Human impact on the sediment loads of Asian rivers

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Abstract The suspended sediment load of a river exerts a key influence on its aquatic ecology, its morphology and the exploitation of its water resources. Changes in the sediment loads of rivers can therefore have wide-ranging environmental and social and economic consequences. There is growing evidence that the sediment loads of many Asian rivers have changed significantly in recent years. Some have increased, whereas others have decreased. It is important that such changes should be seen in a longer term context. Although climate change is increasingly seen as a cause of changing sediment loads, human impact is generally recognised to be the key cause. The key drivers of these changes can be grouped into those causing increases and those causing decreases. The former include land clearance, land-use activities and other forms of catchment disturbance. The latter include sediment trapping by dams, soil conservation and sediment control programmes, and sand extraction from river channels. The changes shown by the sediment load of a river will reflect the spatial and temporal integration of the impacts of these drivers. The temporal pattern of change can reflect the contrasting temporal trajectories of the different drivers and a simple schematic model is presented whereby the records of sediment load for many Asian rivers are initially characterized by increases in response to land clearance and catchment disturbance, but subsequently decline in response to dam construction for both improved water supply and hydropower generation, the introduction of soil conservation and sediment control programmes to address problems of sustainable development, and the extraction of sand from river channels to support the building construction associated with economic development.

Key words suspended sediment loads; Asian rivers; human impact; land disturbance; dam construction; soil conservation; sand mining

INTRODUCTION

The suspended sediment load of a river represents a key component of its hydrology, and in turn exerts an important influence on its aquatic ecology, its morphology and the exploitation of its water resources. Changes in the sediment loads of rivers can therefore have wide-ranging environmental and social and economic implications. There is clear evidence that increased fine sediment loads can cause major problems in degrading aquatic habitats (e.g. Dudgeon, 1992), but it is also important to recognise that fine fluvial sediment can provide an essential source of nutrients in some aquatic systems, including those supporting large fisheries, as well as in coastal waters where fine fluvial sediment may represent an important source of nutrients to both marine biota, coastal wetlands and mangrove stands. Reduced sediment loads may therefore also have negative environmental impacts. Sediment transport and the magnitude of the sediment load also play a key role in the dynamics of river channels. Although the coarser fractions of the sediment load are generally more important in this context, fine sediment may also exert a significant control on river morphology in some river systems. Deltas can also be considered to be an integral part of the fluvial system. Such areas are highly dependent on a continuing supply of sediment, and particularly fine sediment, for their continued evolution and stability. As depositional sinks, deltas are commonly areas of subsidence and an input of sediment is required to balance such subsidence and maintain the delta. Reductions in sediment load can therefore have important implications for delta evolution (e.g. Syvitski *et al.*, 2009). High or increasing sediment loads can also pose major problems for water resource development, particularly in terms of loss of reservoir storage due to sedimentation and siltation of water distribution systems. A recent assessment of the loss of storage in the world's large reservoirs (Basson, 2008) indicates that the large reservoirs of Asia (including the Middle East) currently represent a total original storage volume of ~1450 × 10^9 m^3 and that this storage is being reduced by 0.8% per year as a result of sedimentation. In some countries, such as Mongolia, the loss of storage is considerably greater and exceeds 1.3% per year. Of the order of 40% of the original storage of Asian reservoirs is currently occupied by sediment and such loss of storage clearly has important implications for their longer-term sustainability as a source of water for both hydropower generation and water supply.

In recent years there have been many reports of changes in the sediment loads of Asian Rivers (e.g. Walling, 2006, 2009). Perhaps the most striking is that relating to the sediment load of the Yellow River in China. Based on the data available for this river from the middle years of the 20th century up to the 1980s, it was frequently identified as possessing the highest sediment load of any world river. The value of 1.6 Gt year^{-1} that is often cited, relates to the measuring station at Sanmenxia, which is located about 800 km from the delta where the river flows out of the Loess Plateau. Much deposition occurred downstream from this site, and the equivalent value of sediment load for the measuring station at Lijin, which is located about 40 km from the delta is 1.08 Gt year^{-1}. This value represented about 7% of the total sediment flux from the land to the oceans at that moment in time. As noted above, the sediment load of the Yellow River has changed markedly in recent years, and the load measured at Lijin fell to approx. 0.4 Gt year^{-1} in the 1990s, and declined further in the early years of the present century. The current value may be as low as 0.15 Gt year^{-1}. This reduction has been attributed to several causes, including sediment trapping by reservoirs, increased water abstraction, the impact of soil conservation and sediment control programmes, and climate change, which has resulted in reduced precipitation over the Loess Plateau. Similar, albeit less marked, reductions in sediment load have been reported for most major Chinese rivers and Liu *et al*. (2009) analysed the runoff and sediment load records for 10 major Chinese rivers for the period 1955–2007, and calculated the change in the total sediment flux to the Pacific Ocean over the period of record. This flux decreased from 2087 Mt year^{-1} at the beginning of the period of record, to 575 Mt year^{-1} at its end. The causes of such reductions in sediment flux have been assessed by many studies. Climate change impacts have been demonstrated in some of the river basins (see Lu *et al*., 2011, this volume), but the dominant control has been human impact, through dam construction, soil and water conservation programmes, water abstraction and sand extraction.

