these platforms and much of this information is being made online to students around the world, in addition to the scientists that use the data.

Summary

Offshore structures are concentrated in areas of oil and gas development off most coastal countries of the world. Platforms will be a common sight along the world's coastlines for as long as hydrocarbon resources are present. Although the industry provides the energy to fuel the world, the presence of offshore structures has both positive and negative impacts concerning pollution, navigation, and fisheries production. Current development and research is being implemented for the best use of offshore structures concerning these issues. Offshore structures are the result of remarkable feats of engineering, and engineers are continually challenged in the design and in the removal guidelines within the constraints of current technology.

See also

Acoustic Scattering by Marine Organisms. Coral Reef Fishes. Coral Reefs. Demersal Fishes. Metal Pollution. Oil Pollution. Pelagic Fishes.

Further Reading

American Petroleum Institute (1995) *Impact on U.S. Companies of a Worldwide Ban on Disposal of Offshore Oil and Gas Platforms at Sea*. IFC Resources Inc.

Boesch DF and Rabalais NW (1987) *Long-term Environmental Effects of Offshore Petroleum Development*. New York: Elsevier Applied Science.

Love MS, Nishimoto M, Schroeder D and Caselle J (1999) *The Ecological Role of Natural Reefs and Oil and Gas Production Platforms on Rocky Reef Fishes in Southern California: Final Interim Report*. US Department of the Interior, US Geological Survey, Biological Resources, Division, USGS/BRD/CR-1999-007.

Pulsipher AG (ed.) (1996) *Proceedings: An International Workshop on Offshore Lease Abandonment and Platform Disposal: Technology, Regulation and Environmental Effects*. MMS contract 14-35-0001-30794. Baton Rouge, LA: Center for Energy Studies, Louisiana State University.

Reggio VC Jr (1987) *Rigs to Reefs: The Use of Obsolete Petroleum Structures as Artificial Reefs*. OCS Report/MMS 87-0015. New Orleans, LA: US Department of the Interior. Minerals Management Service. Gulf of Mexico OCS Region.

Reggio VC Jr (1989) *Petroleum Structures as Artificial Reefs: A Compendium*. Fourth International Conference on Artificial Habitats for Fisheries, Rigs-to-Reefs Special Session, Miami, FL, November 4, 1987. New Orleans, LA: US Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office.

Wilson CA and Stanley DR (1990) A fishery-dependent based study of fish species composition and associated catch rates around oil and gas structures off Louisiana. *Fishery Bulletin US* 88: 719–730.

Wilson CA, Stickle VR and Pope DL (1987) *Louisiana Artificial Reef Plan*. Louisiana Department of Wildlife and Fisheries Technical Bulletin No. 41. Baton Rouge, LA: Louisiana Sea Grant College Program.

RIVER INPUTS

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Introduction

Rivers represent the major link between land and the ocean. Presently rivers annually discharge about 35 000 km^3 of freshwater and 20–22 $\times$ 10^9 tonnes of solid and dissolved sediment to the global ocean. The freshwater discharge compensates for most of the net evaporation loss over the ocean surface, groundwater and ice-melt discharge accounting for the remainder. As such, rivers can play a major role in defining the physical, chemical, and geological character of the estuaries and coastal areas into which they flow.

Historically many oceanographers have considered the land–ocean boundary to lie at the mouth of an estuary, and some view it as being at the head of an estuary (or, said another way, at the mouth of the river). A more holistic view of the land–ocean interface, however, might include the river basins that drain into the estuary. This rather unconventional view of the land–sea interface is particularly important when considering the impact of short- and medium-term changes in land use and climate, and how they may affect the coastal and global ocean.

Uneven Global Database

A major hurdle in assessing and quantifying fluvial discharge to the global ocean is the uneven quantity and quality of river data. Because they are more likely to be utilized for transportation, irrigation, and damming, large rivers are generally better documented than smaller rivers, even though, as will be seen below, the many thousands of small rivers collectively play an important role in the transfer of terrigenous sediment to the global ocean. Moreover, while the database for many North American and European rivers spans 50 years or longer, many rivers in Central and South America, Africa and Asia are poorly documented, despite the fact that many of these rivers have large water and sediment inputs and are particularly susceptible to natural and anthropogenic changes.

The problem of data quality is magnified by the fact that the available database spans the latter half of the twentieth century, some of the data having been collected >20–40 years ago, when flow patterns may have been considerably different to present-day patterns. In many cases, more recent data can reflect anthropogenically influenced conditions, often augmented by natural change. The Yellow River in northern China, for example, is considered to have one of the highest sediment loads in the world, 1.1 billion tonnes y^{-1}. In recent years, however, its load has averaged <100 million tons, in response to drought and increased human removal of river water. How, then, should the average sediment load of the Yellow River be reported – as a long-term average or in its presently reduced state?

Finally, mean discharge values for rivers cannot reflect short-term events, nor do they necessarily reflect the flux for a given year. Floods (often related to the El Ninõ/La Niña events) can have particularly large impacts on smaller and/or arid rivers, such that mean discharges or sediment loads may have little relevance to short-term values. Despite these caveats, mean values can offer sedimentologists and geochemists considerable insight into the fluxes (and fates) from land to the sea.

