Implications of changes in river sediments during the 21st century for freshwater ecosystems in northeast India

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Abstract Sediment delivery to the river and stream network in the north-eastern region of India is expected to increase from 601 million tonnes in 2001, to about 981 and 1167 million tonnes by the years 2050 and 2100, respectively. This will substantially increase the river sediments, thereby increasing flood incidence and magnitude and affecting freshwater resources and environmental quality. The Doolittle method was used to develop a model based on a partial regression equation: *runoff* (% of rainfall) = 9.293 + 0.147 × *slope* (%) + 0.048 × *rainfall* (cm) – 1.469 × *vegetation* + 0.054 × *soil moisture* (%) – 0.125 × *soil clay* (%), for runoff generation. In pursuit of increasing agricultural production, a rapid increase in the use of agricultural chemicals will further degrade the freshwater resources, affect the health of humans and aquatic ecosystems, and alter the carbon cycle and biological and life support ecosystem in the region.

Key words implications; river sediments; freshwater resources; northeastern region of India; 21st century

INTRODUCTION

Water is critical for the health of both human and ecological systems and is an important element in many social and economic activities. The susceptibility of freshwater to degradation is a matter of concern in the northeastern region of India and will be a key issue during the 21st century. The major problem facing the harmonious development and management of water resources in the region, apart from economic constraints, is the prevalence of shifting cultivation, a paucity of reliable data and the lack of human and institutional capacity necessary to face the complex interactions of the hydrological cycle with societal needs and the environment. *Homo sapiens* was under the awe of natural objects, such as oceans, rivers, forests, etc., from ancient times. They were small in number and their needs were extremely limited but with a rapid increase in the population of the region, these needs also multiplied, putting tremendous pressure on natural resources. The gradual degradation, pollution and spatial and temporal scarcity of freshwater in the northeastern region demands integrated water resources planning and management that considers quantity and quality aspects (Sharma & Sharma, 2004). Human interference has been identified as the major cause of degradation of the freshwater ecosystems due to the very large amount of sediment generation caused by shifting cultivation, deforestation and mismanagement of rainwater (Sharma, 1999). Soil erosion is the major agent of lateral material transport in the anthropogenically disturbed areas of the region. The demand for water will increase as a result of population increase, as well as the temperature increase due to greenhouse gases, decline in rainfall and other human activities.

Soil erosion and sediment transport are part of the landscape evolution, but to keep them within limits is of great importance for the security of freshwater resources. The measures required to ensure restoration, maintenance and sustainability of freshwater resources in the region are: introduction of eco-friendly, economically viable, socially acceptable and sustainable land-use systems; an increase in vegetative cover; the judicious management and more *in situ* retention of rainwater; discouragement of free range grazing; and awareness and government will. A multidisciplinary long-term study, based on a watershed approach, has been in progress since 1983 to investigate these aspects and much useful data has been generated and will be discussed in the present paper.

STUDY AREA AND METHODOLOGY

The northeastern region of India, comprising the seven states of Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland and Tripura (Fig. 1), is predominantly hilly. A runoff generation model was developed with five independent variables based on a partial regression equation of the form:

$$Runoff\text{ (\% rainfall)} = a + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 \quad (1)$$

where b_1, b_2, b_3, b_4, b_5 are the partial regression coefficients for the slope (x_1) in %, annual rainfall (x_2) in cm, vegetation (x_3) on a 1–5 scale, soil moisture (x_4) in %, and clay content (x_5) in %, respectively. The equation was developed using the Doolittle method as described by Goulden (1952), and it gave a reasonably high degree of accuracy in prediction or estimation of runoff. The vegetation is the only independent variable for which the values (1 to 5) have to be based on visual estimates. The classification used for the vegetation values is: 1: bare ploughed soil surface; 2: scrub or effective covered area below 25%; 3: cropped soil surface or effective covered area 25 to 50%; 4: open forest vegetation or effective covered area 50 to 75%; 5: dense forest vegetation, including bushes and grasses or effective covered area more than 75%. The data used for developing the model were obtained from several studies undertaken at various locations by different researchers (Anonymous, 1982–2003; Singh, 1978–1990; Singh & Singh, 1978; Sharma & Prasad, 1995; Sharma, 1999). The required range of values was not available for some variables. More systematic studies can improve the validity of the model. In principle, the model can be used for predicting runoff under a wide range of conditions. The sediment yield from the region was estimated using the model:

$$Sediment\ yield\ (\text{t ha}^2) = 41.73 + 0.181 \times slope\ (\%) + 0.046 \times rainfall\ (\text{cm}) - 0.387 \times clay\ content\ (\%) - 8.125 \times vegetation\ (\text{1 to 5 scale}) \quad (2)$$

as proposed by Sharma & Sharma (2003). The soil analysis was undertaken as per methods described by Jackson (1973).

