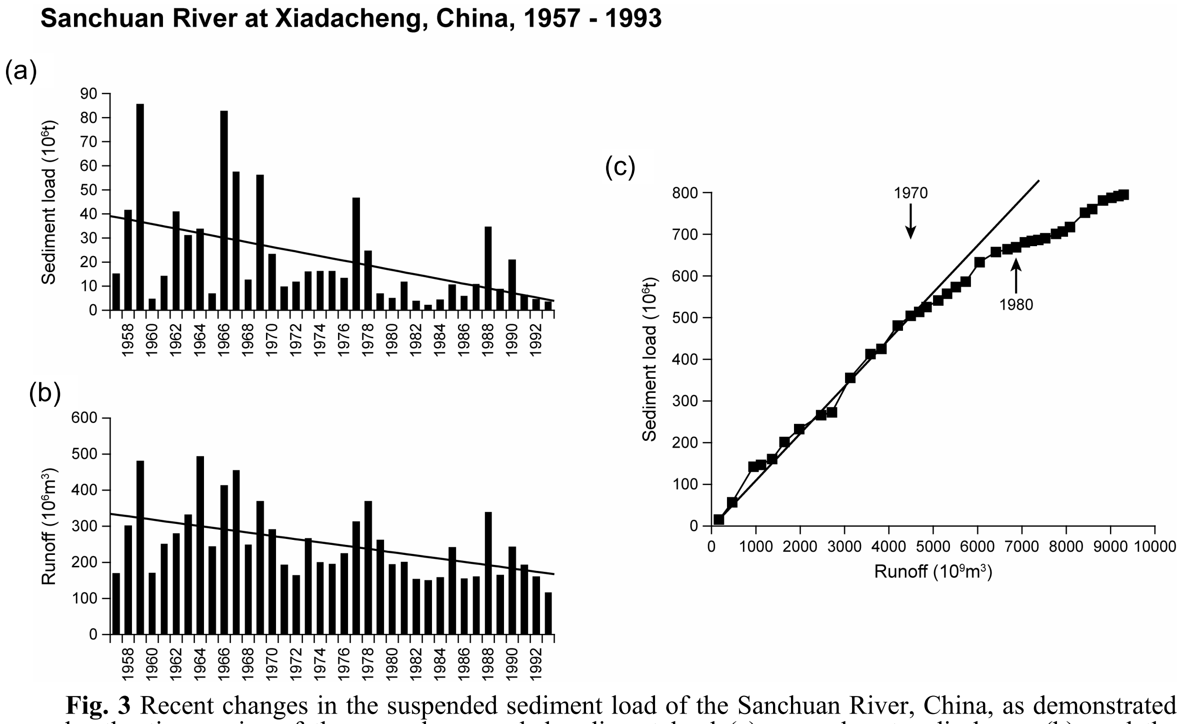

Fig. 3 Recent changes in the suspended sediment load of the Sanchuan River, China, as demonstrated by the time series of the annual suspended sediment load (a); annual water discharge (b); and the associated double mass plot (c).

about 25% of those in 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%. This must be seen as a very substantial reduction for a basin of this size and a clear indication of the potential of soil conservation and sediment control strategies to reduce sediment loads. The results of applying soil conservation and sediment control measures over an even wider area are shown in Fig. 1(a), which presents data for the entire 752 500 km^2 basin of the Yellow River, for which approx. 40% of the reduction in sediment load has been attributed to the implementation of soil conservation and sediment control measures.

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 shown in Fig. 1(a) highlights the need to recognise that climate change can also interact with these more specific anthropogenic impacts in causing changing sediment loads. In this case, the reduction in sediment load in recent decades also reflected a reduction in annual precipitation. In most rivers, however, 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 as a cause of recent changes in the sediment loads of the world's rivers. Equally, however, the clarity of the signal reflecting the impact of human activity could be reduced by climatic variability, for example where they are superimposed on changes associated with variation of the Southern Oscillation Index and associated shifts between El Nino and La Nina 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 focused on trends during the period 1973–1992 and involved values of instantaneous load rather than estimates of annual load. However, the data suggested that the sediment loads transported by the two rivers decreased by approx. 48% and 75%, respectively, over the study period, as a result of the spring cooling and a decrease in the incidence of heavy precipitation events in the autumn. Further investigation of the impact of climate change and increased climate variability on the sediment loads of the world's rivers may require more detailed studies of the sediment load and runoff records, involving, for example, the intra-annual distribution, as well as the annual totals.