Because of the uneven database (and the often difficult access to many of the data), only in recent years has it been possible to gather a sufficient quantity and diversity of data to permit a quantitative understanding of the factors controlling fluvial fluxes to the ocean. Recent efforts by Meybeck and Ragu (1996) and Milliman and Farnsworth (2002) collectively have resulted in a database for about 1500 rivers, whose drainage basin areas collectively represent about 85% of the land area emptying into the global ocean. It is on this database that much of the following discussion is based.

Table 1 Basin area, runoff, and discharge for various global rivers

River	*Basin area ($\times 10^3$ km^2)*	*Runoff (mm y^{-1})*	*Discharge (km^3 y^{-1})*
Amazon	6300	1000	6300
Congo	3800	360	1350
Ganges/Bramaputra	1650	680	1120
Orinoco	1100	1000	1100
Yangtze (Changjiang)	1800	510	910
Parana/Uruguay	2800	240	670
Yenisei	2600	240	620
Mekong	800	690	550
Lena	2500	210	520
Mississippi	3300	150	490
Choshui (Taiwan)	3.1	1970	6.1
James (USA)	20	310	6.2
Cunene (Angola)	100	68	6.8
Limpopo (Mozambique)	380	14	5.3

The first 10 rivers represent the highest discharge of all world rivers, the Amazon having discharge equal to the combined discharge of the next seven largest rivers. Basin areas of these rivers vary from 6300 (Amazon) to 800 (Mekong) $\times 10^3$ km^2, and runoffs vary from 1000 (Amazon) to 150 mm y^{-1} (Mississippi). The great variation in runoff can be seen in the example of the last four rivers, each of which has roughly the same mean annual discharge (5.3–6.8 km^3 y^{-1}), but whose basin areas and runoffs vary by roughly two orders of magnitude.

Quantity and Quality of Fluvial Discharge

Freshwater Discharge

River discharge is a function of meteorological runoff (precipitation minus evaporation) and drainage basin area. River basins with high runoff but small drainage area (e.g., rivers draining Indonesia, the Philippines, and Taiwan) can have discharges as great as rivers with much larger basin areas but low runoff (**Table 1**). In contrast, some rivers with low runoff (such as the Lena and Yenisei) have high discharges by virtue of their large drainage basin areas. The Amazon River has both a large basin (comprising 35% of South America) and a high runoff; as such its freshwater discharge equals the combined discharge of the next seven largest rivers (**Table 1**). Not only are the coastal waters along north-eastern South America affected by this enormous discharge, but the Amazon influence can be seen as far north as the Caribbean >2000 km away. The influence of basin area and runoff in controlling discharge is particularly evident in the bottom four rivers listed in **Table 1**, all of which have similar discharges (5.3–6.2 km^3 y^{-1}) even though their drainage basin areas and discharges can vary by two orders of magnitude.

Sediment Discharge

A river's sediment load consists of both suspended sediment and bed load. The latter, which moves by traction or saltation along the river bed, is generally assumed to represent 10% (or less) of the total sediment load. Suspended sediment includes both wash load (mostly clay and silt that is more or less continually in suspension) and bed material load (which is suspended only during higher flow); bed material includes coarse silt and sand that may move as bed load during lower flow. A sediment-rating curve is used to calculate suspended sediment concentration (or load), which relates measured concentrations (or loads) with river flow. Sediment load generally increases exponentially with flow, so that a two-order of magnitude increase in flow may result in three to four orders of magnitude greater suspended sediment concentration.

In contrast to water discharge, which is mainly a function of runoff and basin area, the quantity and character of a river's sediment load also depend on the topography and geology of the drainage basin, land use, and climate (which influences vegetation as well as the impact of episodic floods). Mountainous rivers tend to have higher loads than rivers draining lower elevations, and sediment loads in rivers eroding young, soft rock (e.g., siltstone) are greater than rivers flowing over old, hard rock (e.g., granite) (**Figure 1**). Areas with high rainfall generally have higher rates of erosion, although heavy floods in arid climates periodically can carry huge amounts of sediment.

The size of the drainage basin also plays an important role. Small rivers can have one to two orders of magnitude greater sediment load per unit basin area (commonly termed sediment yield) (**Figure 1**) than larger rivers because they have less flood plain area on which sediment can be stored, which means a greater possibility of eroded sediment being discharged directly downstream. Stated another way, a considerable amount of the sediment eroded in the headwaters of a large river may be stored along the river course, whereas most of the sediment eroded along a small river can be discharged directly to the sea, with little or no storage.

