

# A sediment budget for the Ganga–Brahmaputra catchment

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**Published data are used to construct an approximate sediment budget for the  $1.656 \times 10^6$  km<sup>2</sup> catchment of the Ganga and Brahmaputra rivers. From these data, it has not been possible to identify the major sources of sediment. Recently published Nd/Sr tracer results suggest that the High Himalaya is the main source of sediment, providing for the first time a focus for more detailed research on the role of land use and other factors in the generation of sediment. Much is yet to be learned about this globally important catchment, and the budget provides a framework for further research.**

THE catchment of the combined Ganga–Brahmaputra rivers is  $1.656 \times 10^6$  km<sup>2</sup> in area<sup>1</sup>, yields  $\sim 1000 \times 10^6$  tonnes/yr of suspended sediment at a point  $\sim 200$  km from the ocean in Bangladesh<sup>2,3</sup> ( $\sim 8\%$  of the total sediment load reaching the global oceans)<sup>3</sup>, and appears to be the highest suspended sediment load of any river system in the world. The Ganga–Brahmaputra rivers contribute almost all of the sediment making up the Bengal Delta and Submarine Fan, a vast structure that extends from Bangladesh to south of the Equator, is up to 16.5 km thick, and contains at least  $1.13 \times 10^{16}$  tonnes of sediment<sup>4</sup> accumulating over the last  $17 \times 10^6$  years at an average rate of  $665 \times 10^6$  t/yr. From about  $0.9 \times 10^6$  years ago, the rate of accumulation in the Bengal Fan has increased by a factor of 4.5 from the previous  $6 \times 10^6$  years, coincident with global cooling and drying<sup>5</sup>. The Fan has buried organic C at a rate since the early Miocene of  $\sim 1.1 \times 10^{12}$  mol/yr, representing between 10 and 25% of the total global burial flux of organic carbon during this period<sup>5</sup>. The rivers currently contribute  $\sim 8\%$  of the TOC delivered to the global ocean<sup>6</sup>.

Beginning most recently in 1976 (ref. 7), but stretching back to the 1870s (ref. 8), there has been much discussion of the causes of floods on the Gangetic Plain. Of the  $59 \times 10^6$  ha flooded in India in the worst year,  $\sim 16 \times 10^6$  ha (or 27%) is in the Ganga catchment<sup>9</sup>. This is  $\sim 40\%$  of the Ganga Plain in India, and most of the flooding is in Bihar and Uttar Pradesh<sup>9</sup>. Explanation of what appears to be worsening flooding in India<sup>9</sup> but unchanged flooding in Bangladesh<sup>10</sup> include increased soil erosion and runoff from the Himalaya following defor-

estation, and sedimentation of river channels; river embankments; and regionally different precipitation changes<sup>11</sup>. Floods and sedimentation, in an area of very high population density, cause severe damage to crops, houses, roads, railways, bridges, cities, irrigation canals, and embankments. Official data show a rising trend in the area of flooding, number of people affected, and crop damage. In the entire Ganga–Brahmaputra plains, about 100 million people are affected by floods, and global warming is likely to increase runoff during the next 100 years<sup>12</sup>.

Because of the catchment-wide significance of sediment transport in this catchment, and its possible role in exacerbating floods and causing problems for agriculture, the remainder of this paper is devoted to the construction of a sediment budget.

Such an accounting of the sources and sinks of sediment in the catchment will provide a framework for scientific synthesis and analysis, and as a basis for both policy development and improvement of the budget.

## A sediment budget

A sediment budget for a river catchment is usually presented as rates of sediment production from source soils and bedrock, specified by process (e.g. sheet and rill erosion, gully erosion, landsliding, channel erosion and glacial processes); rates of deposition in sinks, specified by landform or landscape element (e.g. colluvium, alluvial fan, floodplain, channel bed/bars); and finally the rate of loss from the catchment, usually called the yield<sup>13</sup>. The sources and sinks ideally should be spatially defined.

The soil, sediment and rocks of the catchment are most simply divided into three categories for the purpose of budgeting: the Peninsular (or Shield) to the south of the catchment; the Himalaya; and the Plain including the delta. Estimates of the output from the soils and rocks of the Peninsular consist mainly of calculations using the Universal Soil Loss Equation (USLE) and some results of sheet and rill erosion rate measurement<sup>14</sup>. There are also a few estimates of gully erosion rate, and transport rates of sediment in some rivers are also known<sup>15</sup>. Estimates are also available for sheet and rill erosion on the Plain and for the Indian part of the Himalaya, and for landslide erosion rates, and river sediment flows in the Himalaya and on the Plain<sup>14,15</sup>.