BLURRING THE SIGNAL OF CHANGING SEDIMENT FLUX

In the various examples cited above, the records of annual sediment yield have provided clear evidence of changing sediment flux and these changes have been linked to changes in the upstream drainage basin. It is, however, important to recognise that there are a number of situations where substantial changes in sediment load within the upstream basin may not be reflected by a clear downstream signal. Three such potential situations can be highlighted. In the first, changes occurring in one part of the upstream basin could be offset or cancelled by changes occurring in other areas of the basin. A good example of this is provided by the sediment load record for the Upper Yangtze River at Yichang, China, prior to the construction of the Three Gorges Dam. At this measuring point the river drains a catchment of 1 005 000 km^2 and the longer-term record of sediment load extending over the period 1950 to the 1990s provides no evidence of any significant trend. This is despite a major increase in population from approx. 60 million in 1953 to approx. 140 million in the 1990s, widespread forest clearance and the expansion of cultivated land. However, more detailed analysis of changes in the sediment load of individual tributaries reported by Lu & Higgitt (1998) and Zhang & Wen (2004) showed that increases in sediment load in some

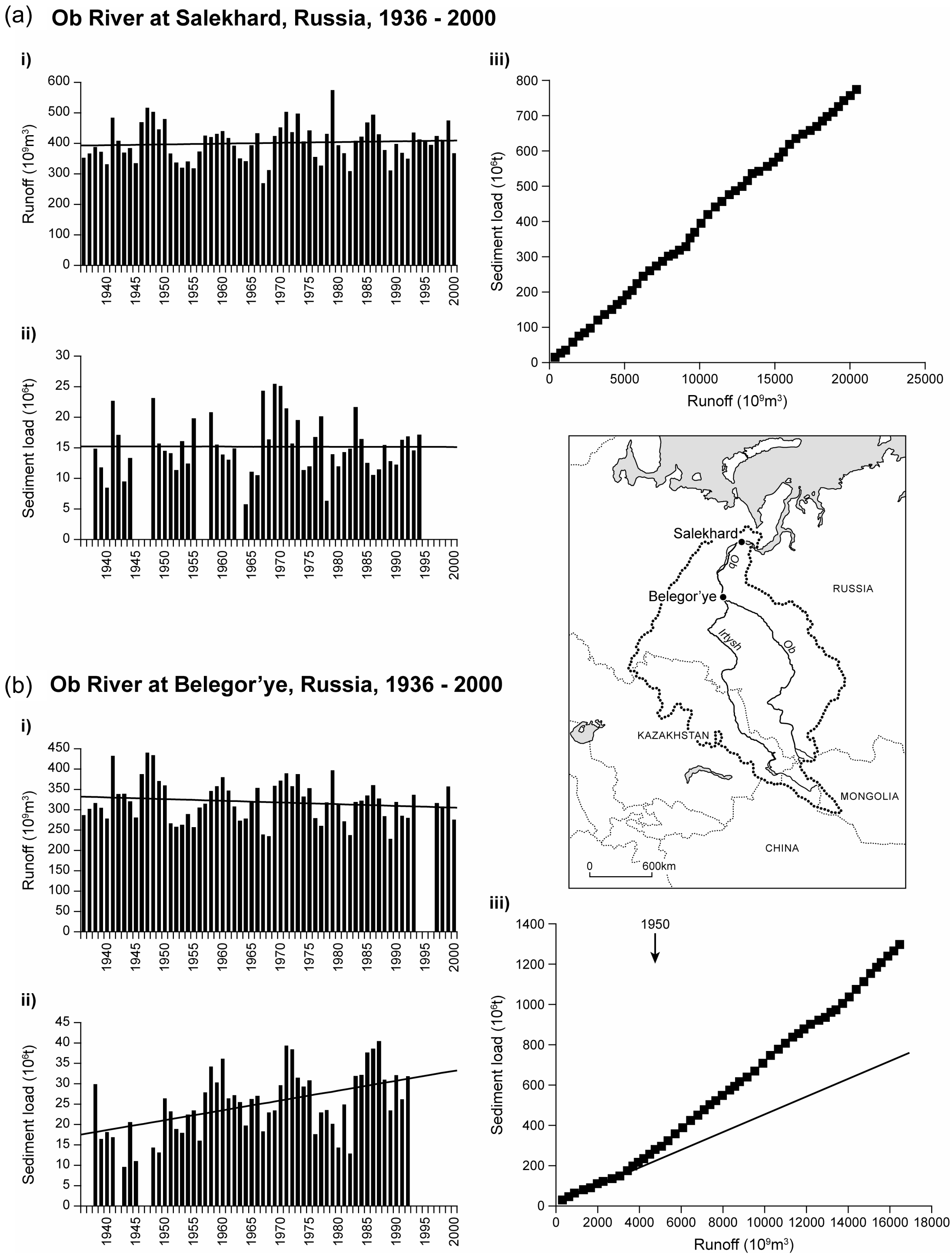

Fig. 4 Contrasts in recent trends in the suspended sediment load of the lower Ob River at Belegor'ye (upstream) and Salekhard (downstream), as demonstrated by the time series of the annual suspended sediment load (i) and annual water discharge (ii) and the associated double mass plot (iii).

tributary basins (e.g. the Jinsha River), caused by forest clearance and increased agricultural activity were offset by reductions in other tributary basins (e.g. the Jialing River), resulting from dam construction and the implementation of soil conservation measures.

The second situation is rather different and involves instances where the presence of significant sediment storage within the lower reaches of a river attenuates the signal of changing sediment flux generated upstream. The Ob River in Russia provides a good example of this phenomenon. This river drains a large 2 950 000 km^2 catchment in Siberia to the Arctic Ocean. 