Small rivers are also more susceptible to floods, during which large volumes of sediment can be transported. Large river basins, in contrast, tend to be self-modulating, peak floods in one part of the basin are often offset by normal or dry conditions in another part of the basin. The impact of a flood on a small, arid river can be illustrated by two 1-day floods on the Santa Clara River (north of Los Angeles) in January and February 1969, during which more sediment was transported than the river's cumulative sediment load for the preceding 25 years! The combined effect of high sediment yields from small rivers can be seen in New Guinea, whose more than 250 rivers collectively discharge more sediment to the ocean than the Amazon River,

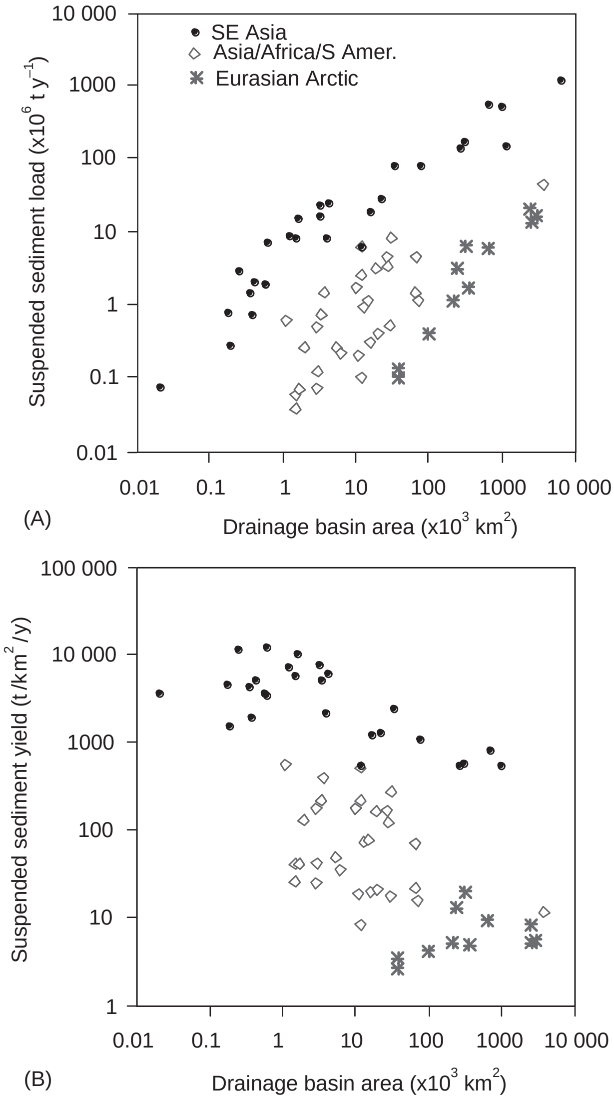

Figure 1 Suspended sediment discharge from rivers with various sized basins draining wet mountains in south-east Asia with young (assumed to be easily erodable) rocks (dots); wet mountains in south Asia, north-eastern South America, and west Africa with old (assumed to be less erodable) rocks (open diamonds); and semi-arid to humid mountainous and upland rivers in the Eurasian Arctic. Sediment loads generally increase with basin size, and are one to two orders of magnitude greater for south-east Asian rivers than for rivers with equal rainfall but old rocks, which in turn are greater than for rivers with old rocks but less precipitation (A). Sediment yields for smallest south-east Asian rivers are as much as two orders of magnitude greater than for the largest, whereas the yield for Eurasian Arctic rivers shows little change with basin size (B).

Table 2 Basin area, TSS ($mg\,l^{-1}$), annual sediment load, and sediment yield ($t\,km^2$ per year) for various global rivers

River	*Basin area ($\times 10^3\,km^2$)*	*TSS ($g\,l^{-1}$)*	*Sediment load ($\times 10^6\,t\,y^{-1}$)*	*Sediment yield ($t\,km^{-2}\,y^{-1}$)*
Amazon	6300	0.19	1200	190
Yellow (Huanghe)	750	25	1100	1500
Ganges/Bramaputra	1650	0.95	1060	640
Yangtze (Changjiang)	1800	0.51	470	260
Mississippi	3300	0.82	400 (150)	120 (45)
Irrawaddy	430	0.6	260	600
Indus	980	2.8	250 (100)	250 (100)
Orinoco	1100	0.19	210	190
Copper	63	1.4	130(?)	2100
Magdalena	260	0.61	140	540
Fitzroy-East (Australia)	140	0.31	2.2	16
Arno (Italy)	8.2	0.69	2.2	270
Santa Ynez (USA)	2	23	2.3	1100
Mad (USA)	1.2	1.7	2.2	1800

Loads and yields in parentheses represent present-day values, the result of river damming and diversion. The first 10 rivers represent the highest sediment loads of all world rivers, the Amazon, Ganges/Brahmaputra and Yellow rivers all having approximately equal loads of about $1100 \times 10^6\,t\,y^{-1}$. No other river has an average sediment load greater than $470 \times 10^6\,t\,y^{-1}$). Discharges for these rivers vary from 6300 (Amazon) to $43 \times km^3\,y^{-1}$ (Yellow), and basin areas from 6300 (Amazon) to $63 \times 10^3\,km^2\,y^{-1}$ (Copper). Corresponding average suspended matter concentrations and yields vary from 0.19 to 25 and 190 to 2100, respectively. The great variation in values can be seen in the example of the last four rivers, which have similar annual sediment loads ($2.2–2.3 \times 10^6\,t\,y^{-1}$), but whose average sediment concentrations and yields vary by several orders of magnitude.

whose basin area is seven times larger than the entire island.

