*Sediment Problems and Sediment Management in Asian River Basins*
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# The changing sediment loads of the Hindu Kush-Himalayan rivers: an overview

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**Abstract** The rivers originating from the Hindu Kush-Himalayas (HKH) are an important water resource for billions of people in Asia. These rivers used to contribute a large proportion of the global land–ocean suspended sediment flux and the Huanghe and the Ganges/Brahmaputra were characterized by the highest sediment loads of all world rivers. This paper identifies the key sediment source areas and identifies the main causes behind the recent dramatic changes in sediment load. The large river basins of this region can be broadly divided into several critical zones based on their elevations. The high plateau, with an elevation of >3500 m, has or will be affected by melting glaciers and snow as a result of global warming, and this in turn could generate increased sediment loads. The high mountainous areas with elevations ranging from 1000 to 3500 m on the northern side of the HKH and >1000 m on the southern side are the main sediment source areas, due to frequent slope failures and severe surface erosion. The main sediment source areas for some of the large rivers also include areas of lower elevation (around 500 m above sea level) with intensive human activity. Such areas include, for example, the Loess Plateau for the Huanghe, the hilly areas of the Sichuan Basin for the Changjiang, and the dry area in Bagan for the Irrawaddy. Most of these large river systems have been subject to a dramatic decline in sediment loads in recent years, due to both climate change and human impacts. The total sediment load transported from the HKH and neighbouring regions to the oceans has decreased by about half, from about 4.3 Gt year$^{-1}$ prior to the 1980s, to ~2.1 Gt year$^{-1}$ currently**.** The ranking of the large Asian rivers in terms of the annual sediment fluxes to the oceans has changed from the Brahmaputra, Huanghe, Ganges, Changjiang, and Irrawaddy in the pre-1980s to the Brahmaputra, Irrawaddy, Ganges, Changjiang, and Mekong in the post-1990s. The major Chinese rivers have become less important than those in the South, especially the Southeast Asian rivers, in terms of land–ocean sediment flux. It is anticipated that the sediment loads of the HKH rivers will continue to change due to intensive economic activity and the rapid pace of climate change in the region and throughout all the main river basins. It is possible that it will take a long time for the rivers to achieve equilibrium or quasi equilibrium. These dramatic changes can also give rise to important problems, including river channel/bank instability, loss of habitats, coastal instability, and sea water intrusion.

**Key words** sediment load; water discharge; human impact; climate change; large Asian rivers; Hindu-Kush Himalayas (HKH); Tibet plateau

## INTRODUCTION

The large Asian rivers originating from the Hindu Kush-Himalayas (HKH) and nearby regions are an important water resource for billions of people in Asia (Fig. 1). Population densities are lower in the highlands than on the plains, and very high in the river deltas and coastal regions. Many mega-cities are located along the rivers or in the coastal regions; for example, Shanghai in the Yangzte River delta, Guangzhou in the Pearl River delta, Bangkok in the Chao Phraya delta, and Calcutta in the Ganges/Brahmaputra delta. The HKH represent the source of 10 large rivers, namely, the Amu Darya, the Indus, the Ganges, the Brahmaputra-Yarlungtsanpo, the Irrawaddy, the Nujiang-Salween, the Lancang-Mekong, the Changjiang, the Huanghe, and the Tarim, Three further rivers, the Chao Phraya, the Red River (Song Hong), and the Zhujiang originate from adjacent areas (Table 1). Many of these rivers are subject to severe degradation due to intensive human impacts, including pollution, over-fishing, dam construction and over-extraction of water, as well as climate change (Wong *et al*., 2007). These large Asian rivers are also important for the sediment discharge to the Western Pacific and Indian oceans, and particularly to the river delta regions. They have been studied as key sediment sources by geoscientists from a range of disciplines and there have been numerous studies of sediment generation, transport, and deposition for the large Asian rivers.