Although the evidence of human impact on the sediment loads of Asian rivers cited above relates to reduced sediment loads, there are also many instances where sediment loads have increased in recent years due to land clearance, forest cutting, intensification of agriculture and other human activities resulting in land disturbance. The literature contains many reports of .small catchment studies that have documented such increases in sediment yield. Douglas (1996), for example, cites available data for small catchment experiments in southeast Asia, which demonstrate that logging and conversion of land from forest to agriculture causes sediment yields to increase by an order of magnitude or more. These increases will be transmitted downstream and Kao *et al*. (2005) provide a valuable example of the potential impact of catchment disturbance on a larger river basin. This relates to the 1584 km^2 mountainous basin of the Bei-Nan River in Taiwan. This basin is characterised by steep unstable slopes, tectonic instability, and frequent typhoons which generate heavy rainfall and must he seen as being highly sensitive to disturbance and resulting increases in erosion. The available records of the sediment load of this river showed that the mean annual sediment yield was of the order of 1500 t km^{-2} year^{-1} prior to the end of the 1960s. Thereafter, land clearance and road construction caused the sediment yield to increase by an order of magnitude, with sediment yields in some years exceeding 35 000 t km^{-2} year^{-1}. In this river basin, land disturbance greatly increased the incidence of landslides triggered by the heavy typhoon rainfall. Similar, although perhaps less marked, increases in sediment yield are likely to have occurred in many of the rivers draining small mountainous basins in the Pacific Rim, where forest clearance and land disturbance have been widespread in recent decades. Although the scales of the river basins are very different, the examples of the Yellow River in China and the Bei-Nan River in Taiwan cited above provide examples of where the sediment loads of rivers have reduced and increased by about an order of magnitude as a result of human impact, and thereby emphasise the important influence of such impacts on the sediment loads of Asian rivers.

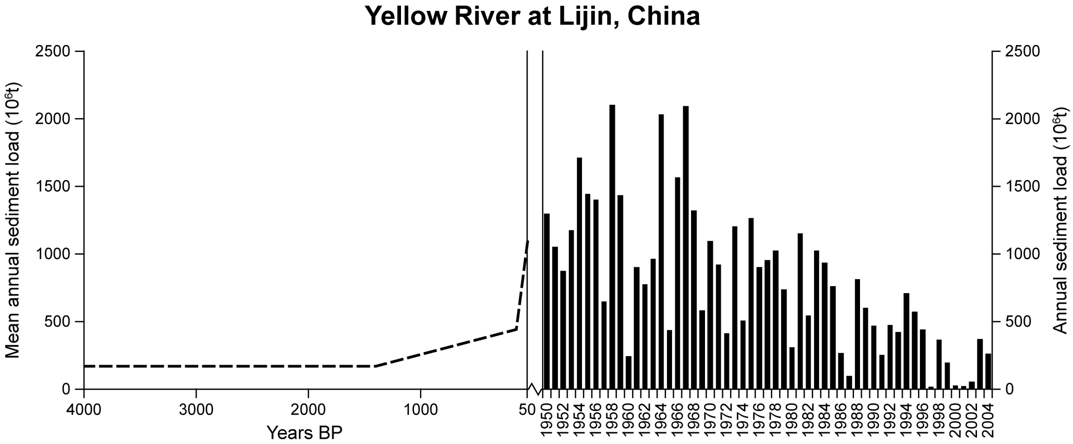

Fig. 1 A tentative reconstruction of the longer-term trend in the suspended sediment load of the Lower Yellow River over the past 6000 years, using information presented by Milliman *et al.* (1987), Saito *et al.* (2001) and Xu (1998). (Based on Walling, 1999.)

THE TEMPORAL PERSPECTIVE

When considering human impact on the sediment loads of Asian Rivers, it is important to recognise that the temporal trajectory of human impact will vary in different areas of the continent and that 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 temporal perspective is provided by Fig. 1, which presents a tentative reconstruction of the longer-term record of the sediment load transported by the Lower Yellow River at Lijin. The reconstruction is based on the work of Saito *et al.* (2001), Milliman *et al.* (1987) and Xu (1998), 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, Fig. 1 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, 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 present situation and that 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 has been reported to “dry up” for extended periods. 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. In some rivers, such as described above for the Bei-Nan River in Taiwan, the recent increase in sediment load represents the first major perturbation of the system and its sediment load.

THE KEY DRIVERS

In reviewing the key drivers related to human impact on sediment yield, it is convenient to distinguish those causing increases and decreases in sediment yield and to focus on the most important human activities. Emphasis will therefore be placed on activities such as land clearance, land use, and other forms of catchment disturbance which result in increased sediment yields, and dam construction which causes sediment trapping and reduced sediment yields. In addition, consideration will be given to two other important activities, namely the implementation of soil and water conservation and sediment control programmes in river basins, and sand mining, which results in removal of sediment from the river channel and a reduction in the downstream sediment flux.

Land clearance, land use and catchment disturbance

Land clearance, land use and other forms of catchment disturbance must be seen as embracing a wide range of human activities leading to increased sediment mobilisation and transport. The impact of such activities on the sediment loads of larger rivers downstream will depend on both the nature of the disturbance and the proportion of the river basin area that is affected by such disturbance. As indicated above, clearance of the natural vegetation for the establishment of agriculture and the creation of settlements, etc., took place many decades or even centuries ago in some areas of Asia and there are no contemporary records of river sediment loads to demonstrate their impact. However, where these changes occurred more recently their impact has been documented. Although some studies, such as that undertaken in northern Thailand by Alford (1992), have suggested that catchment disturbance may not result in a significant increase in sediment yield, even in relatively small catchments, there are many examples of where the sediment loads of rivers have increased due to land clearance and catchment disturbance. Three examples are provided here. The first relates to the Upper Citarum River at Nanjung in Indonesia for which records of water discharge and sediment load exist for the past approx. 35 years (Fig. 2). This 1718 km^2 catchment is characterized by steep terrain and underlain by erodible Quaternary

