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Catchment Scale Analysis of Human Induced Nutrient Flux in River Water: An Emerging Field of Applied Geomorphology

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Prof. Subhas Ranjan Basu was my teacher, while I was a student in the Post Graduate Department of Geography, University of Calcutta. He guided us during our M.Sc. field work at Panchmarhi, Madhya Pradesh. It was a memorable experience at the Jatha Sankar cave at Panchmarhi, where he explained formation of stalactite and stalagmite, and that the Shivalinga, deity of the cave was a stalagmite. I was fortunate to draw his attention as a student. Our academic relationships continued and grew stronger in subsequent years during my professional carrier at the Centre for Earth Science Studies, Thiruvananthapuram. Prof. Basu was kind enough to accept our invitation and visit our institute for academic deliberations. He was a nationally and internationally known geomorphologist with keen interest in societal application of geomorphology. A great motivator, he was capable of inspiring students and instil confidence. Some of his students excelled in their academic carrier and made a mark in their chosen field at the national and international levels. I selected this topic of applied geomorphology for the memorial lecture to pay my humble homage to our beloved teacher.

Abstract: *Human induced nutrient flux in river water is a matter of global concern as it affects fresh water availability and interferes with biogeochemical cycles. Studies on interlinkage between geomorphic processes and biogeochemical processes are slowly gaining importance in recent years across the world. Drawing examples from Kerala this paper argues that catchment characteristic plays an important role in human induced nutrient flux in the river water. Topography, water yield, shape of the basin, and floodplain characteristics are some of the important parameters contributing in nutrient movement. Micro-geomorphology has its impact, both on the nutrient pathways within the floodplains and also on the provenance of the nutrients, which is necessary to decipher the feedback chain. Such studies will contribute to earth system science research and environmental management and through that route to societal development. 21st century geomorphology warrants such a turn and an interdisciplinary approach to address the emerging issues.*

Key words: Applied geomorphology, environmental change, nutrient flux, Kerala rivers.

Introduction

Geomorphology research witnessed a gradual shift from historical description of evolution of landforms, to process-based analysis and now to study the interplay of landform and life (Dadson, 2022). This evolution, aided by methodological development and technological advancement, is linked to several drivers like growing thrust on societal concern for environmental management, science-based public policy decision, interdisciplinary studies and adopting earth system science approach to address earth surface changes including climate change, both at global and regional level. The earth system science is a holistic proposition "to obtain a scientific understanding of the entire earth system on a global scale by describing how its component parts and their interactions have evolved, how they function, and how they may be expected to continue to evolve on all time scales" (Bretherton, 1988). The International Council for Science (ICSU) and International Social Science Council (ISSC) jointly stressed on rethinking the focus and framework of earth system science research to improve our understanding of the earth system and human impacts, and deliver knowledge for human development in the face of human induced global environmental change (Reid, *et al.*, 2010). These developments were significant for progress of geomorphology as a discipline not only in the applied field but also conceptually. Traditionally, geomorphological analysis was primarily based on Newtonian principles (Church, 2010). From this rather, linear and reductionist approach, the earth system science perspective offers an opportunity for a broader landscape-planetary scale analytical view (Dadson, 2022). This shift reintroduces systems approach in geomorphology, which was first advocated by Chorley (1962) and subsequently articulated in the context of geography by Chorley and Kennedy (1971). The basic premise in a systems approach is that, there is complex ecological interdependence and interaction among various components (sets) of the earth system. A fragmented approach is not sufficient to explain the earth surface variabilities and is inadequate to address the mounting environmental problems besetting development initiatives.

