Factors controlling variations in river sediment loads

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Sediment transfer from continents to oceans via rivers is one of the important processes regulating river-bank stabilization, soil formation, biogeochemical cycling of elements, crust evolution and many other earth-related processes. Due to changes in continental positions during the geologic past, water flow and sediment loads in rivers have also shown variations during different time periods. Recent estimations budget sediment flux from rivers to oceans of about 18×10^9 tons annually. However, it is estimated that the present-day sediment load in rivers has been greatly altered due to large-scale human perturbations. Factors such as relief, channel slope, basin size, seasonality of rains and tectonic activities control sediment loads in rivers. Human interventions in the form of reservoirs for water storage have impounded and trapped huge sediment loads on the continental parts. Similarly, land use patterns also had their effects on sediment flux to the oceans. Rivers flowing over the Pacific islands have large sediment yield as also the Himalayan rivers, Ganga and Brahmaputra, due to high relief and tectonic disturbances, whereas rivers in North America, China and Africa show decrease in sediment flux due to trapping of sediments in the reservoirs.

CONTINENTAL erosion and the subsequent transfer of these products to oceans play an important role in the understanding of many activities of global significance such as crust evolution, climate change, soil erosion/formation, uplift rates, continental processes, biogeochemical cycling of pollutants and nutrients, etc. The two fundamental processes of weathering, chemical and mechanical, act complementarily and result in dissolved and suspended loads respectively, in rivers which quantitatively represent the most important inputs to the oceans. Recent suggestions that creation of topography associated with orogenesis can significantly affect rates of chemical denudation and thereby perturb global carbon budget and consequently global climate, has further reinforced the need for a clear understanding of factors controlling denudation rates[1,2]. Although studies on dissolved river components and their implications are also important, the present article is aimed only at reviewing variations in river-suspended sediment load and flux globally.

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While it is difficult to estimate exactly the palaeoflux of sediment to the coastal oceans, Milliman and Syvitski[3] argue that the modern estimations of global sediment flux are at least 100% higher than 2000 years ago when human impact was less, in concurrence with the estimates by Hay[4] for the Holocene fluxes to marginal seas, which are typically 1.5–4 times higher than those for similar periods during the Pleistocene. The recent activities of man in changing river courses and setting obstacles against natural river flows have significantly altered natural mechanical erosion rates and sediment fluxes. Such interventions can have severe consequences for agriculture by loss of fertile soils. In estuaries and coastal zones which are major sinks for sediments, alteration of the natural river sediment supply can cause considerable changes on the metabolism in the coastal zone. Based on the flux data of 62 large rivers, Holeman[5] estimated the first comprehensive global sediment flux of 18.3 billion tons per year, which Holland[6] later revised to 20 billion tons per year taking into account bed load transport. Milliman and Syvitski[3] revised the estimate back to 18 billion tons per year, using the flux data of 280 rivers, that included small mountainous rivers as well as data from gauging stations located near the river mouths. Meade[7] cautions that these estimates are at best flux-calculated at most seaward gauging stations and may not exactly represent the true flux into oceans. Much of the sediments could also be deposited in the deltas between the most seaward gauging station and the open sea. In the case of the Amazon river, 20% of the annually delivered load (1 billion tons per year) is retained by its delta; the remaining 80% is deposited on the continental shelf and coast. In the case of the Himalayan rivers, Ganga and Brahmaputra, 55% of their combined annual sediment load (1.1 billion tons per year) is retained by their delta, with 36% reaching the shelf and 9% reaching the deep sea[8]. It is estimated that about 65% of the water and 80% of the sediment globally comes from southern Asia, Oceania and northeastern South America[9]. Martin and Meybeck[10] estimated that sediment-associated transport accounts for more than 90% of the total river-borne flux of heavy metals such as P, Ni, Mn, Pb, Fe and Al, since these immobile elements normally get associated with sediment fraction of the river components, whereas soluble elements like Ca, Mg, etc. get associated in the dissolved phase. Presently, rivers contribute 95% (Table 1) of sediments entering the ocean[8]. Thus knowing the average flux can help assess the impact of perturbations in the supply and transport of river load.

