# An inventory on the phosphorus flux of major Indian rivers

**R. Ramesh*, R. S. Robin and R. Purvaja**

National Centre for Sustainable Coastal Management, Ministry of Environment, Forests and Climate Change, Anna University Campus, Chennai 600 025, India

**The biogeochemical cycles of phosphorus in rivers are intimately linked to the processes that occur in terrestrial ecosystems. Riverine networks hold a crucial role in the transfer of nutrients from the land and atmosphere to the coastal oceans and often act as pool for numerous inorganic and organic compounds. Biogeochemical transformation of elements in river network is extensively influenced by catchment alteration and anthropogenic inputs. By means of the rising consciousness of human impact on the excellence of rivers, emphasis is given on rivers, as an ecosystem by itself and also on the river-coast continuum. In this study, the major forcing functions that affect the riverine composition of phosphorus have been examined, in Indian context. An attempt has been made to study and inventorize phosphorus flux from major Indian rivers. Relatively high concentrations of dissolved $PO_4^{3-}$ (dissolved inorganic phosphorus – DIP) are observed in few of the Indian rivers, which may be due to modifications in river catchment. The flow of DIP and particulate inorganic phosphorus to the coastal ocean from Indian rivers is estimated to be about $190 \times 10^3$ tonnes year$^{-1}$ and $1367 \times 10^3$ tonnes year$^{-1}$ respectively. Suspended load is significant in Indian rivers and its cumulative flux is in the order of $1450 \times 10^6$ tonnes year$^{-1}$. The DIP concentration in the Indian rivers is more than twice the concentration observed for the other rivers in the world. Such increased nutrient input into the riverine system reflects the imbalances and alterations in terrestrial sources. Thus, the quantity and quality of nutrient input to the rivers need to be monitored to cope with the existing and future climatic and environmental changes.**

**Keywords:** Biogeochemical processes, Indian rivers, nutrient fluxes, phosphorus, water quality.

## Introduction

LAND–OCEAN exchanges in the coastal province are presently the hub of regional and global research, to compute fluxes of matter from land to the coastal area and to verify the alteration and consequence of human exploit on the coastal environment[1]. Global nutrient cycles have been greatly altered by land-use changes resulting from human disturbance over the last century[2]. The universal transport of phosphorus in rivers has augmented to a great extent as a result of human activities[1]. Smith *et al.*[3] reported that the sum of dissolved phosphorus load from rivers has amplified nine times more than pre-industrial levels. These augment are not equally dispersed around the world; they are strongly related with the human population in the catchment area[4]. During recent decades, inputs of anthropogenic nutrients into coastal seas have generally increased steadily[5,6]. Relative concentrations of nutrients and extreme nutrient discharge have been known to result in eutrophication, thereby modifying aquatic food webs and causing severe hypoxic events in coastal environments[7,8].

The global riverine flux of dissolved inorganic phosphorus (DIP) has been estimated and modelled by a number of workers[9,10], and the global average DIP concentration has been estimated to be 0.32 μM (ref. 11) and the global annual riverine flux to be $1.3 \times 10^{10}$ to $8.4 \times 10^{10}$ mol year$^{-1}$ (ref. 12). However, these compilations lack DIP data for the major rivers of the Indian subcontinent. Few authors[13–16] have previously studied the chemical characteristics and transport by the major Indian rivers. Among nutrients, Phosphorus is limiting nutrient in most of the ecosystems[17]. Contrast to C and N, phosphorus supplemented to an aquatic ecosystem or released through the decay of organic matter generally reside within the system, ensuing in an increase of phosphorus in detritus and surface sediment[18]. Phosphorus is present in the water column as particulate inorganic phosphorus (PIP), particulate organic phosphorus (POP), dissolved organic phosphorus (DOP), and DIP. DIP is the most bio available form of phosphorus and may be quickly taken up by organisms. Organic phosphorus microbially alters into bio-accessible inorganic phosphorus by decomposing the organic matter. These courses of action are mainly decided by nutrient content (C, N and P) of the soil, water as well as by the pool of microbial size[18]. Agriculture runoff contains high inorganic phosphorus (on average 20-fold higher than phosphorus levels in the comparatively pristine region) having direct influence on the quality of water. Normally, inorganic phosphorus exists only in exceptionally small amount in natural waters; natural

