The changing suspended sediment loads of the world's rivers and implications for land-ocean sediment fluxes

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Abstract

The sediment loads of rivers are sensitive to changes occurring within their drainage basins and also to climate change and therefore provide a useful indicator of the impact of global change on the functioning of the Earth system. There is a growing body of evidence that the sediment loads of many world rivers are experiencing significant changes and a number of key drivers can be identified. Some of these drivers cause increased loads and others reduced loads and the temporal interaction of the various drivers conditions the resulting trajectory of change. To date it has proved difficult to isolate a clear signal for the impact of climate change relative to other drivers, but there is increasing evidence of its potential importance in the future. Lack of sediment load data for many world rivers and the non-stationary nature of many of the available records make it difficult to quantify the global land-ocean sediment flux and the global sediment budget, as well as the changes occurring. Attempts have been made to establish a global sediment budget and to assess the importance of the perturbation caused by human impacts, but the many uncertainties involved mean that further work is required to produce definitive findings.

1 The Context

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 directed attention to the changes in the functioning of the Earth system caused by human activity. Some have argued that we have now entered a new geological epoch, the Anthropocene, where human activity exerts a dominant influence on the Earth system (see Steffen et al., 2007). Much of this attention has focussed on the increased emission of greenhouse gases, leading to climate change and changes in key geochemical cycles such as the carbon and nitrogen cycles. 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 and land use across the earths surface, wide ranging disturbance of that surface by activities such as infrastructure development and mineral extraction and modification of the hydrological cycle caused by water resource exploitation. Such changes in the surface condition of the earth and the flow of its rivers, as well as ongoing climate change, can be expected to exert a significant influence on the sediment loads of the world's rivers. Sediment loads will be sensitive to both increases and reductions in land erosion caused by human activity, as well as changes in river flows, sediment transport and river network connectivity caused by water resource exploitation, construction of dams and other human uses of river systems. As such they can be seen as representing a sensitive indicator of changes in the functioning of the Earth system.

The significance of changes in the sediment loads of the world's rivers is wide ranging. From a global perspective, changes in land-ocean sediment transfer will result in changes in global biogeochemical cycles, since sediment-asspociated transport is important to the flux of many key elements and nutrients. Equally, sediment loads reflect the intensity of soil erosion and land degradation and thus the longer-term sustainability of the global soil resource. 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, water conveyance systems and harbours, causing problems for water resource development and navigation. Increased fine sediment loads and turbidity can also have important adverse impacts on aquatic habitats and ecosystems, including offshore coral reefs. Conversely, reduced sediment loads can result in the scouring of river channels and erosion of delta shorelines, as well as reduced nutrient inputs to linked aquatic ecosytems, particularly lakes, river deltas and coastal seas.

The temporal trajectories of these anthropogenic impacts on sediment fluxes 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 resulted in changing 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 or even more recently. Nevertheless, the accelerating pace of human impact in many areas of the world means that the changes in the sediment loads of its rivers are likely to be intensifying.

2 The Evidence

The work of researchers such as Walling & Fang (2003), Syvitski et al. (2005), Walling (2006) and Milliman & Farnsworth (2011) has emphasised the sensitivity of river sediment loads to human impact and global change. In Europe, such changes are well illustrated by the reduction in the suspended sediment load of the River Danube at Ceatal-Izmail, Romania, close to its discharge into the Back Sea, over the past 70 years shown in Figure 1. The generalised trend line fitted to the values of annual sediment load indicate that over this period the suspended sediment load of the river reduced by about 70% (see Walling, 2006). The record of annual water discharge for the same period shows little evidence of change. The reduction in sediment load can be linked primarily to the construction of dams on the river and particularly the first Iron Gate dam constructed between 1964 and 1972. This influence is clearly shown by the change in slope of the double mass plot of cumulative sediment load versus cumulative runoff presented in Figure 1, at around this time. A secondary dam was also built downstream of the primary dam and this was completed in 1976. It has been estimated that together these two dams have resulted in the trapping of ca. 20 Mt year^{-1} of sediment.

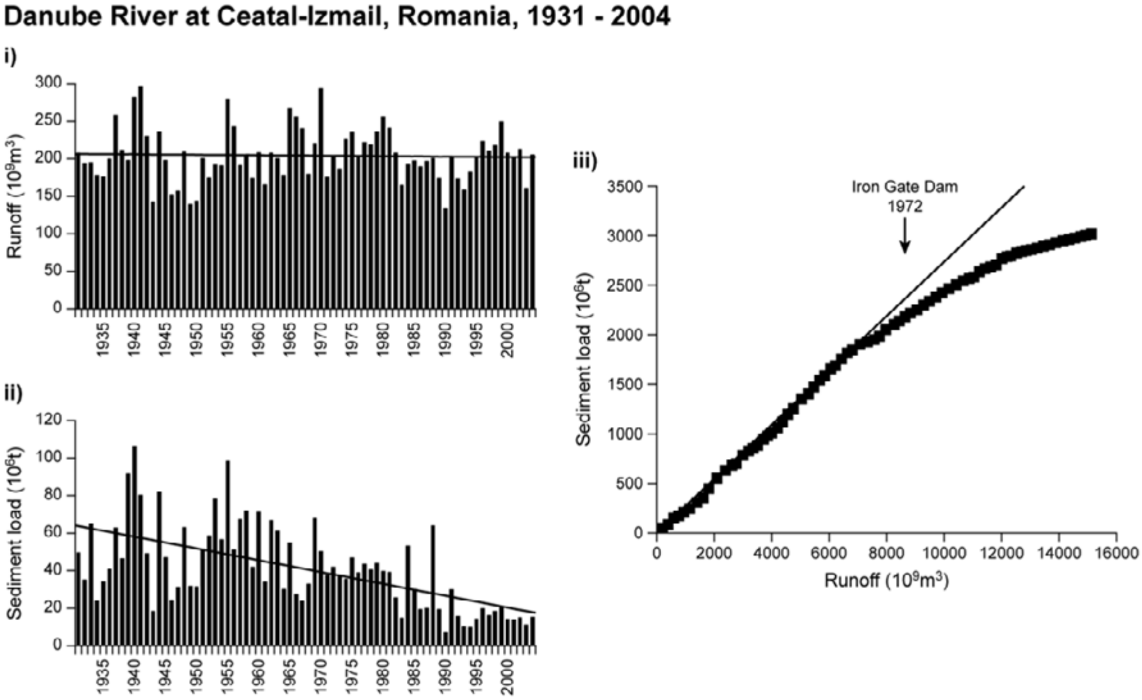

Fig. 1: Recent changes in the suspended sediment load of the River Danube at Ceatal-Izmail, Romania, as demonstrated by the time series of (i) annual water discharge and (ii) annual suspended sediment load, and (iii) the associated double mass plot

Rivers elsewhere in the world also evidence marked changes in their sediment loads. Figure 2 provides a classic example of a river that has shown a major decrease in its sediment load in recent years. It presents information on changes in the annual sediment load of the Yellow River in China over the period 1950–2009, at its lowest gauging station at Lijin, located about 100 km upstream from its delta mouth. The mean annual suspended sediment load of the Yellow River, during the period from the 1950s through to the 1970s, when it was sometimes referred to as the "world's muddiest river" was approx. 1.1 Gt year^{-1}. The Yellow River was frequently cited as having the highest suspended sediment load of all world rivers. However, the sediment load of this river progressive reduced from the 1980s and the mean annual sediment load for the period 2000–2012 was almost an order or magnitude less than that for the period 1950–70 at ~0.15 Gt year^{-1}. This major reduction in sediment load reflects a number of causes, including dam construction, the implementation of soil conservation and sediment control programmes within the middle reaches of the river basin and a reduction in annual rainfall. In this case, the annual runoff also shows a marked decline during the period when the sediment load declined and this can be linked to a reduction in rainfall, implementation of soil and water conservation works, dam construction and increased water abstraction. Other rivers that have experienced major reductions in sediment load include the River Nile, where the mean annual sediment load has reduced from about 120 Mt year^{-1} to approx. 0.1 Mt year^{-1}, after closure of the Aswan Dam in 1964, and the Colorado, Ebro and Volta Rivers, which have evidenced reductions in sediment loads of approx. 100%, 93% and 92%, respectively, over the past approximately 50 years.