Evidences from long-term sediment load records indicate that river sediment fluxes are sensitive to many influences, including reservoir construction, land-use change, mining activity, soil and water conservation measures, sediment control programmes and climate change[11]. Summerfield and Hulton[1] analysed the influence of basin area, channel gradient, relief, mean annual run-off, run-off variability, mean annual temperature and mean annual precipitation on mechanical denudation rates in drainage basins exceeding 5×10^5 km^2 in area. Their observation indicates that, except for channel gradient and basin relief, other physical factors had no significant influence on mechanical denudation rates.

Run-off in geologic past

Long-period discharge fluctuations for 50 major rivers of the world were examined[12,13] to determine stream flow fluctuations since the Phanerozoic, on different continents based on continental size and latitudinal location. The global water cycle over the Phanerozoic (570 Ma), was established by analysis of distribution of rainfall, evaporation and run-off by bands of 10° lat, on the present-day earth, and then extrapolating these values to the Phanerozoic earth. The variables considered were the latitudinal positions of the continents and the relative areas of continents and oceans. Temperature–run-off increase was found to be more sensitive to temperature changes for river basins in humid regions than for those in the subarctic cold regions and warm semi-arid and contrasted regions. During the Cambrian both rainfall (1124 mm yr^{-1}) and evaporation (725 mm yr^{-1}) were the highest (Table 2), because the continents were located close to the equator. The Devonian period was particularly wet, and one of strong erosion, while the dry periods are close to the present day.

The mass–age distribution[14] indicates that the Cambrian, immediately preceding late Precambrian, the Carboniferous and the Permian have much less rock preserved per year of the respective time spans than do other periods. The total rock mass diminished with increasing age, thus indicating accelerated erosion of older rocks which followed a time cycle of about 350 million years. However, present-day rate of denudation of continents (156 tons/km^2/yr) is probably much higher than the average for the geologic past, since the continents are higher and the area of land exposed is greater than that during much of the rest of geologic time[15].

Table 1. Global estimate of flux of sediments from land to ocean[8]

Transport mechanism	Global flux (billion tons/yr)
Rivers: Suspended and bed load	18
Bed load	2
Dissolved load	5
Glaciers, sea ice, icebergs	2
Wind	0.7
Coastal erosion	0.4

Variable components

Rivers result from run-off of water from the continents. River water itself has primarily originated from precipitation, some of which is lost through evaporation, groundwater recharge, etc. On a global scale continental run-off, which includes dominantly river run-off and a small amount of direct groundwater discharge to the oceans, can be thought of as being equal to the excess of oceanic evaporation over precipitation. Hence, in order to have river run-off on a continental scale, there must be net precipitation on land[15]. Average continental evaporation rates are temperature-dependent and hence large rivers flow in temperate, equatorial and tropical zones, where the net tilt is towards precipitation compared to evaporation. In addition, geographical heterogeneity such as the presence of a landmass with high relief like the Himalayan mountains, also induces large river flows such as Ganga and Brahmaputra, which originate from the Himalayas (Table 3). Geographical differences in rainfall distribution arise primarily due to relief, with the windward sides of mountains receiving large amounts of rain and the leeward sides very little. Two distinct methods are used to estimate the mass of river sediments entering the oceans; one estimates the mass being carried oceanward by rivers, while the other method estimates denudation of the continents. Sediment loads based on the latter method are significantly greater than those based on the former, because they include a large amount of eroded sediments that never reach the oceans[16].

