The role of dams in the global sediment budget

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Abstract Dams and their associated reservoirs are a key element of water resource development in most areas of the world and dams have been constructed on many of the world's large rivers. The presence of dams causes sedimentation in the upstream reservoir and such sediment trapping can exert an important influence in reducing downstream sediment transport. Many of the world's rivers now provide evidence of declining sediment loads as a result of dam construction, and it is clear that dams currently exert an important influence on land-ocean sediment transfer and the global sediment budget. There is, however, currently considerable uncertainty regarding the precise impact of dams and reservoirs on the global sediment budget. Two different approaches can be used to quantify this impact. The first focuses on the reduction of the annual global land-ocean sediment flux and the second on quantifying the total amount of sediment being sequestered behind dams. Current estimates of the reduction in the annual land-ocean sediment flux range from 2 to 5 Gt year^{-1}. However, existing estimates of the total amount of sediment being sequestered behind the world's dams are about an order of magnitude greater and in the range 25 to 60 Gt year^{-1}. The apparent discrepancy between the results provided by the two different approaches requires further investigation.

Key words dams; sediment trapping; suspended sediment loads; global sediment budget; reservoir sedimentation

INTRODUCTION

Recent assessments of changes in the sediment loads of world rivers and the global land–ocean sediment flux, as a result of human activity, have pointed to both increases and decreases, according to the driver involved (e.g. Walling & Fang, 2003; Syvitski *et al*., 2005; Walling, 2006, 2009; Syvitski & Milliman, 2007; Syvitski & Kettner, 2011). In the case of decreases, key drivers include sand mining and the implementation of soil conservation and sediment control programmes, but the most important is dam construction (Vörösmarty *et al*., 2003). Dams and their associated reservoirs are a key element of water resource development in most areas of the world, providing water supply, hydropower and flood control. Viewed in terms of the growth of cumulative storage provided by the large dams included in the ICOLD (International Commission on Large Dams) register (ICOLD, 2006), Fig. 1 indicates that dam construction had a limited impact prior to 1950. However, in the latter half of the 20th century, a major programme of dam construction, particularly in the 1960s, 1970s and 1980s, resulted in a rapid increase in reservoir storage capacity, which has now reached a value of approx. 6×10^{12} m^3. It is estimated that dams now intercept about 50% of the flow of the world's rivers and this has resulted in a major impact on the global land–ocean sediment flux. Dams can result in reduced downstream sediment flux through two mechanisms. Firstly, and most importantly, deposition of sediment in the reservoir behind a dam can result in the sequestration of a large proportion of the incoming sediment load. Vörösmarty *et al.* (2003) indicate that the trap efficiency of large dams (i.e. the proportion of the incoming sediment load trapped) is typically ~85%. Secondly, where water is abstracted from the reservoir or the extended storage of water behind the dam causes a major change in the downstream discharge regime, particularly the magnitude and frequency of high discharges, the transport capacity of the river downstream may be reduced resulting in a further reduction of the load transported by the river. In some cases, the upstream reservoir may be used to regulate flows and where water is diverted downstream into irrigation canals and related systems, this may also result in diversion and therefore loss of some of the sediment load of the main river. The reduction of the suspended sediment load of the River Danube at Ceatal Izmail, Romania (catchment area 807 000 km^2) close to its delta, and its discharge to the Black Sea, over the past ~50 years, shown in Fig. 2, primarily reflects the first mechanism, namely sequestration of sediment behind dams within the river basin. The sediment load of this river in recent years is only about 30% of that in