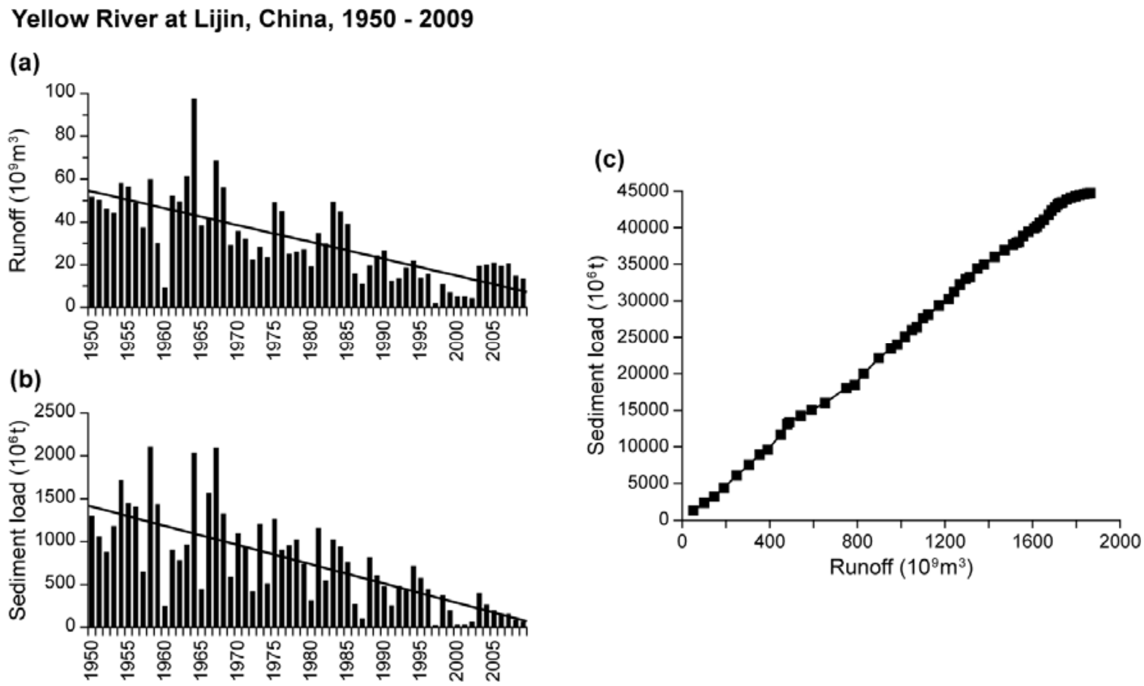

Fig. 2: Recent changes in the suspended sediment load of the Yellow River at Lijin, China, as demonstrated by the time series of (a) annual water discharge and (b) annual suspended sediment load, and (c) the associated double mass plot

Figure 3 provides a contrasting example of where the sediment load of a river has shown a significant increase in recent years. This relates to the Kolyma River in eastern Siberia, which drains to the Arctic Ocean. Here a simple trend line fitted to the records of annual sediment load for the measuring station at Srednekansk, located in the middle reaches of the basin, indicate that the mean annual sediment load increased by about 150% during the latter part of the 20th century, as a result of disturbance of its catchment, and particularly the development of alluvial gold mining (Professor N. Bobrovitskaya, personal communication). The double mass plot suggests that this change began to affect this river in the mid 1950s and continued to intensify up until about 1980, after which there appears to be some reduction in the greatly increased sediment load. The record of annual water discharge shows no significant trend. This is consistent with the above explanation of the increase in sediment load.

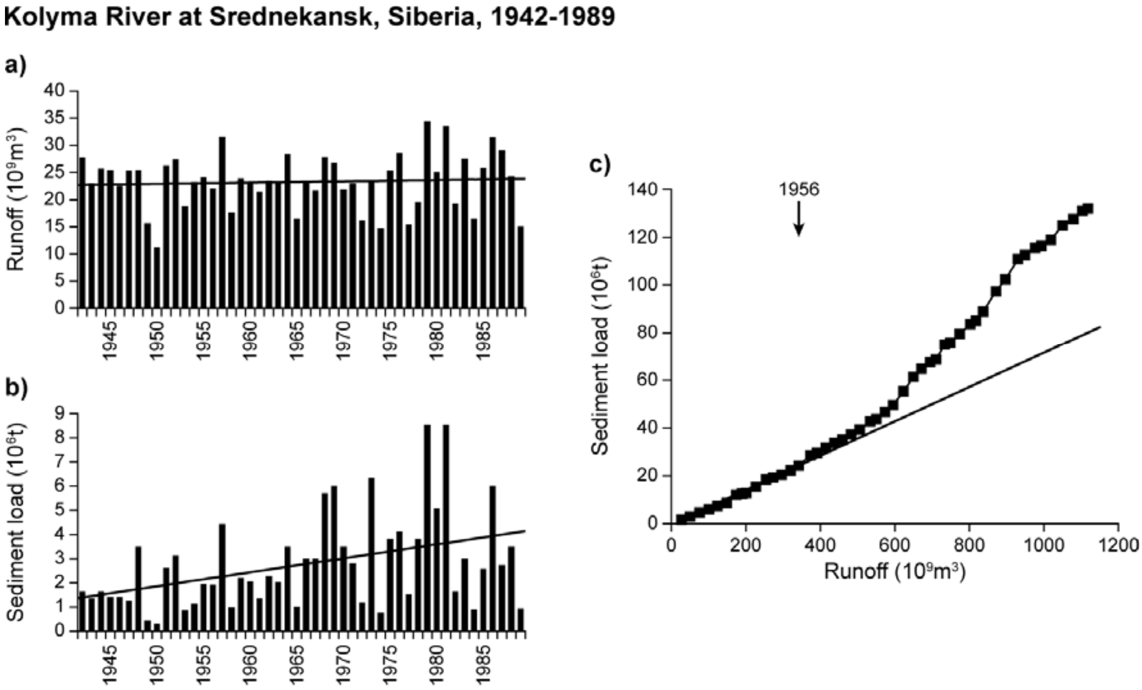

Fig. 3: **Recent changes in the suspended sediment load of the Kolyma River at Srednekansk, Eastern Siberia, as demonstrated by the time series of (a) annual water discharge and (b) annual suspended sediment load, and (c) the associated double mass plot. (Based on data provided by Professor Nelly Bobrovitskaya, State Hydrological Institute, St. Petersburg, Russia)**

Although reliable sediment load records are lacking for many of the world's rivers and the limited length of available records can preclude investigation of longer-term trends, the available data include a considerable number of rivers where the sediment load has changed significantly in recent decades and the primary drivers can be identified. These key drivers are reviewed below.