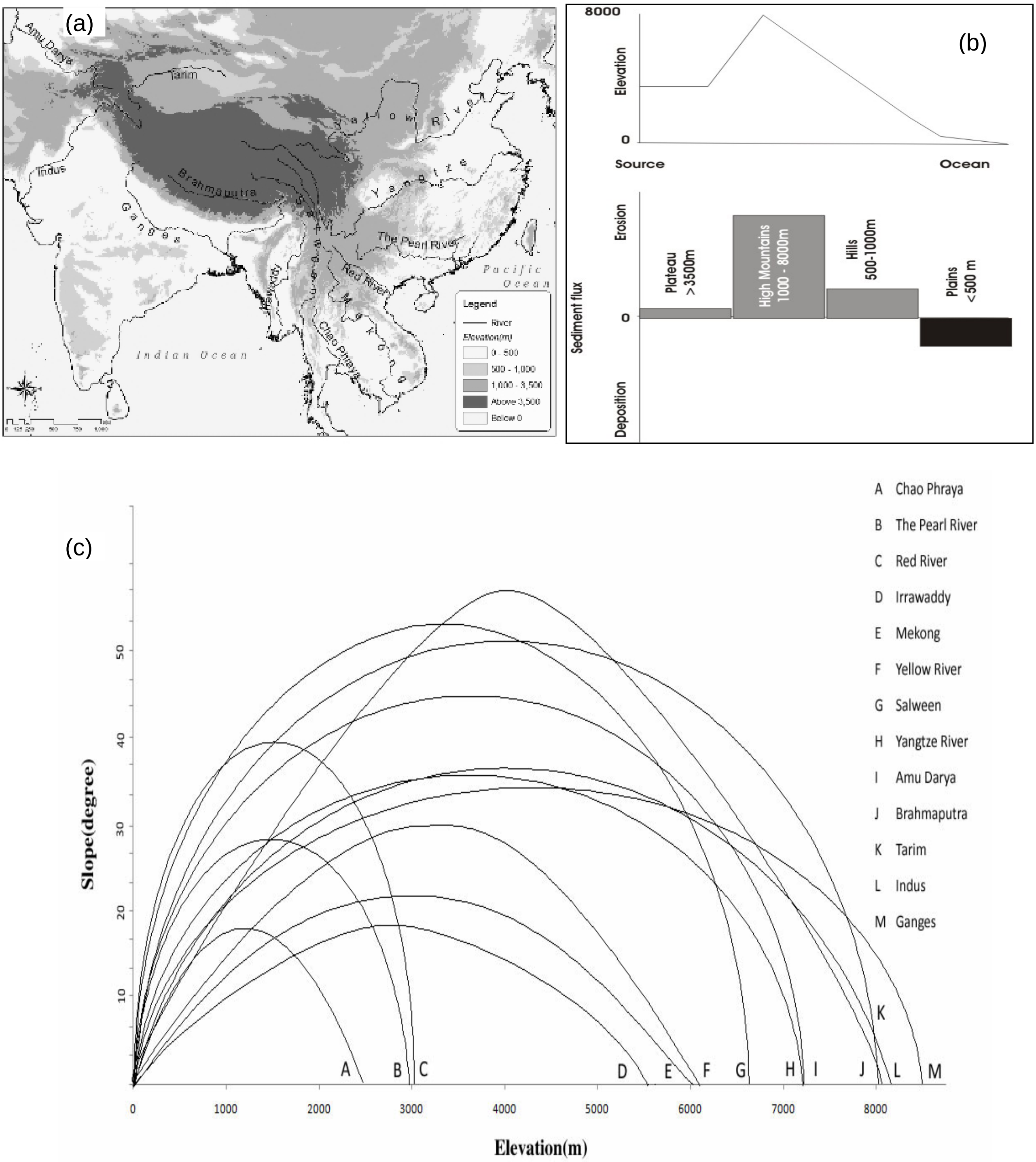

**Fig. 1** (a) and (b) The four critical zones divided according to their elevations. The first zone is the Himalayan mountains and the central Tibetan plateau with elevations of >3500 m, the second zone is the high mountains with elevations from 1000 to 3500 m on the northern side of the HKH and >1000 m on the southern side of the HKH, the 3rd zone is the low mountains with elevations from 500 to 1000 m, and the fourth zone is the area <500 m; (c) Slopes *versus* elevation showing a critical elevation 3500 m: the changing patterns of slopes with elevation below and above this value are distinctive for the 10 HKH rivers.

**Table 1** The 13 river basins originating from the Himalayas and neighbouring regions (Source: IUCN/IWMI; Ramsar Convention and WRI 2003).

| Rivers | Basin area ($km^2$) | Countries | Population (×1000) | Population density (people/$km^2$) | Forest coverage (%) | Crop land (%) | Irrigated crop land (%) | Irrigated of total crop land (%) | Fish species |
|---|---|---|---|---|---|---|---|---|---|
| Changjiang (Yangtze) | 1 722 193 | China | 368 549 | 214 | 6.3 | 47.6 | 7.1 | 14.9 | 322 |
| Zhujiang (Pearl) | 409 480 | Vietnam, China | 79 439 | 194 | 9.6 | 66.5 | 5.2 | 7.8 | 280–300 |
| Song Hong (Red) | 170 888 | China, Vietnam | 32 640 | 191 | 43.2 | 36.3 | 3.9 | 10.7 | 180 |
| Mekong | 805 604 | China, Myanmar, Laos, Thailand, Cambodia, Vietnam | 57 198 | 71 | 41.5 | 37.8 | 2.9 | 7.7 | 1200–1700 |
| Chao Phraya | 178 785 | Thailand | 21 275 | 119 | 35.4 | 44.7 | 12.5 | 28.0 | 222 |
| Salween | 271 914 | China, Myanmar, Thailand | 5982 | 22 | 43.4 | 5.5 | 0.4 | 7.3 | 143 |
| Irrawaddy | 413 710 | Myanmar, China, India | 32 683 | 79 | 56.2 | 30.5 | 3.4 | 11.1 | 79 |
| Brahmaputra | 651 335 | China, India, Bhutan, Bangladesh | 118 543 | 182 | 18.5 | 29.4 | 3.7 | 12.6 | 126 |
| Ganges | 1 016 124 | India, Nepal, China, Bangladesh | 407 466 | 401 | 4.2 | 72.4 | 22.7 | 31.4 | 141 |
| Indus | 1 081 718 | China, India, Pakistan, Afghanistan, | 178 483 | 165 | 0.4 | 30 | 24.1 | 80.3 | 147 |
| Amu Darya | 534 739 | Afghanistan, Tajikistan, Turkmenistan, Uzbekistan | 20 855 | 39 | 0.1 | 22.4 | 7.5 | 33.5 | 68 |
| Tarim | 1 152 448 | Kyrgyzstan, China | 8067 | 7 | 0 | 2.3 | 0.6 | 26.1 | 14 |
| Huanghe (Yellow) | 944 970 | China | 147 415 | 156 | 1.5 | 29.5 | 7.2 | 24.4 | 160 |
| Total | 9 353 908 | | 1 478 595 | | | | | | |

Global assessments have concluded that the large Asian rivers contribute a substantial proportion of the global sediment supply to the oceans (above 50% in some cases) due to the influence of both natural and human factors (Milliman & Meade, 1983; Ludwig & Probst, 1998). However, there have been increasing reports of major changes in the sediment loads of these rivers over the past decades, especially for the large Chinese rivers, such as the Huanghe, Changjiang, and Zhujiang. Measurements of sediment load for Chinese rivers are available for longer time periods than for other rivers in the region (since the 1950s for most gauging stations). These valuable records indicate that most of the Chinese rivers have seen dramatic changes in their sediment loads over the past decades—increasing in general until the 1980s and beginning to decline from the late 1980s or especially the early 1990s. These changes are due primarily to reservoir construction, but other human activities and reduced precipitation could both have also played a role.

Whereas individual studies have provided important insights into the nature of the changes in the sediment loads of these large river systems, there have been no integrated studies of Asian river systems more generally. In particular, there are few reports on the potential impacts of climate change on the sediment loads of large rivers worldwide, and especially the sediment loads of Asian rivers. The lack of such studies is serious, because sediment could be more sensitive than water to both climate change and human activities. Furthermore, climate change is a particularly critical issue for the HKH region, because of the extensive coverage of ice and snow, which is very sensitive to global warming. This paper provides an overview of the sediment loads of the HKH region, and particularly the recent changes in these loads, based on the available information. Our aims are to identify the dramatic changes that have occurred, to highlight the main causes of these changes, and to identify the key problems and management issues associated with such changes in sediment load. In particular, we try to identify some of the possible impacts of climate change on the sediment loads of large river systems. The specific objectives of this paper include: (1) identifying critical zones of sediment generation, transport, and deposition, on the basis of which we attempt to highlight challenges and make suggestions for sediment management, and (2) examining the nature of recent changes in sediment load and identifying their major drivers.

## SEDIMENT SUPPLY, TRANSPORT AND DEPOSITION

Gregory & Walling (1973) argued that geology and basin relief are the key controls on sediment load and Millman & Syvitski (1992) identified elevation as the most important control for rivers worldwide. In order to examine sediment production (or generation), sediment transport, and sediment deposition within the HKH region, an attempt has been made to divide the river basins, albeit crudely, into a small number of critical zones, according to their elevations. We used a digital elevation model (DEM) to divide the HKH region into four zones, namely (1) a plateau with an elevation of >3500 m and flat relief, (2) high mountainous areas with elevations of 1000–3500 m on the northern side of the HKH and >1000 m on the southern side of the HKH, (3) areas of medium elevation from 500 to 1000 m, with medium to steep slopes, and (4) the hilly and flat areas below 500 m (Fig. 1).