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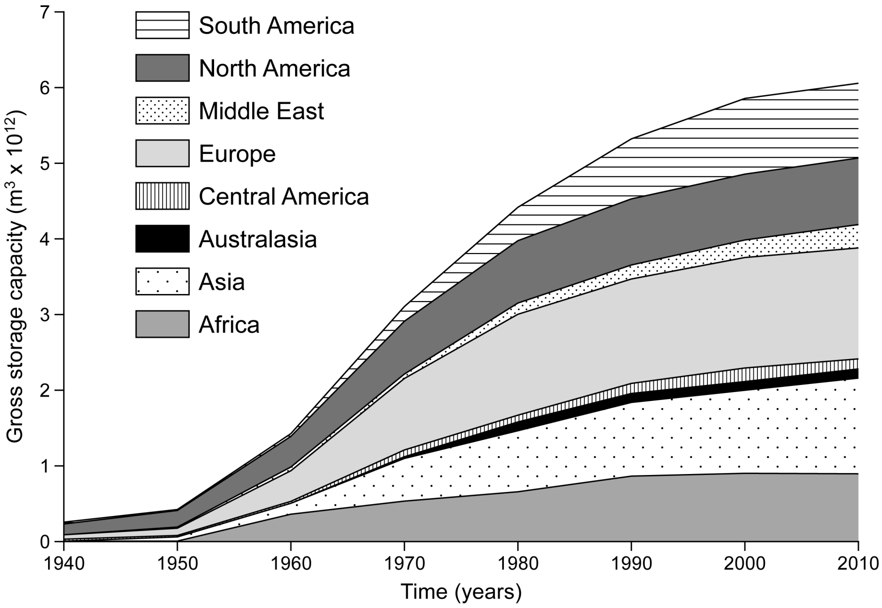

Fig. 1 The growth in global gross reservoir storage capacity (based on Basson, 2008).

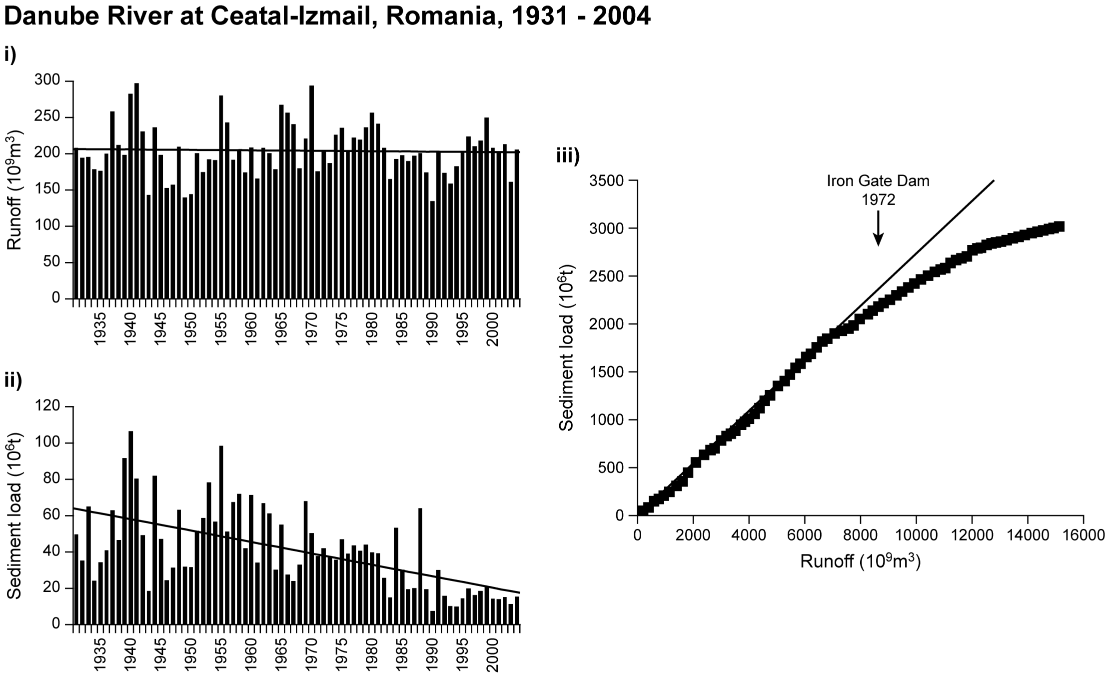

Fig. 2 Recent changes in the suspended sediment load of the River Danube at Ceatal Izmail, Romania, as demonstrated by the time series of (i) annual water discharge and (ii) annual suspended sediment load, and (iii) the associated double mass plots.