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 1936–2000, show no evidence of statistically significant trends and the double mass plot provides further evidence of a stable system (see Fig. 4). However, Bobrovitskaya *et al.* (1996) report that in this river basin the period 1957–1970 was characterised by significant human impact, both on the river channel and within the basin more generally, and cite an increase in the mean annual sediment load at Belgor'ye, some 700 km upstream of Salekhard, from approx. 19.2 Mt year^{-1} during the period 1938–1956, which was seen as representing the "natural" regime, to 28.4 Mt year^{-1} during the period 1957–1990, an increase of almost 50% (see Fig. 4). 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^2 of well-developed flood plain that border the 870 km reach of the Ob River between Belegory'e 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 the latter currently being only about 50% of those of the former. This is despite an increase in catchment area of almost 10% and an increase in the annual runoff of about 25% between the two monitoring sites. Bobrovitskaya *et al.* (1996) suggest that the amounts of sediment deposited on the flood plain between Belegor'ye and Salekhard have increased more than 3-fold 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.

The third situation effectively represents the reverse of that presented above and involves cases where the reduction in sediment load caused by the construction of a dam is offset or greatly reduced by sediment mobilisation downstream of the dam, as a result of channel incision and channel erosion. This situation occurred after the construction of the Sanmenxia Dam on the Middle Yellow River in 1960, when the reduced sediment load downstream of the dam initially caused widespread channel incision and erosion, which significantly decreased the reduction in the downstream sediment flux caused by the Dam. Another, even more clear example, is provided by the 46 100 km^2 drainage basin of the Trinity River in eastern Texas, USA, investigated by Phillips *et al.* (2004). Here, much of the reduction in sediment load caused by sedimentation behind the Livingston Dam constructed in 1968 was offset by remobilisation of sediment from alluvial storage downstream and the upper basin is effectively decoupled from the basin outlet, by virtue of sediment storage in the extensive alluvial flood plain 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.