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The various estimates of losses from sources and of sediment transport have been previously used to infer which sources are eroding fastest, the location of these sources, where the largest flows occur, and, by correlation and deduction, the respective roles of natural processes and land use in the fluxes of sediments<sup>15</sup>. But there has not been a systematic attempt to identify either the major components of a basin-wide budget, or which component is adequately quantified and thereby define where additional data are required.

The sources in the Ganga Basin lose material by sheet and rill erosion, channel processes (including glacier lake-burst floods, GLOFs, and landslide lake-burst floods, LLFs), gullying, landslides and other mass movements, glacial erosion, and aeolian processes. The sinks gain material by: settling of fines from water and, in the case of dust, from the atmosphere; cessation of bedload flow in channels; deposition on hillslopes by landslides; glacial deposition; and by density currents on the Bengal Fan.

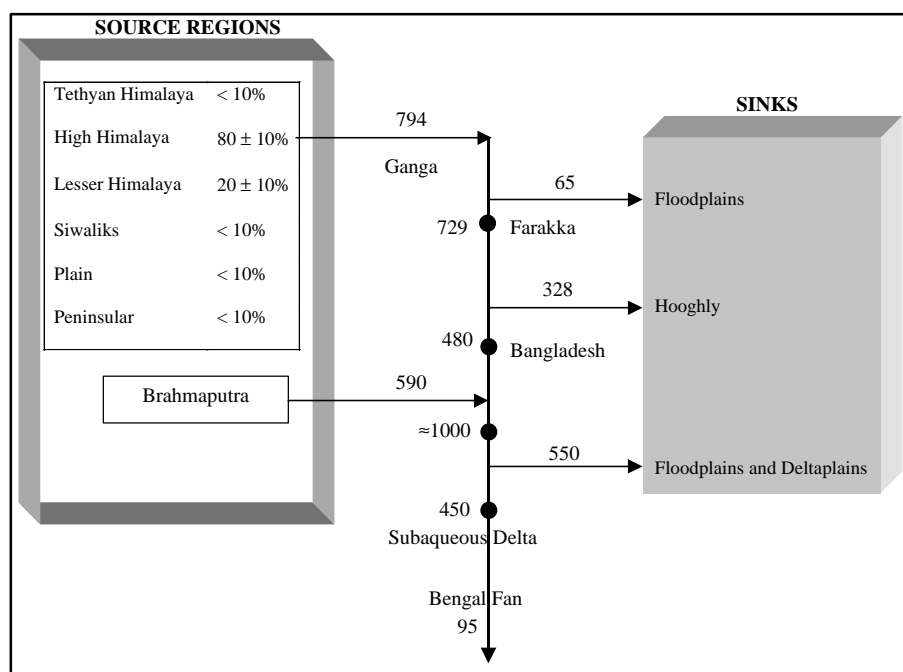
Major source regions are identified in Figure 1, based upon this author's current geomorphic understanding, and upon the major geochemical provinces of the basin that can be identified by tracers (see below). The major source regions are subdivided in the Himalaya into the Tethyan, High, and Lesser. The Siwalik foothills are also identified. The Plain includes all of the alluvium of the Ganga–Brahmaputra system, and the Peninsular is at this

time not subdivided. The major sinks are also shown on the figure.

The major source regions are topographically and lithologically distinct, and some erosion and transport processes are confined to particular regions. The major features and erosion processes are given in Table 1. At the sub-catchment scale, lithological, topographic differences, and tectonic features such as shear zones and faults contribute to spatial variations in erosion processes and rates. But insufficient data exist at the Basin scale to quantify these relationships, although some evidence can be drawn upon to reach tentative conclusions. It is important to link rates of loss from sources, and rates of accumulation in sinks, to processes so that soil conservation and land use adaptation can be identified at an appropriate spatial scale.

### Quantifying the sediment budget

The mean annual flows of suspended sediment in the basin are known for some rivers, although often on the basis of perilously few samples. The total measured flow of suspended sediment in the tributaries to the Ganga River is  $488 \times 10^6$  t/yr (Figure 1), while the quantity of sediment moving in the Ganga at Farakka, near the Bangladesh border, is  $729 \times 10^6$  t/yr of which  $328 \times 10^6$  t/yr is transported down the Hooghly River, a dis-



**Figure 1.** A suspended sediment budget for the Ganga–Brahmaputra Catchment. Flows are  $10^6$  t/yr. The percentage contributions from the source regions in the Ganga Tributaries are based on Nd/Sr tracers for the High and Lesser Himalaya, and for the remainder it is assumed that they are less than the errors on the tracer-based estimates. The amount coming from the Tethyan Himalaya is unknown, but maybe less than that from the Plain. The bedload in this system is estimated to be between  $600$  and  $2500 \times 10^6$  t/yr.