3 The Drivers of Change

The drivers of change can conveniently be divided into those that result in *reduced* sediment loads and those causing *increased* sediment loads. Dam construction is the primary driver of reduced loads. Sand mining is another important cause of declining sediment loads in many areas of the world and where effective soil conservation and sediment control measures are applied to large areas they can also result in a significant reduction in sediment load. The various aspects of land disturbance, including deforestation, land clearance for agriculture, poor management of agricultural land, mining and mineral extraction, building construction and infrastructure development represent the main cause of increasing sediment loads.

3.1 Dam construction

Many of the world's rivers provide evidence of reduced sediment loads resulting from dam construction. The extreme example of the River Nile, where the sediment load has been effectively reduced to zero, has been cited above. The precise magnitude of the reduction in the sediment load of a river caused by construction of a dam will be influenced by several factors, including the position of the dam within the river basin, the trap efficiency of the associated reservoir and the proportion of the flow withdrawn from storage for use and the nature of that use. The greatest reductions in sediment loads are generally found where the runoff passing through the river system is also reduced due to water abstraction for irrigation and other uses. In the case of the lower Indus River illustrated in Figure 4, the annual runoff is now less than ca. 20% of that prior to the development of the extensive irrigation systems, that commenced in the 1940s with the building of numerous barrages and irrigation channels on the main river and two major dams, the Mangla Dam and the Tarbela Dam, on its upstream tributaries. The current annual sediment load has similarly declined to ca 20% of its previous value (see Milliman et al., 1984; Walling, 2007).

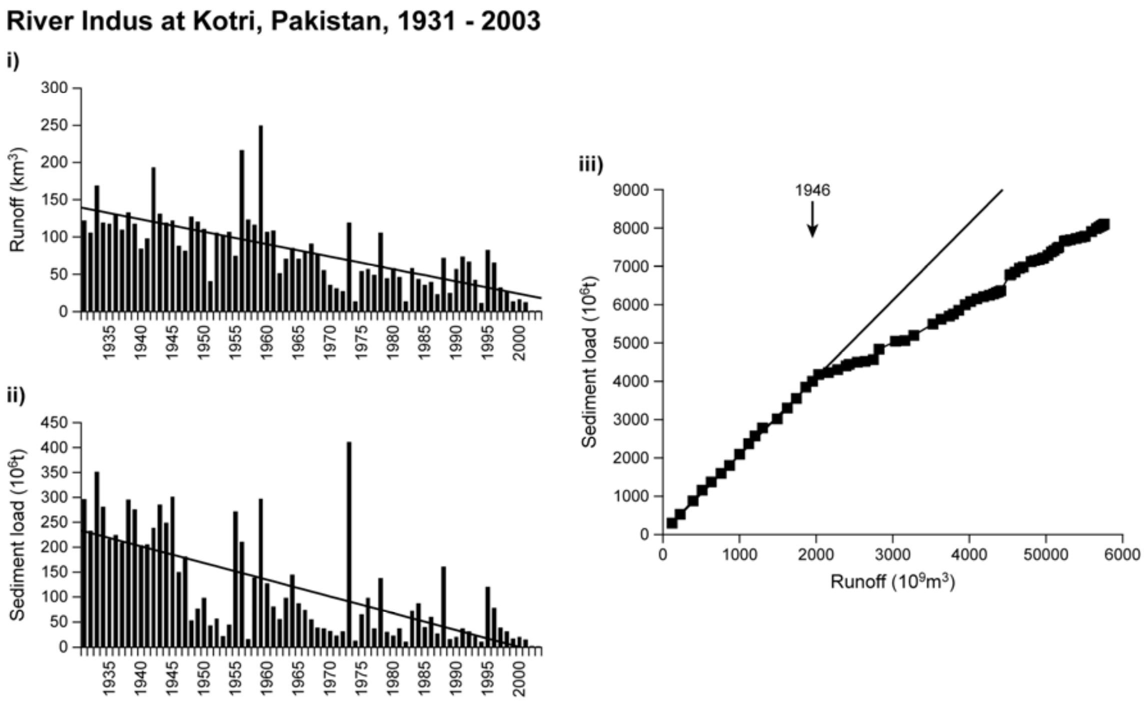

Fig. 4: Recent changes in the suspended sediment load of the River Indus at Kotri, Pakistan, as demonstrated by the time series of (i) annual water discharge and (ii) annual suspended sediment load, and (iii) the associated double mass plot. (Based on data compiled by Professor John Milliman, Virginia Institute of Marine Science, USA)

3.2 Sand Mining

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. However, the extraction of sand from river channels for use in the construction industry may represent a significant loss from the fluvial transport system. When attempting to quantify the impact of sand mining on the sediment load of the river it is important to recognise that in some locations the sediment removed may be coarser than that represented by the measured suspended sediment load. In other situations it may not have been in active transport, if, for example, it was extracted from the alluvial fill of a valley floor. However, in many situations it will represent part of the contemporary sediment load. 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 licence. However, a useful indication of the potential importance of this driver is provided by data relating to the Middle and Lower Yangtze basin in China. Chen et al. (2006) report that in-channel sand extraction developed as an important industry in this region since the late 1980s, with individual dredgers being capable of removing up to 10000 t day^{-1}. These authors estimate that the total quantity of sediment extracted could have reached as much as 80 Mt year^{-1} in the late 1990s. Wang et al. (2007a) suggest that as much as 110 Mt year^{-1} was being extracted from the entire Yangtze. The magnitude of these estimates serves to demonstrate the potential impact of sand mining on the sediment load of the Yangtze River. Chen (2004) indicates that along with soil conservation and sediment control programmes and sediment trapping by dams, sand mining was an important cause of the progressive reduction of the suspended sediment load of the Lower Yangtze River during the latter part of the 20th century and prior to the further reduction caused by the closure of the Three Gorges Dam. During that period, the mean annual suspended sediment load progressively reduced from ca. 500 Mt year^{-1} during the 1960s and 1970s to ca. 200 Mt year^{-1} at the beginning of the current century.

3.3 Soil Conservation and Sediment Control Programmes

Land use impacts are commonly seen as causing increased sediment loads. 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. Soil and water conservation programmes have a history stretching back more than 70 years and are being increasingly adopted in many areas of the world to promote sustainable use of the soil resource. Recent concern for the detrimental impacts of fine sediment on aquatic and marine ecosystems has provided another reason for promoting erosion and sediment control. Such programmes are being widely implemented in many countries including Europe, North America and Australia. This potential driver of reduced sediment loads must be assuming increasing importance. For example, Uri and Lewis

(1999) indicate that the widespread implementation of soil conservation measures and other financial incentives for land use change introduced by the Food Security Act of 1985 reduced the total erosion from U.S. cropland from 3.4 Gt year^{-1} in the early 1980s to 2.0 Gt year^{-1} in the latter half of the 1990s. Although the literature provides many examples of plot and small catchment experiments, which clearly demonstrate success in reducing local soil loss and sediment yields, there is currently only limited quantitative evidence of the impact of such measures in reducing the sediment fluxes from larger river basins.