Sediment yield and controlling factors

Run-off

The amount of water discharged by the world rivers to the present-day oceans[17] is estimated to be between 32 and 37×10^3 km^3 yr^{-1}. Run-off or water flow of rivers does not necessarily indicate proportionate sediment load, as large rivers such as Amazon with high water flow carry less suspended sediments. The reason for this is that the Amazon river gets most of its sediment load from the Andes mountains, which constitute only about 10% of the river basin area[18] and not from the Brazilian lowlands. As a result, for such a large river, the Amazon does not have a particularly high sediment yield per unit area[15]. Water flow is important in determining the river energy and thus the scouring capacity of rivers, but it alone is not a deciding factor for sediment concentrations in rivers. Seasonality of water flow controls the sporadically high sediment loads in rivers. The small rivers in the Pacific island oceans are good examples of rivers carrying huge sediment loads. For example, the subtropical climate of Taiwan, with an average of four

Table 2. Global water cycle through the Phanerozoic[13]

Time period	Age (Ma)	Continental area (10^3 km^2)	Oceanic area (10^3 km^2)	Continental rainfall (10^{20} g/yr)	Continental evaporation (10^{20} g/yr)	Continental run-off (10^{20} g/yr)
Present	0.0	148, 904	361, 110	1.11	0.71	0.40
Cenozoic	34.0	143, 132	366, 882	1.21	0.75	0.46
Cretaceous	99.0	140, 450	369, 564	1.22	0.71	0.51
Jurassic	153.5	170, 337	339, 677	1.06	0.66	0.41
Triassic	201.0	187, 121	322, 893	1.12	0.69	0.43
Permian	252.5	175, 077	334, 937	1.04	0.63	0.41
Carboniferous	311.0	177, 697	332, 317	1.01	0.57	0.44
Devonian	371.0	152, 426	357, 588	1.04	0.55	0.49
Silurian	420.0	124, 993	385, 021	1.01	0.47	0.55
Ordovician	470.0	131, 600	378, 414	1.40	0.83	0.58
Cambrian	550.0	159, 321	350, 693	1.79	1.15	0.64

Table 3. Water and sediment discharge in some large rivers of the world[17]

River	Water discharge (km^3/yr)	Drainage area (10^6 km^2)	Sediment discharge (10^6 t/yr)	Sediment yield (t/km^2/yr)
Amazon	6300	6.15	1200	195
Colorado	20	0.64	0.01	0.02
Columbia	251	0.67	10	15
Congo (Zaire)	1250	3.72	43	12
Danube	206	0.81	67	83
Ganges/Brahmaputra	971	1.48	1060	716
Huang He	49	0.75	1050	1400
Indus	238	0.97	59	61
Mackenzie	306	1.81	42	23
Mekong	470	0.79	160	202
Mississippi	580	3.27	210	64
Niger	192	1.21	40	33
Nile	30	3.03	0	0
Orinoco	1100	0.99	150	152
St. Lawerence	447	1.03	4	4

typhoons per year and mean annual precipitation of 2.5 m per year, combined with frequent earthquakes, together drive rapid mass-wasting and result in high sediment flux in the rivers[19]. Sediment yield of some of the smaller rivers in the Pacific island oceans is enormous, as most of the sediment eroded from these basins is directly dumped into the adjacent seas, whereas large river basins store sediments in their channels as large rivers with large basin area and extensive river banks help in deposition of sediments on the channels at reduced flow. The suspended sediment discharge or denudation rates from various rivers indicate that large variations occur in sediment yield across rivers in different regions over the globe. The sediment yield of the Amazon river is much less compared to some of the smaller rivers in southern Asia (Figure 1). The large islands of the western Pacific Ocean produce enormous sediments in rivers due to active tectonic activities, volcanism, steep slopes, heavy rainfall and intense human activity. The sediment load of rivers in Taiwan (300×10^6 t yr^{-1}), although consists of smaller rivers, equals the total river sediment load from USA[15]. Hence, information on sediment load in smaller rivers gains enormous significance. Small rivers (drainage basins < 10,000 km^2) drain only about 20% of the land area, but they number in many thousands and collectively may contribute much more sediment[4].

Inman and Jenkins[20] observed a dry climate for southern California, extending from 1944 to about 1968, and a wet climate extending from about 1969 to the present, which resulted in dry periods characterized by low sediment flux. The wet period has an annual suspended sediment flux about five times greater than the dry period, caused by strong El Nino events that produce floods with an average recurrence of about 5 years. The average sediment flux out of southern Californian rivers during the three major flood years was 27 times greater than that during the 1944–68 dry climate period. These contrasting numbers indicate the flurry of heavy floods on the increased sediment loads in rivers.