---

*For correspondence. (e-mail: rramesh_au@yahoo.com) cycling ensures that phosphorus is effectively utilized during photosynthesis by larger plants, algae and subsequently regenerated by microbes for later use[19–21]. Conversely, due to use of $PO_4^-$ fertilizer, an excess of bioavailable phosphorus (chiefly inorganic) is generated, ensuing changes in water quality and higher plant assembly. Besides, increased net primary productivity and phosphorus hold by wetland vegetation[22], increased decomposition of detritus[23] and increased organic soil accretion[24] have been documented. The decay of organic matter by microbes re-mineralizes organic phosphorus, thus preparing it as bio-available phosphorus to plants and further intensifying the production of organic matter.

Measurements of dissolved phosphorus and in suspended loads are rather limited in Indian rivers. In this regard, the present study was undertaken to inventorize the available data on transport of phosphorus from major peninsular and Himalayan rivers of India.

## River basin characteristics

A number of rivers in India receive water mainly from both south-west and north-east monsoons. However, during summer, the rivers draining from Himalayas are supplied with water from the glacier melt. In India, a total area of ~$3.1 \times 10^6$ sq. km is drained and ~1650 $km^3$ of water[25] is discharged annually by rivers, with a mean run off of about 500 mm $year^{-1}$ for the entire country. It is estimated that approximately 4.5% global river discharge is from India[25]. The monthly pattern of river discharge follows the rainfall, with maximum for most rivers being July–August, which coincides with the peak of south-west monsoon. Among the four different types of Indian rivers, Himalayan rivers and peninsular rivers form a significant natural resource as they make a great contribution to irrigation, domestic and industrial water supply, hydropower generation and inland water transport. Depending on the degree of urban development, agricultural and industrial practices, water pollution across the Indian river basins differs significantly. Most of the urban areas in India are located in and around the polluted stretches of the rivers. Municipal sewage supplies about 75%, whereas industrial pollution contributes to the rest of the point-source pollution[26]. Class-I and class-II cities of India together produce an estimated 38,254 million litres per day (MLD) of sewage[26]. This leads to poor water quality causing severe crisis in the river basins. Low water quality will further reduce the availability of freshwater for diverse human uses. Due to indiscriminate discharge of wastewater from the agriculture, industry and households sectors, about 70% of the surface water resources and large extent of groundwater reserves have been ruined. The peninsular rivers, such as the Mahanadi, Godavari, Krishna, Cauvery, Narmada and Tapti, together drain a significant portion of the Indian subcontinent, which is considered to be both religiously and culturally important.

## Phosphorus transport and flux

The DIP concentration and their fluxes obtained from various Indian rivers are summarized in Table 1 and Figure 1. For this study, data collected from earlier studies that were conducted during the last three decades were considered. It was also noted that all the studies followed almost similar methodologies, which compares various studies systematically. Total suspended solids (TSS) was measured by filtering, a known volume of water through 0.45 μm membrane filters, by determining the difference of initial and final weights of the filter. Samples for $PO_4^{3-}$-P were analysed following the standard methods[27]. For PIP, particulate matter retained in the filters was treated with perchloric acid, evaporated and the residue was heated to oxidize the organic matter and liberate phosphorus as inorganic phosphate. The phosphate was then determined by following the molybdenum blue method[27].

DIP concentrations in the peninsular rivers were in contrast to the Himalayan rivers. It can be noted that the Himalayan rivers, such as the Indus, Brahmaputra and Ganges, carry more than ~$30 \times 10^3$ tonnes of DIP per year (82% of total DIP influx is transported by the Himalayan rivers), in comparison to the peninsular rivers, such as Godavari, Krishna and Cauvery, which carry, on an average, about ~$5 \times 10^3$ tonnes $year^{-1}$. Among the three Himalayan rivers, Brahmaputra alone contributed ~37% of DIP flux to the coastal waters annually. Peninsular rivers together contribute ~18.22% of total DIP flux to the coastal waters with a major contribution from the river Godavari.