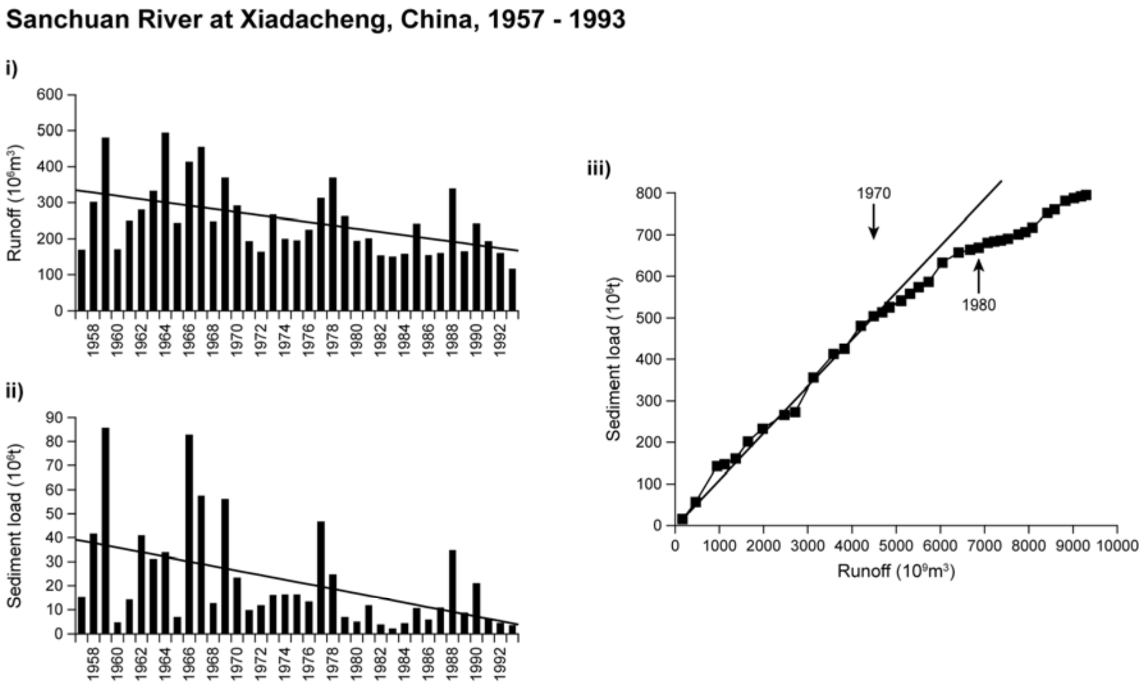

Fig. 5: Changes in the suspended sediment load of the Sanchuan River, China, as demonstrated by the time series of the annual suspended sediment load (i) and annual water discharge (ii) and the associated double mass plot (iii)

However, convincing evidence of the potential impact of such activities in larger river basins is now available from 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. Figure 5 presents information on the changing sediment response of 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 nearly 30% of the basin area was actively controlled. Figure 5 shows a significant (P> 99%) decrease in both runoff and sediment load over the period of record and the double mass plot suggests that this impact commenced around 1970 and intensified after 1980. Over the period of record, the sediment load decreased to about 25% of its original value. 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 itself responsible for reducing the sediment load of the Sanchuanhe basin by between 36 and 41%. The impact of applying similar soil conservation and sediment control measures over an even wider area is demonstrated by the sediment load of the main Yellow River, with a basin area of 752 500 km^2, where the annual sediment load has decreased by almost an order of magnitude since the 1970s (see Fig. 1). Again some of this reduction can be attributed to climate change and trapping of sediment by larger dams is also important, but Wang et al. (2007b) have estimated that of the order of 40% of the reduction in the sediment load of the Yellow River can be attributed to the implementation of soil conservation measures.

3.4 Land Clearance and Catchment Disturbance

The impact of deforestation, land clearance for agriculture, intensification of agriculture and related activities on sediment yields is well known. In some areas of the world such increases in sediment load will have occurred many centuries, or even millennia ago, and the associated increase will not be directly reflected by contemporary sediment load records. Equally, in developing countries, where land use change and intensification and related disturbance associated with mining and infrastructure development have occurred much more recently, long-term sediment monitoring programmes are frequently absent. As a result 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. However, the available evidence again emphasises the potential importance of this driver. Figure 3 presented data from the Kolyma River in Siberia which showed that the sediment load had more than doubled during the second half of the 20^{th} century. Walling (2006) also cites the example of the Rio Magdalena River in Columbia, which drains a catchment of ca. 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 mining activity within the river basin. A more extreme example of the magnitude of the increase in response disturbance 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. 6). 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.

The importance of surface disturbance by 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 ca. 10 Mt year^{-1} showed a marked increase in the late 1980s and early 1990s as a result of mining activity (Markham & Day, 1994). Much of the basin of the Fly River remains pristine, but, beginning in 1985, ca. 60 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 floodplain of the Fly River, downstream of its confluence with the Ok Tedi River. However, approx imately 40% 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 from ca 10 Mt year^{-1} to ca. 35 Mt year^{-1}. The total sediment input to the ocean by the combined Fly-Strickland River system under natural conditions has been estimated to be ca. 80 Mt year^{-1}, and this was increased by about 50% to 120 Mt year^{-1}, as a result of the waste discharge from the Ok Tedi mine.

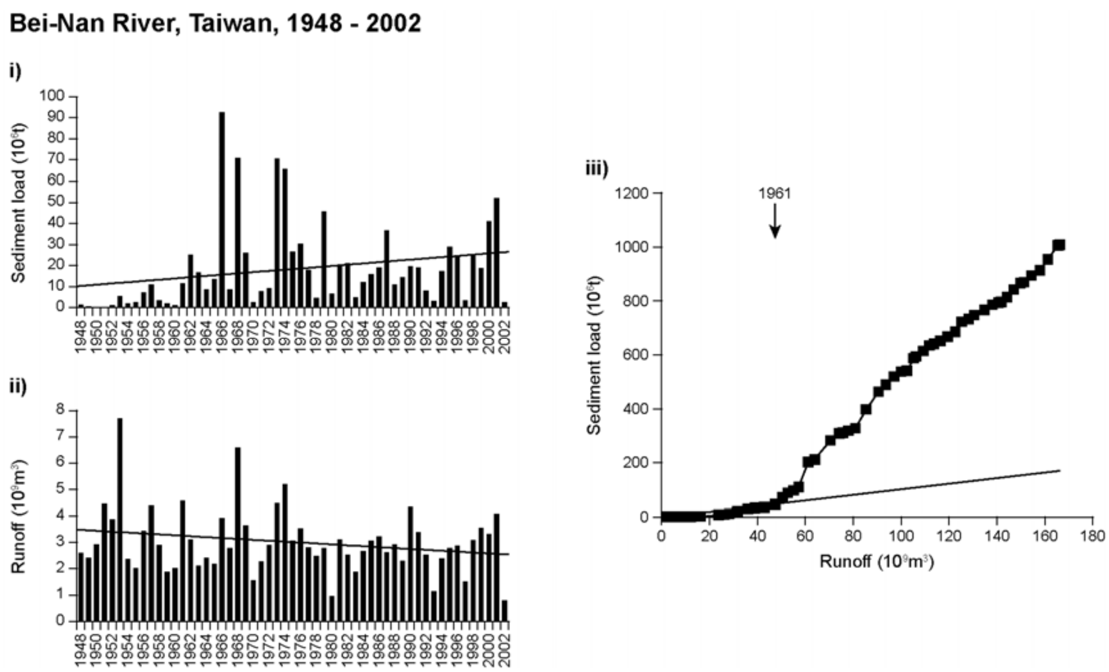

Fig. 6: Recent changes in the suspended sediment load of the Bei-Nan River, Taiwan, as demonstrated by the time series of the annual suspended sediment load (i) and annual water discharge (ii) and the associated double mass plot (iii)

3.5 Climate Change

Most of the examples of recent changes in the annual sediment loads of the world's rivers cited above are linked to specific anthropogenic impacts, such as catchment disturbance and dam construction. There are as yet few clear examples of the impact of climate change on annual 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 direct human impacts are at present likely to be more significant as a cause of recent changes in sediment load. Lu et al. (2013) report an analysis of the recent changes in the sediment loads of the eight major rivers of China draining to its coast, aimed at assessing the relative importance of climate change to the overall change demonstrated by their sediment loads. The change in the sediment load was assessed by comparing the mean annual sediment load for the period 1950–1990 with that for 1991–2007. The results of this study presented in Table 1 demonstrate that all the rivers show changes in their sediment loads over the period considered. All the rivers show a decline except for the Songhuajiang, located in the northeast of the country. In most cases the change due to change in the precipitation regime is relatively small and for six out of the ten rivers it contributes less than 11% of the overall change.