Relief

Measurement of suspended sediment discharge divided by drainage area and corrected for dissolved load, bed load and flood discharge, results in an estimate of regional denudation. Numerous problems are associated with such estimates, the most important being that measurements commonly are based on samples collected from stations far off from the seas inward land, for lack of discharge measurement stations[12].

Many studies have pointed to the significant influence of basin elevation and morphology on river sediment fluxes, but only a few mathematical relationships are available. Pinet and Souriau[21] found river sediment fluxes to be linearly correlated with mean basin elevation. Looking mainly at river sediment yields of large world rivers, they proposed the following two equations to describe mechanical denudation globally:

$$D_s = 419 \times 10^{-6}\ \text{Elev} - 0.245$$
(regions related to orogenesis < 250 Ma),

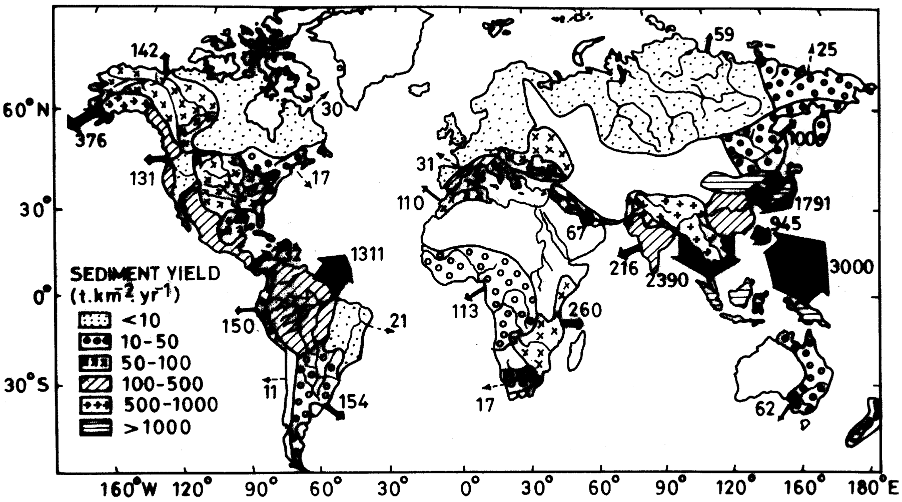

Figure 1. Sediment yield in global rivers[16].

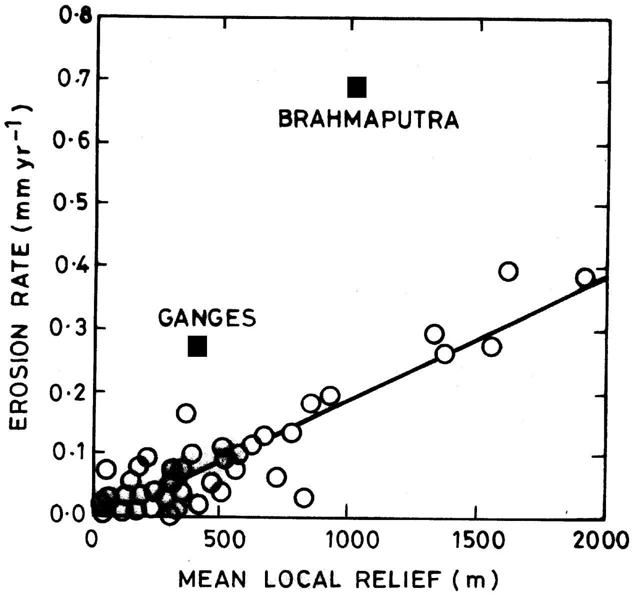

Figure 2. Relationship of local relief with erosion rates in river basins[19].