Our expanded database allows us to group river basins on the basis of geology, climate, and basin area, thereby providing a better understanding of how these factors individually and collectively influence sediment load. Rivers draining the young, easily eroded rocks in the wet mountains of south-east Asia, for instance, have one to two orders of magnitude greater sediment loads (and sediment yields) than similar-sized rivers draining older rocks in wet Asian mountains (e.g., in India or Malaysia), which in turn have higher loads and yields than the rivers from the older, drier mountains in the Eurasian Arctic (**Figure 1**).

Because of the many variables that determine a river's sediment load, it is extremely difficult to calculate the cumulative sediment load discharged from a land mass without knowing the area, morphology, geology, and climate for every river draining that land mass. This problem can be seen in the last four rivers listed in **Table 2**. The Fitzroy-East drains a seasonally arid, low-lying, older terrain in north-eastern Australia, whereas the Mad River in northern California (with a much smaller drainage basin), drains rainy, young mountains. Although the mean annual loads of the two rivers are equal, the Mad has 112-fold greater sediment yield than the Fitzroy-East. The Santa Ynez, located just north of Santa Barbara, California, has a similar load and yield, but because it has much less runoff, its average suspended sediment concentration is 13 times greater than the Mad's.

Dissolved Solid Discharge

The amount of dissolved material discharged from a river depends on the concentration of dissolved ions and the quantity of water flow. Because dissolved concentrations often vary inversely with flow, a river's dissolved load often is more constant throughout the year than its suspended load.

Dissolved solid concentrations in river water reflect the nature of the rock over which the water flows, but the character of the dissolved ions is controlled by climate as well as lithology. Rivers with different climates but draining similar lithologies can have similar total dissolved loads compared with rivers with similar climates but draining different rock types. For example, high-latitude rivers, such as those draining the Eurasian Arctic, have similar dissolved solid concentrations to rivers draining older lithologies in southern Asia, north-eastern South America and west Africa, but lower concentrations than rivers draining young, wet mountains in south-east Asia (**Figure 2**).

The concentration of dissolved solids shows little variation with basin area, small rivers often having concentrations as high as large rivers (**Figure 2B**). At first this seems surprising, since it might be assumed that small rivers would have low dissolved

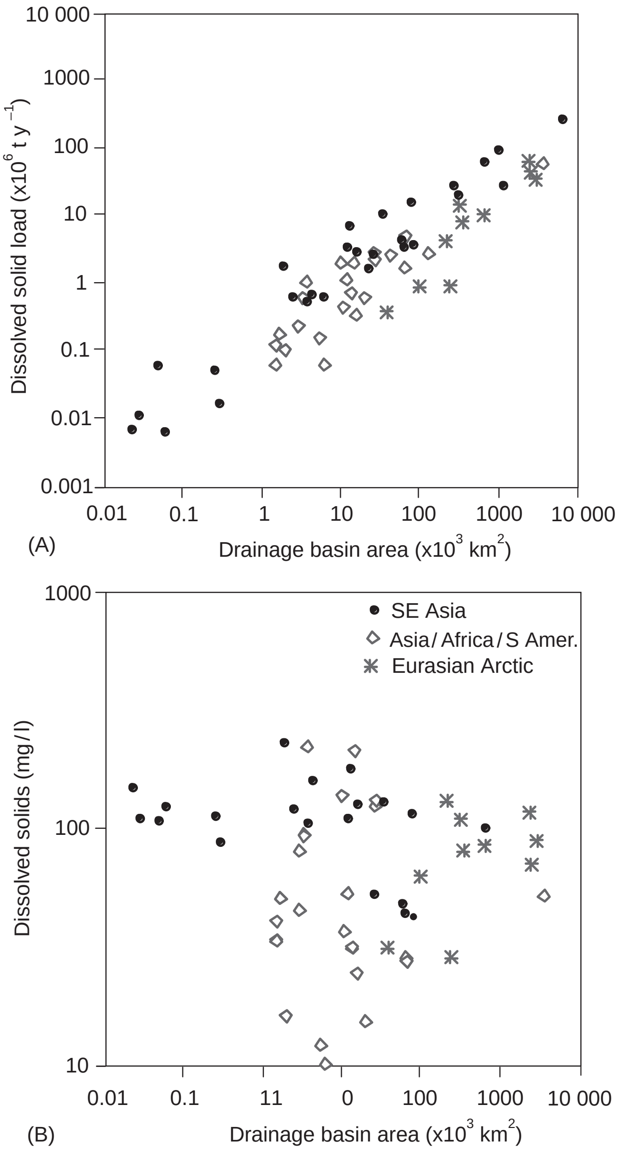

Figure 2. Dissolved solid load versus basin area for rivers draining south-east Asian rivers (solid dots), south Asia, west Africa, north-east South America (open diamonds – high rainfall, old rocks), and the Canadian-Eurasian Arctic (asterisks – low precipitation, old rocks). Note that while the dissolved loads relative to basin size are much closer than they are for suspended load, the difference seems to increase with decreasing basin area (A). The lack of correlation between dissolved concentrations and basin area (B) suggests that residence time of a river's surface water may play less of a role than ground water in determining the quantity and character of the dissolved solid fraction.

concentrations, given the short residence time of flowing water. This suggests an important role of ground water in both the dissolution and storage of river water, allowing even rivers draining small basins to discharge relatively high concentrations of dissolved ions.