Table 1: The change in the annual suspended sediment loads of eight major Chinese rivers between 1859-90 and 1991-2007, the change ascribed to the changing precipitation regime and the change ascribed to change in the precipitation regime as a proportion of the total change. (Based on Lu et al., 2013)

River	Total Change (%)	Change due to Precipitation (%)	Proportion of total change (%)
Songhuajiang	+29	-12	42
Lioahe	-55	-34	61
Haihe	-100	-4	4
Huanghe (Yellow)	-72	-3	4
Huaihe	-56	+3	5
Chanjiang (Yangtze)	-29	0	0
Minjiang	-56	+6	10
Zhujiang	-26	+3	11

Despite the difficulty of isolating the impact of climate change, there is a growing body of evidence that climate change must increasingly be seen as a potentially important driver of changing sediment fluxes. For example, Kao et al. (2011) emphasise how global warming can be seen as causing increases in both the frequency of typhoons hitting Taiwan and the intensity of the associated rainfall. In mountain environments such as Taiwan, typhoons are associated with both high amounts of flood runoff and high flood discharges, as well as an increased incidence of landslides, and together these result in increased sediment mobilisation and transport. Kao et al (2011) provide evidence that the island-wide export of sediment from the island of Taiwan has increased significantly over the past 50 years. This parallels an increase in the frequency of typhoons, which clearly contributes to the increased sediment loads, but human impact, linked to land clearance, road development etc. must also be important, as shown by the example of the Bei-Nan river presented in Figure 6 above. A contrasting example is provided by the assessment of trends in the annual sediment load of the rivers of Peninsula India presented by Panda et al. (2011). Here the majority of the rivers showed strong evidence of declining sediment yields. In many cases this trend could be attributed to sediment trapping by dams and possibly the success of soil conservation programmes. However, the widespread evidence of reduced sediment loads was also linked to declining annual precipitation across the region, and thus a change in the rainfall regime.

4 The Temporal Perspective

It is important to recognise that the recent changes in suspended sediment load which have been reported above for a range of rivers represent only a very short snapshot of the longer-term trajectory of change that will have affected most rivers. The timeframe of these trajectories will have varied in different areas of the world. Whereas some river basins may be responding to land clearance, logging, land use change and other forms of land disturbance at present, in other river basins such changes may have occurred decades or even centuries previously. The lack of long-term records of sediment load for most rivers means that it is not possible to document such past changes, unless surrogate data are available. Equally, the opposing effects of human activity, leading to both increases and reductions in sediment loads may interact, possibly cancelling each other out in some river basins, depending on their temporal trajectories. A useful example of this longer-term temporal perspective is provided by Figure 7, which presents a tentative reconstruction of the long-term record of the sediment load transported by the Lower Yellow River at Lijin in China. The reconstruction is based on the work of Saito et al. (2001), Milliman et al. (1987) and others, which makes use of dated sediment cores from both a wide area of the North China Plain and the Yellow River Delta and from offshore sediment deposits, to reconstruct the past variation of the sediment load of the river. This evidence suggests that prior to approximately 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 two factors. Firstly the effects of forest clearance and the expansion of agriculture, linked to a growing population, resulted in increased erosion and sediment mobilisation. Secondly, the progressive stabilisation and control of the course of the Lower Yellow River by levees, restricted the widespread deposition formerly 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. The subsequent decline in sediment load since the 1980s has been discussed above and reflects the combined effect of reservoir construction, water abstraction, soil and water conservation programs within the loess region, and a trend towards a drier climate. Interestingly, Figure 7 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, has restored the load to a magnitude similar to that existing several millennia ago, prior to major human impact. 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, to the extent that the river was reported to have 'dried up' for extended periods in the 1990s. Construction of the Xiaolangdi reservoir completed in 2001 upstream of the lower reaches on the river provided the potential to regulate flows and this problem has been overcome. For other rivers, the precise relationship between recent changes and longer-term changes will depend on the history of anthropogenic impact on the sediment load of the river and the nature and intensity of recent impacts.

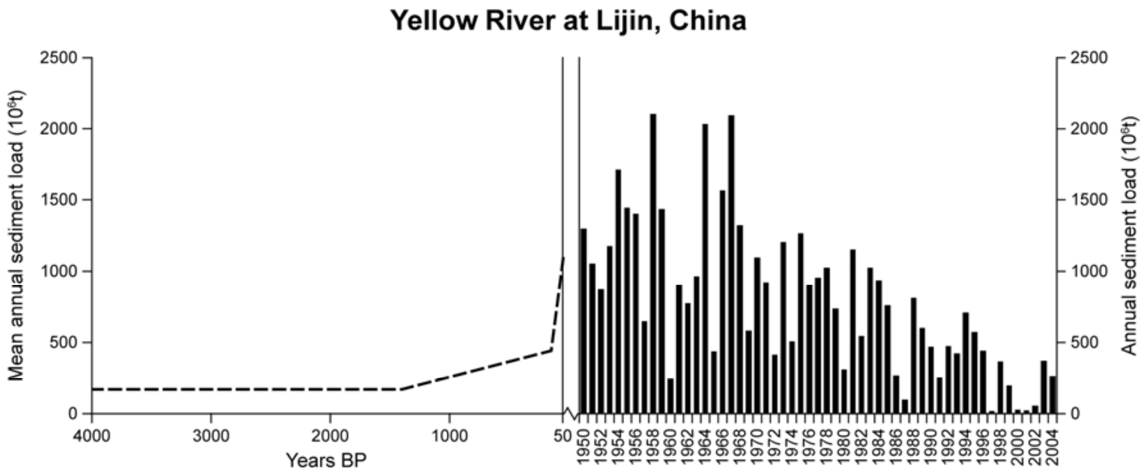

Fig. 7: A tentative reconstruction of the longer-term trend in the suspended sediment load of the Lower Yellow River over the past 6000 years, using information presented by Milliman et al. (1987), Saito et al. (2001), and Xu (1998)