$D_s = 61 \times 10^{-6}$ Elev
(regions related to orogenesis > 250 Ma),

where D_s is the denudation rate in m kyr^{-1} and Elev is the mean basin elevation in metres. From the above, Ludwig and Probst[22] estimated that 5.2 billion tons yr^{-1} originated from old continental crust (73% of the total area), while 11 billion tons yr^{-1} originated from young continental crust (27% area). However, the high denudation rate in the young continental crust is also associated with high sedimentation rates as observed by the considerable intercept in the equation obtained for regions related to orogenies < 250 Ma. The high erosion rates in young continental crust is due to the relatively easy weatherability compared to the highly resistant old continental crust, and low relief and slope factors.

Relief is a major factor as it induces greater mechanical erosion[23]. Data of Ganga and Brahmaputra, which have their headwaters in the Himalayas, plot well above the trend defined by data of other rivers (Figure 2). Although factors such as lithology, climate, run-off and vegetation influence erosion rates, mean local relief is a primary control on erosion rates.

Milliman and Syvitski[3] sub-divided the 280 rivers studied by them globally on the basis of relief. These rivers together account for > 62×10^6 km^2 or about two-thirds of the land surface draining into the oceans. Five categories based on the maximum elevations are (i) high mountain (headwaters at elevations > 3000 m, (ii) mountain (1000–3000 m), (iii) highland (500–1000 m), (iv) lowland (100–500 m) and (v) coastal plain (< 100 m). Based on the studies of rivers categorized on the basis of elevations, mountainous rivers showed greater loads and yields.

Geology

The role of geology in mechanical erosion is less understood. However, the influence of lithology on mechanical erosion rates is probably high with respect to channel erosion, but less important with respect to hill slope erosion because the outcropping lithologies are normally covered with soils. Rivers flowing over crystalline terrains erode with difficulty, whereas unconsolidated sedimentary rocks yield greater sediment loads to rivers. The enormous sediment loads in the Huang He is due to the presence of yellow loess derived from the deserts in Mongolia, whereas the Ganga–Brahmaputra rivers carry huge sediment loads because they flow over the easily erodible carbonates and through the Himalayan terrains. Kattan *et al.*[24] estimated that in the Senegal river, 20% of the total river transport is derived from channel erosion. In the Taiwan orogen, despite low relief, highest erosion rates are observed where weak substrates occur[19]. A negative correlation between sediment yield and weathering history, as measured by the chemical index of alteration (CIA) of the suspended sediments, is observed for many of the world's major rivers. CIA is represented as the molar ratios of $[Al_2O_3/(Al_2O_3 + CaO + Na_2O + K_2O]*100$ as measured in sediments. Values of about 45–55 indicate virtually no weathering, whereas values of 100 indicate intense weathering with complete removal of the alkali and alkaline earth elements[25]. By assigning CIA values representative of unweathered (50) and extremely weathered (100) sources to extreme denudation values, a relationship was constructed between weathering and denudation:

$$\text{Sediment yield (t/km}^2\text{/yr)} = (2.25*10^5)(10^{-0.04335(\text{CIA})}).$$

The global river data were thus divided into three groups[17]. Many of the high-yield areas correspond to the negative sediment yield–weathering relationship and are consistent with weathering intensity, providing a first-order control on sediment yield. These areas are considered to have a sediment discharge that approaches an equilibrium with prevailing weathering conditions termed equilibrium denudation regions, whereas most of the other areas have sediment yield much lower than that predicted from the relationship; four areas (Huang He, Mekong, New Zealand, rivers of Oceanic Islands) are considered to have higher sediment yield, termed non-equilibrium denudation regions. The denudation of areas that deviate substantially from this relationship primarily can be understood in terms of natural and anthropogenic processes that accelerate or moderate erosion rates and provenance from easily eroded glacial debris that has not experienced a normal weathering history[17].

Basin area

Basin area alone is not a determining factor of sediment yield. Smaller basins generally exhibit steeper slopes and steeper stream gradients than large basins and thus aid in large sediment yields, whereas large basins show low slopes and low stream gradients, and hence result in low sediment output. Basin area integrates several factors such as gradient, storage capacity, etc. which influence sediment yields (Figure 3). Because of these variables controls, rivers draining only 10% of the world's drainage basins account for more than 60% of the sediment discharge to the oceans[26].