The first zone is the plateau zone at an elevation of >3500 m. The plateau has low relief or gentle slopes and is characterised by an inverse relationship between elevation and relief or slope (Fig. 1). It can be seen that the threshold for such a plateau is around 3500–4000m. In China, the plateau is termed the first step of the terrain. Generally, the sediment loads of streams on the plateau are low due to the low relief and low precipitation and deposition of transported sediment in the numerous lakes and basins found on the plateau. Wasson (2003) noted that the tributaries of the Ganges-Brahmaputra basin originating on the plateau have very low sediment loads, which are <10% of the total load in the main river further downstream. Contemporary soil erosion rates across much of the Tibetan Plateau are low, as indicated by the studies of Lal *et al.* (2003) using cosmogenic $^{10}$Be exposure histories of *in situ* bedrock surfaces from the Tibetan Plateau. These results confirm that the sources of the sediment carried by the great Asian rivers rising in Tibet lie overwhelmingly at lower altitudes. Similar findings based on cosmogenic isotopes have been presented by Vance *et al.* (2003) and Singh (2006).

When the rivers leave the plateau, they enter the high mountain areas with steep slopes, deeply-cut valleys, and high relief (Fig. 1), which are very susceptible to surface soil erosion, landslides, and other slope failures. This second step of the terrain or the plateau margins constitutes the second zone of the river basins, with elevations ranging from 1000 to 3500 m on the northern side and >1000 m on the southern side of the HKH. Many rivers of South Asia originate in this zone, which is characterized by dramatic relief and high channel and bed erosion, but little deposition. For the Himalayan river systems, the plateau margins and the high mountains with steep slopes are the main source areas for sediment.

The rivers of the Central Himalayas, both those with origins on the plateau and those originating on the southern slopes of the Himalayas, have very high sediment yields, with some values exceeding 6500 t km$^{-2}$ year$^{-1}$ (Lauterburg, 1993). Most of this sediment originates from the southern slopes of the Himalayas. In years with high-intensity storms, tributaries can transport very high sediment loads. For example, a sediment yield of 50 000 t km$^{-2}$ year$^{-1}$ was reported in the Kulekhani catchment of Nepal in 1993 (Schreier & Shah, 1996), whereas the average sediment yield for a period of 13 years was estimated to be about 5300 t km$^{-2}$ year$^{-1}$. Wasson (2003) suggested that the main source areas for sediment in the Ganges-Brahmaputra basin are the High and the Lesser Himalaya, characterised by steep slopes and medium to high relief. About 80% of the sediment is believed to originate from the High Himalaya and about 20% from the Lesser Himalaya. According to Galay *et al.* (2001), this is one of the highest sediment production zones in the world, as demonstrated by the Karnali River in western Nepal. This river has one of the highest specific sediment yields in the world, and it is attributed to uplift and the weak geology.

Overall, the rivers of the western Himalayas, such as the Jhelum, Chenab, and Indus, have relatively low sediment loads of below 1500 t km$^{-2}$ year$^{-1}$. Most of their sediment load originates from the Karakoram through rivers draining into the upper Indus River. These rivers, including the Hunza and the Gilgit rivers, produce very high sediment yields. The Hunza valley has a greater relative relief than any other location in the world and with highly unstable slopes, a wide range of weathering processes, and active glaciers, it is characterized by some of the highest sediment loads in the world (Goudie *et al*., 1984). Together the Gilgit and Hunza rivers contribute 40% of the total sediment load of the Upper Indus, from only 15% of the area. Denudation rates in this area are comparable to the very high denudation rates reported for the Loess Plateau in northern China.

In addition to the plateau margin and the high mountains with steep slopes, some of the large Asian rivers have other important sediment source areas at lower elevations. These include the Loess Plateau (around 500 m) for the Huanghe, the hilly areas of the Sichuan Basin for the Changjiang, the dry area in Bagan for the Irrawaddy, and the Siwaliks for the Ganges. Most of these sediment source areas have been cultivated intensively for centuries. Soil erosion and sediment yields are consequently extremely high.

A typical feature of the rivers of the HKH is that their gradients reduce very quickly below 500 m, when they enter their lower reaches. As a result, large amounts of sediment are deposited before the rivers finally reach the sea. For example, of the total annual suspended sediment load (i.e. 1037 Mt) transported by the Ganges and Brahmaputra rivers, only 525 Mt (approx. 51% of the total load) are delivered to the coastal area of Bangladesh and the remaining 512 Mt are deposited within the lower basin, offsetting the subsidence (Islam *et al*., 1999). Of the deposited load, about 289 Mt (or 28% of the total load) is deposited on the flood plains of these rivers and the remaining 223 Mt (or 21% of the total load) is deposited within the river channels, resulting in aggradation of the channel bed at an average rate of about 3.9 cm year$^{-1}$. Although the Brahmaputra transports a bigger sediment load than the Ganges, the aggradation rate of the channel bed is much greater for the Ganges. Sediment contributions from the tributaries in the flood plains are negligible (Wasson, 2003).

## SEDIMENT FLUXES TO THE OCEANS

### Past sediment flux to the oceans (Pre-1980s)

Estimates of the global flux of sediment to the oceans cover a wide range extending from 10 to 64 Gt year$^{-1}$ and the Himalayan rivers rank amongst the top rivers in terms of suspended sediment load (Milliman & Syvistki, 1992; Summerfield & Hulton, 1994; Ludwig & Probst, 1998). It has been estimated that around one third of the global sediment flux to the oceans, or around 4.3 Gt year$^{-1}$ (Table 2), was generated from the Himalayan region and its neighbouring area (Milliman & Meade, 1983). Three rivers combined, the Ganges, Brahmaputra, and Huanghe (Yellow), transported around 3 Gt year$^{-1}$ or approx. 25% of the total sediment input to the oceans (Summerfield & Hulton, 1994).

These high suspended sediment loads represent substantial denudation of their drainage basins. The average mechanical denudation rate for the Ganges and Brahmaputra basins together is 365 mm / 10$^{3}$ years. The rate is higher in the Brahmaputra Basin than that in the Ganges Basin. The high sediment fluxes have been attributed to both natural (plate margin tectonics, volcanic

**Table 2** Sediment load and sediment yield in the key rivers in the region. The sediment load data pre-1980s are mostly from the compilation of Milliman & Meade (1983). For data from other sources, the references are given. Sediment load in Mt year$^{-1}$; sediment yield in t km$^{-2}$ year$^{-1}$. The two inland rivers, namely the Amu Darya and the Tarim, are excluded from the calculation of the total amount.