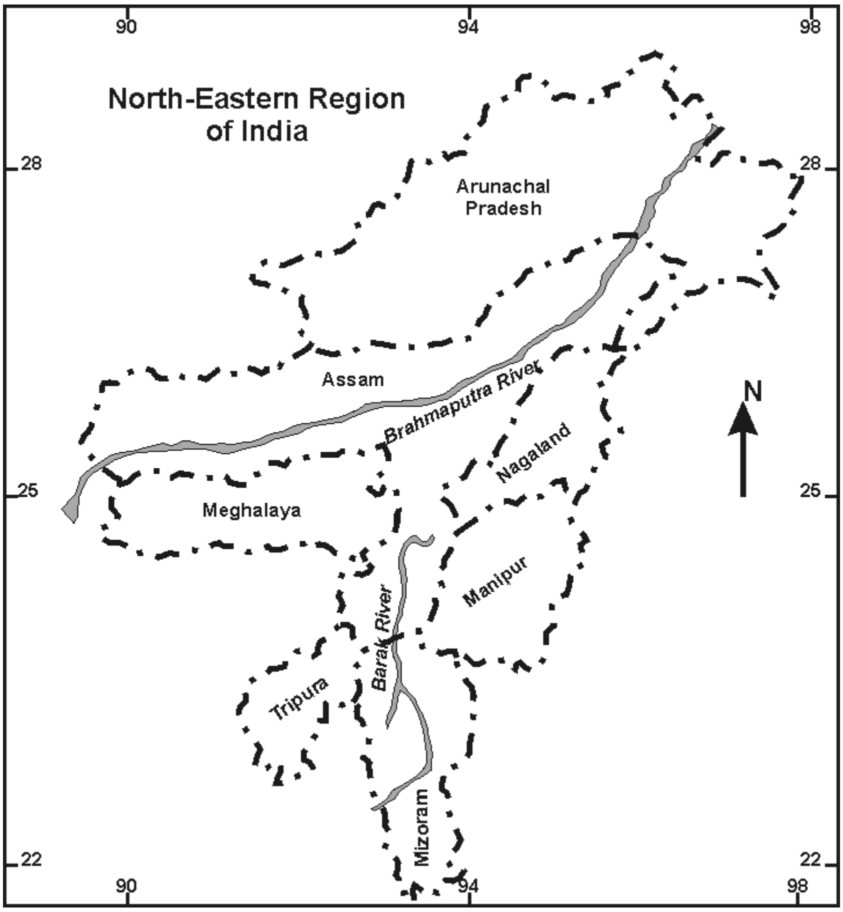

Fig. 1 Northeastern region of India.

RESULTS AND DISCUSSION

Erosion should not be regarded merely as the physical removal of soil and water but rather as deterioration of all components of the habitat in which humans have to exist. The ecological balance, favouring the complex hydrological cycle, has been seriously upset in the northeastern region of India due to ignorance or lack of appreciation of methods of conserving and managing natural resources. The destruction process has increased due to misuse of water and vegetation resources because of a rapid increase in the human and animal population that compete for natural resources. In the absence of suitable water conservation measures and the lack of judicious water use, environmental degradation has become widespread which, in turn, is causing the freshwater ecosystem in the region to deteriorate. The efforts to deal with the problem of soil and water conservation have met with little success because of the enormity of the problem on one hand, and various social, economic and policy, as well as human, material and money constraints on the other. Agricultural development has significantly influenced contemporary geomorphic processes and shifting cultivation has dramatically increased the rates of soil erosion. Integrated water management in the region is constrained by competing demands, intensive development, change of life-style, lack of proper water supply schemes, dilapidated infrastructure, misuse and wastage of water, and the rapidly growing population.