The high rate of discharge from Himalayan rivers (Table 1), coupled with high elevation and rock weathering are the primary contributing factors for the increased DIP flux rates. High-elevation catchments are highly sensitive to even small environmental changes relative to forest catchments[28]. For instance, little alteration in energy, chemical and water fluxes to these catchments may transform into large changes in ecosystem dynamics which, in turn, may influence the quality and quantity of dissolved inorganic matter leached to surface waters. The weathering of rocks leads to release of phosphorus as soluble alkali phosphates and colloidal calcium phosphate, the bulk of which is carried to the coastal waters. In addition, anthropogenic inputs of super phosphate as fertilizer and alkyl phosphate as detergents, lead to an increase in the content of phosphorus in the coastal waters.

It can also be observed from Table 1 that the DIP transport by the Himalayan rivers is in three orders of magnitude, higher than that of the Amazon river ($21.6 \times 10^3$ tonnes $year^{-1}$). DIP concentrations in the

**Table 1.** Hydrological, erosional characteristics and average annual flux of phosphorus of major Indian rivers

| River | Length (km) | Drainage area ($\times 10^6$ sq. km) | Discharge ($\times 10^9$ $m^3$ $year^{-1}$) | Population (million) | TSS ($\times 10^6$ tonnes $year^{-1}$) | PIP (tonnes $km^{-3}$ $year^{-1}$) | DIP (mg $l^{-1}$) | DIP Load to sea ($\times 10^3$ tonnes $year^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| Indus | 3200 | 1.17 | 238 | 59.01 | 59 | – | 0.15 | 36.0 |
| Ganges | 2525 | 0.91 | 393 | 505.54 | 520 | 707 | 0.12 | 47.0 |
| Brahmaputra | 2900 | 0.58 | 603 | 49.71 | 540 | 516 | 0.12 | 72.0 |
| Mahanadi | 858 | 0.14 | 54 | 37.45 | 60 | – | 0.16 | 8.6 |
| Godavari | 1465 | 0.31 | 92 | 76.02 | 170 | 141 | 0.16 | 15.0 |
| Krishna | 1300 | 0.25 | 30 | 85.62 | 4 | 3 | 0.07 | 2.1 |
| Cauvery | 765 | 0.07 | 11 | 41.27 | 1.4 | 0.13 | 0.17 | 1.87 |
| Narmada | 1290 | 0.09 | 47 | 20.70 | 70 | – | 0.10 | 4.7 |
| Tapti | 724 | 0.05 | 10 | 20.85 | 25 | – | 0.10 | 1.0 |
| Periyar | 244 | 0.01 | 19 | 3.50 | 0.74 | – | 0.07 | 1.28 |

TSS, Total suspended solids; PIP, Particulate inorganic phosphorus; DIP, Dissolved inorganic phosphorus; –, Not available; Drainage area and mean annual water discharge are from Central Water Commission and also compiled from refs 15, 40–42.