| River | Drainage area | Water discharge | Past (pre-1980s) | | Recent (post-1990s) | |
|---|---|---|---|---|---|---|
| | (× $10^6$ km$^2$) | (km$^3$ year$^{-1}$) | Sediment load | Sediment yield | Sediment load | Sediment yield |
| Changjiang (Yangtze) | 1.94 | 900 | 478 | 246.4 | ~250[g] | ~128.9 |
| Zhujiang (Pearl) | 0.44 | 302 | 69 | 156.8 | 54[h] | 122.7 |
| Song Hong (Red) | 0.12 | 123 | 130 | 1083.3 | 51[i] | 425 |
| Mekong | 0.79 | 470 | 160 | 202.5 | 106[j]<br>168[k] | 134.2<br>212.7 |
| Chao Phraya | 0.16 | 30[a] | 11[b] | 68 | 5[l] | 31.3 |
| Salween | 0.27 | 300[a] | ~100[a] | 370.4 | – (~100)[$] | – (370.4) |
| Irrawaddy | 0.43 | 428 | 265<br>364[c] | 616.3<br>846.5 | 325[m] | 755.8 |
| Brahmaputra | 0.61 | 605 | 1157<br>617[d]<br>514[e] | 1896.7<br>1011.5<br>842.6 | 721[n] | 1182 |
| Ganges | 0.98 | 366 | 680<br>485[d]<br>520[e] | 693.7<br>494.9<br>530.6 | 316[n] | 322.5 |
| Indus | 0.97 | 238 | 100 | 103.1 | 13[o] | 13.4 |
| Amu Darya | 0.47 | 42 | 94.1[f] | 203 | – | – |
| Tarim | 1.02 | 26 | – | – | – | – |
| Huanghe (Yellow) | 0.77 | 49 | 1080 | 1402.6 | 150[p] | 194.8 |
| Total to the oceans[#] | 7.48 | 3811 | 4329 | | 2091 | |

[$] The sediment load in the Salween in the recent period is assumed to be the same as in the previous period in the calculation of the total amount discharged into the oceans; [a] Meade (1996); [b] Milliman & Syvitski (1992); [c] Robinson *et al.* (2007); [d] Coleman (1969); [e] BWDB (Bangladesh Water Development Board) (1972); [f] Lvovich (1971); [g] Yang *et al.* (2006); [h] Zhang *et al.* (2008); [i] Thanh *et al.* (2004); [j] Kummu & Varis (2007); [k] Walling (2008); [l] Winterwerp *et al.* (2005); [m] Furuichi *et al.* (2009); [n] Islam *et al.* (1999); [o] Inam *et al.* (2007); [p] Wang *et al.* (2007).

deposits, highly erodible lithology, high elevations, steep slopes, and intensive rainfall) and anthropogenic factors (dense populations, deforestation, intensive agriculture, and urbanisation) (Gupta & Krishnan, 1994). For the Ganges and Brahmaputra rivers, Islam *et al.* (1999) identified several factors, including mean trunk channel gradient, relief ratio, runoff, basin lithology, and recurring earthquakes, to be responsible for these high rates of denudation. In particular, rock type and its spatial distribution in the drainage basins of the Ganges and Brahmaputra rivers exerts an important control on their sediment loads (Abbas & Subramanian, 1984; Subramanian & Ramanathan, 1996).

The high erosion rates associated with these river systems have been confirmed by cosmogenic dating. For example, Vance *et al.* (2003) used cosmogenic radionuclides (Be-10 and Al-26) in quartz from river sediments from the Upper Ganges catchment to make the first direct measurements of large-scale erosion rates in a rapidly uplifting mountain belt. The erosion rates are highest in the High Himalaya at 2.7±0.3 mm year$^{-1}$, 1.2±0.1 mm year$^{-1}$ on the southern edge of the Tibetan Plateau and 0.8±0.3 to < 0.6 mm year$^{-1}$ in the foothills to the south of the high mountains. These relative estimates are corroborated by the Nd isotopic mass balance of the river sediment. Analysis of sediment from an abandoned terrace suggests that similar erosion rates have been maintained for at least the last few thousand years. Allison *et al.* (2001) used vibracores and auger samples collected from the lower (tidal) delta plain of the Ganges-Brahmaputra River in Bangladesh to determine whether the area is a significant sink for riverine sediments. Measurements of Cs-137 activity and radiocarbon in the sediments indicate sediment accumulation over decadal and millennial time scales at rates reaching 1.1 cm year$^{-1}$.

## Recent sediment flux to the oceans (post-1990s)

Many large Asian rivers have demonstrated dramatic changes in both water discharge and sediment flux over the past few decades due to environmental change (both climate and human-induced). For example, the Ganges and Huanghe rivers have been reported to be drying up and, along with other rivers in the world, are showing significant changes in water flow under climate change and human impact (Milliman *et al*., 2008; Dai *et al*., 2009). It can be seen from Table 2 that most of the rivers in the region demonstrate a declining trend in sediment loads, when recent data are compared with the data for pre-1980. The total sediment load transported from the HKH and neighbouring regions to the oceans has decreased by more than half, from about 4.3 Gt year$^{-1}$ pre-1980 to 2.1 Gt year$^{-1}$ in recent years (Fig. 2). The ranking of the big Asian rivers in terms of the annual sediment fluxes to the ocean has changed from the Brahmaputra, Huanghe, Ganges, Changjiang and Irrawaddy rivers pre-1980 to the Brahmaputra, Irrawaddy, Ganges, Changjiang, and Mekong in the post-1990s. Although there are some uncertainties about the order, especially for south and southeast Asian rivers, it is certain that the Chinese rivers have become less important than the South and especially Southeast Asian rivers.

Table 2 provides a general indication of the trend of recent changes in the sediment load of the key rivers of the region, as well as the main causes of the changes, as reported in the literature. It