Generalising available information on the key drivers of changes in the sediment loads of the world's rivers and considering available information on the temporal trajectory of such changes, Walling (2011) has proposed a simple schematic model of the likely trajectory of change. This is shown in Figure 8. A river's precise position on this curve will depend on the stage of development of its basin and thus the relative importance of different human impacts. Some basins where development is in a relatively early stage could be seen as being located on the rising limb of the curve. Here the increases in sediment loads associated, for example, with land clearance, the expansion of agriculture and settlements and related infrastructure will dominate and sediment loads are likely to be increasing. Other basins will be in a later stage of development, where dam construction and soil conservation and sediment control programmes become important and these will fall on the declining limb of the curve. Since dam construction on a large scale effectively only began in the 1950s, this constrains the timing of the declining limb of the trajectory. Similarly, widespread soil conservation works and sediment control programmes must be seen as a feature of the second part of the late 20th century the early 21st century, thereby imposing a similar timing constraint. The key elements of the schematic model illustrated in Figure 8 are demonstrated by the available information on changes in the sediment load of the Pearl River in southern China. The Pearl River comprises three main tributaries, with the Xijiang or West River (351,500 km^2 above Gaoyao) accounting for ca. 80% of its basin area. The records of water and sediment discharge for the Xijiang tributary at Gaoyao are shown in Figure 9 and can be seen as demonstrating the interaction of several human impacts with different temporal trajectories. The sediment loads evidence a well-defined and statistically significant (P = 90%) increase over the period extending from the late 1950s to the late 1980s, in response to population growth, land clearance, land use intensification and other facets of land disturbance. The lack of records or available proxy information prevents extrapolation further back in time than the late 1950s, but it would seem likely that the sediment load of the river had already increased above the 'natural' background level at that time, due to human impact, but it is not possible to quantify this background sediment load. However, since the early 1990s, the sediment load of the Xijiang River has shown a significant (P = 90%) decline which can be related to dam construction, the implementation of soil conservation programmes and sand mining activities. Commissioning of the Yantan Dam in 1992 exerted a major influence on the downstream sediment load of the Xijiang River, since this dam controls 37% of the catchment area, which in turn formerly generated more than 60% of the long-term sediment flux (Dai et al., 2008). Dai et al. (2008) suggest that the impact of soil conservation works was of very limited importance. The water discharge records for Gaoyao show no evidence of a clear trend, although Zhang et al. (2008) suggest that there was some decrease in runoff in the headwater areas and a balancing increase in runoff in the downstream areas during this period, due to climate change.

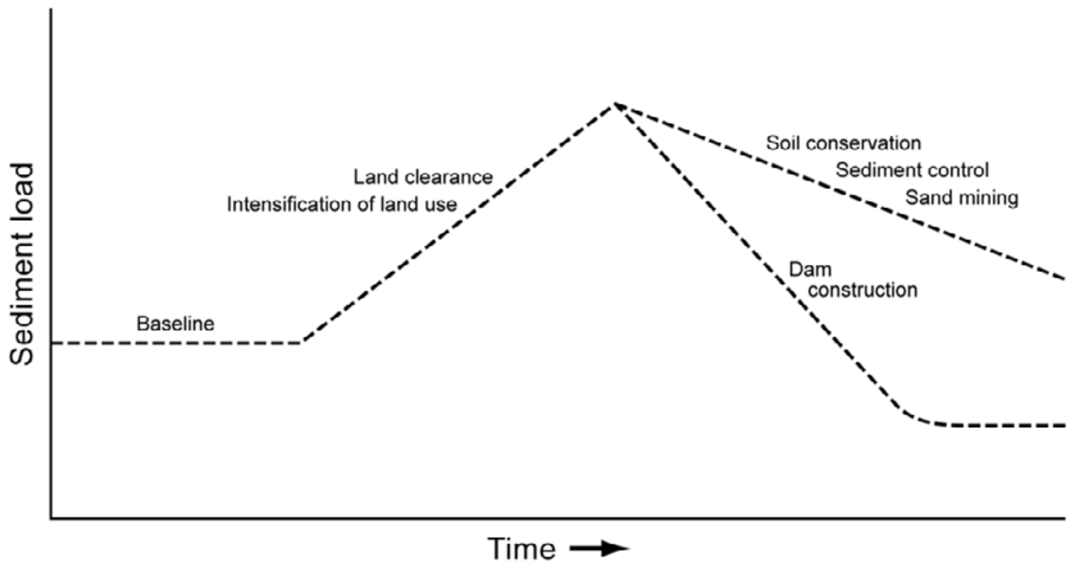

Fig. 8: **A schematic representation of the temporal pattern of human impact on the sediment load of a river**

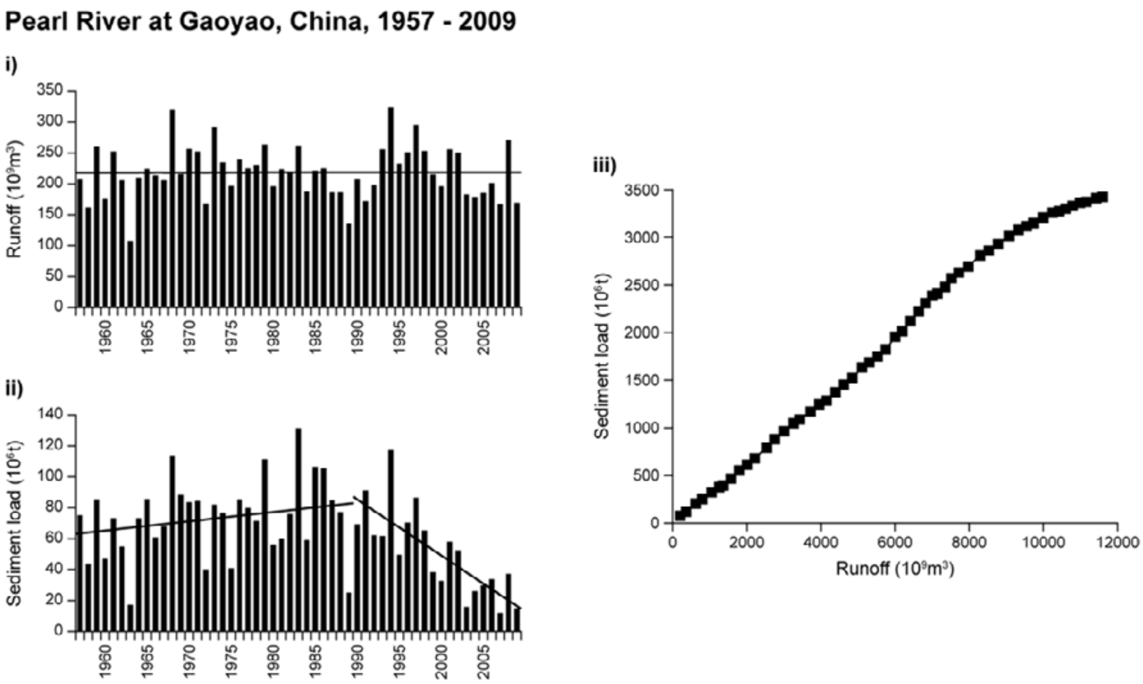

Fig. 9: **Recent changes in the suspended sediment load of the Pearl River at Gaoyao, China, as demonstrated by the time series of annual water discharge (i) and annual suspended sediment load (ii) and the associated double mass plots (iii)**

5 Implications for Global Land-Ocean Sediment Fluxes

It is important to consider the implications of the above information on the changing sediment loads of the world's rivers for global land-ocean sediment transfer and the global sediment budget, since this budget represents a key component of the Earth system. Syvitski et al. (2005) have presented an important attempt to quantify the contemporary global sediment budget and to speculate regarding the extent to which it has been perturbed by human activity. They estimate that the contemporary land–ocean sediment flux is 12.6 Gt year^{-1}, and that dams are currently trapping ca, 3.6 Gt year^{-1}. The value of 3.6 Gt year^{-1} was based on extrapolating the available sediment load data using simple, lumped prediction models incorporating climatic and physiographic variables. These were used to estimate that the "pre-human" global land–ocean sediment flux was ~14 Gt year^{-1}, whereas the modern flux, which reflected the impact of sediment trapping by dams, was 12.6 Gt year^{-1}. By comparing pre- and post-dam load data for a range of rivers, they estimated that large dams were responsible for trapping ~20% of the annual flux and that when the millions of smaller dams were added this figure increased to 26%. Syvitski et al. (2005) estimated that the reduction in sediment load due to trapping by dams represented 26% of the pre-human flux (i.e. 3.6 Gt year^{-1}). This means that the contemporary flux in the absence of reservoir trapping would be 16.2 Gtyear^{-1}. Using these values, human activity is seen as having increased the global land–ocean sediment flux by about 2.2 Gt year^{-1} (16%), with sediment trapping by dams reducing this by approx. 22% to 12.6 Gt year^{-1} (see Table 2). These values suggest that the degree of perturbation of the global sediment budget is limited. However, it is possible to question the budget presented by Syvitski et al. (2005) and to suggest that the degree of perturbation may be considerably greater.