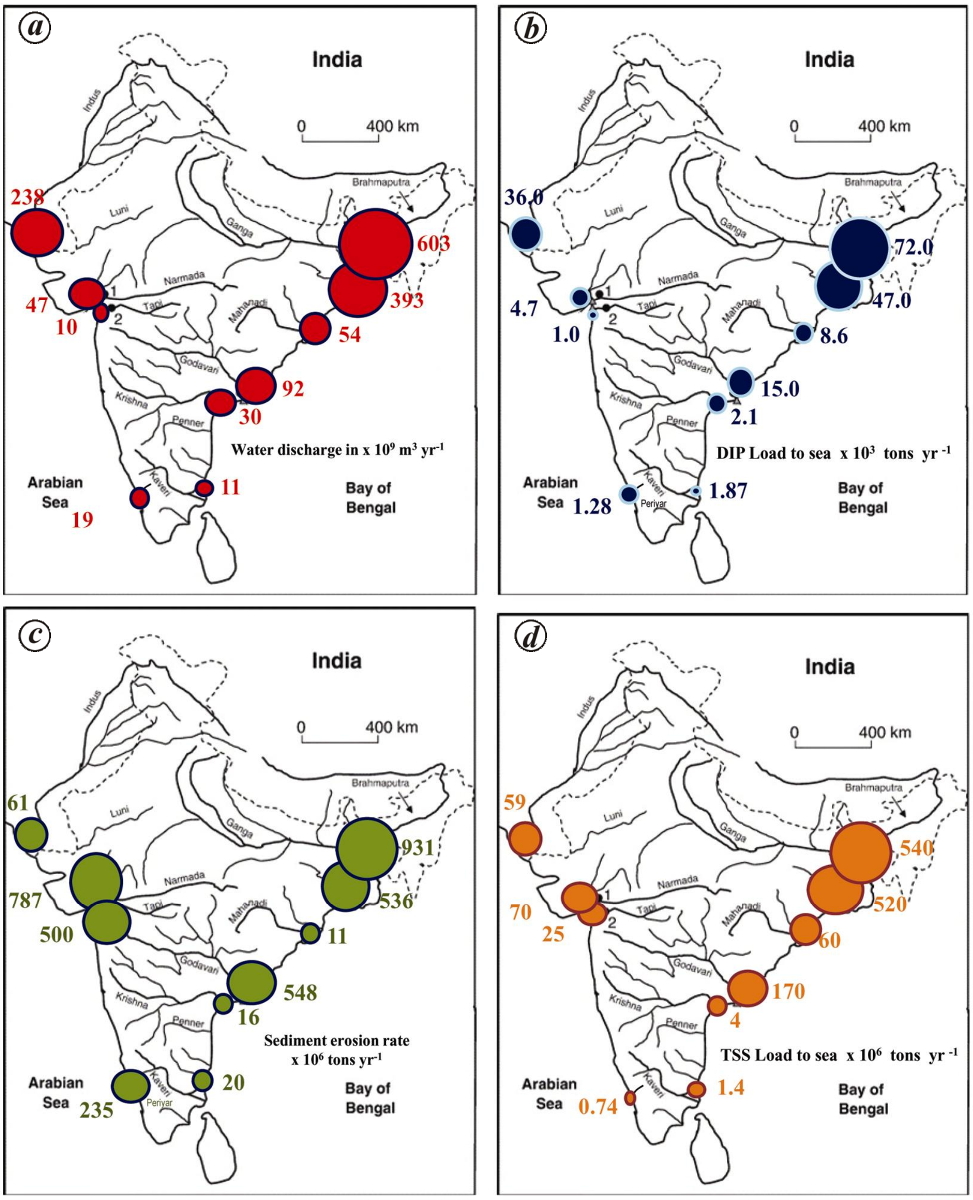

**Figure 1.** Variations in hydrological and erosional characteristics of major Indian rivers: ***a***, Water discharge (× $10^9$ $m^3$ $year^{-1}$); ***b***, Dissolved inorganic phosphorus load to sea (× $10^3$ tonnes $year^{-1}$); ***c***, Sediment erosion rate (× $10^6$ tonnes $year^{-1}$); ***d***, Total suspended solids load to sea (× $10^6$ tonnes $year^{-1}$).

peninsular rivers were in contrast to Himalayan rivers. High concentrations of DIP are observed in all peninsular rivers. On a spatial extent, DIP concentration in river water was in tune with the land-use character of the catchment basin. According to the solubility of various phosphate minerals, such as fluorapatite, the DIP levels should not exceed 0.05 μM (ref. 29). The reported high values of DIP in peninsular rivers reflect the additions from anthropogenic sources, such as deforestation, which increase erosion, the use of phosphorus fertilizers and detergents and the disposal of industrial wastes and domestic sewage. The physiography and microclimatic environments broadly fluctuate in the region and often even inside a single river system. For instance, the Ganges has snow-roofed semi-temperate upper reaches in the Himalayas, whereas in the middle and down-stream, some of its tributary carry water from tropical system weathering soft volcanic rocks[30]. Therefore, water qualities in different regions of the rivers differ widely due to disparity in weathering pattern under local environmental condition. In the upper reaches of the Himalayas, the Ganges water proves to contain moderately low levels of different solute loads[31,32]. While the river flows through the alluvial terrain of mid-stream with a large number of tributaries of varied lithology (varying from hard rock to loose soil) indicative of wider geological age (Precambrian to up to date), the water quality becomes poor as it reaches the major urban centres. By the time the river Ganges reaches Kolkata mega city about 2500 km downstream of the source, the chemical character of the water is completely altered, reflecting both natural weathering and also contribution from anthropogenic input via a very large number of urban and industrial outlet in the mid-stream area. Dutta and Subramanian[33] studied the water quality of the Ganges–Brahmaputra combined river system in the Bengal basin and concluded that the chemistry of water is controlled by rock weathering in the upper reaches and probably limited atmospheric deposition in the lower reaches, while in the mid-reaches human impact is visibly evident. Almost all the phosphorus on land is originally derived from the weathering of calcium and phosphate minerals. The main flux of phosphorus in the global cycle is carried in rivers, which transport about $21 \times 10^6$ tonnes phosphorus year$^{-1}$ to the sea[34]. This flux may be slightly higher than in prehistoric times as a result of erosion, pollution and fertilizer runoff.