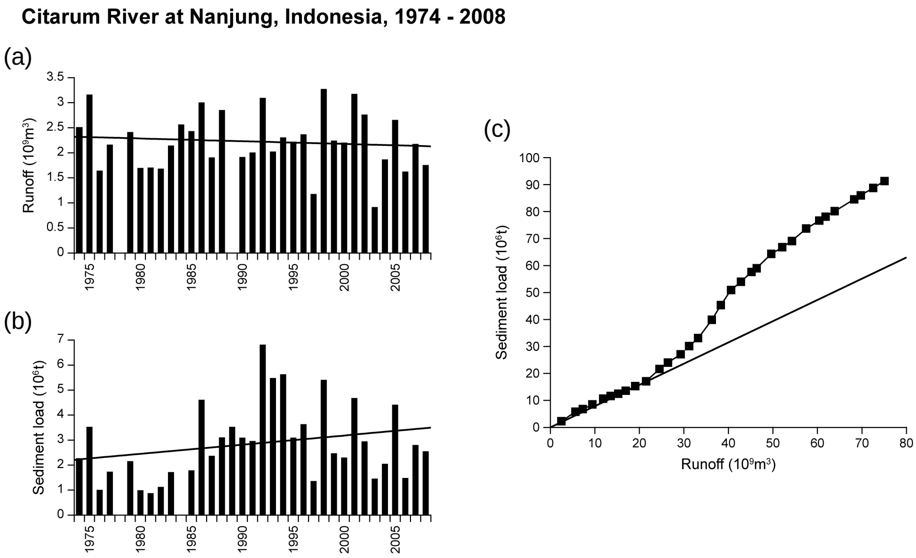

Fig. 2 Recent changes in the annual suspended sediment load of the Upper Citarum River, Indonesia, as demonstrated by the time series of (a) annual water discharge, and (b) annual suspended sediment load, and (c) the associated double mass plot.

volcanic rocks. Landslides, which are a frequent occurrence, make a major contribution to sediment mobilisation. The lower land is occupied by paddy fields, but the steeper upper areas are occupied by cultivated fields, orchards and forest, and there are many urban areas within the basin. In this region a major increase in the population occurred in the 1980s, and this resulted in extensive land clearance and agricultural development. As shown by the double mass plot presented in Fig. 2(c), sediment yields started to increase in the mid-1980s and over the period until 2008 the total sediment output from the basin has increased by about 75%. The record of water discharge for the river showed no significant change over the period, indicating that the main driver of increased sediment yield was land disturbance and associated increases in the susceptibility of the land to erosion.

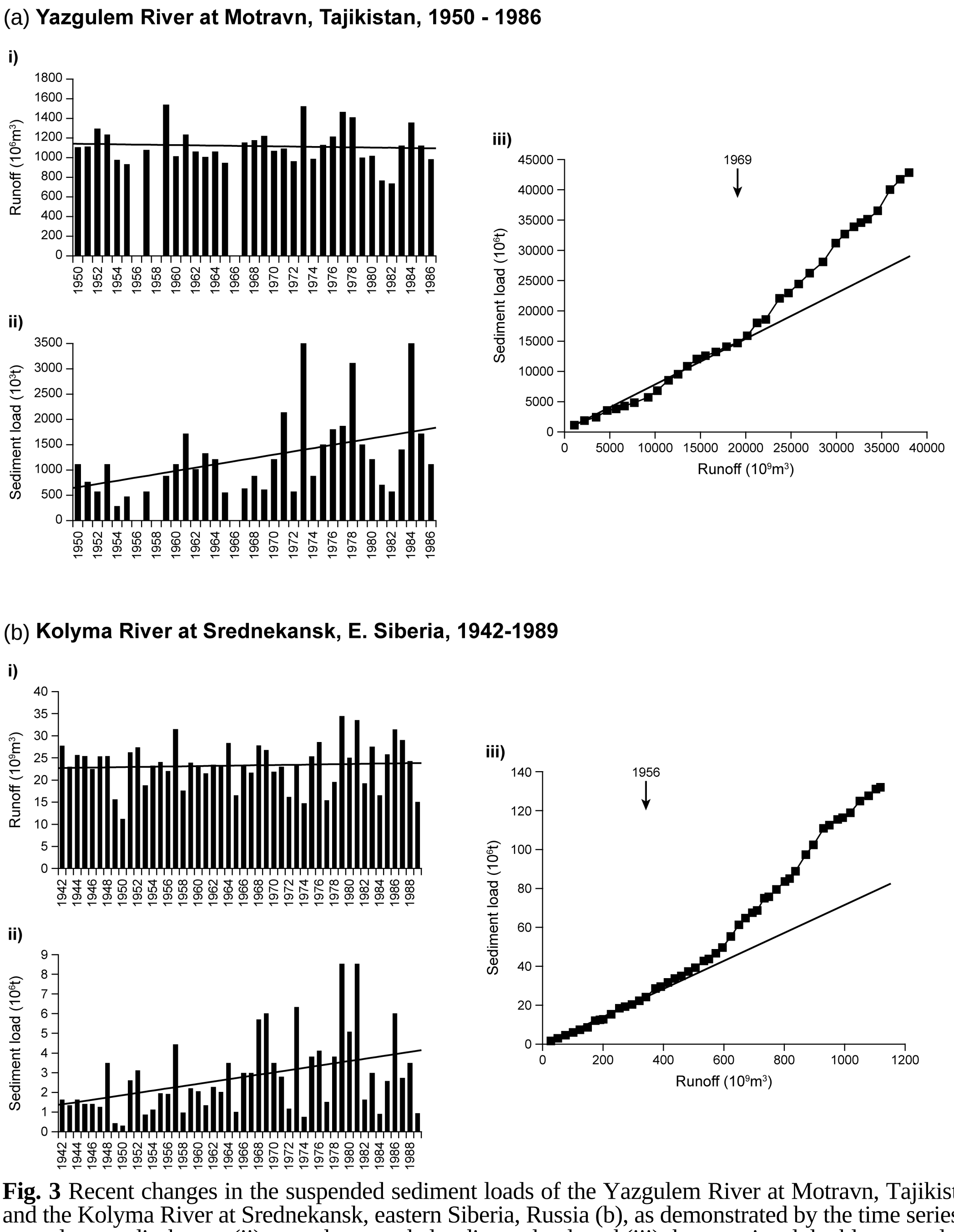

Fig. 3 Recent changes in the suspended sediment loads of the Yazgulem River at Motravn, Tajikistan (a) and the Kolyma River at Srednekansk, eastern Siberia, Russia (b), as demonstrated by the time series of (i) annual water discharge, (ii) annual suspended sediment load, and (iii) the associated double mass plots.