River sediments

River sediment load in the northeastern region is influenced both by natural and anthropogenic factors. The sediment load transported by rivers in the region represents a mixture of sediments derived from different locations and from different sources within the contributing drainage basin. Nonpoint source pollution is the largest source of river water pollution in the region. Most of the sediments in rivers, lakes and reservoirs come from surface erosion in the watersheds and river bank erosion caused by high flow velocities. Fine sediment transport often also carries various forms of soil and agro-chemicals and other pollutants. Consequently, fine sediments have a significant impact on the freshwater eco-system and water quality. The major pollutants in rivers and streams in the region are soil, pathogens, nutrients, agricultural chemicals and metals. The percentage of total pollutants coming from agricultural lands, urban runoff and other sources ranges from 70–75%, 10–15% and 15–20%, respectively. There are about hundred major tributaries which feed sediments to the Brahmaputra river, and 15 of these in the north of the region and five in the south are fairly large. Deforestation as a result of shifting cultivation is one of the major causes of heavy sediment yields in these catchments, yet yield may be reduced to nearly zero if the forest cover is more than 60% (Wang & Wang, 1999).

Water resources

The northeastern region of India has two major rivers, the Brahmaputra and Barak, which drain areas of 1.944×10^5 km^2 and 7.81×10^4 km^2 and have an annual runoff of 537.2 and 59.8 km^3, respectively (Table 1). The region receives about 510 km^3 of water as rainfall, although this varies spatially and temporally. Because of its very large sediment load, the Brahmaputra River has a tendency to change its course, resulting in bank cutting and additional sediment input. The rivers are in a highly dynamic state due to the high channel gradient. Reservoirs, lakes and tanks account for about 1.83×10^5 ha area. Total surface and groundwater potential in the region have been estimated to be 1064 and 16.6 km^3, respectively, which is likely to reduce

Table 1 Water availability in major rivers of the northeastern states.

River	Drainage area (1×10^5 km^2)	Average annual runoff (km^3)	Average runoff per km^2 (m^3)
Brahmaputra	1.94	537.2	276 300
Barak	0.78	59.8	765 600

Table 2 Water potential, sediment yield and per capita water availability.

Year	Surface water potential (km^3)	Groundwater potential (km^3)	Utilizable potential at 20% of maximum water potential (km^3): Surface	Ground	Sediment yield (1×10^6 t)	Per capita availability (m^3)
2001	1064	16.6	212	3.3	601	5665
2051	957	14.9	191	3.0	982	1898
2101	864	13.4	172	2.7	1167	772

significantly in the 21st century (Table 2). Since the full water potential cannot be exploited due to inaccessibility and economic reasons, the total availability of water is about 215.3 km^3. Though the region has plenty of water, for example the estimated per capita availability was about 5665 m^3 in 2001, this amount will decrease to 1898 m^3 in 2051, and 772 m^3 in 2101, mostly due to rapid population growth and a decline in potential water resources. Freshwater stress is expected to begin in the region in 2066, and scarcity in 2095. This may happen earlier if deforestation goes unabated and human interference increases due to population growth.

Magnitude of river sediments, other pollutants and controlling factors

Presently, the annual sediment yield of the region's streams and rivers is estimated at 601 million tonnes, but this is expected to rise to 982 and 1167 million tonnes in the years 2051 and 2101, respectively (Table 2). The future sediment yield has been calculated by using the model (Sharma & Sharma, 2003):

$$\textit{Sediment yield}\ (\text{t ha}^2) = 41.73 + 0.181 \times \textit{slope} + 0.046 \times \textit{rainfall} - 0.387 \times \textit{clay content} - 8.125 \times \textit{vegetative cover}\ (1 \text{ to } 5 \text{ scale}) \quad (3)$$

Sediment delivery to the rivers is expected to increase by about 94.1% compared with 2001, by the year 2101. This will increase the incidence of floods due to a reduction in channel capacity, which in turn will cause increasing pollution of surface watercourses and groundwater. A model of runoff generation comprising:

$$\textit{Runoff}\ (\%\ \text{rainfall}) = 9.293 + 0.147 \times \textit{slope}\ (\%) + 0.048 \times \textit{rainfall}\ (\text{cm}) - 1.469 \times \textit{vegetation} + 0.054 \times \textit{soil moisture}\ (\%) - 0.125 \times \textit{soil clay content}\ (\%) \quad (4)$$

was developed to investigate these changes.