Although invasion of dissolved phosphorus to sediment could also occur, the settling of particulate matter is the primary transfer mechanism of phosphorus to sediments. A combination of particulate inorganic and organic compounds consisting of phosphorus is received by the sediments. The aggregated PIP can be bounded by $Ca^-$, $Mn^-$, $Fe^-$ and $Al^-$, while the POP comprise living and dead algae, plant debris, zooplankton, bacteria and detritus. A fraction of these settled particulate phosphorus acts as inert material and is buried in its original form, whereas part of the phosphorus in mobile phosphorus is involved in a variety of physico-chemical and biological processes before final burial in sediments. More than 50% of the total phosphorus (TP) comprises mobile pools of free Fe-bound and inorganic phosphorus, however, mostly depleted below a depth of few centimetres. Stable minerals such as apatite and refractory organic phosphorus constitute chiefly the non-mobile, buried phosphorus, while a negligible amount of burial flux of phosphorus is made up of Fe-bound phosphorus.

## Possible transfer of nutrients from terrestrial to aquatic ecosystems

The transport pathways of phosphorus to the coastal waters discussed in Indian context is illustrated in Figure 2. The first segment highlights the loss of nutrients from land to riverine system and the second segment emphasizes the transfer of these nutrients to coastal waters. The alternation in the cycle and possible transfer of phosphorus from terrestrial to aquatic ecosystem can often be directly related to human activities and are the result of the augmented use of phosphorus fertilizers in agriculture and wastewater discharge of phosphorus to rivers and coastal waters. Continued loss of phosphorus from land through erosion of phosphorus-rich particles and through surface runoff of untreated wastewater containing phosphorus continues to be released to streams and rivers of the Indian subcontinent. Transport of phosphorus from terrestrial to aquatic systems takes place during diffusive conduit such as subsurface flow and surface runoff or through direct inputs into surface waters, often called as point sources. Mineral erosion and organic constituent from surface soils that include phosphorus (as PIP and POP respectively) through rainfall comprise the major source of phosphorus from agricultural land to streams and rivers[35]. Direct runoff containing dissolved phosphorus is also significant, particularly when the rainfall follows the application of fertilizers[36]. Grassland and forest surface runoff transmit little sediment and phosphorus loads that are usually dominated by DIP from natural sources. In India, conversion of grassland and forest to cropland has increased the loss of particulate and dissolved phosphorus from land, both due to release of phosphorus during mineralization of organic matter and increased erosion and runoff[37]. Increase in population has significantly augmented the total amount of phosphorus in wastewater discharged into the environment[38]. The fate of dissolved and particulate forms of phosphorus depends on the chemical nature of phosphorus, means of release and the biogeochemical and hydrological characteristics of the river basins. Damming of rivers and the construction of reservoirs has significantly increased the retention of particulate matter in the rivers of Indian subcontinent.