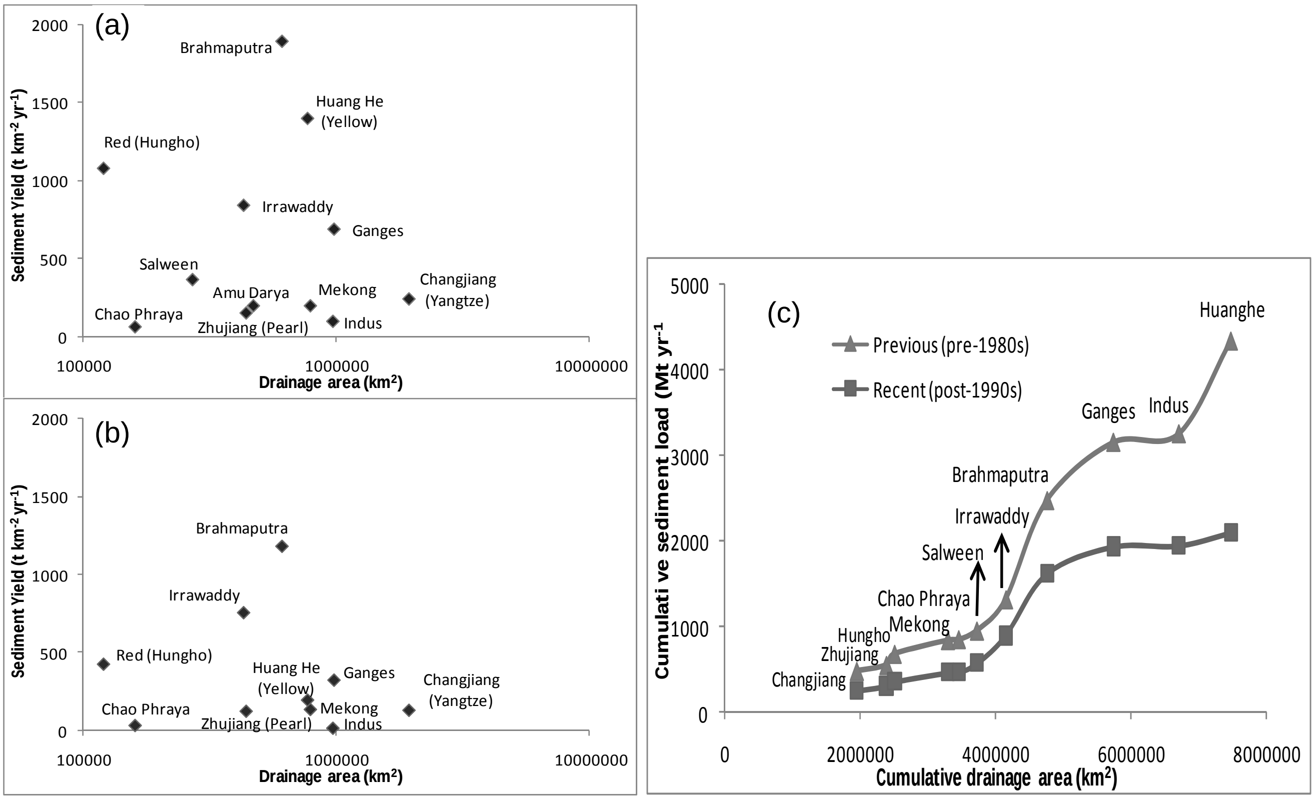

**Fig. 2** Sediment yield *vs* drainage area: (a) Previous (pre-1980s) and (b) Recent (post-1990s) (c) Cumulative plot of sediment fluxes to oceans *vs* cumulative drainage areas. The two inland rivers, namely, the Amu Darya and the Tarim, are not included. The sediment load of the Salween in the recent period is assumed to be the same as in the previous period.

should be noted that, although the time periods were classified as past (pre-1980) and recent (post-1990s) in Table 2, it does not mean there was no human influence on river sediment loads during the earlier period. For example, the construction of various structures (such as barrages and dams) on the Indus River began as early as the late 1940s (Milliman *et al*., 1984; Inam *et al*., 2007). Among the 13 rivers studied, there are some rivers that have no updated information on sediment loads in the international literature. For example, no new estimates of sediment load were found for the Salween and Amu Darya. The other 10 rivers with sediment data available for both past and recent periods can be grouped into three broad categories, as discussed in the following passages.

The first category includes those rivers without significant trends in both sediment load and water discharge, such as the Brahmaputra and Irrawaddy, as shown by recent field measurements

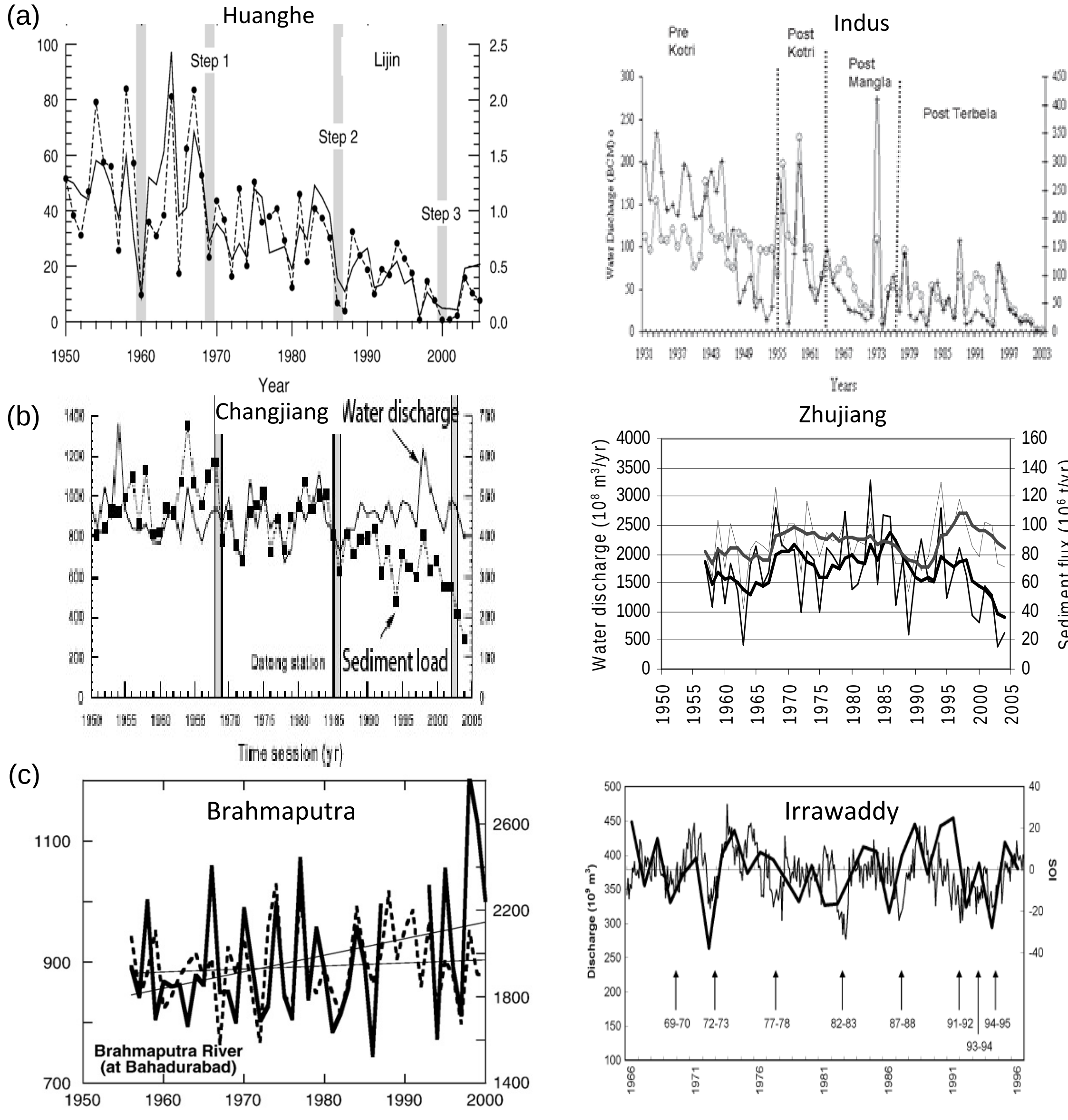

**Fig. 3** Selected water discharge and sediment loads in the big Asian rivers, (a) category 1 rivers: the Huanghe (after Wang *et al.*, 2007) and Indus River (after Inam *et al.* 2007) show a decline in both water discharge and sediment loads ; (b) category 2 rivers: Changjiang (after Yang *et al*., 2007) and Zhujiang (after Zhang *et al*., 2008) show that water discharge remained stable but sediment loads started to decline from the 1990s; and (c) category 3 rivers: Brahmaputra (after Milliman *et al*., 2008) and Irrawaddy (after Furuichi *et al*., 2009): water discharges and possibly sediment loads (no data) were stable or increased lightly.