The geomorphological studies are increasingly directed to contribute to socially relevant issues and become utility oriented since the beginning of 1980s. This trend grew further and deepened over the years. The focus of 21st Century mission of geomorphology is to develop applied geomorphological research, having a major impact on environmental policy and practice and providing a public benefit (Gregory *et al.*, 2013). The necessity of utilitarian research in geomorphology is being given importance, 'especially in the face of inexorable alteration of earth's surface by the profound impact of humans and for the purpose of ensuring disciplinary survival by demonstrating contemporary relevance' (Bauer, 1996). The trend is to re-connect geomorphology with management application and to strengthen this association (Graf, 2005; Downs and Booth, 2011). Human activities are changing the earth system processes at a faster rate than the earth system can assimilate, resulting in irreversible changes in the basic functioning of the earth system processes. Impact of these changes vary spatially and are conditioned through variations in earth surface properties. The discipline of geomorphology, which deals with the earth surface that mediates among various earth spheres and earth processes and houses life forms as the critical zone can hardly ignore these developments. The recent proposals for 'critical zone analysis' extending from the root zone/ groundwater level to the canopy of the vegetation has enlarged the scope of geomorphic research. Co-evolution of landforms and biological community, and humans as the modifiers of landscape are two research themes which were outlined in a meeting of young earth science researchers in the USA titled ‘Dynamic Interactions of Life and its Landscape’ (Reinhardt *et al.*, 2010). It is increasingly realised that geomorphic processes play important role in carbon flux and carbon cycle (Lane, 2012). Movement of terrestrial carbon stock (soil and vegetation) is largely through running water. The British Society of Geomorphology (BSG) in 2010 organised a working group on carbon stock and geomorphology. Considering the potential role of geomorphology in earth system science and environmental management, a couple of key areas have been identified for undertaking future research projects in geomorphology (Dadson, 2010; 2022; Downs and Booth, 2011). Interaction between geomorphological processes and biogeochemical processes is one of those key topics.

With growing concern for ecosystem health there is a pressing need for research that tries to dis-entangle the links and feedbacks between the physical and biogeochemical processes, which is nonlinear and multi scalar. Geomorphic, hydrologic and biogeochemical processes operate on different temporal scales. Hydrological and geomorphological processes are most active during bankfull conditions whereas the biogeochemical processes operate over a longer time including the baseflow period (Atkins *et al.*, 2018). This research area drew considerable interest during the last two to three decades. The integration of ecology and geomorphology however, dates back to the 19th Century; and the second half of 20th Century witnessed initiation of several studies in this field (Wheaton *et al.*, 2011). In a preface to the Special Issue of Geomorphology “Multi scalar Feedbacks in Ecogeomorphology”, Wheaton *et al.* (2011) reviewed the history of this emerging field, discussed various research initiatives in the USA and UK and summarised the findings of the contributed papers. A recent publication discussed importance of knowledge of geomorphological processes to understand the ways in which carbon is stored and recycled in the terrestrial environment (Evans, 2022). There are also papers discussing the role of landforms and micro geomorphology in nutrient cycling and spatial distribution of nutrients across the river system from provenance to the outfall including river corridor and associated floodplains and wetlands (Johnston *et al.*, 2001; Day *et al.*, 2008; Xia *et al.*, 2014; Qu *et al.*, 2017, Li *et al.*, 2017). Attempts are being made to integrate classical geomorphological theory with understanding of microbial processes controlling the decomposition of organic matter. The linkage between weathering-erosion-depositional process and river water geochemistry is now being disentangled and investigated at the catchment scale. This has opened a new domain for the geomorphologists to participate in the frontline interdisciplinary research with huge potential for societal application.

In this paper, we take up human induced nutrient level variations in river water as the subject of deliberation, drawing specific examples from Kerala. Although there are studies to explore the interrelationship between geomorphic and biogeochemical processes, analysis of human induced nutrient level variations in relation to geomorphology is yet to draw required attention from the geomorphologists, particularly in India. The discussion in this paper covers theoretical issues of human dimension of environmental change, concept of planetary boundary, a brief global review of human induced nutrient flux in surface waterbodies and importance of catchment scale analysis in such studies as a prelude to the Kerala case study.