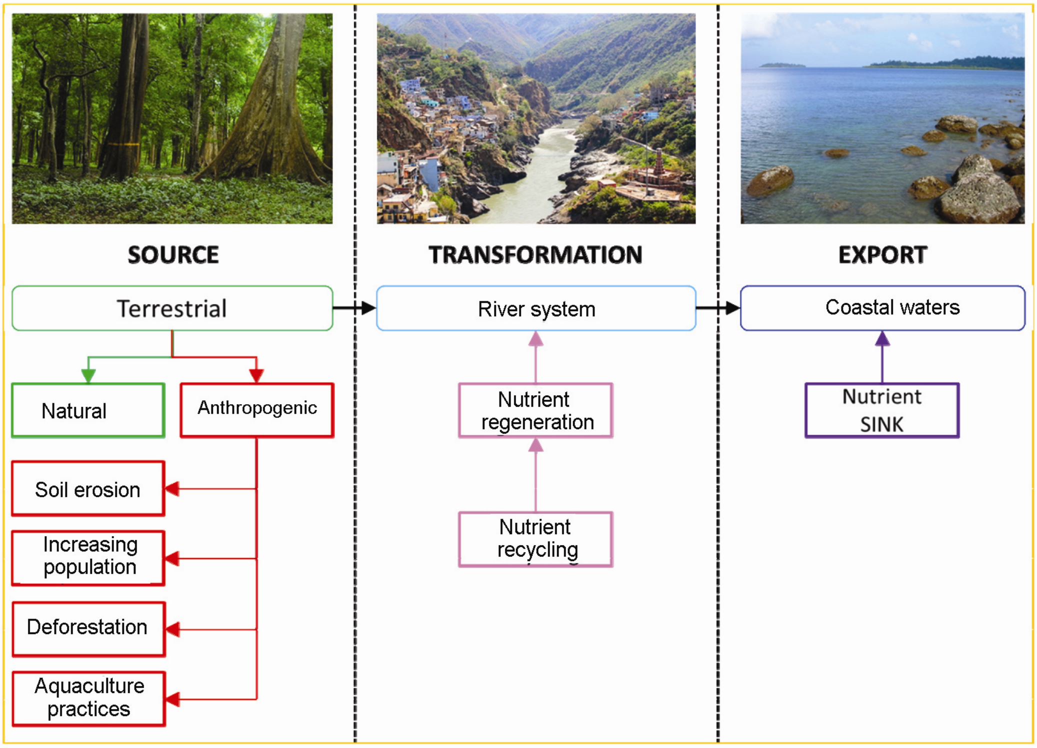

**Figure 2.** Schematic representation of transfer of nutrients from terrestrial to aquatic ecosystems.

It is expected that by 2020 non-agricultural land use in India will expand from 16.2 to 26 million hectares, an increase of 60%. Globally, during 1900–2000, the annual loss of forest area was 17–20 million hectares and for India it was 1.3 million hectares. For India, during this phase, the net spread area increased by 17.8% and gross area by 38% disproportionate to investments in irrigation. Soil losses per hectare by erosion in cereal cropping vary from 30 to 40 tonnes of soil per tonne of grain. The annual desertion of 4800–12,000 hectares of cropland in India is reported to be a result of severe soil erosion and degradation. Increased application of synthetic fertilizers is a result of utilizing non-fertile lands for agriculture to meet the needs of increasing population. The inorganic and organic nutrients originating from land sources, such as agricultural runoff, soil erosion, land alteration and flooding, penetrate the natural waterways such as rivers and estuaries and ultimately the coastal waters.

In India, most of the estuaries and wetlands, with unique marsh vegetation, act as a net sink for phosphorus and hence, organic productivity in the systems is very high. Despite temporary storage of nutrients in the wetlands and estuarine sediments, river waters are always a net source of nutrients to their estuary and coastal zone. The retention of phosphorus is generally dependent on salinity, with higher removal at freshwater and brackish sites compared with salt marshes[39]. This is likely due to less retention of Fe-bound phosphorus in the sediment with increased sulphate availability. Natural and human-induced variations in phosphorus mobilization in terrestrial systems ultimately determine the net input of phosphorus to the coastal oceans. Over the past century, human activity has increased the input of reactive phosphorus to coastal waters by at least a factor of 2 on a global scale. This has a major impact on the nutrient cycling in coastal zones and contributes to coastal eutrophication and hypoxia. Enhanced recycling of phosphorus under low-oxygen conditions may further increase phosphorus availability and promote high productivity in coastal waters.

1. Boyer, E. W., Howarth, R. W., Galloway, J. N., Dentener, F. J., Green, P. A. and Vorosmarty, C. J., Riverine nitrogen export from the continents to the coasts. *Global Biogeochem. Cycles*, 2006, **20**, GB1S91.
2. Downing, J. A. *et al.*, The impact of accelerating land-use change on the N-cycle of tropical aquatic ecosystems: current conditions and projected changes. *Biogeochemistry*, 1999, **46**, 109–148.
3. Smith, S. V. *et al.*, Humans, hydrology, and the distribution of inorganic nutrient loading to the ocean. *Bioscience*, 2003, **53**(3), 235–245.
4. Dumont, E., Harrison, J., Kroeze, C., Bakker, E. and Seitzinger, S., Global distribution and sources of DIN export to the coastal zone: results from a spatially explicit, global model. *Global Biogeochem. Cycles*, 2005, **19**, GB4S02.
5. Rabalais, N. N., Turner, R. E., Justic, D., Dortch, Q., Wiseman, W. J. and Sen Gupta, B. K., Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. *Estuaries*, 1996, **19**, 386–407.
6. Moffat, A. S., Global nitrogen overload problem grows critical. *Science*, 1998, **279**, 988–989.