the 1950s. The most important dam on the Danube is the Iron Gate Dam constructed on the main river in 1972, but there are also a substantial number of other dams and barrages along both the main river and its tributaries. In this case there is little evidence of any change in the annual runoff of the river, although some reduction in flow peaks may have occurred. In contrast, the example of the River Indus at Kotri, Pakistan (catchment area ~ 1 150 000 km^2), presented in Fig. 3, reflects a situation where the downstream flow of the river has declined greatly in the second part of the 20th century. As described by Milliman *et al.* (1984), exploitation and control of the River Indus for

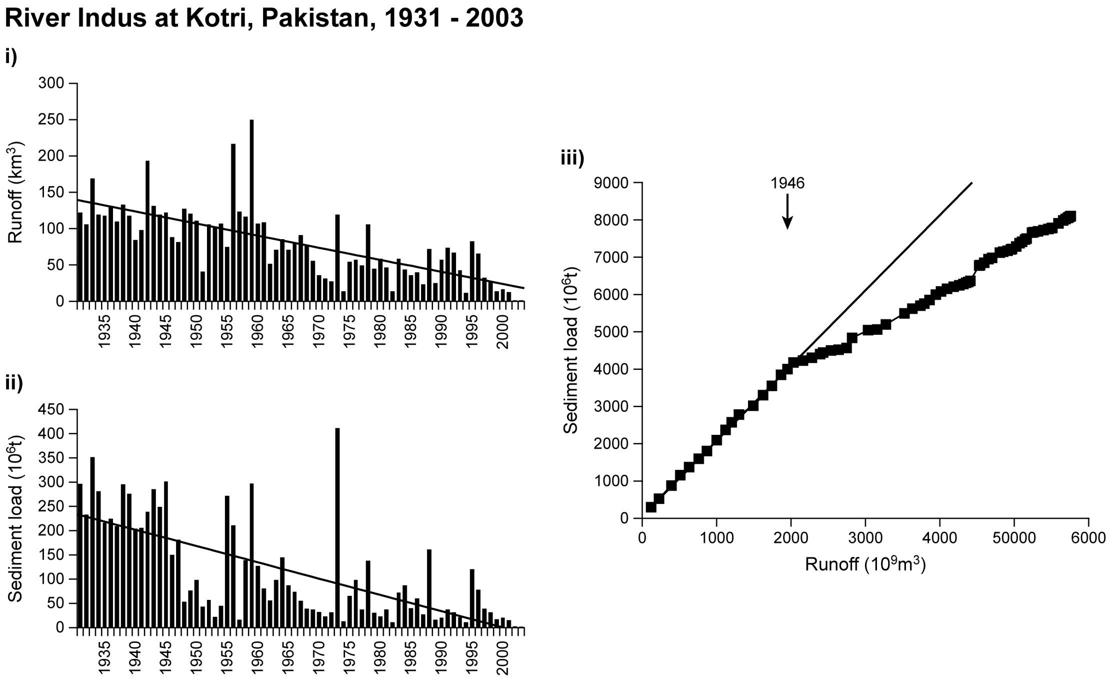

Fig. 3 Recent changes in the suspended sediment load of the River Indus at Kotri, Pakistan, as demonstrated by the time series of: (i) annual water discharge and (ii) annual suspended sediment load, and (iii) the associated double mass plots. Based on data compiled by Professor John Milliman, Virginia Institute of Marine Science, USA.

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. 3. 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. Both mechanisms described above are operating here. 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 changes in sediment load below a dam will reflect the overall sediment budget of the channel system, since the reduction in sediment load caused by a dam may result in increased transport capacity and channel scour and incision, resulting in some restoration of the load lost as a result of deposition behind the dam, at least in the short-term.