Four of the 10 rivers with highest dissolved solid discharge (Salween, MacKenzie, St Lawrence, and Rhine) in **Table 3** are not among the world leaders in terms of either water or sediment discharge (**Tables 1** and **2**). The prominence of the Rhine, which globally can be considered a second-order river in terms of basin area, discharge, and sediment load, stems from the very high dissolved ionic concentrations (19 times greater than the Amazon), largely the result of anthropogenic influence in its watershed (see below).

The last four rivers in **Table 3** reflect the diversity of rivers with similar dissolved solid discharges. The Cunene, in Angola, is an arid river that discharges about as much water as the Citandy in Indonesia, but drains more than 20 times the watershed area. As such, total dissolved solid (TDS) values for the two rivers are similar (51 vs 62 $mg\,l^{-1}$), but the dissolved yield (TDS divided by basin area) of the Cunene is $<1\%$ that of the Citandy. In contrast, the Ems River, in Germany, has a similar dissolved load to the Citandy, but concentrations are roughly three times greater.

Fluvial Discharge to the Global Ocean

Collectively, the world rivers annually discharge about 35 000 km^3 of fresh water to the ocean. More than half of this comes from the two areas with highest precipitation, south-east Asia/Oceania and north-eastern South America, even though these two areas collectively account for somewhat less than 20% of the total land area draining into the global ocean. Rivers from areas with little precipitation, such as the Canadian and Eurasian Arctic, have little discharge (4800 km^3) relative to the large land area that they drain ($>20 \times 10^6\,km^2$).

A total of about $20\text{–}22 \times 10^9\,t\,y^{-1}$ of solid and dissolved sediment is discharged annually. Our estimate for suspended sediment discharge ($18 \times 10^9\,t\,y^{-1}$) is less accurate than our estimate for dissolved sediment ($3.9 \times 10^9\,t\,y^{-1}$) because of the difficulty in factoring in both basin area (see above) and human impact (see below). Given the young, wet mountains and the large anthropogenic influence in south-east Asia, it is perhaps not surprising that this region accounts for 75% of the suspended sediment discharged to the global ocean. In fact, the six high-standing islands in the East Indies (Sumatra, Java, Celebes, Borneo, Timor, and New Guinea) collectively may discharge as much sediment ($4.1 \times 10^9\,t\,y^{-1}$) as all non-Asian rivers combined. Southeast Asia rivers are also the leading exporters of dissolved solids to the global ocean, $1.4 \times 10^9\,t\,y^{-1}$ (35% of the global total), but Europe

Table 3 Basin area, TDS ($mg\,l^{-1}$), annual dissolved load, and dissolved yield (t/km^2 per year) for various global rivers

River	*Basin area ($\times 10^3\ km^2$)*	*TDS ($mg\,l^{-1}$)*	*Dissolved load ($\times 10^6\ t\,y^{-1}$)*	*Dissolved yield ($t\ km^{-2}\ y^{-1}$)*
Amazon	6300	43	270	43
Yangtze (Changjiang)	1800	200	180	100
Ganges/Bramaputra	1650	130	150	91
Mississippi	3300	280	140	42
Irrawaddy	430	230	98	230
Salween	320	310	65	200
MacKenzie	1800	210	64	35
Parana/Uruguay	2800	92	62	22
St Lawrence	1200	180	62	52
Rhine	220	810	60	270
Cunene (Angola)	110	51	0.35	3
Torne (Norway)	39	30	0.37	9
Ems (Germany)	8	180	0.34	42
Citandy (Indonesia)	4.8	62	0.38	79

The first 10 rivers represent the highest dissolved loads of all world rivers, only the Amazon, Yangtze, Ganges/Brahmaputra, and Mississippi rivers having annual loads $> 100 \times 10^6\,t\,y^{-1}$. Discharges vary from 6300 (Amazon) to $74 \times km^3\,y^{-1}$ (Rhine), and basin areas from 6300 (Amazon) to $220 \times 10^3\,km^2$ (Rhine). Corresponding average dissolved concentrations and yields vary from 43 to 810 and 43 to 270, respectively. The bottom rivers have similar annual dissolved loads ($0.34–0.38 \times 10^6\,t\,y^{-1}$), but their average sediment concentrations and yields vary by factors of 6–26 (respectively), reflecting both natural and anthropogenic influences.

and eastern North America are also important, accounting for another 25%.