(Islam *et al.*, 1999; Furuichi *et al.*, 2009) (Fig. 3). Recent sediment loads in these two rivers do not show significant differences from the values reported previously; and neither does water discharge.Although Milliman *et al.* (2008) identified a significant increasing trend in the water discharge of the Brahmaputra for the period from the mid-1950s to 2000, Dai *et al.* (2009) indicated that the increasing trend is not statistically significant for the period 1948–2004.

The second category includes rivers with significant decreasing trends in sediment load, whereas water discharge remained relatively stable. The second category of rivers can generally be found in the humid climate region and they are predominantly affected by dam construction, e.g. the Changjiang and Zhujiang in China (Fig. 3). The annual sediment load in the Changjiang has decreased by >40% from about 480 Mt in the 1950s and 1960s to about 250 Mt in the early 2000s (Yang *et al.*, 2006). However, no significant change was observed in the river flow of the Changjiang (Xu *et al.*, 2007). Similarly, the annual sediment load of the Zhujiang decreased sharply from 80.4 Mt for the period before 1996 to 54.0 Mt for the period after 1996, but annual water discharge only changed from 283 $km^3$ to 294.5 $km^3$ for the corresponding periods (Zhang *et al.*, 2008). Such trends are also applicable to some of the other Southeast Asian rivers. For example, the reduction in sediment flux from the Chao Phraya has been very dramatic, from more than 30 Mt $year^{-1}$ before 1965 to less than 5 Mt $year^{-1}$ by the 1990s (Winterwerp *et al.*, 2005). Similar dramatic trends have been observed in the Red River by Thanh *et al.* (2004) where sediment load declined from 114 Mt $year^{-1}$ during the period 1959–1986 to 51 Mt $year^{-1}$ for the period from 1992 to 2001.

The third category includes those rivers with significant decreasing trends in both sediment loads and water discharge such as the Huanghe and the Indus (Fig. 3). In the Huanghe, the average annual sediment load in recent years (2000–2005) became extremely low (0.15 Gt) and represents only 14% of the widely cited estimate of 1.08 Gt (Wang *et al.*, 2007). At the same time, water discharge has declined steadily (Wang *et al.*, 2006). The average annual water discharge from the Huanghe for the period from 1990 to 1999 was 13.2 $km^3$, which is only 28.7% of the value for the 1950s (48 $km^3$) (Yang *et al.*, 2007). The Ganges River has also been reported as indicating significant decreases in both sediment load and water discharge (Adel, 2001; Rahman, 2004; Dai *et al.*, 2009) (Fig. 3). The two inland rivers, the Tarim and the Amu Darya, also showed significant declines in water discharge due to drier conditions and extensive diversion of water for agricultural use. Although there are no available records for long-term sediment load, it can be conjectured that sediment load in these two rivers probably declined following a decrease in water discharge.

## THE DRIVERS OF THE CHANGING SEDIMENT LOADS

### Dam construction and water diversion

It is generally accepted that dam construction has had a major impact on the global land–ocean sediment flux (Walling, 2006). On a global river-by-river basis (4462 rivers >100 $km^2$), Syvitski *et al.* (2005) estimated a net reduction in sediment flux to the oceans by about 1.4 billion tonnes per year over pre-dam loads, due to sediment retention in reservoirs, although soil erosion simultaneously increased the river sediment transport. The construction of dams is prevalent in the Southeast Asian region, with major dams having been constructed on almost every major river, with the exception of the Salween River. However, even the Salween River, currently Southeast Asia's longest undammed river, will be permanently changed if dams planned in China and Myanmar are completed in the near future.

Of the 13 rivers under consideration, the rivers with significant reductions in sediment load due to dam construction include the three large Chinese rivers (Changjiang, Huanghe, and Zhujiang) and the Indus, Mekong, Red, and Chao Phraya. For example, the Huanghe, originally one of the most turbid rivers in the world, has experienced a stepwise decrease in sediment load due to the commissioning of several large reservoirs (the Sanmenxia Reservoir in 1960, the Liujiaxia Reservoir in 1968, the Longyangxia Reservoir in 1985, and more recently the Xiaolangdi Reservoir in 1999) (Wang *et al.*, 2007). Similar stepwise decreases in sediment load have been observed in the

Changjiang following dam construction, particularly following the operation of the Three Gorges Dam (TGD) in 2003 (Yang *et al*., 2006). Post-TGD, the sediment load of the Changjiang has been estimated to be about 200 Mt year$^{-1}$ (Yang *et al*. 2006) or even less (about 100 Mt year$^{-1}$) (Chen *et al*., 2008). In the Zhujiang basin, the construction of Yantan Dam in 1992 caused a decline in the sediment load in the neighbouring downstream section, although reduced sediment loads at most stations further downstream were only observed after several years, due to downstream channel erosion as well as increased sediment inputs from other tributaries (Zhang *et al*., 2008). It is alarming to see that the average annual sediment load of the Indus has declined from about 200 Mt in the pre-dam period, from 1931 to 1954, to about 10 Mt in the recent period from 1993 to 2003 (Inam *et al*., 2007). Similarly, the Manwan Dam constructed in 1993 on the Mekong River, the Hoa Binh Dam constructed in 1989 on the Red River (Thanh *et al*., 2004), and the Bhumipol Dam constructed in 1965 and the Sirikit Dam in 1972 on the Chao Phraya (Winterwerp *et al*., 2005) have caused dramatic reductions in the sediment loads of these large rivers (Thanh *et al*., 2004; Winterwerp *et al*., 2005; Lu & Siew, 2006; Kummu & Varis, 2007).

Water diversion is another important factor when analysing reductions in sediment load. The rivers impacted most by water diversions are those located in the dry and/or semi-dry regions, such as the Huanghe, Indus, Ganges, and Tarim. In the Huanghe, sediment loss due to water abstraction in the lower reaches has increased with increasing use of water for agriculture (Wang *et al*., 2007). The flow of the Indus has been greatly regulated by large-scale management of the water system (Inam *et al*., 2007). Currently it is claimed that about 60% of the Indus water is used for irrigation, supporting about 80% of Pakistan's agricultural fields. There are three major storage reservoirs, 19 barrages or head works, and 43 major canals with a total conveyance length of 57 000 km. Systematic removal of water from the Indus has occurred with the construction of barrages and canals. It has been reported that only half the water from upstream (measured at Massan) flows downstream (measured at Sehwan, the lowest gauging station on the Indus) due to use for irrigation or loss to groundwater aquifers (Beg, 1977). The annual flow downstream has decreased from >150 billion m$^3$ to <45 billion m$^3$. The number of zero-flow days below the Kotri Barrage increased from 0 before the construction of the Kotri Barrage in 1955, to 100 days from 1962 to 1967, to 250 days in the post-Kotri and post-Mangla period (1967–1975), and even more in recent years (Inam *et al*., 2007). The flow of the Ganges was regulated after the construction of a barrage at Farakka in 1975, and huge quantities of water have been diverted from the Ganges River for irrigation through the head works and pumping stations (Sarkar *et al*., 2003; Singh, 2007). Consequently, the sediment load has declined dramatically in these regulated rivers, as a result of the engineering structures established to divert the water.