Human dimension of environmental change and concept of planetary boundary

Human dimension of environmental change has a long history. Perhaps it began with flourishing of human civilisation. However, the pace of change is faster with the advent of industrial revolution, technological development, intensive agriculture, growing extraction of natural resource, and spread of urbanisation. Marsh (1864) drew our attention to this change as part of changing physical geography in the nineteenth century. The pressure on earth system due to human intervention is building up. The average per capita global CO_2 emission (production) is 4.6 tonnes and the per capita material footprint is 12.3 tonnes (UNDP, 2020). Human activities are so intense, penetrating and materially voluminous that the recent years, more particularly the period beginning from industrial revolution in the latter part of eighteenth century is considered as the 'Anthropocene' (Crutzen and Stoermer, 2000). In this era of the Anthropocene, human dimension of global environmental change is emerging as a separate field of study, positioned in the science-society interface (Stern, *et al.*, 1992, Griffith, 2009).

A group of scientists and academicians across the world proposed the concept of Planetary Boundary Framework (PBF) for scientific analysis of the risks of human interventions that affect the critical processes which regulate earth system functioning (Rockstrom *et al.*, 2009). There are growing evidences indicating that due to population pressure and shock of human intervention, stability of the earth system to persist the Holocene-like state is being threatened. Out of nine earth system processes, viz. climate change, change in biosphere integrity, stratospheric ozone, ocean acidification, biogeochemical flow (phosphorus and nitrogen cycle), land system change, global freshwater use, atmospheric aerosol loading; four processes (climate change, biosphere integrity, biogeochemical flow and land system change) have crossed the resilience limit (Rockstrom *et al.*, 2009; Steffen *et al.*, 2015). Freshwater has crossed the stable system boundary at the regional/ local level in many countries, which is a matter of great concern as it plays a central role in maintaining global biosphere integrity, regulating climate, mediating carbon and nutrient cycling. This has necessitated assessment of the water planetary boundary (attempts to provide a limit to anthropogenic water cycle modifications) at the regional and local scale, where water management problems typically occur. The proposed approach for such an exercise suggests capturing data of local water cycle modifications and interactions between water stores and earth system components (Zipper *et al.*, 2020). It is necessary to identify human interventions in the water system as manifested through sedimentation, nutrient enrichment, water pollution, alteration of hydrological pathways, occupation of riparian zones and reshaping of topography. All these are linked to land change, which is emerging as a new area of scientific investigation for understanding global change and sustainability (Turner II, *et al.*, 2007). Geomorphology has a very important role in this context.

Human induced nutrient flux in surface water: A brief global review

One of the major interventions noted globally is increasing nutrient load in the water system due to various human activities. During past 200 years and particularly over the last five to six decades humans have substantially altered global nitrogen cycle by increasing both availability and mobility of nitrogen over the earth's surface, consequently inorganic nitrogen enters aquatic system through point and non-point sources (Vitousek *et al.*, 1997; Galloway and

Cowling, 2002; Howarth, 2008). Organic character of the waterbodies is slowly but persistently altering. Globally, dissolved P (phosphorus) and N (nitrogen) increased by a factor of two and locally (Western Europe and North America) by factors of 10 to 50 (Meybeck, 1982). Human induced nitrogen has increased from an estimated amount of 150 Tg yr^{-1} in mid 90s (Galloway *et al.*, 1995) to more than 200 Tg yr^{-1} by early 2010 (Fowler *et al.*, 2013). Nitrogen flux in the rivers has increased from a pre-industrial value of 27Tg yr^{-1} to a current value of 61.5 Tg yr^{-1} (Schlesinger, 2009). More than 50% of this comes from fertilisers. Industrial fixation of nitrogen for fertiliser increased from <10 Tg yr^{-1} in 1950 to 80 Tg yr^{-1} in 1990 and is expected to increase to 135 Tg yr^{-1} by 2030 (Galloway *et al.*, 1994).