The second example relates to a different area of Asia and to the 1940 km^2 basin of the Yazgulem River in the mountains of Tajikistan, Central Asia (Fig. 3(a)). Again, the record of annual water discharge for this river shows no significant trend, but the sediment record is characterized by a significant (P = 99%) increase over the period 1950–1986, with the sediment load approximately doubling over this period. The double mass plot suggests that this increase commenced in the late 1960s. The catchment of the Yazgulem River is in a mountain area and this increase in its suspended sediment load can be linked to the general expansion of human activity in the region, with associated construction of roads and settlements, as well as increased grazing pressure.

The final example is drawn from another contrasting area of Asia, in this case eastern Siberia, and relates to the 99 400 km^2 basin of the Upper Kolyma River over the period 1942–1989. This is a semi-mountainous wilderness area characterized by coniferous forests and alpine vegetation with a very low population density. However, the time series of annual suspended sediment loads (Fig. 3(b)ii) shows a significant increase (P > 99%) over the period of record, with annual loads doubling over this period. The discharge record shows no significant change over the period. The double mass plot (Fig. 3(b)iii) indicates that the change in the sediment response of the basin dates from around 1956 and Bobrovitskaya (personal communication) has indicated that the primary cause of this increase was the expansion of gold mining activity within the basin, which caused major disturbance of river channels and flood plains.

Soil conservation and sediment control programmes

Although land-use impacts on sediment yields are commonly seen as resulting in increased sediment loads, the implementation of soil and water conservation and sediment control programmes in river basins can have the reverse effect. By virtue of the growing importance of soil and water conservation and sediment control programmes in many regions of Asia, this component of human impact is likely to be assuming increasing importance. Although there have been many small-scale plot and watershed studies of the benefits of soil conservation and sediment control measures in reducing soil erosion and sediment fluxes, robust quantitative evidence of the impact of such programmes in reducing the sediment loads of larger rivers is currently limited. This situation is in part a reflection of the problems of separating the impacts of several drivers, which in some cases will include the impact of climate change, as well as the spatially limited extent of many soil conservation and sediment control programmes, which means that their effects are less easy to discern within a larger river basin. The objective of such programmes is also important. If the primary aim is to reduce on-site soil loss from the better agricultural land, the impact on downstream loads may be limited, since some areas which represent important sediment sources may be unaffected. If, however, the primary aim is sediment control and to reduce downstream sediment fluxes, in order to reduce reservoir sedimentation, facilitate channel management downstream or to improve water quality and the ecological status of a river system, the impact should be greater, because attention will focus on reducing sediment mobilisation more generally. Clear evidence of the potential impact of this driver is, however, 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. In this region, much emphasis has been placed on reducing downstream sediment loads, as well as 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 seriously impact on flood control measures.

Figure 4 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, 267 km^2 of bench terraces had been constructed in the catchment, 703 km^2 of highly erodible land had been planted with forests and 46.7 km^2 with grass, and nine reservoirs and numerous check dams had been constructed. Overall, nearly 30% of the basin area was actively controlled. The data presented in Fig. 4 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 decreased to only 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 reflects the onset of drier conditions in the 1980s. Zhao *et al.* (1992) estimate that the implementation of soil conservation and sediment control measures after 1970 reduced 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 catchment management strategies to reduce sediment loads.

Similar catchment management strategies to that employed in the Sanchuanhe basin were implemented in many other areas of the Middle Yellow River basin from the late 1960s and their aggregate effect in reducing sediment loads in the Lower Yellow River represents an important cause of the major reduction in the sediment load of the Lower Yellow River shown in Fig. 1. As indicated previously, the marked reduction in sediment load of the Yellow River at Lijin also reflected several other factors, including the reduced precipitation over the basin, sediment trapping by large reservoirs and increased water abstraction. However, Xu (2003) suggests that during the period 1970–1997 approx. 55% of the overall reduction in the sediment load transported by the Lower Yellow River could be attributed to human impact and approx. 45% to reduced precipitation. Looking more specifically at the effects of human impact in reducing sediment input to the Lower Yellow River from the Middle Yellow River basin during the 1980s, Mou (1996) estimates that soil conservation works were responsible for reducing the annual load by approx. 176 Mt, whereas sediment control measures and reservoir siltation generated a reduction of 124 Mt and thus soil conservation measures accounted for almost 60% of the reduction due to human impact. It must, however, be recognised that the marked reduction in sediment load achieved through the implementation of soil conservation and sediment control measures in the Middle Yellow River basin may be something of an optimum example of the potential impact of such measures, due to the very high erosion rates in the loess region, the almost unique characteristics of the loess soils and the associated gully erosion and the widespread use of check dams for gully stabilisation and sediment trapping.