7. Ragueneau, O. *et al.*, Biogeochemical transformations of inorganic nutrients in the mixing zone between the Danube River and the Northwestern Black Sea. *Est. Coast. Shelf Sci.*, 2002, **54**, 321–336.
8. Piehler, M. F., Twomey, L. J., Hall, N. S. and Paerl, H. W., Impacts of inorganic nutrient enrichment on phytoplankton community structure and function in Pamlico Sound, NC, USA. *Est. Coast. Shelf Sci.*, 2004, **61**, 197–209.
9. Turner, R. E., Rabalais, N. N., Justic, D. and Dortch, Q., Global patterns of dissolved N, P and Si in large rivers. *Biogeochemistry*, 2003, **64**(3), 297–317.
10. Harrison, J. A., Seitzinger, S. P., Bouwman, A. F., Caraco, N. F, Beusen, A. H. W. and Vorosmarty, C. J., Dissolved inorganic phosphorus export to the coastal zone: results from a spatially explicit, global model. *Global Biogeochem. Cycles*, 2005, **19**; doi: 10.1029/2004GB002357.
11. Meybeck, M., Carbon, nitrogen, and phosphorus transport by World Rivers. *Am. J. Sci*., 1982, **282**(4), 401–450.
12. Turner, R. E., Rabalais, N. N., Justic, D. and Dortch, Q., Global patterns of dissolved N, P and Si in large rivers. *Biogeochemistry*, 2003, **64**(3), 297–317.
13. Subramanian, V., Biksham, G. and Ramesh, R., Environmental geology of Peninsular river basins of India. *J. Geol. Soc. India*, 1987, **30**, 393–401.
14. Sarin, M. M., Krishnaswami, S., Dilli, K., Somayajulu, K. and Moore, W. S., Major ion chemistry of the Ganga–Brahmaputra river system: Weathering processes and fluxes to the Bay of Bengal. *Geochim. Cosmochim. Acta*, 1989, **53**, 997–1009.
15. Ramesh, R., Purvaja, G. R. and Subramanian, V., Carbon and phosphorus transport by the major Indian rivers. *J. Biogeogr*., 1995, **22**, 2047–2053.
16. Mukhopadhyay, S. K., Biswas, H., De, T. K. and Jana, T. K., Fluxes of nutrients from the tropical river Hooghly at the land-ocean boundary of Sundarbans, NE coast of Bay of Bengal, India. *J. Mar. Syst*., 2006, **62**, 9–21.
17. Jickells, T. D., Nutrient biogeochemistry of the coastal zone. *Science*, 1998, **281**, 217–222.
18. Reddy, K. R., Kadlec, R. H., Flaig, E. and Gale, P. M., Phosphorus retention in streams and wetlands: a review. *Environ. Sci. Technol*., 1999, **29**, 83–146.
19. Poister, D., Armstrong, D. E. and Hurley, J. P., A 6-year record of nutrient element sedimentation and recycling in three North Temperate Lakes. *Can. J. Fish. Aquat. Sci*., 1994, **51**, 2457–2466.
20. Caraco, N. F., Cole, J. J. and Likens, G. E., New and recycled primary production in an oligotrophic lake: insights for summer phosphorus dynamics. *Limnol. Oceanogr*., 1992, **37**, 590–602.
21. Benitez-Nelson, C. and Buesseler, K., Variability of inorganic and organic phosphorus turnover rates in the coastal ocean. *Nature*, 1999, **398**, 502–505.
22. Chiang, C., Craft, C. B., Rogers, D. W. and Richardson, C. J., Effects of four years of nitrogen and phosphorus additions on Everglades plant communities. *Aquat. Bot*., 2000, **68**, 61–78.
23. Davis, S. M., Growth, decomposition and nutrient retention of Cladium jamaicense Crantz and Typhadomingensis Pers. in the Everglades. *Aquat. Bot*., 1991, **40**, 203–224.
24. Craft, C. B. and Richardson, C. J., Recent and long-term organic soil accretion and nutrient accumulation in the everglades. *Soil Sci. Soc. Am. J*., 1998, **62**, 834–843.