THE LONGER-TERM PERSPECTIVE

It is important to recognise that the changes in the sediment fluxes of the world's rivers discussed above relate to a relatively short period, covering approximately the last 50 years. This period coincides with a period of major changes in the drainage basins of many rivers, associated, for example, with population growth, land clearance, the expansion of agriculture and dam construction. The major phase of dam building on the world's rivers did not begin until 1950. However, when assessing the impact of Global Change on the sediment loads of the world's rivers, there is a need to take account of the fact that in some areas of the globe human activity has had an important impact on erosion and sediment transport over a much longer period, with, for example, the clearing of forests and cultivation of farm land commencing several millennia ago. In these areas, the recent changes in sediment load must be seen as reflecting part of a longer record of change. In many cases, however, they will still represent important changes. This situation is usefully demonstrated by Fig. 5, which presents a tentative reconstruction of the longer term variation of the sediment load transported by the Lower Yellow River at Lijin, China based on the work of Saito *et al.* (2001), Milliman *et al.* (1987) and Xu (1998).

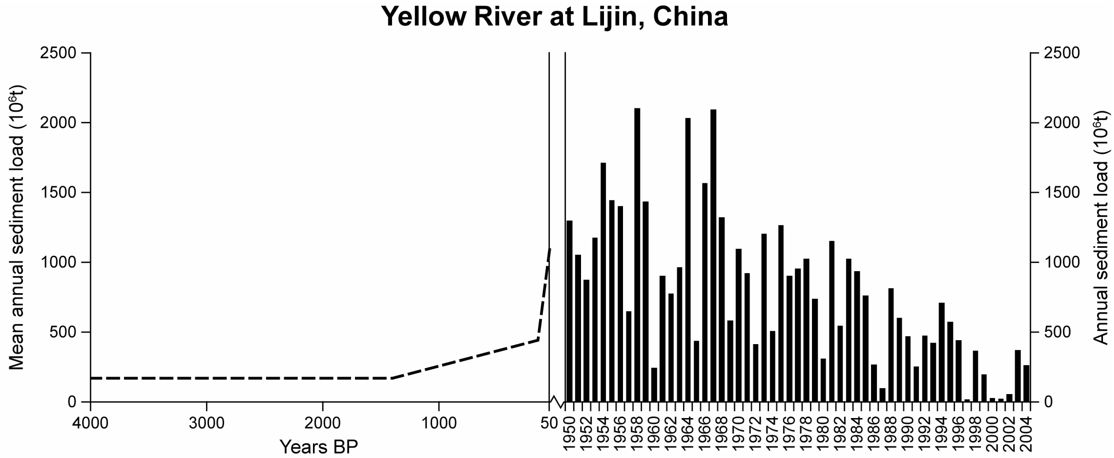

Fig. 5 A tentative reconstruction of the longer-term trend in the suspended sediment load of the Lower Yellow River over the past 6000 years, based on information presented by Milliman *et al.* (1987), Saito *et al.* (2001) and Xu (1998).

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 approx. 1400 BP, the sediment load of the Lower Yellow River was only about 10–20% of that associated with the period of maximum sediment load in the middle 20th 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 and the progressive stabilisation and control of the course of the Lower Yellow River by levees, which restricted the widespread deposition 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, Fig. 5 suggests that the reduction in the sediment load of the river that commenced in the latter part of the 20th century and which has continued to the present (see also Fig. 1(a)) 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" (see Shi *et al.*, 2002). There are, however, important differences between the situation in the past, 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 (see Fig. 1(a)), to the extent that the river has been reported to "dry up" for extended periods. For other rivers, the precise 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 Fig. 2, the recent increase in sediment load reported here represents the first major peturbation of the sediment flux.

IMPLICATIONS FOR THE GLOBAL SEDIMENT BUDGET

It is important to consider the implications of the above information on the changing sediment loads of the world's rivers for the global sediment budget, since this budget represents a key component of the Earth's 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 Panin, 2004; Walling, 2006) 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 attempt to establish the magnitude of the global land–ocean sediment flux is dealing with a "moving target". For example, whereas a sediment load of 1.08 Gt year^{-1} was widely cited for the Yellow River in the 1980s and the early 1990s, an estimate of the current value is likely be around 0.15 Gt year^{-1}. This reduction of approx. 0.9 Gt year^{-1} is equivalent to of the order of 5–7% of the likely total land-ocean sediment flux.