**Table 1.** Major features and erosion processes in the sediment source regions of the Ganga Basin

Source region	Major features	Major erosion processes
Tethyan Himalaya	Sedimentary and volcanic rocks, moderate to high relief; grazing	Sheet and rill erosion, channel erosion, glaciation, landslides
High Himalaya	Crystalline rocks, steep slopes; high relief; little forest; extensive grazing	Landslides, glaciation, channel erosion, sheet and rill erosion, GLOFs and LLFs
Lesser Himalaya	Sedimentary and metasedimentary rocks; steep slopes; moderate to high relief; forested in part; cultivation, grazing and forestry.	Landslides, sheet and rill erosion, channel erosion, LLFs
Siwaliks	Sedimentary rocks, often partly lithified; steep slopes, moderate to low relief; forested in part; cultivation, grazing and forestry	Landslides, sheet and rill erosion, channel erosion
Plain	Unconsolidated alluvium and aeolian deposits; very gentle slopes and very low relief except along incised rivers; cultivation and grazing	Sheet and rill erosion, channel erosion, wind erosion
Peninsular	Sedimentary and crystalline rocks; moderate slopes and moderate to low relief; cultivation, grazing and forestry	Sheet and rill erosion, channel erosion, wind erosion

tributary of the Ganga<sup>16</sup>. In Bangladesh the Ganga carries  $440 \times 10^6$  t/yr (ref. 3), and is joined by the Brahmaputra which transports  $540 \times 10^6$  t/yr (ref. 3). The combined rivers transport  $980 \times 10^6$  t/yr to the Bay of Bengal, ~ 21% of which is deposited in the subaqueous delta and ~ 29% in the fan<sup>17</sup>. This differs markedly from an earlier estimate<sup>2</sup>.

Storage of sediment in sinks has been estimated from measurements of the active floodplain dimensions and estimates of deposition rate using IRSL dates from the floodplains of the Ghaghara, Ganga and Yamuna Rivers<sup>18</sup>. Also included are estimates of deposition on the N. Bihar Plains<sup>19</sup> and on the Ganga–Brahmaputra floodplain and delta in Bangladesh<sup>17,20</sup>.

If at least  $488 \times 10^6$  t/yr is provided by tributaries to the Ganga,  $65 \times 10^6$  t/yr is deposited on floodplains upstream of Farakka, and  $729 \times 10^6$  t/yr passes Farakka, then by difference  $306 \times 10^6$  t/yr is unaccounted for and must be added to the Ganga by tributaries for which measurements are not available. Therefore, only ~ 62% of the total tributary inputs have been measured.

Of the  $729 \times 10^6$  t/yr that passes Farakka,  $328 \times 10^6$  t/yr is lost down the Hooghly (a sink on Figure 1) leaving an estimated  $401 \times 10^6$  t/yr to pass into Bangladesh down the Ganga compared with  $440 \times 10^6$  t/yr measured in Bangladesh. The difference is unlikely to be significant, given errors in these estimates. There must also be some deposition on floodplains between Farakka and the gauging station in Bangladesh. The Brahmaputra in Bangladesh adds a further  $540 \times 10^6$  t/yr, giving a total of  $980 \times 10^6$  t/yr (rounded to  $1 \times 10^9$  t/yr in Figure 1)<sup>17</sup>. If  $550 \times 10^6$  t/yr is being deposited on the Bangladesh floodplain and delta plain<sup>17,20</sup>, then  $450 \times 10^6$  t/yr is reaching the subaqueous delta and fan. Of the  $450 \times 10^6$  t/yr, ~ 21% ( $131 \times 10^6$  t/yr) reaches the fan<sup>17,20</sup>. This modern rate of fan accumulation is only ~ 20% of the rate over the last  $17 \times 10^6$  years (ref. 4), showing that in the past there have been higher rates of transport. Over

the last 7,000 years, however, deposition on the floodplain and delta plain has been 26% higher than the modern rate; ~  $40 \times 10^6$  t/yr compared with  $554 \times 10^6$  t/yr (ref. 17).