The precise impact of a dam or dams on the sediment load of a river will depend on the location of the dam within the river basin, particularly in relation to the main sediment source areas and the proportion of the basin area controlled by the dam or dams. In general, a downstream location can be expected to result in the greatest impact on sediment transport, since it will control a larger proportion of the total catchment area and there will be less potential for the sediment load to increase again below the dam. For some rivers, the availability of sediment load data for the period prior to dam construction, as well as more recent years, affords a means of assessing the impact of dam construction on its sediment load. However, any such assessment can only be approximate since drivers other than dam construction could be responsible for changes in sediment load. Climate change and reduced precipitation and runoff, may, for example, also cause the sediment load of a river to reduce. Such information has, however, been used to show that the sediment loads of the River Nile and the Colorado River have declined from a mean annual load of

Table 1 Estimates of the reduction in sediment load of some major rivers as a result of dam construction based on data compiled by Milliman & Farnsworth (2011).

River	Country	Reduction in sediment load (%)	Load reduction (Mt year^{-1})
Colorado	Mexico	100	120
Nile	Egypt	100	120
Cauvery	India	99	32
Krishna	India	98	63
Asi	Turkey	98	19
Kizil Irmak	Turkey	97	17
Rio Grande	USA	97	19
Indus	Pakistan	96	240
Sebou	Morocco	95	35
Sao Francisco	Brazil	95	14
Moulaya	Morocco	93	11
Ebro	Spain	93	16
Volta	Ghana	92	17
Mahi	India	91	20
Chao Phraya	Thailand	90	27
Drini	Albania	87	14
Limpopo	Mozambique	82	27
Zambezi	Mozambique	81	39
Orange	South Africa	81	72
Namada	India	79	55
Mahanadi	India	74	45
Godavari	India	72	123
Red River	Vietnam	60	60
Mississippi	USA	48	190
TOTAL			**1395**

~120 Mt year^{-1} to essentially zero as a result of dam construction. Table 1 presents estimates of the percentage reduction in annual sediment load for 24 world rivers for which pre- and post-dam data are available in the river load database published by Milliman & Farnsworth (2011). The data presented relate to rivers where the pre-dam mean annual suspended sediment load exceeded 10 Mt year^{-1}.

ASSESSING THE IMPACT OF DAMS ON THE GLOBAL SEDIMENT BUDGET

Reduced sediment loads and reduced sediment inputs to the coastal ocean can have a number of adverse impacts, including reduced nutrient flux and, where the sediment load feeds a delta, reduction of the sediment supply can cause delta recession and coastal erosion. Furthermore, deltas are frequently areas of subsidence and reduced sediment input can result in increased inundation by floodwaters and rising sea levels (Syvitski, 2008). Looking more generally, however, reductions in the sediment loads of large rivers and the resulting reduction in the land–ocean sediment flux could have important implications for the global sediment budget that, in turn, plays a key role in global geochemical cycling and land–ocean material transfer. It is important to assess the extent to which the budget has been perturbed. Existing attempts to provide such assessments have taken two approaches. In the first, an attempt is made to estimate the degree of reduction of the land–ocean sediment flux due to sediment trapping by dams. In the second, attention is directed to the loss of storage in the world's reservoirs due to sedimentation and resulting estimates of the amount of sediment currently being sequestered. The results provided by both approaches will be considered below.