Lack of reliable records of sediment load for many world rivers 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 with data precludes a detailed assessment of the likely magnitude of recent changes in that flux. Walling & Fang (2003) presented a study of the longer-term records of annual sediment load for 145 rivers, and reported that approx. 48% were essentially stationary, whilst the remaining 52% provided evidence of statistically significant trends. Of these, about one tenth were increasing and the remainder were decreasing. However, the sample of rivers involved was not really representative of the world's rivers more generally, 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) analysed 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, 19 out of the 20 rivers provided evidence of either an increasing or a decreasing trend, with 12 rivers showing a decrease and 7 showing an increase. It is important to recognise that the opposing directions of possible changes in the sediment loads of individual rivers, such that increases in some could be offset by decreases in others, could mean that there has been little change in the overall global land–ocean sediment flux over the past 25–50 years, despite the changes described above. Interestingly, the various attempts to derive estimates of the global land–ocean sediment flux over the past 25 years have generally produced values around 15 Gt year^{-1} and this 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 are likely to have been characterised 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, however, currently considerable uncertainty associated with existing estimates of the amount of sediment sequestered behind dams on the world's rivers. Vorosmarty *et al.* (2003) estimate that more than 40% of the global river discharge is currently intercepted by large ($\geq$0.5 km^3 maximum storage capacity) reservoirs and by coupling this information with estimates of reservoir trap efficiency they estimated that reservoirs are currently sequestering approx. 4–5 Gt year^{-1}, with the potential for this value to be higher if the large number of smaller reservoirs are also taken into account. This value is, however, very significantly lower than suggested by a recent study involving the approx. 33 000 dams included in the ICOLD World Register of Dams (ICOLD, 2006) undertaken by the ICOLD Reservoir Sedimentation Committee and reported by Basson (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 6000 km^3, this is equivalent to an annual loss of storage of approx. 48 km^3 year^{-1}. Assuming, a dry bulk density for the deposited sediment of ~1.2 t m^{-3}, this is equivalent to annual sequestration of ~60 Gt year^{-1}, a value which is more than an order of magnitude greater than that proposed by Vorosmarty *et al.* (2003). This value is also about four times the likely annual land–ocean sediment flux, assuming a value for the latter of approx. 15 Gt year^{-1}. The value of ~60 Gt year^{-1} is, in fact, likely to be an underestimate, since 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 recognise that the estimate of the current rate of sediment sequestration in the world's reservoirs of ~60 Gt $year^{-1}$ 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, due to deposition and storage within the river system, and particularly on river flood plains. In the case of the Lower River Ob, discussed above (see Fig. 4), the conveyance loss associated with sediment transfer through the lower reaches of the river system is of the order of 40%. This value is likely to be much higher if the whole river system is considered. Similar conveyance losses of the order of 40–60% have been cited for flood plains 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 flood plain by Mertes (1994). A conveyance loss of 60% has also been cited by Phillips (1991) for the sediment delivered to the channel systems of several larger (>1000 km^2) 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 is likely to decrease in heavily managed channels, where the flow is constricted and flood inundation restricted. It is therefore difficult to propose a typical value for the conveyance loss likely to be associated with the ~60 Gt $year^{-1}$ of sediment currently being sequestered behind dams constructed on the world's rivers. However, a value of 60% could be tentatively suggested as a first order estimate. Use of this value would mean that 40% of the total ~60 Gt $year^{-1}$ 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 $year^{-1}$, a value that is considerably in excess of the likely contemporary global land–ocean sediment flux. This value of 24 Gt $year^{-1}$ is approaching an order of magnitude greater than the values of 3–5 Gt $year^{-1}$ suggested by Vorosmarty *et al.* (2003) and Syvitski *et al*. (2005) as representing the reduction in the contemporary global annual land-ocean flux resulting from sediment trapping by reservoirs.