For the Tarim River and the Amu Darya there is no sediment information available, particularly for recent decades. However, the history of water diversion points to it causing impacts on sediment load. For the Tarim River located in the arid area of northwest China, the flows from the glacial headwaters of the river have shown increasing trends with the change in climate. However, dramatic decreases in water flow have been observed downstream and reported widely since the 1970s (Xu *et al*., 2004; Hao *et al*., 2008; Ye *et al*., 2009). This emphasises the dominant influence of human activities on water resources in the lower Tarim River (Xu *et al*., 2004). Large-scale agricultural exploitation and corresponding water diversion activities are claimed to be the dominant factor in the decrease in downstream flow. The construction of the Daxihaizi Reservoir in 1972, in particular, caused a complete cut-off of the supply to its downstream course, which has a length of 321 km, and the drying up of the Taitema Lake at the outflow of the Tarim River. Other eco-environmental problems, such as the lowering of the groundwater table, degeneration of natural vegetation, land desertification, and increased weather-induced disasters occurred subsequently (Ye *et al*., 2009). The Amu Darya, located in the Central Asian region, also suffers from critical water shortages in its lower reaches, which will likely extend further upstream with increasing development activities. Since the 1980s, the Amu Darya has failed to reach the Aral Sea (ESIG Alert, 2002). In the Amu Darya River, a complex system of dams with an aggregate capacity exceeding 29.8 km$^3$ was built from the mid-20th century onwards, mainly in the lower reaches, for irrigation and flood control.

## Soil and water conservation measures

The impact of deforestation/reforestation is currently a topic of debate in the Himalayan region, due to its complex environment (Hofer & Messerli, 2006). Wasson *et al*. (2008) confirmed that deforestation had impacts on soil erosion and river sediment load for a large erosional event in the catchment of the Upper Ganges, with landslides occurring in deforested areas. However, high rates of erosion in the region make the importance of land use difficult to assess. Similarly, the effects of reforestation are not clearly defined in such regions (Sinha, 2001).

There can be no doubt that soil and water conservation measures have had a significant effect in reducing sediment fluxes at a small scale, such as from plots, hillslopes, and small catchments. Several studies indicate that the efficiency of soil and water conservation measures on sediment reduction could be >90% (Li, 1992; Zhu & Hu, 2004). The efficiency of sediment reduction drops dramatically in the larger river systems. For example, for the Jialingjiang River (drainage area 160 × $10^3$ $km^2$), the efficiency of soil and water conservation measures in sediment reduction during the period 1989–1996 was reported to be only 10–25% (Lei *et al*., 2006), where one third of the sediment reduction was attributed to soil conservation practices (Yang *et al*., 2006). Another study showed that for the whole of the Changjiang basin, soil and water conservation measures only contributed ~15±5% to the overall decline in sediment flux (Dai *et al.*, 2008). On the basis of a thorough literature review, the FAO (2002) concluded that land-use impacts on hydrological parameters and sediment transport are inversely related to the spatial scale at which the impact is observed. In this respect, the normal extent of land-use change may show an impact on sediment fluxes of up to a catchment scale of the order of 100 $km^2$.

The generally limited contribution of soil and water conservation measures to the decline of sediment loads in large rivers can reflect a number of reasons. First, the effects of biological measures of soil conservation (trees and grass plantation) can take a long time to become apparent, particularly on highly degraded soils, such as those in the karst regions in southwest China and the red weathered regolith regions in south China. Secondly, although soil and water conservation measures can reduce local soil loss and sediment load effectively at the local scales (e.g. plot, hillslope, and small catchment), the findings cannot be extrapolated easily to large river basins due to the buffering effects of alluvial storage (Walling, 2006). The stored sediment could be remobilised from valley floors and channel sinks into new sediment sources. As emphasised by Trimble (1999), improved soil conservation measures can reduce upstream soil erosion, but downstream sediment yields may remain relatively constant due to remobilisation of stored sediment.

There are, however, some long-term studies of the Huanghe which demonstrate the effectiveness of soil conservation measures in reducing the sediment export from a river basin. Mou (1996) estimated that, in the middle basin, the contribution of soil conservation measures to sediment reduction caused by human activities was as high as 60%, while the contribution of reservoir deposition was 40%. Wang *et al*. (2007) attributed 70% of the total sediment decrease in the Huanghe to human activities, among which soil conservation practices accounted for 40% and reservoir and dam operations for 30% of the reduction. Although such studies in the Huanghe have demonstrated the potential importance of soil conservation practices in reducing sediment loads in large river basins, the findings may not be applicable to other river basins, because of different soil erosion and sediment control measures. In the Huanghe Basin, there are three main measures used for soil erosion and sediment control, namely, land terracing, tree and grass planting and checkdam construction for interception of sediment (Xu, 2003). Terracing and tree and grass planting can reduce on-site soil erosion on hillslopes and checkdams are effective in controlling gully erosion, trapping the eroded sediment in gullies and gradually flattening the land for farming. The third measure, checkdam construction, has been recommended as the most effective means of conserving soil and water in the Loess Plateau. It has been estimated that sediment reduction by checkdam construction accounted for 64.7% of the total sediment reduction by soil and water conservation measures in the middle reaches of the Huanghe during the period 1970–1996. However, this approach to sediment reduction is somewhat unique to the Loess Plateau region of the Huanghe and cannot be used in other river basins. It could be partly responsible for the efficiency of soil conservation measures in reducing sediment loads in the Huanghe Basin.

## Climate change and glacial melting

Although human activities, such as damming, in the downstream regions play important roles in changing the sediment loads of rivers, the impacts of climate change on river systems, particularly in the upper regions, are being increasingly emphasised in relation to both water discharge and sediment load (Lu *et al*., 2010). Climate change in the HKH region is manifested in two main ways: increase in temperature and change in precipitation, for which both increasing and decreasing trends have been reported (Eriksson *et al*., 2009). The Hindu Kush-Himalayan (HKH) region is one of the most critical regions affected by melting glaciers, due to the extensive area covered by ice, second only to the Arctic and Antarctic (Qiu, 2008). Because most HKH rivers originate from glaciers in ice-covered areas, they are more susceptible to climate change. Warming in the Himalayan region has taken place at a greater rate than the global average. Glacier melting is undoubtedly taking place in the region, as is evident from observations in China (Li *et al*., 2008), Pakistan (Roohi, 2007), and India (Kulkarni *et al*., 2007). Current assessments of the impacts of melting glaciers and snow on rivers in the region is focused on water flow, and earlier spring streamflow maxima and increased glacial runoff have been reported (Singh & Kumar, 1997; Ahmad *et al*., 2003; Xie *et al*., 2006). Glacial lake outburst floods (GLOFs) have also been reported during the recent past and the situation could worsen with glacier melting (Qiu, 2008). However, there have been few studies which have addressed the potential increase in sediment flux from the region as a result of climate change.