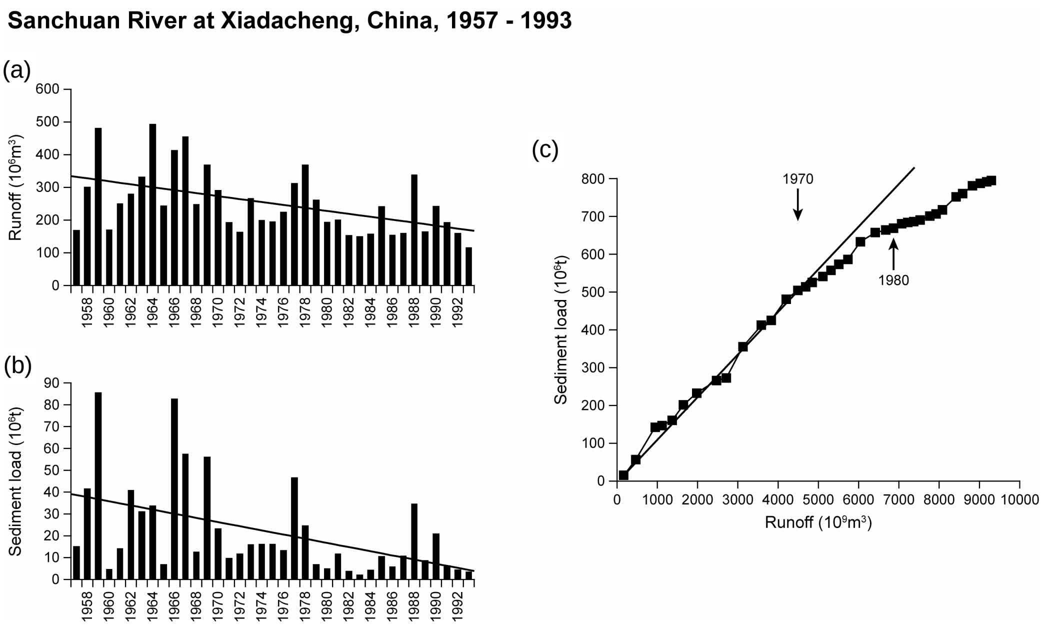

Fig. 5 Recent changes in the suspended sediment load of the Sanchuan River, China, as demonstrated by the time series of (a) annual water discharge, (b) annual suspended sediment load, and (c) the associated double mass plot.

Sediment trapping by dams

Reference has already been made to the use of check dams in soil conservation and sediment control programmes in reducing downstream sediment loads. Here, attention is directed to the impact of larger dams constructed for water supply, hydropower generation, and flood control. In contrast to the impacts described above, such dams are primarily located in the lower reaches of river basins rather than in the headwater areas. The efficiency of a dam in trapping sediment and thereby reducing the sediment load of a river will reflect a number of factors, but particularly the grain size of the sediment and the residence time of water stored in the upstream reservoir. The latter will reflect the relationship between the capacity of the reservoir and the volume of inflow. A high capacity/inflow ratio commonly results in a high trap efficiency. Another key factor which will influence the impact of the reservoir on downstream sediment loads is the purpose of the dam. Where dams are used for hydropower generation or flood control there may be little change in the downstream runoff volume, when viewed at the annual scale. In this situation the capacity of the river to transport sediment will be maintained, although it is likely to be reduced as a result of changes in the flow regime and a reduction in flood magnitude. However, where the dam is used primarily to create storage for water supply, abstraction of water from the reservoir and more particularly diversion of the stored water into irrigation canals and distribution systems can greatly reduce the downstream flows and the associated sediment transport capacity. Two examples of the impact of dams on the sediment loads of Asian Rivers can usefully be considered. The first relates to the River Indus in Pakistan and the second to the Chao Phraya River in Thailand.

As described by Milliman *et al*. (1984), exploitation and control of the River Indus for irrigation and water supply, flood control and hydropower generation commenced in the 1940s with the building of numerous barrages and irrigation channels and two major dams, the Mangla Dam on its tributary the Jhelum River, and the Tarbela Dam on the main Indus near Darband were completed in 1967 and 1974, respectively. The impact of these developments on the annual discharge and sediment load of the River Indus is clearly evident in Fig. 6(a), which presents annual runoff and sediment load data for the river at the Kotri gauging station located close to the river mouth and with a basin area of approx. 1 150 000 km^2. Both runoff and sediment load show a marked and progressive decline over the period of record, with the recent annual runoff representing only about 20% of that in the 1930s and recent annual suspended sediment loads being only about 15% of the earlier value. Most of the sediment load of the River Indus is generated in the upper part of its basin and the downstream diversion of water for irrigation and trapping of sediment behind dams and barrages causes the sediment load to progressively reduce through the middle and lower reaches of the river.

The Chao Phraya River at Ban Phai Lom, Thailand, drains a relatively large catchment of 110 569 km^2 and the records of runoff and sediment load for the period 1961–2002 are presented in Fig. 6(b). The annual sediment load provides clear evidence of a statistically significant ($P >$ 99%) reduction over the period of record, declining by nearly 80% 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 the Bhumibol and Sirkit hydropower and water supply dams on major headwater tributaries, which were commissioned in 1965 and 1972, respectively, as well as other smaller dams. The change in the sediment response of the river caused by the construction of these dams is clearly demonstrated by the double mass plot.

With the recent increase in dam construction on rivers in many areas of Asia, sediment trapping by dams must be seen as exerting an increasingly important influence on the sediment loads of Asian Rivers. The recent decline in the sediment load of the Yellow River discussed above and illustrated in Fig. 1 reflects in part the construction of large dams on this river including the Xiaolandi Dam, which was constructed in the late 1990s. Likewise, the construction of the Three Gorges Dam on the Yangtze River has been identified as a key contributor to the recent decrease in the sediment load of that river, which has declined from ~350 Mt year^{-1} in the 1990s to ~120 Mt year^{-1} in the late 2000s. The Red River in Vietnam has experienced a similar reduction in sediment load, primarily as a result of the commissioning of the HoaBinh Dam in 1989. In this case the average sediment load of the Red River at SonTay (155 000 km^2) declined from about 120 Mt year^{-1} during the period from the 1960s to the 1980s to about 50 Mt year^{-1} in the 1990s and the 2000s (Dang *et al*., 2010). Construction of large dams on the headwaters of the Mekong River in China have already caused a reduction in the sediment load of the Mekong River and this can be expected to decline further with future dam closures (Walling, 2008, 2010).