Humans add as much fixed N to terrestrial ecosystem as all natural systems combined. Mean nitrate level rose by an estimated 36% in global waterways between 1990 and 2000 and in some places, it was doubled (Pacific Institute, 2010). Apart from accelerating the global biogeochemical N cycle, human activities have also increased the mobility of reactive N within and between terrestrial and aquatic systems and the atmosphere (Vitousek *et al.*, 1997). Landscape change contributes in this acceleration. Global trend towards concentration of agricultural activities related to livestock and intensive crop production and horticulture in peri-urban areas have led to large local surpluses of N and P from animal manure and associated losses to aquatic systems and atmosphere (Bouwman, 1997). As a result, non-point source pollution is turning into a more local problem, to be addressed at the site level. A comparative study of three basins, namely the Vembanad lake basin, Kerala, India; Citanduy river basin, Java, Indonesia and the Weser river basin, Germany has indicated that the problem is evident is all the countries irrespective of their position in the economic ladder (Chattopadhyay and Jennerjahn, 2016). Tackling non-point source is a major challenge both in developed and developing countries. Analysis of N and P concentration in water samples brought out that the Weser river fell in the category of mesotrophic to eutrophic. In fact, most of the western European rivers are severely eutrophic (van Dijk *et al.*, 1994). The rivers of Pamba (Vembanad basin) and Citanduy show the characteristics of oligotrophic category. There were also temporal variations in N and P concentration in all three cases, which were linked to rainfall/freshwater discharge through the rivers. Human interventions in the form of physical modification, land use change, livestock concentration and fertilisation are important factors contributing to these changes. Spatial variations in each basin are linked to the catchment characteristics.

Importance of catchment-scale analysis

Catchments are geohydrological units with well-demarcated landscape boundaries and are important for analysis of earth system processes. Schumm (1977) defined catchments as 'physical-systems with history'. Catchment-scale analysis is necessary for unravelling historical development of landscape and to capture contemporary processes. Relict landforms present at the catchment boundary provide database to apply space-for-time substitution model (Xiaoli *et al.*, 2019), whereas the hillslope and the channel corridor carry the evidences of contemporary processes. It is also important to adopt catchment scale analysis as geomorphic processes are scale dependent. Although, each scale enables observation and study of certain processes but not others; and observations at all scales of catchment are useful and serve specific purposes (Garcia-Ruiz, 2015). Applied geomorphologists often face this challenge at the decision-making level and during their investigation. Catchments with definite measurable input-output parameters; offers a broad system boundary to integrate functioning of all earth system processes.

As fundamental units of hydrological, geomorphological and biogeochemical processes, the catchments help in estimating hydrological and biogeochemical fluxes. The biophysical control on flux dynamics and insight into short-term and long-term ecosystem responses to global environmental change are well manifested in the catchments (Covino *et al.*, 2021). The geomorphic template of a catchment is the resultant of various interacting physical, chemical and biological factors which also control movement of water, solutes and sediments from the head water to the outfall of the streams. In-stream human interventions through modification of streamflow pattern, removal of bedload, channelisation of drainage lines and mechanical reshaping of slopes and change in land use alter the nature and movement of water and sediments. Spatial variations of hydrological and biogeochemical interactions, their pathways, production and dispersal of water and sediment are mediated through landforms within the catchment. Quality and quantity of water and sediment draining out of a catchment are symptomatic of process-response behaviour and geo-ecologic characteristics of the concerned catchment. Through the drainage network and topographic elements, a catchment provides a matrix for multi-scale analysis, and hierarchic aggregation, disaggregation and interpolation of measured data. Catchment-scale analysis is also useful for cross-site comparison for hydrological and biogeochemical analysis.

The case of Kerala rivers

Kerala, located in the southwestern corner of the Indian Peninsula is sandwiched between the Lakshadweep Sea and the Western Ghats. Out of 44 rivers that drain Kerala, 41 rivers flow westward to the Lakshadweep Sea and the rest three rivers are east-flowing. Steep slope and undulated topography characterise all the rivers in Kerala. Most of the rivers are swift flowing and residence time of water is short. Average drainage density of Kerala is 2.25 km km^{-2}. On an average, 1 km^2 of catchment area yields 1.81 Mm^3 of water with high fluctuation between dry and monsoon seasons. Large or small, all the rivers in Kerala have originated in the Western Ghats and traverse all the three landform zones of high land, midland and lowland. Therefore, all river basins show similar diversity in geomorphic characteristics and land use pattern. Rivers in Kerala are under stress due to large scale human interventions. These interventions can be categorised into two — (i) direct and (ii) indirect (Chattopadhyay and Chattopadhyay, 2014). The direct interventions can be either physical intervention or biogeochemical intervention. Dams, reservoirs, encroachment on river bank, floodplain occupancy, removal of floodplain materials, river-bed mining, removal of riparian vegetation, and similar activities altering the configuration of land come under the first category. The biogeochemical intervention includes discharge of solid and liquid waste in the river, urban and industrial effluents, excessive use of fertiliser and pesticides in agriculture and other interventions causing water quality problem. Expansion of human settlements and use of chemical inputs for agriculture have enlarged non-point pollution sources. All rivers in Kerala are facing water quality problem and there are reports indicating that river water can hardly be used for domestic purposes (Chattopadhyay, 2020). The conditions are alarming for the river stretches passing through urban centres, located mostly in the lowlands. Indirect interventions are population growth, urbanisation, government policy, and similar other factors.