Another way to view river fluxes is to consider the ocean basins into which they empty. While the Arctic Ocean occupies $< 5\%$ of the global ocean basin area ($17 \times 10^6\,km^2$), the total watershed draining into the Arctic is $21 \times 10^6\,km^2$, meaning a land/ocean ratio of 1.2. In contrast, the South Pacific accounts for one-quarter of the global ocean area, but its land/ocean ratio is only 0.05 (**Table 4**). The greatest fresh water input occurs in the North Atlantic (largely because of the Amazon and, to a lesser extent, the Orinoco and Mississippi), but the greatest input per unit basin area is in the Arctic ($28\,cm\,y^{-1}$ if evenly distributed over the entire basin). The least discharge per unit area of ocean basin is the South Pacific ($4.5\,cm\,y^{-1}$ distributed over the entire basin). In terms of suspended sediment load, the major sinks are the Pacific and Indian oceans (11.1 and $4 \times 10^9\,t\,y^{-1}$, respectively), whereas the North Atlantic is the major sink for dissolved solids ($1.35 \times 10^9\,t\,y^{-1}$; **Table 4**), largely due to the high dissolved loads of European and eastern North American rivers.

This is not to say, of course, that the fresh water or its suspended and dissolved loads are evenly distributed throughout the ocean basins. In fact, most fluvial identity is lost soon after the river discharges

Table 4 Cumulative oceanic areas, drainage basin areas, and discharge of water, suspended and dissolved solids of rivers draining into various areas of the global ocean

Oceanic area	*Basin area ($\times 10^6\ km^2$)*	*Drainage basin ($\times 10^6\ km^2$)*	*Water discharge ($km^3\ y^{-1}$)*	*Sediment load ($\times 10^6\ t\,y^{-1}$)*	*Dissolved load ($\times 10^6\ t\,y^{-1}$)*
North Atlantic	44	30	12 800	2500	1350
South Atlantic	46	12	3300	400	240
North Pacific	83	15	6000	7200	660
South Pacific	94	5	4300	3900	650
Indian	74	14	4000	4000	520
Arctic	17	21	4800	350	480
Total	358	98	35 200	18 000	3900

For this compilation, it is assumed that Sumatra and Java empty into the Indian Ocean, and that the other high-standing islands in Indonesia discharge into the Pacific Ocean. Rivers discharging into the Black Sea and Mediterranean area are assumed to be part of the North Atlantic drainage system. (Data from Milliman and Farnsworth, 2001.)

into the ocean due to mixing, flocculation, and chemical uptake. In many rivers, much of the sediment is sequestered on deltas or in the coastal zone. In most broad, passive margins, in fact, little sediment presently escapes the inner shelf, and very little reaches the outer continental margin. During low stands of sea level, on the other hand, most fluvial sediment is discharged directly to the deep sea, where it can be redistributed far from its source(s) via mass wasting (e.g., slumping and turbidity currents). This contrast between sediment discharge from passive margins during high and low stands of sea level is the underlying basis for sequence stratigraphy. However, in narrow active margins, often bordered by young mountains, many rivers are relatively small (e.g., the western Americas, East Indies) and therefore often more responsive to episodic events. As such, sediment can escape the relatively narrow continental shelves, although the ultimate fate of this sediment is still not well documented.

Changes in Fluvial Processes and Fluxes – Natural and Anthropogenic

The preceding discussion is based mostly on data collected in the past 50 years. In most cases it reflects neither natural conditions nor long-term conditions representing the geological past. While the subject is still being actively debated, there seems little question that river discharge during the last glacial maximum (LGM), 15 000–20 000 years ago, differed greatly from present-day patterns. Northern rivers were either seasonal or did not flow except during periodic ice melts. Humid and subhumid tropical watersheds, on the other hand, may have experienced far less precipitation than they do at present.

With the post-LGM climatic warming and ensuing ice melt, river flow increased. Scattered terrestrial and marine data suggest that during the latest Pleistocene and earliest Holocene, erosion rates and sediment delivery increased dramatically as glacially eroded debris was transported by increased river flow. As vegetation became more firmly established in the mid-Holocene, however, erosion rates apparently decreased, and perhaps would have remained relatively low except for human interference.

Few terrestrial environments have been as affected by man's activities as have river basins, which is not surprising considering the variety of uses that humans have for rivers and their drainage basins: agriculture and irrigation, navigation, hydroelectric power, flood control, industry, etc. Few, if any, modern rivers have escaped human impact, and with exception of the Amazon and a few northern rivers, it is difficult to imagine a river whose flow has not been strongly affected by anthropogenic activities. Natural ground cover helps the landscape resist erosion, whereas deforestation, road construction, agriculture, and urbanization all can result in channelized flow and increased erosion. Erosion rates and corresponding sediment discharge of rivers draining much of southern Asia and Oceania have increased substantially because of human activities, locally as much as 10-fold. While land erosion in some areas of the world recently has been decreasing (e.g., Italy, France, and Spain) due to decreased farming and increased reforestation, deforestation and poor land conservation practices elsewhere, particularly in the developing world, have led to accelerated increases in both land erosion and fluvial sediment loads.