Table 2: The global sediment budget as proposed by Syvitski et al. (2005) and an alternative budget

Budget Component (Gt year^{-1})	**Syvitski et al. (2005)**	**Alternative Estimate**
Pre-human Land – Ocean sediment flux	14.0	10
Contemporary Land-Ocean sediment flux	12.6	12.6
Reduction in flux due to reservoir trapping	3.6	24.0
Contemporary flux without reservoir trapping	16.2	36.6
Increase over pre-human flux due to human impact	2.2	26.6

Walling (2012) has used the global assessment of reservoir sedimentation undertaken by the ICOLD Reservoir Sedimentation Committee and reported by Basson (2008) to produce an alternative, although perhaps extreme, estimate of the contemporary trapping of sediment behind dams. The survey reported by Basson (2008) was based on the approximately 33 000 dams included in the ICOLD World Register of Dams and incorporated information on the annual reduction in reservoir storage reported by individual countries. Such data, as depicted in Figure 10, indicate an annual average storage loss of 0.96%, and Basson (2008) provided a best estimate for the global reduction of storage of 0.8% year^{-1}. 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 sediment sequestration of ~60 Gt $year^{-1}$. This value is more than an order of magnitude greater than the estimates of the reduction in land–ocean sediment flux due to reservoir trapping reported by Syvitski et al. (2005) (3.6 Gt $year^{-1}$). It is also about four times greater than the annual land–ocean sediment flux in the absence of reservoir trapping suggested by those workers. Since the ICOLD register may not include all dams that should be considered and it does not include the multitude of smaller dams that will also sequester sediment, the value of ~60 Gt $year^{-1}$ could represent an underestimate.

It is important to consider the apparent discrepancy between the estimate of the current rate of sediment sequestration in the world's reservoirs of ~60 Gt $year^{-1}$ and the estimate of the reduction in the global annual land–ocean sediment flux of 3.6 Gt $year^{-1}$ The values differ by more than an order of magnitude. Some of this difference may reflect errors and uncertainties in the calculations. In the case of the estimate of sediment sequestration in reservoirs, for example, the use of a mean rate of storage loss of 0.8% $year^{-1}$ as representative of all reservoirs is clearly a gross oversimplification. Use of alternative values of bulk density would also influence the result. Equally, the lack of long-term sediment load data for many rivers introduces important problems in attempting to extrapolate the available data in both space and time, in order to establish the reduction in annual land–ocean sediment flux caused by sediment trapping behind dams. However, it is also important to recognise that the two contrasting estimates present different measures of the global sediment budget. The former represents the total amount of sediment sequestered behind dams and the latter represents the reduction in downstream sediment flux resulting from sediment trapping by dams. Much of the sediment now stored behind dams would not have previously reached the oceans, due to deposition and storage within the river system, and particularly on river flood plains. As a result, it cannot be viewed as equivalent to the reduction in land-ocean flux. Existing understanding of the conveyance losses associated with the transfer of sediment through river systems suggest that these are likely to be of the order of 40–60% (see Walling, 2011). However, even if such conveyance losses were assumed to be of the order of 60%, this would mean that dams are responsible for reducing the global land–ocean sediment flux by ~24 Gt $year^{-1}$. This value is more than six times greater than that suggested by Syvitski et al. (2005) cited above. Some support for an increase in the magnitude of the estimate of the reduction in the annual land–ocean sediment flux might, however, be found in the relatively small increase of the contemporary sediment flux without reservoir trapping over the "natural" or "pre-human" sediment flux proposed by Syvitski et al. (2005). This was of the order of 2.2 Gt $year^{-1}$ and seems likely to greatly underestimate the role of land disturbance and accelerated soil erosion in increasing sediment flux. If this value is increased, it must be balanced by an increase in the amount of sediment trapped by dams to conform to the modern sediment flux. Walling (2011) has suggested that in many Asian Rivers the sediment loads increased significantly in the recent past as a result of land clearance and intensification of agriculture, and that this substantial increase has been offset by increased sediment trapping by dams. Further work is clearly required to reconcile these apparent contradictions related to the role of reservoir trapping in the global sediment budget.

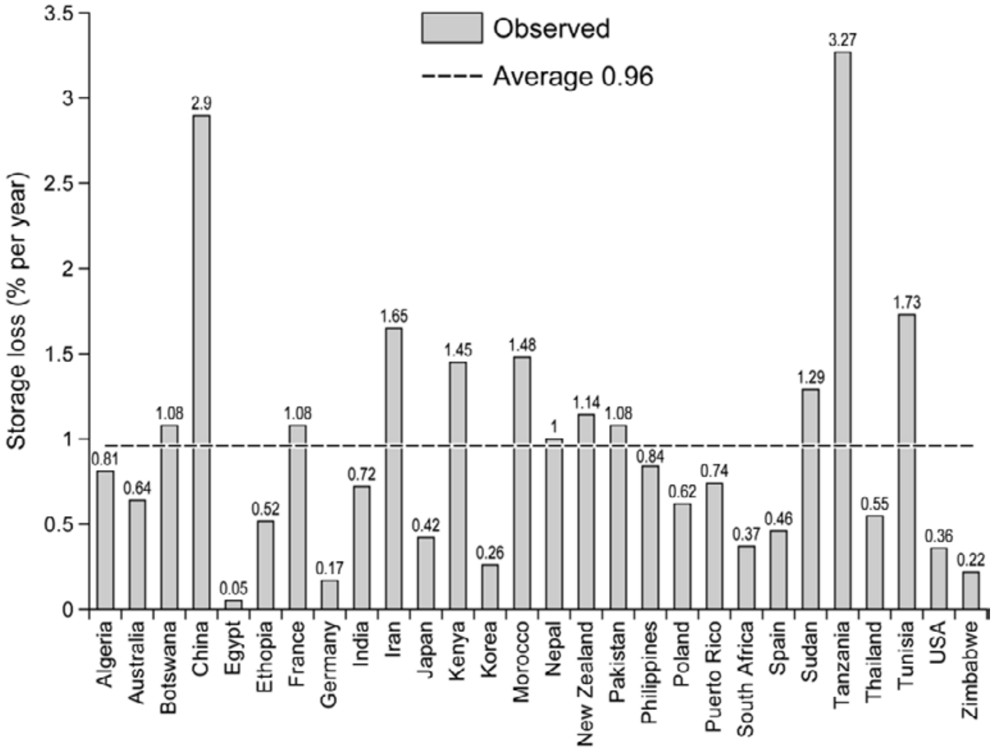

Fig. 10: A compilation of annual rates of storage loss documented for large dams in different countries, based on Basson (2008)

An 'alternative' global sediment budget is also presented in Table 2, in order to demonstrate the potential implications of a greatly increased estimate of the amount of sediment currently being sequestered behind dams. For this budget, the value of 12.6 Gt year^{-1} proposed by Syvitski et al. (2005) for the contemporary land-ocean sediment flux has been retained. Since it can be suggested that the estimate used by those authors for the pre-human sediment flux of 14 Gt year^{-1} is too high, this value has been reduced to 10 Gt year^{-1}, in view of the wide-ranging evidence that human activity such as forest clearance and cultivation greatly increased sediment yields and that such activities have been widespread across much of the land surface of the globe. Combining these two estimates with the alternative estimate of sediment trapping by dams of 24 Gt year^{-1}, results in an estimate of the contemporary sediment flux in the absence of reservoir trapping of 36.6 Gt year^{-1} and an estimate of the increase of the contemporary sediment flux in the absence of reservoir trapping over the pre-human flux of 30.6 Gt year^{-1}. Inclusion of these alternative estimates in Table 2 suggests that the perturbation of the global sediment budget by human activity could be far greater than suggested by Syvitski et al. (2005). Further work is clearly required to explore this further.