Reduction of the land–ocean sediment flux

Table 1 provides an estimate of the total reduction in sediment flux associated with the 24 rivers listed, which amounts to ~1.4 Gt year^{-1}. It is not easy to express this as a percentage reduction of the total land–ocean flux, since the latter must be seen as a "moving target" due to the various controls on its magnitude that can result in increases in the sediment loads of some rivers and decreases in others. However, Syvitski & Kettner (2011) cite a value of 15.1 Gt year^{-1} as an estimate of the "natural" land–ocean sediment flux and a reduction by ~1.4 Gt year^{-1} is equivalent to a reduction of about 10%. Table 1 includes many of the world's large rivers, whose sediment loads have been severely impacted by dams, but lack of sediment load data for many world rivers means that it is necessarily incomplete. Furthermore, it does not include many rivers where smaller, but nevertheless significant, reductions are likely to have occurred. In addition, Table 1 specifically excludes Chinese rivers, which have demonstrated major reductions in sediment load in recent years. Liu *et al.* (2009) have reported that the mean annual sediment load of the 10 main rivers of China has decreased from 2087 Mt year^{-1} during the period 1955–1968, to 575 Mt year^{-1} for 1997–2007. This represents a 72% reduction. Much of the total load is contributed by just two rivers, the Yellow River and the Yangtze River, which together account for 83% of the load over the period 1955–2007. This reduction reflects a number of factors, including reduced precipitation and runoff in some river basins, the impact of soil conservation programmes and water abstraction, as well as sediment trapping by dams. It is difficult to apportion the reduction to the various causes, but it is clear that sediment trapping by dams is an important contributor. If dam construction is assumed to be responsible for 50% of the recent reduction in the sediment loads of Chinese rivers, this would add a further 0.75 Gt year^{-1} to the reduction shown in Table 1, providing a total reduction in excess of 2 Gt year^{-1}, and therefore a reduction approaching 15%. However, as indicated above, this value is likely to underestimate the overall reduction due to the incomplete data set.

Several workers have attempted to overcome the problems introduced by lack of data for many rivers by extrapolating the available data. Vörösmarty *et al.* (2003) based their assessment on a GIS-based analysis of a global database of river runoff linked to information on the size and location of the world's 633 registered large reservoirs (maximum storage capacity ≥0.5 km^3) and >44 000 registered smaller reservoirs. The 633 large reservoirs were estimated to intercept ~40% of global runoff and detailed analysis of their sediment trapping efficiency indicated that they potentially trapped ~30% of the sediment flux transported by the impounded rivers. This value increased to 53% if the smaller reservoirs were also considered. Taking account of the relative discharges of regulated and unregulated rivers, it was estimated that 25–30% of the global land–ocean sediment flux was trapped by reservoirs. Assuming that the global flux prior to damming was 15–20 Gt year^{-1}, the mass of sediment trapped by the reservoirs was estimated to be 4–5 Gt year^{-1}.

Syvitski *et al.* (2005) employed a different approach to extrapolating the available data and developed simple, lumped prediction models for individual river basins, 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 the reduction in sediment load due to trapping by dams as representing 26% of the prehuman flux (i.e. 3.64 Gt year^{-1}). However, it seems more logical to assume that the modern flux of 12.6 Gt year^{-1} incorporates this 26% reduction. This would represent a trapping of 4.4 Gt year^{-1}, a larger value, more similar to that estimated by Vörösmarty *et al.* (2003).

Loss of reservoir storage

Whereas the above assessments of the impact of dams on the global sediment budget have focused on the reduction of the global land–ocean sediment flux due to sediment trapping by dams, an alterative approach makes use of the available information on the reduction in reservoir storage capacity due to sedimentation, and conversion of such estimates of storage loss to values of sediment mass. Early estimates of the amount of sediment being sequestered in the world's reservoirs commonly cited the report of Mahmood (1987), which indicated that the world's major reservoirs were losing storage at a rate of about 1% per year. White (2001) suggested that the true value was likely to lie in the range 0.5% to 1.0% and provided an estimate of 30 km^3 for the volume involved. Walling (2006) took the latter value and assumed a bulk density of 0.8 t m^{-3} to produce an estimate for the annual trapping of sediment by reservoirs of 25 Gt $year^{-1}$.