While increased river basin management has led to very low suspended loads for most northern European rivers, mining and industrial activities have resulted in greatly elevated dissolved concentrations. Compared to south-east Asian rivers, whose waters generally contain 100–200 mg l^{-1} dissolved solids, some European rivers, such as the Elbe, can have concentrations greater than 1000 mg l^{-1} (**Figure 3**), in large part due to the mining of salt deposits for potassium. Since the fall of the Soviet empire, attempts have been made to clean up many European rivers, but as of the late

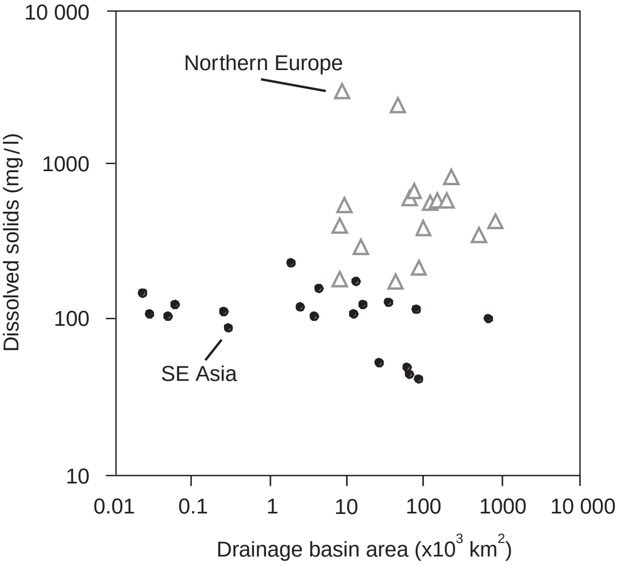

Figure 3 Dissolved solid concentration for south-east Asian rivers (also shown in **Figure 2**) compared with the much higher concentrations seen in northern European rivers (excluding those in Scandinavia). The markedly higher levels of dissolved solids in northern European rivers almost certainly reflects greater mining and industrial activity.

1990s, they still had the highest dissolved concentrations in the world.

Interestingly, while sediment loads of rivers may be increasing, sediment flux to the ocean may be decreasing because of increased river diversion (e.g., irrigation and flood protection through levees) and stoppage (dams). As of the late 1990s there were $>24\,000$ major dams in operation around the world. The nearly 200 dams along the Mississippi River, for example, have reduced sediment discharge to the Gulf of Mexico by $>60\%$. In the Indus River, construction of irrigation barrages in the late 1940s led to an 80% reduction in the river's sediment load. Even more impressive is the almost complete cessation of sediment discharge from the Colorado and Nile rivers in response to dam construction. Not only have water discharge and sediment flux decreased, but high and low flows have been greatly modulated; the effect of this modulated flow, in contrast to strong seasonal signals, on the health of estuaries is still not clear.

Decreased freshwater discharge can affect the circulation of shelf waters. Many of the nutrients utilized in coastal primary production are derived from upwelled outer shelf and slope waters as they are advected landward to offset offshore flow of surface waters. Decreased river discharge from the Yangtze River resulting from construction of the Three Gorges Dam might decrease the shoreward flow of nutrient-rich bottom shelf waters in the East China Sea, which could decrease primary production in an area that is highly dependent on its rich fisheries.

Retaining river water within man-made reservoirs also can affect water quality. For example, reservoir retention of silicate-rich river water can lead to diatom blooms within the man-made lakes and thus depletion of silicate within the river water. One result is that increased ratios of dissolved nitrate and phosphate to dissolved silica may have helped change primary production in coastal areas from diatom-based to dinoflagellates and coccolithophorids. One result of this altered production may be increased hypoxia in coastal and shelf waters in the north-western Black Sea and other areas off large rivers.

Taken in total, negative human impact on river systems seems to be increasing, and these anthropogenic changes are occurring faster in the developing world than in Europe or North America. Increased land degradation (partly the result of increased population pressures) in northern Africa, for instance, contrasts strongly with decreased erosion in neighboring southern Europe. Dam construction in Europe and North America has slackened in recent years, both in response to environmental concerns and the lack of further sites of dam construction, but dams continue to be built in Africa and Asia.

Considering increased water management and usage, together with increased land degradation, the coastal ocean almost certainly will look different 100 years from now. One can only hope that the engineers and planners in the future have the foresight to understand potential impacts of drainage basin change and to minimize their effects.

See also

Estuarine Circulation. Flows in Straits and Channels. Ocean Circulation.

Further Reading

Berner RA and Berner EK (1997) Silicate weathering and climate. In: Ruddiman RF (ed.) *Tectonic Uplift and Climate Change*, pp. 353–365. New York: Plenum Press.

Chen CTA (2000) The Three Gorges Dam: reducing the upwelling and thus productivity in the East China Sea. *Geophysics Research Letters* 27: 381–383.

Douglas I (1996) The impact of land-use changes, especially logging, shifting cultivation, mining and urbanization on sediment yields in tropical Southeast Asia: a review with special reference to Borneo. *Int. Assoc. Hydrol. Sci. Publ.* 236: 463–472.