Further confirmation of the general validity of the above scenario is provided by considering two examples of the impact of large reservoir systems on downstream sediment loads. The first relates to the impact of the recently constructed Three Gorges Dam on the sediment load of the Yangtze River and the second the impact of the six large dams constructed on the Missouri River in the mid 20th century, on the sediment load of the Mississippi River. In the case of the Three Gorges Dam on the Yangtze River, which commenced impoundment in 2003, Yang *et al.* (2007) used the information on the amount of sediment deposited in the reservoir and the changes in the downstream sediment load at the basin outlet at Datong to construct a sediment budget for the Reservoir and the downstream river system, and to predict the longer term response of the sediment load of the Yangtze River at Datong to deposition of sediment in the Three Gorges Reservoir and other dams that are projected to be constructed upstream. These authors estimated that, together, these dams would result in the trapping of approx. 212 Mt $year^{-1}$ and that the downstream load at Datong would be reduced to <150 Mt $year^{-1}$, representing a reduction of the recent sediment flux of the Yangtze River, prior to construction of the Three Gorges Dam, by >125 Mt $year^{-1}$. In this scenario, the reduction in the annual land–ocean sediment flux would be equivalent to approx. 50% of the amount of sediment deposited within the Three Gorges Reservoir and the other upstream reservoirs, and therefore provides some confirmation of the value of 40% proposed above.

In the case of the Missouri River dams, the impact of six major dams on the sediment load of the Missouri and Mississippi rivers has already been well documented by Meade & Parker (1984), who indicated that the annual sediment flux from the Mississippi basin was reduced to about one half of its earlier value. The availability of estimates of the recent rate of sediment sequestration in the six reservoirs constructed between 1940 and 1963 (US Army Corps of Engineers, personal communication) provides a basis for exploring the link between sediment storage in the reservoirs and the downstream reduction in the land–ocean flux (see Fig. 6). Based on the available reservoir survey data for the six reservoirs and assuming a sediment bulk density for the deposited sediment of 1.2 t m^{-3}, the total amount of sediment sequestered annually in the reservoirs over the period 1965 to 1985 is estimated to be approx. 155 Mt $year^{-1}$. The short period of record available for the