Long-term hydrological measurements since the 1950s in the headwaters of the large Chinese rivers may provide good illustrations of the potential impacts of glacier melting and freeze-thaw on changes in sediment load. In recent years, a trend of increasing sediment loads coupled with increasing river flows has been reported in various headwaters of the large Chinese rivers, e.g. in the Tuotuo River, one of the glacier-fed tributaries of the Changjiang (Wu & Yu, 2002), and in the upper Yarkant River, one of the major tributaries of the Tarim River (Sun *et al*., 2008).

Glacier and snow melt are even more important in terms of contributions to water and sediment flux in South Asian rivers, such as the Indus, Ganges, and Brahmaputra. For example, 70% of the summer flow in the Ganges comes from melting glaciers (Barnett *et al*., 2005). Thirty-five per cent of the discharge at the mouth of the Indus and 60% of the sediment load of rivers in the Karakoram are derived from glaciers (Collins & Hasnain, 1995). There are no long-term observations of sediment load for these river systems, but studies based on glacier-hydrological data collected over short durations are available for some rivers such as the Indus (Ali & Boer, 2007) and Ganges (Hasnain & Chauhan, 1993; Hasnain, 1996). These process-based studies demonstrate the importance of precipitation and fluvial transport in controlling sediment yields in glacial streams. The sediment flux from glacier-fed rivers depends to a great extent on the amount of water draining through the glaciers.

The increase in precipitation projected by the Intergovernmental Panel on Climate Change (IPCC) and the change in the balance between rain and snow will very likely occur in the high-altitude regions: a 10–30% increase in average annual precipitation over the Tibetan Plateau as a whole by 2080 has been predicted (IPCC, 2007). Elevated levels of runoff resulting from a combination of increased precipitation and glacier meltwater could be expected to produce an increase in sediment flux from high-altitude regions. Other factors likely to contribute to increased sediment loads in the region under a warming climate are increased availability of sediment from proglacial areas after glaciers have receded, increased geomorphic hazards associated with glacier retreat (Moore *et al*., 2009), reworking of paraglacial sediment (Church & Slaymaker, 1989; Ballantyne, 2002), and permafrost degradation (Zhao *et al*., 2004; Goudie, 2006). Elevated sediment loads in glacial environments have been reported elsewhere (Moore *et al*., 2009).

In addition to glacier melting, the changes in temperature and variability of precipitation would also cause changes in surface runoff, soil erosion, and sediment loads. Little work has been carried out on the impacts of observed climate change on sediment loads in rivers and streams (IPCC, 2007), especially those taking place in large river systems, because of lack of data and the difficulty of modelling these impacts. A few studies have indicated that the decline in the sediment load of the Huanghe was partially due to a reduction in rainfall (Xu, 2003; Wang *et al.*, 2007). Another good example is that of the Upper Changjiang, especially the Jialingjiang tributary, where a reduction in precipitation contributed to an approx 15% decline in the sediment load (Xiong *et al.*, 2008). It is thought that the rivers in the third category, i.e. water and sediment load declining simultaneously, have been affected by an increasingly dry climate. These rivers are located in areas with an arid or semi-arid climate and are particularly vulnerable to climate change and human activities such as large-scale water extraction.

In contrast, many rivers located in a (sub)tropical environment have been subject to increasing rainfall over the past decades and thus potential increases in sediment load. For example, sediment loads increased by 3–5% in the middle and lower reaches of the Changjiang due to increased rainfall (Dai *et al.*, 2008). Increasingly warmer and wetter climates in (sub)tropical zones could yield more sediment, but such increases are likely to be offset by human activities, such as reservoir construction, and thus would be difficult to differentiate from other influences.

### Sand extraction

In-channel sand extraction from river beds for construction is another factor responsible for the decrease in sediment load in large Asian rivers such as the Changjiang, Zhujiang, and Chao Phraya (Chen, 2004; Yang *et al*., 2004; Chen *et al*., 2005; Lu *et al*., 2007; Saito *et al*., 2007). Because the division between suspended load and bed load is not absolutely fixed and mutual exchange might occur during different hydraulic conditions, sand extraction could cause a decrease of suspended load in rivers (Yang *et al*., 2004). It is estimated that annual sand extraction amounted to about 40 × $10^6$ t in the early 1980s and increased to about 80 × $10^6$ t in the late 1990s in the Changjiang (Chen, 2004; Chen *et al*., 2005). In the Zhujiang, during the period 1984–1999, the average annual amount of sediment extracted through mining from the Pearl River Delta was 46–53 × $10^6$ $m^3$, equivalent to 59.8–68.9 × $10^6$ t (Peng *et al*., 2003). This is close to the annual suspended load of the Xijiang and Beijiang. The amount extracted, however, is much more than the bed load (normally 5–10% of the suspended load), which is the principal load component from which sand is extracted. Sand exploitation from the Chao Phraya at Nakhon Sri Ayuthaya, about 120 km upstream from Bangkok, during the last 30 years was considered an important factor in reduction of the sediment load in the Chao Phraya (Saito *et al*., 2007).

## CONCLUSION AND PERSPECTIVES

We have surmised that the high plateau, with an elevation of >3500 m, will be affected by melting glaciers and snow, and this could generate heavy sediment loads as a result of global warming. The high mountainous areas with elevations of 1000–3500 m on the northern side of the HKH and >1000 m on the southern side are the main sediment source areas due to frequent slope failures and severe surface erosion. The focus in this zone is slope failure, as well as melting ice and snow. The source areas for sediment in specific rivers, such as the Loess Plateau for the Huanghe, the Sichuan Basin and the South China hill areas for the Changjiang, and the dry areas of Bagan for the Irrawaddy, require more attention because of intensive human activities in these fragile environments.

The upper reaches of the large Asian rivers may have been subject to increased sediment generation due to land degradation and/or accelerated melting of ice and snow, but in most cases the increased sediment has been either trapped by reservoirs or diverted when water diversions have taken place. As a result, the large Asian rivers that were previously characterized by very high sediment fluxes have discharged significantly less sediment into the oceans over the past 20 years or so. Such dramatic reductions in sediment load can have a significant impact on associated material fluxes, such as nutrient fluxes, and on wider ecological and environmental issues in the estuaries and coastal regions of these rivers. They even have impacts in the continental shelf areas.

It is anticipated that the impacts of climate change on the sediment loads of large Asian rivers will be far-reaching, due to the large proportion of ice and snow cover at high elevations.

Compared to water, sediment can be more sensitive to changes in climate and in land surface conditions. Thus, it is necessary to devote increased effort into studying the dynamics of sediment loads in the river systems of Asia.

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