A chemical budget indicates that the total erosion of the Himalaya is 60–350% higher than the measured flux of suspended sediment in the Ganga–Brahmaputra<sup>21</sup>; that is,  $1600$ – $3500 \times 10^6$  t/yr. But this conclusion assumes that there is no input from either the Peninsular or Plains, and so all that can be concluded is that the flow of total sediment in the combined rivers is much higher than currently believed. The chemical budget does not discriminate between sediment coming from the Himalaya and Plains, because most of the sediment from the Plains has come from the mountains, and so is chemically indistinguishable; and the Peninsular sediment component in the Ganga alluvium cannot be chemically distinguished because it is a small fraction of the total.

The large difference between the total sediment flow estimated in ref. 21 from a chemical mass balance and the measured suspended load must be partly the result of the bedload flux which is unmeasured. It might also be a result of errors in the estimated suspended load. For example, the suspended loads in the Ganga and Brahmaputra total ~  $1000 \times 10^6$  t/yr, but another estimate of this total is  $1620 \times 10^6$  t/yr (ref. 2). If we assume that  $1000 \times 10^6$  t/yr is an accurate estimate of the suspended load, then bedload is  $600 \times 10^6$  t/yr, or ~ 38% of the total, at least. At the other extreme, bedload is  $2500 \times 10^6$  t/yr, or ~ 70% of the total load.

### Sediment source regions

The next question to ask is: where does the sediment come from? The Peninsular rivers on average transport 2.5% of the rivers that rise in the Himalaya<sup>15</sup>. Therefore, given the errors on all estimates of sediment flux, the

Peninsular rivers will no longer be considered here. Rivers rising in the Himalaya begin their descent in the Tethyan (or Trans), High, Lesser Himalaya, or in the Siwalik Hills at the foot of the Himalaya. All of the estimates of suspended load reported in refs 11, 15, 16 have been classified into groups according to where the rivers rise.

There are seven reliable estimates of suspended load at or near the mountain front for rivers rising in the High Himalaya. An equation relating mean annual specific yield ( $Y$ , t/km<sup>2</sup>/yr) to catchment area ( $A$ , km<sup>2</sup>) for 100,000 <math>A > 500 \text{ km}^2</math> is  $Y = 36,381A^{-0.31}$ .

This is not a significant relationship ( $r^2 = 0.36$ ) but it provides the only possible estimate using 'traditional' measurements of the flux from the high mountains. It also shows the usual decline of  $Y$  with  $A$ , indicating both the large contribution to streams of sediment from small, steep catchments, and downstream storage in floodplains and channel sinks. This equation excludes an estimate of load in the Ganga at Hardwar<sup>16</sup> which at  $14 \times 10^6$  t/yr is anomalously low. The equation suggests that this quantity should be  $\sim 100 \text{ t} \times 10^6$  t/yr. At Rishikesh, only a few kilometres upstream of Hardwar, another estimate of  $33 \times 10^6$  t/yr is available<sup>21</sup>, although its accuracy is uncertain.

Loads for rivers rising in the Tethyan Himalaya are very few in number, but appear to be  $\sim 25$  times smaller than those rising in the High Himalaya. Lesser Himalaya river loads are comparable with the average load from the High Himalaya, but  $\sim 2$  times less than maximum High Himalaya loads. Siwaliks rivers carry between 6 and 2 times less than High Himalaya streams, and the two estimates for Plains rivers are 4 to 9 times less than High Himalayan loads.

From these very limited data, the spatial sources of sediment in the Himalaya and Siwaliks are, in order of significance: High Himalaya, Lesser Himalaya, Siwaliks, Plains, and Tethyan Himalaya.

### Sediment source types

Measured sediment loads and hillslope erosion rates on plots and from small catchments in various parts of the Himalaya are also limited in number and spatial coverage. The available data are summarized in Table 2. While these results suggest that mass movements (landslides, debris flows) and rockfall, rock glaciers, glaciers and glacial outwash yield most sediment, the spatial significance of each process and land-type is unknown except in some small catchments; and the quantitative significance of extreme processes (such as GLOFs and LLFs) is uncertain.

To illustrate the difficulty of the problem of deriving catchment-wide sediment production rates, the data in Table 2 have been applied to mapped land types in the

Patalganga, Garudganga and Birahiganga catchments in Garhwal, on the boundary of the Lesser and High Himalaya in the upper Ganga catchment in India<sup>22</sup>. This area is in the Chamoli District and the location of the 1999  $M_s$  6.6 earthquake, the 1894 and 1970 LLFs, and is on the Main Central Thrust, an area of shattered rock believed to be highly susceptible to landsliding. It is also an area where large-scale deforestation occurred between 1959 and 1969, one result of which, it is argued, was the 1970 LLF and Alaknanda flood<sup>22</sup>.