6 Conclusion

Any attempt to assess the magnitude of recent changes in the sediment loads of the world's rivers is heavily dependent on data availability. Records of sediment load are unavailable for many rivers and many of the records that are available are of short duration making it difficult to assess change. In addition, it is necessary to recognise that in some areas of the world human activity will have begun to change the sediment loads of rivers several millennia ago. However, the available records provide clear evidence that the sediment loads of many of the world's rivers are changing. In some cases they are increasing and in others they are decreasing. A number of key drivers can be identified and these have been explored further in this contribution. When a temporal dimension is added, it is possible to propose a simple schematic model of changing sediment loads, which will be applicable to many rivers. This involves in initial increase in sediment load in response to land disturbance (e.g. forest clearance and the expansion of agriculture), followed by a reduction caused by dam construction the implementation of soil and water conservation and sediment control programmes and possibly sand mining. The pattern of current change shown by the sediment loads of different rivers will reflect their current position along this trajectory. The lack of sediment load data for many world rivers, as well as the markedly non-stationary nature of the available records make it difficult to estimate past and present land-ocean sediment fluxes, and the global sediment budget. However, attempts have been made to establish a global sediment budget and to assess the degree to which this has been perturbed by human activity. Many uncertainties are involved, particularly in terms of establishing the amount of sediment sequestered behind dams and incorporating the temporal dimension. Further work on this topic is clearly required.

7 References

Basson, G. R. (2008): Reservoir sedimentation – an overview of global sedimentation rates and predicted sediment deposition. In: Erosion, Transport and Deposition of Sediments (Abstracts CHR International Workshop Berne, Switzerland, April 2008), pp. 74–79.

Chen, X., (2004): Sand extraction from the mid-lower Yangtze River channel and its impacts on sediment discharge into the sea. Proceedings, 9th International Symposium on River Sedimentation. Vol. 3, pp. 1699-1704.

Chen, X., Zhou, O. & Zhang, E. (2006): In-channel sand extraction from the Mid-Lower Yangtze channels and its manaqgement problems and challenges. J. Environ. Plann. Man. 49, 309-320.

Dai, S.B., Yang, S.L. & Cai, A.M. (2008): Impacts of dams on the sediment flux of the Pearl River, southern China. Catena 76, 36-43.

Kao, S-J., Lee T-Y. & Milliman, J.D. (2005): Calculating highly fluctuated suspended sediment fluxes from mountainous rivers in Taiwan. Tao 16, 653-675.

Kao, S-J., Huang, J.C., Lee, T.Y., Liu, C.C. & Walling, D.E. (2011): The changing rainfall-runoff dynamics and sediment response of small mountainous rivers in Taiwan under a warming climate. In: Sediment Problems and Sediment Management in Asian River Basins (ed. by D.E. Walling), pp.114-129, IAHS Pub.349, IAHS Press, Wallingford, UK.

Lu, X.X., Ran, L.S., Liu, S., Jiang, T., Zhang, S.R. & Wang, J.J. (2013): Sediment loads response to climate change: A preliminary study of eight large Chinese rivers. Int. Journal of Sediment Res. 28, 1-14.

Markham, A. & Day, G. (1994):. Sediment transport in the Fly River basin, Papua New Guinea. In: Variability in Stream Erosion and Sediment Transport. (Proc. Canberra Symp.), pp. 233-239, IAHS Publ.224, IAHS Press, Wallingford, UK.

Milliman, J.D. & Farnsworth, K.L. (2011): River Discharge to the Coastal Ocean: A Global Synthesis. Cambridge, 384 pp.

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

Milliman, J.D., Quraishee, G.S. & Beg, M.A.A., (1984): Sediment discharge from the Indus River to the Ocean: Past, present and future. In: Marine Geology and Oceanography of Arabian Sea and Coastal Pakistan (ed. by B.U. Haq & J.D. Milliman) pp. 65-70, Van Nostrand Rheinhold, New York.

Panda, D.K., Kumar, A. & Mohanty, S. (2011): Recent trends in sediment load of the tropical (Peninsular) river basins of India. Global Planet. Change 75, 108-118.

Restrepo, J.D., Kjerfve, B., Hermelin, M. & Restrepo, J.C. (2006): Factors controlling sediment yield in a major South American drainage basin: the Magdalena River, Colombia. J. Hydrol. 316, 213-232.

Saito, Y., Yang, Z. & Hori, K. (2001): The Huanghe (Yellow River) and Changjiang (Yangtze River) deltas: a review on their characteristics, evolution and sediment discharge during the Holocene. Geomorphology 41, 219-231.

Steffen, W., Sanderson, A., Tyson, P., Jager, J., Matson, P., Moore, B., Oldfield, F., Richardson, K., Schellenhuber, H.J., Turner, B.L. & Wasson, R.J. (2004): Global Change and the Earth System: A Planet under Pressure. Springer-Verlag.

Steffen, W., Crutzen, P.J.and McNeill, J.R. (2007): The Anthropocene: Are humans now overwhelming the great forces of nature. Ambio 36, 614-621.

Syvitski, J. P. M., Vörösmarty, C., Kettner, A. J. & Green, P. (2005): Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science 308, 376–380.

Uri, N.D. & Lewis, J.A. (1999): Agriculture and the dynamics of soil erosion in the United States. J. Sustain. Agric. 14, 63-82.

Walling, D.E. (2006): Human impact on land-ocean sediment transfer by the world's rivers. Geomorphology 79, 192-216.

Walling, D.E. (2007): Global change and the sediment loads of the world's rivers. In: Proceedings of the Tenth International Symposium on River Sedimentation, Moscow, August, 2007, Vol. 1, pp. 112-130.

Walling, D.E. (2011): Human impact on the sediment loads of Asian rivers. In: Sediment Problems and Sediment Management in Asian River Basins (ed. by D.E. Walling), 37-51. IAHS Pub.349, IAHS Press, Wallingford, UK.

Walling, D.E. & Fang, X. (2003) Recent trends in the suspended sediment loads of the world's rivers. Global and Planetary Change 39, 111-126.

Wang, Z., Li, Y & He, Y. (2007a) Sediment budget of the Yangtze River. Water Resour. Res. 43, DOI 10.1029/2006WR005012

Wang, H. Yang, Z., Saito, Y., Liu, J.P. & Xiaoxia, S. (2007b) Stepwise decreases of the Huanghe (Yellow River) sediment load (1950-2004): Impacts of climate change and human activities, Global Planet. Change 57, 331-354

Zhang, S., Lu, X.X., Higgitt, D.L., Chen, C-T. A., Han, J. & Sun, H. (2008) Recent changes in the water discharge and sediment load in the Zhujiang (Pearl River) Basin, China. Global and Planetary Change 60, 365-80.

Zhao, W., Jiao, E., Wang, G. & Meng, X. (1992) Analysis on the variation of sediment yield in the Sanchuanhe river basin in 1980s. Internat. J. Sediment Res. 7, 1-19.

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