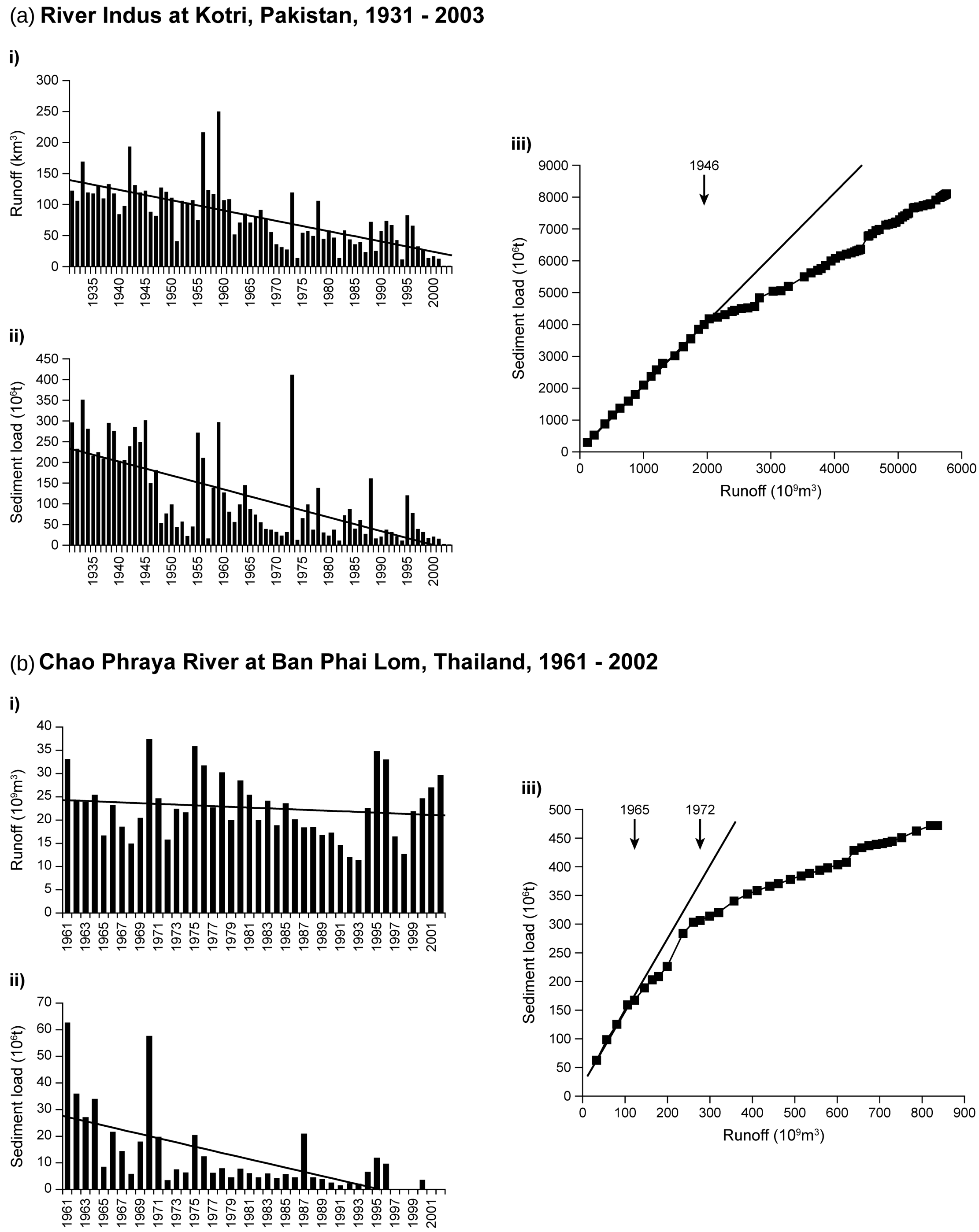

Fig. 6 Recent changes in the suspended sediment load of the River Indus, Pakistan (a) and the Chao Phraya River, Thailand (b), as demonstrated by the time series of (i) annual water discharge and (ii) annual suspended sediment load, and (iii) the associated double mass plots. The data for the River Indus were compiled by Professor John Milliman, Virginia Institute of Marine Science, USA.

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 through a river system to its outlet, there is increasing recognition that in many parts of Asia, and particularly those experiencing rapid development of infrastructure, the extraction of sand from river channels for use in the construction industry can represent a substantial loss from the system (see Piyadasa, 2011, this volume). It is often difficult to obtain reliable information on the quantities of sediment involved, since much of the material may be removed illegally without the required license. However, a useful indication of the potential importance of this driver in reducing sediment loads is 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.* (2007) 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. Saito *et al*. (2007) similarly suggest that sand extraction from the Chao Phraya River in the vicinity of Bangkok over the last 30 years accounts for some of the decline in the sediment load of this river since the 1960s, which was discussed above and illustrated in Fig 6(b). Sand mining is likely to have caused a significant reduction in the sediment load of other Asian Rivers, although it must be recognised that in some situations the sediment removed could represent long-term alluvial deposits, rather than sediment in active transport, or be substantially coarser than the suspended sediment load for which records are available. In such situations the removal of sediment by sand mining is likely to have minimal effect on the suspended sediment load of the river.

SPATIAL AND TEMPORAL INTEGRATION OF HUMANS IMPACTS

Spatial integration

When considering the impact of human activity on the sediment loads of larger Asian rivers, it is important to consider the potential effects of spatial integration in influencing the downstream response to upstream perturbations. Three different examples of such situations can be identified. In the first, changes occurring in one part of the upstream basin could be offset or even cancelled by changes occurring in other areas of the basin. A useful 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 1950–1990s 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 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 somewhat different and involves situations where the presence of substantial 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 situation (see Walling, 2009). 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 However, Bobrovitskaya *et al.* (1996) report that in this river basin the period 1957–1970 was characterised by significant human impact through disturbance and they report 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. This represents an increase of almost 50%. The lack of evidence of an increase in annual sediment load over the period of record at Salekhard can be attributed to overbank deposition on the 15 000 km^2 of well-developed flood plain that border the Ob River between Belegor'ye and Salekhard. The significance of this deposition is clearly demonstrated by a comparison of the annual suspended sediment loads at Belegor'ye and Salekhard, with 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 sediment deposition rates on the flood plain between Belegor'ye and Salekhard have increased more than three-fold in recent years and it would seem that the increased deposition rates have effectively cancelled the signal of increasing sediment loads, which was clearly apparent at Belegor'ye.

The third situation effectively represents the reverse of that presented above and involves instances where the reduction in sediment load caused by the construction of a dam is offset or significantly 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 reduced the reduction in the downstream sediment flux caused by the dam.