Human induced nutrient enrichments in Kerala

The Central Pollution Control Board (CPCB) under Government of India monitors the water quality of Kerala in regular interval (5 years) covering rivers (70 stations), lakes and ponds(18), canals (3), and groundwater (30) for different parameters (CPCB, 2010, 2015, 2020). It is a part of an all India programme. Comparing CPCB data for the years 2012 and 2017 it emerges that number of stations recording BOD value of >2 mgl^{-1} (cut off value for polluted water) has increased in all cases (Chattopadhyay, 2020). The Water quality is deteriorating over the years and more and more waterbodies are recording elevated values of BOD (Biological Oxygen Demand).

Table 1. Characteristics of selected catchments in Kerala

Catchments	Yield index	Avg. rainfall (mm)	Catchment shape (length:width)	Highland area in % (>75m)	Area under forest (%)	Population density	Selected water quality indices (Maximum value) in mgl^{-1}		
							DO	BOD	N
Chalakudy	0.99	265	4.4	59.6	57.7	1026	8.2	1.9	0.94
Periyar	1.19	238	4.0	69.3	51.5	1069	9.7	7.6	1.91
Muvattapuzhua	1.35	278	2.2	26.5	13.5	1069	8.1	1.0	0.38
Meenachil	1.01	256	2.0	14.1	Nil	896	7.7	1.9	0.47
Pamba	1.14	272	5.2	72.4	39.6	1501	7.7	4.1	1.50
Kallada	0.65	238	4.1	61.2	40.3	1056	7.2	2.0	0.78
Karamana	0.35	168	2.6	51.8	6.2	1509	2.5	9.0	1.90

Source: CPCB: Water quality of medium and minor rivers under NWMP data, 2020. Monitoring stations for water quality: Periyar-Alwaye, Chalakudy-Pulickalka-Davu, Muvattapuzha-Vettikkattumukhu, Meenachil-Kidangoor, Pamba downstream, Kallada-Perumthottamkadavu and Karamana-Moonnattumukku. Population density (Persons km^{-2}) approximated with the districts. DO: Dissolved Oxygen; BOD: Biological Oxygen Demand, N: Nitrate-N + Nitrite-N

Seven catchments located to the south of Palghat gap in Kerala are considered for the present analysis. Only a couple of parameters are used to elucidate catchment scale variations in human induced nutrient enrichments (Table 1). All data points refer to the down-stream stations. The Periyar is the longest river (244 km) in Kerala. Out of the seven rivers considered for analysis, five rivers debouch into the Vembanad lake, the largest brackish waterbody (230 km^2) in the west coast of India. These rivers mark high fluctuations in discharge over the seasons, and the flow of water in these rivers are also arrested in their upstream stretches, interfering with the natural hydrological processes.

The rivers of Periyar, Pamba and Karamana recorded elevated BOD and N (both NO_3 and NO_2) values. The Karamana river is the most polluted river with low DO (Dissolved Oxygen) and high BOD and N value. The CPCB identified the Karamana river as the Priority I for restoration in an all India scale. The N value is high (>1.5 mgl^{-1}) for all these three rivers (Table 1). A limit of total nitrogen lower than 0.5 to 1.0 mgl^{-1} (35.7 to 71.4μMl^{-1}) is safe to maintain normal functioning of aquatic system (Camargo and Alanso, 2006). Considering the data for three time points, 2010, 2015 and 2020 it is found that N concentration is high in all these three rivers (Fig. 1). The devastating flood of 2018 has impacted water quality in most of the rivers