In undisturbed drainage basins from the western Southern Alps in New Zealand, high sediment yields, more than ten times the world average are reported[27], caused mainly due to steep catchments and rise in elevation from sea level to over 3000 m. Locally, the influence of certain rivers can have a great influence on the regional budget, as in the Ganga/Brahmaputra into the Indian Ocean, which show extremely high mechanical denudation rates compared to chemical denudation rates or the Huang He and Chanjiang rivers into the Pacific Ocean[22].

Temperature

Sediment discharge is related to basin relief, basin area and temperature by the relation[9]

$$Qs = aR^{3/2}A^{1/2}e^{kT},$$

where Qs is the long-term sediment load (kg/s), R is relief defined as the highest point of elevation (m) minus the elevation of discharge station (m), A is basin area (km^2), T is mean surface temperature of the drainage basin and k and a are constants (2×10^{-5} and 0.1331 respectively). Syvitski *et al.*[9] divided the known global river data into different climatic zones, polar, temperate and tropical based on the above formulation. Calculations based on this model indicate that the polar rivers with sub-zero temperatures show the lowest values in sediment yield (120 t/km^2/yr), whereas tropical rivers with temperatures of more than 30°C have extreme sediment yields (3648 t/km^2/yr).

Human influence

Among all the categories of human influences that alter sediment loads in rivers, none exerts as much influence as the reservoirs. Together with land-use changes, deforestation and soil conservation practices, the natural sedimentary cycle has been greatly altered. River impoundments provide important benefits to society through flood control, power generation, water storage and release for agriculture, industry and domestic supplies. The adverse environmental effects include dislocation of human populations, silting of reservoirs, reduced sediment flux to the oceans, downstream scouring of channels, life cycle and habitat of aquatic organisms, eutrophication, anoxia and toxic conditions. Between 1951 and 1982, large dams were being constructed at a rate of 900 per year[9]. A decrease in sediment load to the river through damming results in increase in coastal erosion and deterioration of coastal marine ecosystem. For example, after the Aswan Dam was completed in 1964, the sardine fish catch was reduced by 95% and the delta shrank rapidly[28]. Sediment discharge of the Colorado river decreased from about 125 million tons per year to 3 million tons per year owing to the construction of the Hoover dam[29]. Similarly, the Krishna river in India has sediment flux of $67,000 \times 10^3$ tons per year at Morvakonda, but damming of the river down-stretches has reduced the load to 4100×10^3 tons per year at its mouth at Vijayawada[30].

Vorosmarty *et al.*[31] estimate that 30% of the global sediment flux is trapped behind large reservoirs. Several large basins such as the Colorado and Nile show nearly complete trapping of sediments due to large reservoir construction and flow diversion. Humans are perennial dam-builders with present-day estimations of more than 45,000 registered dams over 15 m high in operation today worldwide[32], which is nearly an order of magnitude greater than that in