Temporal integration

As indicated above, it is also important to consider the temporal perspective when assessing the impact of human activity on the sediment load of a river. Some of the key impacts of human activity may have preceded the period of record and will therefore not be evident from the available record. Equally, the period of record may reflect the integration of several contrasting impacts, with some causing increases in sediment load and others resulting in a reduction and each possessing a different temporal trajectory. The latter situation can be identified in the available records for several rivers and is demonstrated by the Pearl River in Fig. 7 and the Mekong River in Fig. 8.

The Pearl River comprises three main tributaries, with the Xijiang or West River (351 500 km^2 above Gaoyao) accounting for approx. 80% of its basin area. The records of water and sediment discharge for the Xijiang tributary at Gaoyao are shown in Fig. 7 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. 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 >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. Plans for a

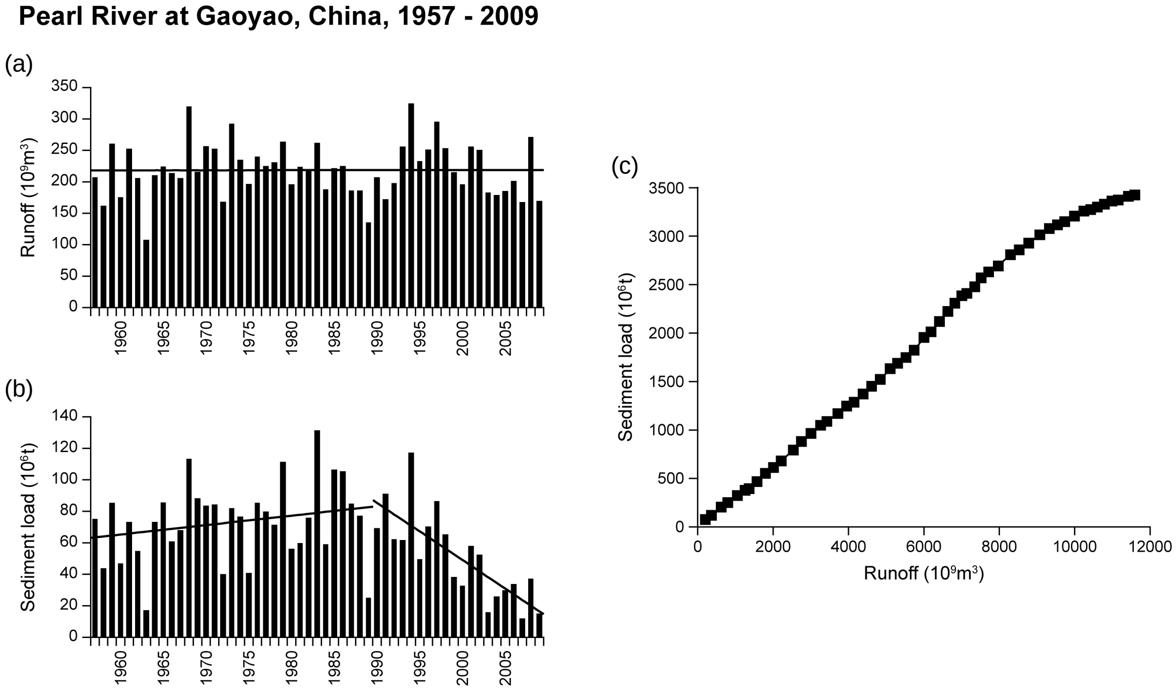

Fig. 7 Recent changes in the suspended sediment load of the Pearl River at Gaoyao, China, as demonstrated by the time series of (a) annual water discharge and (b) annual suspended sediment load and (c) the associated double mass plot.

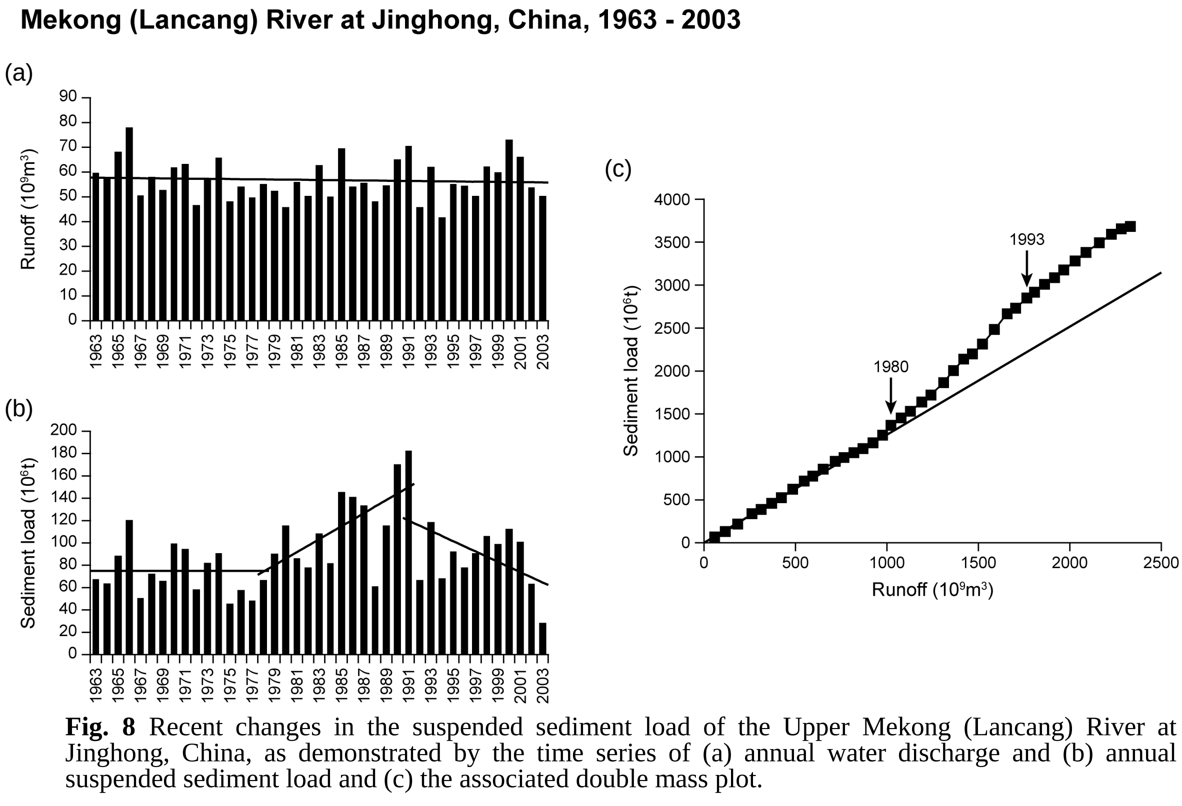

Fig. 8 Recent changes in the suspended sediment load of the Upper Mekong (Lancang) River at Jinghong, China, as demonstrated by the time series of (a) annual water discharge and (b) annual suspended sediment load and (c) the associated double mass plot.