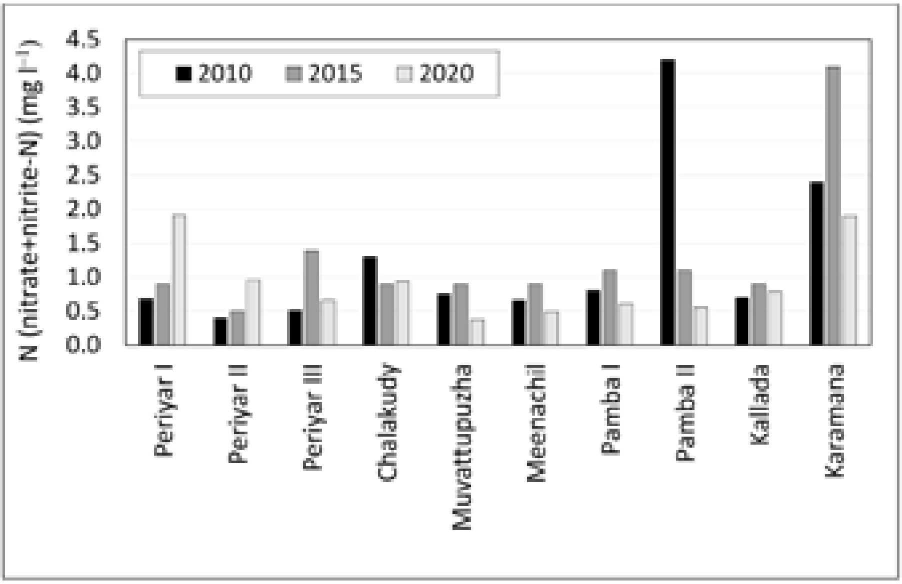

Figure 1. Temporal variations in Nitrate+Nitrite-N concentration in selected sampling stations. Data source: Central Pollution Control Board, 2010, 2015, 2020.

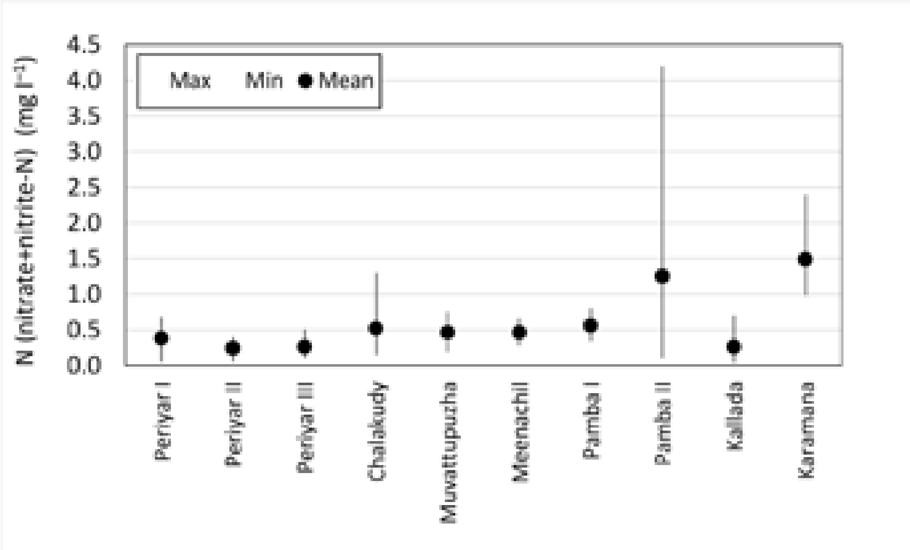

Figure 2. Range of N concentration in selected sampling stations.

due to swiping inundation of all polluting sources. The N concentration also varies seasonally as evident from the distribution of minimum, mean and maximum values (Fig. 2). An earlier study brought out that the Pamba river is one of the polluted rivers impacted by cultural factors like congregation of pilgrims, besides the use of fertilisers, raring of livestock and waste discharge from urban and rural settlements (David *et al.*, 2016). A large floodplain characterises this catchment in its lower course. There are intensive paddy cultivation and concentration of population surrounding this floodplain.