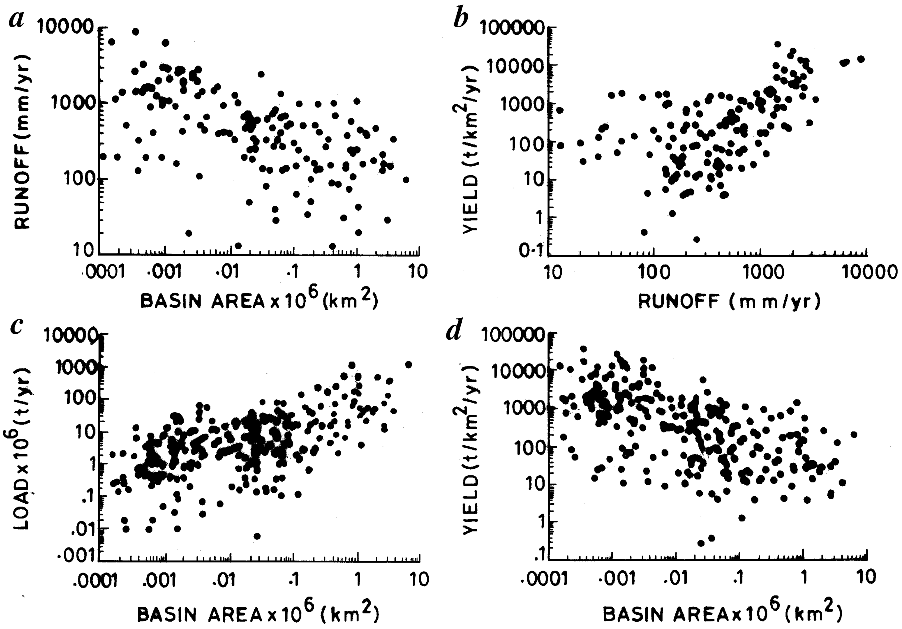

Figure 3. Physical parameters controlling sediments loads in rivers[23].

1950. Dam-building has resulted in a substantial distortion of freshwater run-off from the continents, thus increasing the residence time of water in the continents.

The effects of human activities on suspended sediment concentration during the late 20th century were examined at 57 sites along major rivers in central Japan[33]. Analysis of the relationship between mean sediment concentration and land use has revealed that patterns in suspended sediment concentrations in these rivers are primarily linked to agricultural land, construction work and domestic and industrial effluent sources in populated areas, whereas natural erosion in steep areas plays only a limited role. Deforestation and cultivation of hill sides were the main causes for the increase of ~ 10% in sediment discharge in the Yangtze river[34]. Dedkov and Mozzherin[35] argue, that the Mediterranean landscape may be the most human impacted drainage area in the world wherein around 75% of the average sediment yield (1100 t/km^2/yr) of Mediterranean headwater river basins may have been contributed by human activities.

Future trends

Over the next hundred-year period, sea-level fluctuations may not greatly impact the drainage areas of rivers[36], but on higher order timescales, the futuristic assessment may not be encouraging. The water balance in the tropical regions may not be manifested in large-scale changes in topography or climate; however, in permafrost regions such as the arctic, there could be large-scale release of stored water. It is difficult to assess the impact of changes in the sediment flux to the coastal zone, because of the conflicting impacts of humans. Globally, soil erosion is accelerating (deforestation, agriculture practices), while at the same time sediment flux to the coastal zone is globally decelerating (water diversion schemes, dams). Reduced loads delivered to the coastal zone result in accelerated coastal erosion and a decrease in habitat. Thus, understanding sediment discharge across a broad timescale allows for better predictions of the impact of humans[37].

The disadvantage associated with global flux estimates is that most of the observed data are based on estimations derived for a few years and from a few locations. In many cases, either rivers are not being monitored on a regular basis or where the monitoring has been satisfactory, data are not disseminated because of conflicting national interests. Improvizations on the inter-annual and intra-annual observations in river basins need to be focused upon more seriously. Much of the sediment carried by rivers does not make it to the seas. It gets flocculated or aggregated in the estuarine region. Except for large rivers such as Ganga–Brahamaputra or Mississippi, which discharge significant amounts of their sediments beyond the shelf break[38], many of the other major and medium rivers on plain lands store sediment on the river banks or often flood into the adjacent agricultural fields and return subsequently to the main channel after considerable time. With the exception of Arctic rivers, where human civilization has had a minimal impact, most other rivers reflect the results of human activity on the erosion capacity of the rivers, both through deforestation and poor soil conservation[39]. A few degrees rise in temperature in the permafrost regions could convert solid ice to liquid water and increase the denudation rates in the arctic regions. Sea-level rise would have a major consequence on the marginal marine environments such as estuaries, coastal lagoons and mangrove ecosystems. However, in the absence of lesser flux of water and sediment to the coastal seas, estuaries show reduction in volume as has been observed in the Mersey estuary, UK[40].

The future flux of sediments to the coastal oceans will continue to be influenced by humans and/or climate change. To understand the balance between sediment erosion and retention and the exact nature of flux of sediments, is of utmost importance for sound and sustainable management of coastal zones. We need time-series data to determine trends with particular attention during the last 50 years and more focused research on the behaviour of the river systems, both present and past.

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