A more recent and more detailed assessment of global reservoir sedimentation undertaken by the ICOLD Reservoir Sedimentation Committee and reported by Basson (2008) was used by Walling (2008) to update this earlier estimate of 25 Gt $year^{-1}$. 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 Fig. 4, indicated 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 (see Fig. 1), this is equivalent to an annual loss of storage of approx. 48 km^3 $year^{-1}$. Assuming, a dry bulk density for the deposited sediment of ~1.2 t m^{-3}, this is equivalent to annual sequestration of ~60 Gt $year^{-1}$. This value is an order of magnitude greater than the estimates of the reduction in land–ocean sediment flux due to reservoir trapping reported above, which were of the order of 4–5 Gt $year^{-1}$. It is also about four times greater than the likely annual land–ocean sediment flux, if this is assumed to be approx. 15 Gt $year^{-1}$. 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. The information presented in Fig. 1 can also be combined with the estimate of the annual global reduction in reservoir storage of 0.8% $year^{-1}$ reported above to provide an estimate of the total volume of sediment sequestered in the world's reservoirs over the period extending from the onset of the boom in dam construction in the mid 20th century through to 2050 (see Fig. 5). Figure 5 indicates that this volume currently totals about 2×10^{12} m^3 and will have increased to about 4×10^{12} m^3 by 2050. Much of this lost storage is located in Asia and Europe, although the dams of North and South America are clearly also important sediment sinks. Forecasts such as this clearly have important implications for the

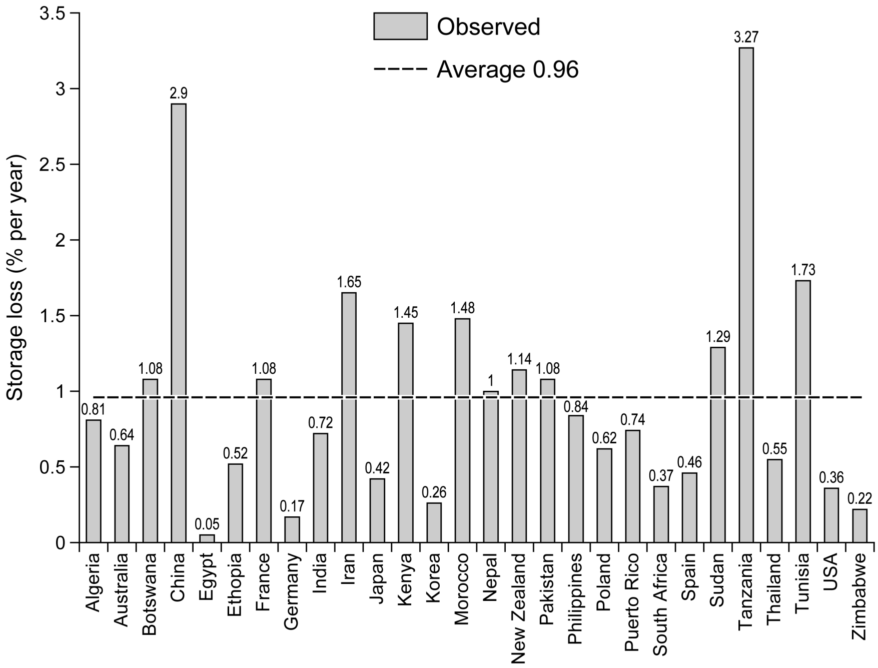

Fig. 4 A compilation of annual rates of storage loss documented for large dams in different countries, based on Basson (2008).