Both point and non-point sources contribute. As the pilgrim movement is seasonal there are wide temporal variations in nutrient flux (Fig 2). The Periyar and Karamana rivers show the urban river syndrome as two major urban centres in Kerala, namely Kochi and Thiruvananthapuram are located downstream of these two rivers respectively. Topography impacts significantly the settlement distribution pattern in Kerala.

High inorganic nitrogen loading causes three major environmental problems — acidification, eutrophication and high toxicity impairing survival of aquatic animals besides inducing adverse effects on human health and economy. Kerala has recorded a 35.6% increase in waterborne diseases from 2012 to 2016 (Chattopadhyay, 2020). Inorganic nitrogen enters into the aquatic system through point and non-point sources. Eutrophication is a foremost problem in protecting fresh water and coastal water ecosystems. The trophic state of all these waterbodies may be compared following the method proposed by Smith *et al.* (1999). The TN (total nitrogen) and TP (total phosphorus) values considered for assessing the trophic state differs depending on nature of the waterbody. We considered data for three rivers, Chalakudy, Pamba and Kallada for which Nitrate and phosphate data are available from our previous studies (Table 2). Data obtained from various studies for some of the most polluted rivers and unpolluted rivers are also provided for comparison. Both Kallada and Chalakudy rivers recorded lower N/P ratio than Pamba. The Pamba recorded the N/P ratio well above the Redfield ratio of 16 (Redfield *et al.*, 1963) indicating disturbance in its water systems. The average nutrient levels of unpolluted major rivers in the world amount to 0.375 mgl^{-1} of total dissolved N and 0.025 mgl^{-1} of total P and average N/P ratio is 15 (Meybeck, 1982).

Fertilisation (considered essential for agriculture in Kerala because the dominant lateritic soils in the State are deficient in nutrient), is a major source of inorganic nitrogen along with effluent discharged from settlements and industries. So far as phosphorus is concerned, it differs from nitrogen as soil pH directly affects P uptake of plants. In acidic soils of pH <6.5, phosphate ions react with aluminum (Al) and iron (Fe) to form less soluble compounds which are not available to plants (Dinesh *et al.*, 2014). Phosphate is applied during basal field preparation for agriculture. Significant amount of P finds their way to the rivers and waterbodies after rainfall. In Kallada river, Kerala, phosphate concentration increased from 1.3 in July, 2002 to 5.0 in the month of October, 2002 (Jennerjahn *et al.*, 2008). High concentration of phosphate in the river segments dominated by urban land use was noted for the Chalakudy river (Chattopadhyay *et al.*, 2005). In a catchment scale study of Europe using models, it was found that soil erosion and surface runoff contributed 53% of the phosphorus in the river water (Kronvang *et al.*, 2007). Both soil erosion and surface runoff vary spatially depending on watershed characteristics. Using a large data set Reich and Oleksyn (2004) found that plant foliar N:P ratio increased from high to low latitudes, coinciding with biogeographical gradients of soil substrate age and climate. These variations can occur in the catchment scale analysis from the watershed boundary towards downstream. It is also indicated that local biological expression of nutrient enrichment can be modified by site-specific factors including food web structure (Smith *et al.*, 2006).

Table 2. N/P ratio of selected rivers

River name	N/P Ratio	Source	Remarks
Chalakudy	7.1 – 28.1	Chattopadhyay *et al.*, 2005	Kerala
Pamba (M)	29.6	David et al, 2016	Kerala
Kallada	5.5 – 8.0	Jennerjahn *et al.*, 2008	Kerala
Selected rivers with high human impact			
Brahmaputra (Bangladesh)	31.2	Jennerjahn *et al.*, 2009	Bangladesh
Geum river (regional mean)	>24 -143	Yun and An, 2016	South Korea
Yangtze	22.29	Dai *et al.*, 2022	China
Brantas (Indonesia)	44.0	Jennerjahn *et al.*, 2009	Indonesia
Ebro (Spain)	92.7	Jennerjahn *et al.*, 2009	Spain
Selected unpolluted rivers (Meybeck, 1982)			
Sweden	6		Sweden
Niger	7.7		Niger
Zaire	3.8		Zaire
Amazon	3.3		Brasil
Average of large rivers	15		