25. Krishnaswami, S. and Singh, S. K., Chemical weathering in the river basins of the Himalaya, India. *Curr. Sci.*, 2005, **89**(5), 841–849.
26. Central Pollution Control Board (CPCB), Status of Waste Supply, Wastewater Generation, and Treatment in Class I Cities and Class II Towns of India, available at 2009, http://www.cpcb.nic.in
27. Grasshoff, K., Ehrhardt, M. and Kremling, K. (eds), *Methods of Sea Water Analysis*, Verlag Chemie, Weinheim, Germany, 1999, 3rd edn, pp. 89–224.
28. Baron, J. (ed.), *The Biogeochemistry of a Subalpine Ecosystem: Loch Vale Watershed, Ecological Studies, 90*, Springer-Verlag, New York, 1992, p. 247.
29. Subramanian, V., River transport of phosphorus and genesis of ancient phosphorites. *Special Publ. Geol. Surv. India. Misc. Publ*., 1984, **44**, 308–313.
30. Gupta, L. P., Subramanian, V. and Ittekot, V., Nature of organic matter in the sediments of the Godavari River Basin. *Biogeochemistry*, 1997, **38**(2), 103–128.
31. Sarin, M. M. and Krishnaswami, S., Major ion chemistry of the Ganges–Brahmaputra river system, India. *Nature*, 1984, **312**, 538–541.
32. Subramanian, V., *Transfer of Phosphorus from the Indian Subcontinent to the Adjacent Oceans*. Society of Sedimentary Geology, SEPM Special Publication, 2000, vol. 66, pp. 77–88.
33. Datta, D. and Subramanian, V., Nature of solute load in the rivers of Bengal Basin, Bangladesh. *J. Hydrol*., 1997, **198**, 196–208.
34. Meybeck, M., Carbon, nitrogen and phosphorus transport by World Rivers. *Am. J. Sci*., 1982, **282**(4), 401–450.
35. Kronvang, B., Vagstad, N., Behrendt, H., Bogestrand, J. and Larsen, S. E., Phosphorus losses at the catchment scale within Europe: an overview. *Soil Use Manage.*, 2007, **23**, 104–116.
36. Kleinman, P. J. A., Sharpley, A. N., Saporito, L. S., Buda, A. R. and Bryant, R. B., Application of manure to no-till soils: phosphorus losses by sub-surface and surface pathways. *Nutr. Cycl. Agroecosyst*., 2009, **84**, 215–227.
37. Sharpley, A. N., Hedley, M. J., Sibbesen, E., Hillbricht-Ilkowska, A., House, W. A. and Ryszkowski, L., Phosphorus transfers from terrestrial to aquatic ecosystems. In *Phosphorus in the Global Environment – Transfers, Cycles and Management* (ed. Tiessen, H.), SCOPE 54, Wiley, New York, 1995, pp. 171–200.
38. Caraco, N. F., Influence of human populations on phosphorus transfers to aquatic systems: a regional scale study using large rivers. In *Phosphorus in the Global Environment – Transfers, Cycles and Management* (ed. Tiessen, H.), SCOPE 54, Wiley, New York, 1995, pp. 235–244.
39. Loomis, M. J. and Craft, C. B., Carbon sequestration and nutrient (nitrogen, phosphorus) accumulation in river-dominated tidal marshes, Georgia, USA. *Soil Sci. Soc. Am. J*., 2010, **74**, 1028–1036.
40. Subramanian, V., Biksham, G. and Ramesh, R., Environmental geology of Peninsular river basins of India. *J. Geol. Soc. India*, 1987, **30**, 393–401.
41. Sarin, M. M., Krishnaswami, S., Dilli, K., Somayajulu, K. and Moore, W. S., Major ion chemistry of the Ganga–Brahmaputra river system: weathering processes and fluxes to the Bay of Bengal. *Geochim. Cosmochim. Acta*, 1989, **53**, 997–1009.
42. Milliman, J. D. and Syvitsky, J. P. M., Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *J. Geol*., 1992, **100**, 525–536.