The results of this calculation are given in Table 3. The range of sediment production values (t/yr) reflects the range of estimates in Table 2. At both extremes of the ranges, glacial outwash dominates the production of sediment, and therefore even large changes in the area of forest will have a negligible effect on the overall sediment budget. But these calculations highlight the need to know which of the values in Table 2 apply to which parts of the Chamoli catchments, and particularly the accuracy and spatial representativeness of the single estimate of glacial outwash<sup>23</sup>. To properly gauge the role of land cover change in sediment production in these catchments, it is, paradoxically, necessary to focus on the rate of sediment production by glacial outwash, and erosion of the grassland area.

The total sediment production for these Chamoli catchments is between 840 and 2200 t km<sup>-2</sup> yr<sup>-1</sup> (Table 3) compared with 4000 t km<sup>-2</sup> yr<sup>-1</sup> in the Alaknanda River which these catchments join<sup>24</sup>. Another source of data for

**Table 2.** Ranges of measured sediment yields from plots and small catchments in the Himalaya

Land type/process	A	t km <sup>-2</sup> yr <sup>-1</sup>	Ref.
Forests*	< 1 km <sup>2</sup>	20–150	14, 15
Cultivated and terraced*	< 1 km <sup>2</sup>	250–6440	14, 15
Pasture*	< 1 km <sup>2</sup>	40–4000	14
Landslides	1–2 km <sup>2</sup>	600–8600	14, 32
Debris flows	0.08–1.8	2300–11,000	32
Rock glaciers	< 1 km <sup>2</sup>	$7.1 \times 10^6$	44
Debris on glaciers	145	$1.2 \times 10^7$	44
Rockfall	50	$1.2 \times 10^7$	44
Glacier outwash	10	15,000	23

\*Mostly eroded by sheet and rill processes.

**Table 3.** Calculated sediment production in small catchments of Chamoli District, Garhwal

Land type	km <sup>2</sup>	t/yr	% of sediment
Forest	24.16	4,800–36,000	3
Grassland	56.56	2,300–226,000	22
Agriculture	14.82	7,700–95,000	9
Wasteland	10.14	100–41,000	4
Landslides	13.26	8,000–114,000	10
Glaciers	18.25	275,000	52
Total	137.19	298,000–787,000	100

comparison comes from former Gona Lake in the Birehiganga catchment. The lake was created in 1894 by a landslide of limestone and dolomite of  $56 \times 10^6$  t (ref. 25). The lake received  $\sim 1.2 \times 10^6$  t/yr of sediment between 1894 and 1936, based on observations of lake dimensions in the two years 1894 and 1936. When examined just prior to the breach in 1920 (ref. 9), the lake's dimensions show a net sedimentation rate of  $3.6 \times 10^6$  t/yr between 1936 and 1970. These two estimates, presented as specific yield, are  $4400 \text{ t km}^{-2} \text{ yr}^{-1}$  and  $13,000 \text{ t km}^{-2} \text{ yr}^{-1}$  respectively. The rate of sedimentation, which is a minimum value for sediment yield from the upper catchment of the Birehiganga (because of loss of sediment from the lake), is three times higher in the latter period than in the former. Was this caused by the deforestation between 1959 and 1969, or, for example because of change in the outwash of glaciers? Currently available data do not allow an answer.

The 1894 landslide produced, in a brief period, between 70 and 188 times the mean annual sediment production calculated from estimates in Table 3. The 1970 rainstorm produced  $3.4 \times 10^6$  t of sediment from the area considered in Table 3 (ref. 9), which is between 4 and 11 times the mean annual sediment production.

These figures, and those discussed in the preceding paragraphs, show the need for comprehensive sediment budgets, resolved both in space and time, before any attempt can be made to properly assess the effect of land cover change on erosion in the Himalaya. A few such budgets are available.