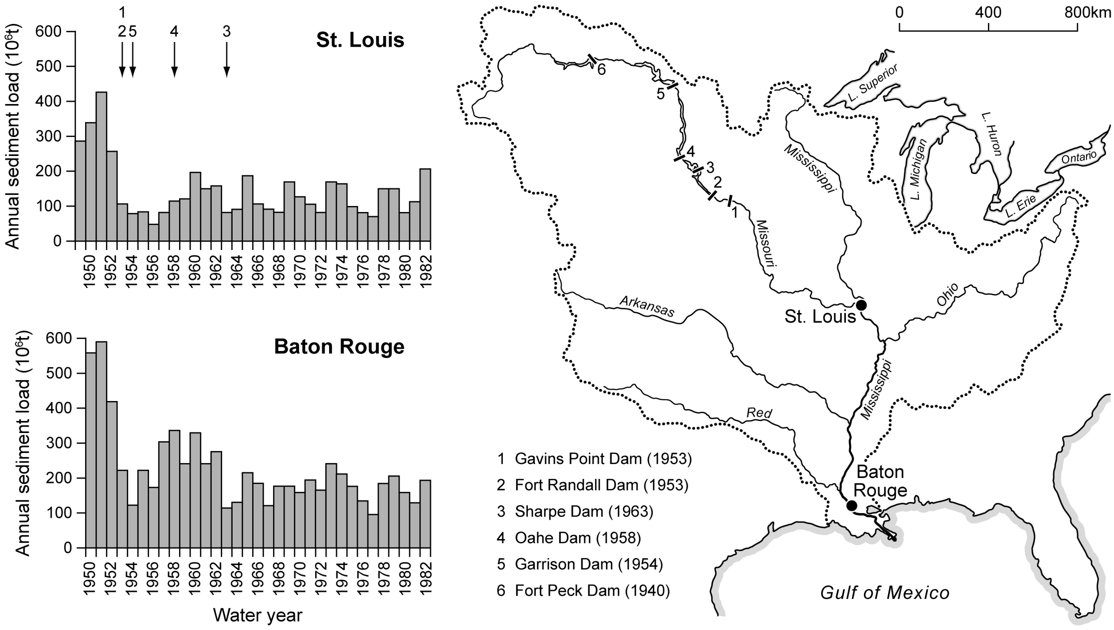

Fig. 6 The location of the major reservoirs on the Missouri River and the impact of their construction on the sediment load of the Missouri and Mississippi rivers, as demonstrated by the records of annual sediment load available for the Mississippi River at St Louis and Baton Rouge.

Mississippi River at St Louis, prior to the construction of the dams, makes it difficult to estimate the mean annual suspended sediment load of the Mississippi River for that period. However, with a mean annual load of approx. 120 Mt year^{-1} after the closure of the dams, it seems likely that most, if not all, of the 155 Mt year^{-1} sequestered behind the dams is directly reflected by the reduction in the load of the river. This in turn means that most of that sediment would previously have reached St Louis. This is not unreasonable, bearing in mind the relatively short distance involved and the heavily managed nature of the river itself, which restricts inundation during flood events and sediment deposition. Looking at the situation downstream at Baton Rouge, the picture is more complex due to sediment inputs from other tributaries, particularly the Arkansas and Red rivers and construction of reservoirs on those rivers. However, there would seem to be clear evidence that sediment sequestered behind the dams on the Missouri River is reflected by a significant reduction in the sediment load of the river and thus that much of the trapped sediment would have previously reached the ocean. In this case, therefore, the estimate of a conveyance loss of 60% applied to the global total appears unreasonably high, although, as indicated previously, this is not unexpected due to the heavily managed nature of the Mississippi and Missouri rivers which restricts deposition and conveyance losses. These findings suggest that use of the value of 40% of the trapped sediment to estimate the magnitude of the reduction in the downstream flux resulting from sediment sequestration by dams could underestimate the magnitude of the reduction.

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 estimated by Syvitski *et al.* (2005) to speculate further on the likely nature of the global sediment budget and the extent to which it has been perturbed by human activity. Syvitski *et al.* (2005) estimate that the contemporary land–ocean sediment flux is 12.6 Gt year^{-1}, and that the contemporary flux in the absence of reservoir trapping would be 16.2 Gt year^{-1}. They also provide an estimate of the pristine flux for the pre-human period of 14 Gt year^{-1}. 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 year^{-1} to 16.2 Gt year^{-1}, with sediment trapping by dams reducing this by approx. 22% to 12.6 Gt year^{-1} (see Table 1). If, following Syvitski *et al.* (2005), it is assumed that that the contemporary land–ocean sediment flux is approx. 12.6 Gt year^{-1}, the estimate of 24 Gt year^{-1} introduced above for the reduction associated with reservoir trapping would mean that the total flux in the absence of reservoir trapping would be approx. 36.6 Gt year^{-1}. Using again the estimate of the pre-human flux provided by Syvitski *et al.* (2005) of 14 Gt year^{-1}, would now suggest that human activity has increased this by 160% to 36.6 Gt year^{-1} and that reservoir trapping has reduced this total by approx. 66% to 12.6 Gt year^{-1} (see Table 1). 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 1 differ substantially. The new estimates developed in this contribution 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.

Table 1 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 in this contribution.

Component	Syvitski *et al.* (2005)	This contribution
Pre-human land-ocean flux (Gt year^{-1})	14.0	14.0
Contemporary land–ocean sediment flux (Gt year^{-1})	12.6	12.6
Reduction in flux associated with reservoir trapping (Gt year^{-1})	3.6	24
Contemporary flux in the absence of reservoir trapping (Gt year^{-1})	16.2	36.6
Increase in pre-human flux due to human activity (%)	22	160
Reduction in contemporary gross flux due to reservoir trapping (%)	16	66

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