large hydropower dam on the Xijiang River at Datengxia, which would control approx. 56% of the drainage area of the Xijiang basin, are likely to result in a further reduction of the sediment load of the river.

The second example relates to the 140 933 km^2 basin of the Upper Mekong River in China, where it is named the Lancang River. Reliable sediment load records are available for a measuring station at Jinghong, which is located close to the border with Thailand, for the period 1963–2003. The temporal variation of the sediment load over the period of record, is similar to that shown by the Pearl River. Here there is clear evidence of increasing sediment loads during the late 1970s through to the late 1980s that can be related to the expansion of population and associated land clearance and expansion of agriculture. Using data for the period 1965–1987, You (1999) demonstrated the importance of population growth as a driver of the increased sediment yields, by establishing a statistically significant multivariate linear relationship (R = 0.83) between annual sediment yield and annual runoff and population magnitude for the Lancang basin for this period. From the early 1990s, however, the temporal trend in sediment yield reversed and the sediment load demonstrates a significant reduction during the period extending from the early 1990s to the early 2000s. This decline can again be attributed primarily to the impact of dam construction, with the commissioning of the Manwan Dam in 1993 and the Dachaoshan Dam in 2003. The implementation of soil conservation programmes may also have had some impact in terms of reducing sediment yields, but this is likely to have been of limited importance. Further larger dams, including the Xiaowan and Nuozhadu Dams, will be commissioned around 2012 and these will lead to a further reduction in the sediment load of the Lancang River. At that point, most of the sediment input from the headwaters of the Mekong River in China will cease, and with this contribution originally accounting for approx. 50% of the downstream sediment load of the river, it is clear that major changes in the sediment load of the Mekong are likely to occur.

It would seem that the pattern of temporal variation of sediment load demonstrated by the Pearl River and the Upper Mekong River is likely to be reflected by the behaviour of many Asian rivers, with increases in sediment load generated by catchment disturbance being subsequently balanced and even countered by reductions in sediment load associated with dam construction, the implementation of soil conservation and sediment control programmes and sand mining activity. This trend is incorporated in the simple schematic model presented in Fig. 9, which could be seen as a model applicable to many Asian rivers. The precise position of a river 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 will be dominant and sediment loads are likely to be increasing. Other basins will be at 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.

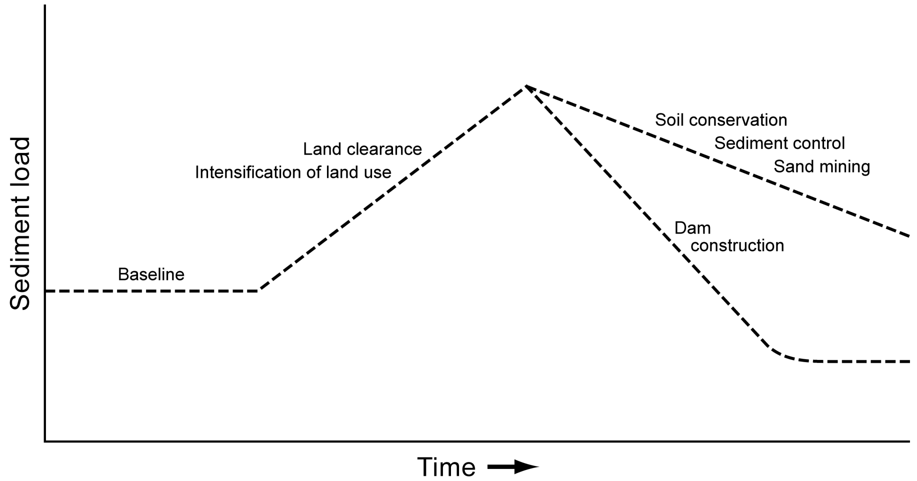

Fig. 9 A schematic representation of the temporal integration of human impact on the sediment load of an Asian river.

CONCLUSION

The available records of the sediment loads of Asian rivers provide much evidence of changes resulting from human impacts. In some instances human impact resulted in a major increase in load, whereas in others major decreases have occurred. The key drivers of such changes include land clearance, land-use activities and other forms of catchment disturbance, which result in increased sediment loads, and soil conservation and sediment control programmes, dam construction, and sand extraction from rivers, which result in reduced sediment loads. When assessing the changes in sediment load generated by these drivers, it is important to recognize that the short periods of record available for Asian rivers may only reflect some of the human impacts that have occurred in a river basin. In particular, the initial stages of land clearance and agricultural development may have occurred many decades or even centuries ago. The changes in sediment load documented in a particular river basin will frequently reflect the integration of the effects of several drivers, often with opposing effects and different temporal trajectories, with the result that the direction and magnitude of change will vary through time. A simple schematic model has been presented which reflects the changes in sediment load often shown by Asian rivers. Based on this model, sediment loads will often initially increase in response to land clearance and disturbance for agriculture and human occupation, and this increase will be followed by a decline in sediment loads due to recognition of the need to promote sustainable development and the associated implementation of soil conservation and sediment control programmes, as well as the construction of dams for water supply and hydropower generation and the extraction of sand from river channels for building construction.

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