In the Lesser Himalaya near Pokhara, Nepal, the catchment of Phewa Tal of  $117 \text{ km}^2$  yields  $914 \text{ t km}^{-2} \text{ yr}^{-1}$  (ref. 26). Between 6 and 10% of this sediment comes from surface erosion by sheet and rill processes<sup>27</sup>. Erosion has increased in the catchment along with the expansion of agriculture in the early to mid 1900s (ref. 26). In the Lahore catchment of the Lesser Himalaya of W. Nepal, an area of  $0.65 \text{ km}^2$ ,  $\sim 17\%$  of total erosion is by sheet and rill processes<sup>28</sup>. At Pipal Chaur ( $0.55 \text{ km}^2$ ), also in the Lesser Himalaya of Nepal, about one third of total erosion is by landsliding, although this figure could be as high as 60% (ref. 15), the remainder coming from surface and channel erosion. Of the small  $12 \text{ t km}^{-2} \text{ yr}^{-1}$  deposited in Khecheopalri Lake in Sikkim, it is claimed that most comes from sheet erosion of agricultural land, with forest and cardamom agroforestry yielding much less; but there is no estimate of channel erosion<sup>29</sup>.

Landslides are clearly an important source of sediment in the Himalaya, but the cause of landsliding is often obscure, as demonstrated in the case of the Birehiganga catchment. Factors implicated in landslide size, site and frequency are relief, slope, rock type and fracturing/faulting, drainage, vegetation cover, microclimate, and location of roads<sup>30,31</sup>. Many landslides occur as a result of road construction<sup>9</sup>; but are these quantitatively significant? Once again, a catchment-wide budget is required to

answer this question. While such budgets are rare, one study has quantified the effect of roads, footpaths, and agricultural terrace construction on landslide quantity<sup>32</sup>. Approximately two-thirds of the landslides produced in 1999 are affected by human activities in an area of  $225 \text{ km}^2$  in the upper Ganga catchment, amounting to between 140 and  $1400 \text{ t km}^{-2} \text{ yr}^{-1}$ .

These few sediment budgets from small catchments are not adequate to determine the dominant processes of erosion, and the spatial location and types of sources being eroded, so as to determine the major controls on sediment flows in the lowland rivers of the Ganga–Brahmaputra system. The 'traditional' methods used to construct budgets are unlikely to yield adequate results for large tracts of the Himalaya and Siwaliks, without a vastly increased research effort. Sediment source tracers are therefore required, a field of investigation that has only recently begun in this region.

The major litho-tectonic units of the Himalaya which are the same as the major topographic zones used in this paper, can be distinguished by their  $eNd$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  contents as follows: the Tethyan Sedimentary Series (Tethyan Himalaya); the High Himalaya Crystalline Series (High Himalaya); and the Lesser Himalaya Series (Lesser Himalaya)<sup>33–35</sup>. The Siwaliks geochemically overlap the High Himalaya, showing that these foreland sediments are largely derived from the High Himalaya. Most of the sediments in the Bengal Fan have also been derived from the High Himalaya, since  $23 \times 10^6$  years ago when it is believed the high mountains were uplifted and the crystalline rocks exposed by erosion<sup>33</sup>. Modern bedload and suspended sediment in the Brahmaputra and Ganga, and surface floodplain sediment in Bangladesh, show that the High Himalayan Crystalline unit is the ultimate main source, with 10–20% from the Lesser Himalaya in the Ganga. The Tethyan Himalaya contribute some of the modern Brahmaputra's load<sup>21,34</sup>. Because the High Himalaya, Siwaliks and modern alluvium have very similar geochemical 'fingerprints', it is not possible to estimate the proportion of the modern sediment derived from the High Himalaya, and the Siwaliks. However, a substantial increase in recent times of sediment coming from the Lesser Himalaya would be geochemically detectable in the Bengal Fan. This is not the case. Sampling of river sediments from the High Himalaya to the Plains will be required to resolve this critically important matter.

The final source to be discussed is the alluvium of the Plains. Sheet and rill erosion of the low gradient surface of the Plains is surprisingly high; between  $500$  and  $1000 \text{ t km}^{-2} \text{ yr}^{-1}$ , with ravine (gully) lands yielding  $\sim 3000 \text{ t km}^{-2} \text{ yr}^{-1}$  along river terrace margins<sup>14,36</sup>. But there are no estimates of the Sediment Delivery Ratio for these parts of the Ganga Basin. However, in the Burhi–Gandak river system, the suspended load of the river increases downstream on the Plain. Some  $9 \times 10^6$  t/yr are

added to the river between Sikanderpur and Rosera at a specific yield of  $8400 \text{ t km}^{-2} \text{ yr}^{-1}$  from the Plain surface and, presumably, from bank erosion<sup>37,38</sup>. The Kamla-Balan River at Jhanjharpur transports  $2650 \text{ t km}^{-2} \text{ yr}^{-1}$  (ref. 37, 38), all from sources on the Plain. These differences probably reflect the rate of lateral reworking of riverbanks, variation in delivery of sediment eroded from the Plain surface, and pulses of sediment along the channels. So these yields reflect more than just Plain sources. Once again, there is a need for source tracer studies on the Plain, in this case using the topsoil tracers  $^{210}\text{Pb}$  (excess) and  $^{137}\text{Cs}$ .