Geomorphic analysis provides the base-level information for site-specific factors. Correlation co-efficient between nutrient concentration and area under highland is positive (r = 0.70) in the case of these seven rivers. Swift flow of water washes the slopes and contributes to increasing nutrient concentration level in the downstream, where water accumulates. Mapping of areas of divergence and convergence of water at micro-level provides meaningful information in this respect. Positive correlation (0.67) between population density and N supports the observation that human settlements are major contributors to nutrient loading of water. The water yield index and N value recorded negative correlation (–0.34). Flushing controls the distribution of nutrient pollution. Rivers with higher discharge can flush out the pollutants, although it will be accumulated in the coastal water contributing to hypoxia. Shape of the basin is another important factor governing the time for concentration of runoff. Concentration of nutrient does not depend on a single factor, rather multiple factors are involved and they act at different levels. The floodplains, where majority of settlements and agriculture are concentrated, are most significant contributors in riverine nutrient loading. The micro-geomorphic features found in the floodplains are active and relict river channels, point bars, oxbow lakes, meander scrolls, natural levees, backwater sloughs and wetlands. Spatial variability of geomorphological characteristics can affect many biogeochemical processes (Opdyke *et al.*, 2006). The natural levees are hotspots of nitrate. Riverine wetlands regulate fluxes of water borne materials. Mechanisms by which wetlands remove nutrients form river water are sedimentation, organic matter accumulation, chemical sorption, denitrification and biotic uptake (Johnston *et al.*, 1997).

Flood frequency and duration, hydrologic connectivity, soil texture, soil organic matter content, soil aeration, and plant growth have definite impact on status of nutrients in the river. The organic matter content of floodplain soils increases with distance from the actively flooded stream banks to less actively flooded slack water areas. Sedimentation rate and nutrient concentration in floodwater will decrease with distance from the river channel (Johnston et al, 2001). Geomorphic processes have considerable impact on nitrogen budget in the hill slopes. The shola forests of Kerala covering the hill slopes, helps to maintain water courses and are store houses of soil organic matter (Thomas and Sankar, 2001). Small variations in the topography of riverine wetlands affect N forms and availability because aerobic conditions are required for nitrification and anerobic conditions are required for denitrification. Vegetation biomass and primary productivity are highest in streamside levees that are slightly elevated but receive regular flood pulses. Most of these levee-sites are now occupied, thereby hindering the organic nitrogen supply and at the same time increasing inorganic nitrogen load. Micro-geomorphic analysis is necessary to integrate hydrological and biogeochemical data and to identify pathways for human induced nutrient movement.

Conclusion

Research in applied geomorphology is gaining importance across the world to address issues arising out of human dimension of environmental change and societal development. Anthropogenic nutrient flux in river system is one of the emergent issues of global concern. Biogeochemical processes, pedogenesis and geomorphic processes are entangled. It is important to investigate this linkage and understand the pathways. Various technological developments have enhanced the capability of the subject to have a system perspective and assimilate laboratory and field data. The Kerala case study indicates gradual building up of nutrient loads in the river system and there are catchment scale variations. It is important to probe at micro-geomorphic scale to assess sub-catchment contribution to nutrient flux so that policy decisions are informed and spatially coordinated. Like all research fields, the current approach of geomorphological research may be interdisciplinary and collaborative. It is important for geomorphologists to participate in policy formulation by defining the problems and finding solutions. The present approach of geomorphologists to work on silos might have to be redirected to coordinated efforts and problem-based deliberations. Although, geography provides the maximum breadth and diversity to geomorphology by interfacing it with real world problems; interaction between geomorphologists and human geographers are limited. It is important to understand that geomorphic process analysis will be more comprehensive when observed through the lens of human geography. The Indian Institute of Geomorphologists (IGI) can provide the national platform for issue-based deliberations covering emerging challenges and promote an appropriate ambience for such an endeavour.

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