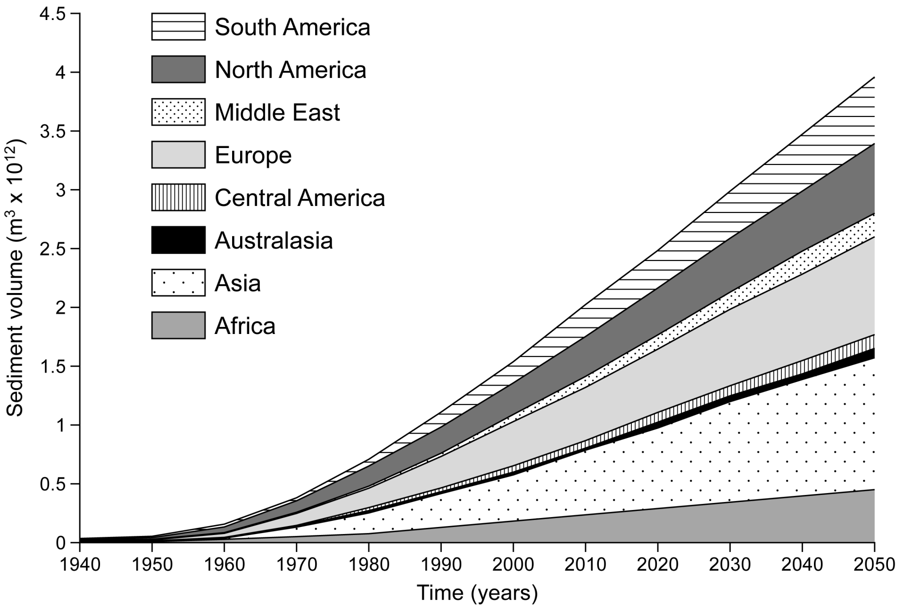

Fig. 5 Estimates of the total volume of sediment sequestered in the world's large reservoirs over the period extending from 1940 to 2050, based on Basson (2008).

longer-term sustainability of the world's large dams, because Fig. 5 indicates that by 2050 as much as two thirds of the original storage capacity of the world's dams could have been lost to sedimentation. However, here attention focuses on the significance of the sediment storage for the global sediment budget. Conversion of the values of sediment volume cited above to values of mass suggests that by 2050 of the order of 5000 Gt of sediment will have been sequestered by the world's large reservoirs. This must be seen as a major perturbation of the global sediment budget, when it is recognised that it is equivalent to about 300–400 times the annual land–ocean sediment transfer. However, the precise significance of these values needs further discussion, as indicated below.

Reconciling values of reduced flux and loss of reservoir storage

It is important to draw attention to 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 estimates of the reduction in the global annual land–ocean sediment flux of 4–5 Gt year^{-1} presented above. 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 will 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 a reduced downstream load. 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% (e.g. Phillips, 1991; Mertes, 1994; Walling *et al.*, 1999; Sweet *et al.*, 2003; Walling, 2008). However, even if such conveyance losses were assumed to be of the order of 60%, this would mean that dams would be responsible for reducing the global land–ocean sediment flux by ~24 Gt year^{-1}. This value is about five times greater than that suggested by Vörösmarty *et al*. (2003) and 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 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 the differences between the two approaches.

CONCLUSION

The results presented above emphasise that sediment trapping by dams now exerts a substantial influence on the global sediment budget. However, attempts to quantify this impact in terms of the reduction in the annual global land–ocean sediment flux and the amount of sediment sequestered behind dams each year provide results that differ by an order of magnitude. This difference reflects, in part, the many uncertainties involved in deriving the estimates, including lack of reliable information on the pre- and post-dam sediment loads of many of the world's rivers, and on the rate of reservoir storage loss due to sediment deposition in some areas of the world. However, the difference is also not unexpected, since the two sets of estimates provide different measures of the functioning of the global sediment budget. Much of the sediment currently being sequestered behind dams would not have reached the ocean under pre-dam conditions, due to deposition and storage during downstream transfer through the river system. An estimate of the mass of sediment currently being sequestered by dams is therefore not equivalent to an estimate of the reduction in land–ocean sediment flux. Conveyance losses must be considered, but their magnitude is currently uncertain. Further work is required to establish the uncertainties associated with the two sets of estimates and to reconcile the different magnitudes of the values obtained.

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