The final sink to be considered is the accumulation of bedload in the main channels of the Plain. The proportion of the active channels of the Ganga occupied by braid bars increased between 1911 and 1967 at Bijnor and Kanpur, but decreased at Baksar<sup>39</sup>. On the Ghaghara, the area has increased from 53 to 77% between 1964 and 1992 (ref. 40). Tributaries of the Ghaghara have migrated upstream, also indicating bed aggradation<sup>40</sup>. Neither the change in channel capacity resulting from this postulated aggradation nor the rate of aggradation have been estimated.

The causes of the aggradation are not clear, but include increased sediment delivery to the channels and/or neotectonic deformation of the channels. Increased sediment delivery could result from increased erosion in the mountains or on the plains, possibly induced by a period of seismic activity, climatic variation, or land use change. Tectonic deformation of the plain would induce aggradation in downwarped areas and incision in upwarped areas<sup>41</sup>.

## Conclusions

A suspended sediment budget for the Ganga-Brahmaputra catchment shows that of the  $794 \times 10^6 \text{ t/yr}$  transported in the rivers of the Ganga catchment,  $80 \pm 10\%$  comes from the High Himalaya,  $20 \pm 10\%$  from the Lesser Himalaya and the proportions from the Tethyan Himalaya, Siwaliks, Plain, and Peninsular while unknown are each likely to be  $< 10\%$ . About 8% of the river sediment is deposited on floodplains and deltaplains in Bangladesh. The remaining  $\sim 45\%$  is deposited in the subaqueous delta and the Bengal Fan.

The Plain rivers, like the floodplains, in the Ganga catchment appear to be aggrading, thereby exacerbating the annual overbank flood. Aggradation may be the result of enhanced sediment delivery to the rivers as a result of land use, rainfall change, or neotectonics in the Himalaya. Or the aggradation could be caused by neotectonics on the Plain, warping the riverbed.

The relationship between land use, erosion, and sedimentation is not clear, despite many decades of research. The only substantive progress made since the 1980s is

the identification of the High Himalaya as the likely dominant source of sediment; based on Nd/Sr tracers. This result, which still requires testing, implies that high altitude grazing, forest management, limited cultivation, and road building in the High Himalaya could all play a role. Limited data suggest that up to two thirds of landslide debris is in some way produced by human activity but the proportionate contribute of this source to river loads is unclear.

Much is yet to be learned about this globally important catchment. It deserves coordinated and concentrated policy-oriented research beginning with the application of sediment source tracers to better define those areas where detailed studies of the role of land use will yield regionally useful results.