Edmond JM and Huh YS (1997) Chemical weathering yields from basement and orogenic terrains in hot and cold climates. In: Ruddiman RF (ed.) *Tectonic Uplift and Climate Change*, pp. 329–351. New York: Plenum Press.

Humborg C, Conley DJ, Rahm L *et al.* (2000) Silicon retention in river basins: far-reaching effects on biogeochemistry and aquatic food webs in coastal marine environments. *Ambio*.

Lisitzin AP (1996) *Oceanic Sedimentation, Lithology and Geochemistry*. Washington, DC: American Geophysics Union.

Meybeck M (1994) Origin and variable composition of present day river-borne material. In: *Material Fluxes on the Surface of the Earth, National Research Council Studies in Geophysics*, pp. 61–73. Washington: National Academy Press.

Meybeck M and Ragu A (1996) *River Discharges to the Oceans. An Assessment of Suspended Solids, Major Ions and Nutrients*. GEMS-EAP Report.

Milliman JD (1995) Sediment discharge to the ocean from small mountainous rivers: the New Guinea example. *Geo-Mar Lett,* 15: 127–133.

Milliman JD and Farnsworth KL (2002) *River Runoff, Erosion and Delivery to the Coastal Ocean: A Global Analysis*. Oxford University Press (in press).

Milliman JD and Meade RH (1983) World-wide delivery of river sediment to the oceans. *J Geol* 91: 1–21.

Milliman JD and Syvitski JPM (1992) Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *J Geol* 100: 525–544.
Milliman JD, Ren M-E, Qin Y-S and Saito Y (1987) Man's influence on the erosion and transport of sediment by Asian rivers: the Yellow River (Huanghe) example. *J Geol* 95: 751–762.
Milliman JD, Farnworth KL and Albertin CS (1999) Flux and fate of fluvial sediments leaving large islands in the East Indies. *Journal of Sea Research* 41: 97–107.
Thomas MF and Thorp MB (1995) Geomorphic response to rapid climatic and hydrologic change during the late Pleistocene and early Holocene in the humid and sub-humid tropics. *Quarterly Science Review* 14: 193–207.
Walling DE (1995) Suspended sediment yields in a changing envirionment. In: Gurnell A and Petts G (eds) *Changing River Channels*, pp. 149–176. Chichester: John Wiley & Sons.

ROCKY SHORES

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Introduction

Intertidal rocky shores have been described as 'superb natural laboratories' and a 'cauldron of scientific ferment' because a rich array of concepts has arisen from their study. Because intertidal shores form a narrow band fringing the coast, the gradient between marine and terrestrial conditions is sharp, with abrupt changes in physical conditions. This intensifies patterns of distribution and abundance, making them readily observable. Most of the organisms are easily visible, occur at high densities, and are relatively small and sessile or sedentary. Because of these features, experimental tests of concepts have become a feature of rocky-shore studies, and the critical approach encouraged by scientists such as Tony Underwood has fostered rigor in marine research as a whole.

Rocky shores are a strong contrast with sandy beaches. On sandy shores, the substrate is shifting and unstable. Organisms can burrow to escape physical stresses and predation, but experience continual turnover of the substrate by waves. Most of the fauna relies on imported food because macroalgae cannot attach in the shifting sands, and primary production is low. Physical conditions are relatively uniform because waves shape the substrate. On rocky shores, by contrast, the physical substrate is by definition hard and stable. Escape by burrowing may not be impossible, but is limited to a small suite of creatures capable of drilling into rock. Macroalgae are prominent and *in situ* primary production is high. Rocks alter the impacts of wave action, leading to small-scale variability in physical conditions.

Research on rocky shores began with a phase describing patterns of distribution and abundance. Later work attempted to explain these patterns – initially focusing on physical factors before shifting to biological interactions. Integration of these focuses is relatively recent, and has concentrated on three issues: the relative roles of larval recruitment versus adult survival; the impact of productivity; and the effects of stress or disturbance on the structure and function of rocky shores.

Zonation

The most obvious pattern on rocky shores is an up-shore change in plant and animal life. This often creates distinctive bands of organisms. The species making up these bands vary, but the high-shore zone is frequently dominated by littorinid gastropods, the upper midshore prevalently occupied by barnacles, and the lower section by a mix of limpets, barnacles, and seaweeds. The low-shore zone commonly supports mussel beds or mats of algae. Such patterns of zonation were of central interest to Jack Lewis in Britain, and to Stephenson, who pioneered descriptive research on zonation, first in South Africa and then worldwide.

In general, physical stresses ameliorate progressively down the shore. In parallel, biomass and species richness increase downshore. Three factors powerfully influence zonation: the initial settlement of larvae and spores; the effects of physical factors on the survival or movement of subsequent stages; and biotic interactions between species.

Settlement of Larvae or Spores

Many rocky-shore species have adults that are sessile, including barnacles, zoanthids, tubicolous polychaete worms, ascidians, and macroalgae. Many others, such as starfish, anemones, mussels,