- Ludwig, W. and Probst, J. L., *Am. J. Sci.*, 1988, **298**, 265–295.
- Milliman, J. D. and Meade, R. H., *J. Geol.*, 1983, **91**, 1–21.
- Milliman, J. D. and Syvitski, J. P. M., *J. Geol.*, 1992, **100**, 525–544.
- Curray, J. R., *Earth Planet. Sci. Lett.*, 1994, **125**, 371–383.
- France-Lanord, C. and Derry, L. A., *Geochim. Cosmochim. Acta*, 1994, **58**, 4809–4814.
- Subramanian, V. and Ittekkot, V., in *Biogeochemistry of Major World Rivers* (eds Degens, E. T. et al.), John Wiley, 1991, pp. 157–168.
- Eckholm, E., *Losing Ground: Environmental Stress and World Food Prospects*, Norton, New York, 1976.
- Saberwal, V. K., *Pastoral Politics*, Oxford University Press, Delhi, 1999.
- Floods, Flood Plains and Environmental Myths*, CSE, Delhi, 1991.
- Hofer, T., *Floods in Bangladesh. A Highland–Lowland Interaction?* Institute of Geography, University of Berne, Switzerland, 1998.
- Ives, J. D. and Messerli, B., *The Himalayan Dilemma, Reconciling Development and Conservation*, Routledge, London, 1989; Tiwari, K. M., *Indian For. Rec.*, 1984, **3**, 14.
- Mirza, M. M. Q. and Dixit, A., *Water Nepal*, 1997, **5**, 71–100.
- Trimble, S. W., *Am. J. Sci.*, 1983, **283**, 454–474.
- Narayana, D. V. V. and Babu, R., *J. Irrig. Drainage Eng.*, 1983, **109**, 419–434.
- Bruijnzeel, L. A. and Bremmer, C. N., *Highland and Lowland Interactions in the Ganges Brahmaputra River Basin: A Review of Published Literature*, ICIMOD Occasional paper No. 11, Kathmandu, 1989, p. 136.
- Abbas, N. and Subramanian, V., *J. Hydrol.*, 1984, **69**, 173–182.
- Goodbred, S. L. and Kuehl, S. A., *Geology*, 1989, **27**, 559–562.
- Rao, M. S., Bisaria, B. K. and Singhvi, A. K., *Curr. Sci.*, 1997, **72**, 663–669.
- Sinha, R., Friend, P. F. and Switsur, V. R., *Geol. Mag.*, 1996, **133**, 85–90.
- Goodbred, S. L. and Kuehl, S. A., *Sediment. Geol.*, 1998, **121**, 239–258.
- Galy, A. and France-Lanord, C., *Geology*, 2001, **29**, 23–26.
- Kimothi, M. M. and Juyal, N., *Int. J. Remote Sensing*, 1996, **17**, 1391–1405.
- Hasnain, S. I. and Thayyen, R. J., *J. Hydrol.*, 1999, **218**, 191–198.
- Sinha, R., Das, S. and Dikshit, O., *Z. Geomorphol.*, 2001, in press.
- Heim, A. and Gansser, A., *Central Himalaya Geological Observations of the Swiss Expedition*, Hindustan Publ. Co., Delhi, 1939.
- Ross, J. and Gilbert, R., *Geomorphology*, 1999, **27**, 307–323.

27. Euphrat, F. D., quoted in ref. 15.
28. Carson, B., *Erosion and Sedimentation Processes in the Nepalese Himalaya*, ICIMOD Occasional Paper, 1985, p. 39.
29. Jain, A., Rai, S. C. and Sharma, E., *Catena*, 2000, **40**, 263–278.
30. Naithani, A. K., Prasad, C., Bisht, M. P. S. and Kumari, G., *Himalayan Geol.*, 1997, **18**, 135–143.
31. Haigh, M. J., Rawat, J. S., Bartarya, S. K. and Rawat, M. S., *Trans. Jpn. Geomorphol. Union*, 1993, **14**, 99–123.
32. Barnard, P. L., Owen, L. A., Sharma, M. C. and Finkel, R. C., *Geomorphology*, 2001, **40**, 21–35.
33. France-Lanord, C., Derry, L. and Michard, A., in *Himalayan Tectonics* (eds Treloar, P. J. and Searle, M. P.), Geological Society Spl. Publ., 1993, pp. 603–621.
34. Huyghe, P., Galy, A., Mugnier, J. L. and France-Lanord, C., *Geology*, 2001, **29**, 1007–1010.
35. Ahmad, T., Harris, N., Bickle, M., Chapman, H., Bunbury, J. and Prince, C., *Geol. Soc. Am. Bull.*, 2000, **112**, 467–477.
36. Singh, G., Babu, R., Narain, P., Bhushan, L. S. and Abrol, I. P., *J. Soil Water Cons.*, 1992, **47**, 97–99.
37. Sinha, R. and Friend, P. F., *Sedimentology*, 1994, **41**, 825–845.
38. Jain, V., Ph D thesis, IIT, Kanpur, 2000.
39. Singh, M., *The Ganga River: Fluvial Geomorphology Sedimentation Processes and Geochemical Studies*, Heidelberger Beitr. Umwelt-Geochmie 8, 1996.
40. Tangri, A. K., in *Fluvial Geomorphology with Special Reference to Floodplains* (ed. Sinha, R.), IIT, Kanpur, pp. 3–1 to 3–12.
41. Schumm, S. A., Dumont, J. F. and Holbrook, J. M., *Active Tectonics and Alluvial Rivers*, 2000, CUP.
42. Sen, K. K., Rao, K. S. and Saxena, K. G., *Int. J Sustainable Dev. World Ecol.*, 1997, **4**, 65–74.
43. Watanabe, T., Dali, L. and Shiraiwa, T., *Geomorphology*, 1988, **26**, 185–198.
44. Barsch, D. and Jakob, M., *Geomorphology*, 1998, **26**, 215–222.

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