Information on suspended sediment provenance is an important requirement in the examination of sediment routing and delivery and in the construction of sediment budgets (Walling, 1988). Traditionally, suspended sediment has been regarded as a physical pollutant in the riverine environment (Guy & Fergusan, 1970), and it has been recognized that it may have an important control upon geomorphic and biological processes (Walling & Webb, 1992). Pollution by sewage and other domestic products, poisonous industrial effluents, agricultural chemicals, etc., has increased, resulting in eutrophication of water bodies. To feed the ever increasing population in the region, the use of nitrogenous, phosphatic and potassic fertilizers increased by 102%, 387% and 286%, respectively, within the five year period 1997–2002. Soil and nutrient loads in flood water are given in Table 3 (Sharma & Sharma, 2004). This nutrient load will contribute to the tainting of freshwater in the 21st century and affect the health of human beings and aquatic ecosystems.

Table 3 Sediment load in flood waters.

Soil/Nutrient	Range (mg L^{-1})	Soil/Nutrient	Range (mg L^{-1})
Soil	1 500–30 000	Micronutrients	7.5–22.7
NO_3-N	6.4–25.8	Ca	2.5–6.4
P-PO_4	2.3–8.5	Mg	6.5–14.0
K_2O	15.4–33.8	SO_4	5.0–8.5

IMPLICATIONS AND IMPACTS

Soil erosion has important implications for landscape ecological conditions. Though the region has abundant water resources, there is an acute shortage of water after the rainy season is over. The Cherrpunji-Mawsynram range, which receives the highest rainfall in the world (annual average of 11 500 mm), has a dry and highly degraded look during winters, and even fresh drinking water is scarce. Soil erosion is widespread, causing silting of river beds and floods in the valley areas. The flood disasters cause large losses of human life and immense damage to the infrastructure and to economic activities. The ecosystem has been seriously affected by rapid population growth, uncontrolled development works, deforestation and other human activities. The population has increased by about four times during the last half-century and the annual compound growth rate (ACGR) in the region has been about 2.43%. The indiscriminate human use of rainwater has taken precedence over its environmental impacts. Beyond immediate economic gains, the practice of shifting cultivation has left the legacy of degraded aquifers, land subsidence and ecological damage. The three major factors responsible for sediment yield and its delivery to the rivers, viz. social, economical and ecological, are interlinked in the region. About 8.86×10^6 ha land has been degraded due to soil erosion and other problems. This has affected freshwater resources, which may lead to a crisis of enormous magnitude in the coming years. Contamination of freshwater resources is likely to cause diseases such as malaria, dysentery, typhoid, dengue fever, etc., while a change in the rainfall pattern, hydrological cycle and vegetation cover, may alter the carbon cycle and biological systems as well as contaminant pathways. The magnitude of change in river sediments will further exert severe ecological stress and an increasing incidence of floods will affect the quality of irrigation water, leading to low crop productivity.

A multidisciplinary study conducted to develop new land-use systems to replace the practice of shifting cultivation revealed that the sediment delivery to the rivers can be drastically reduced (Table 4). The average sediment yield varied between 16.2 and 82.2 t km^2 in new land uses compared with 3621.3 t km^2 under shifting cultivation. The sediment yield varied significantly with the amount of rainfall received.

Table 4 Effect of land use and precipitation on the sediment yield (t km^{-1}).

Land use	Annual rainfall (mm)						
	2195	2705	2770	2599	2388	1992	Mean
Fodders/grasses	14.2	16.3	28.8	18.6	10.6	9.0	16.2
Forestry (trees)	60.1	115.4	141.1	131.7	69.9	65.3	97.2
Agriculture	3.9	9.8	24.3	22.7	3.7	3.1	11.2
Horticulture	65.0	101.4	124.8	80.2	70.5	51.7	82.2
Shifting cultivation	2950.0	4580.0	4499.7	3610.0	3419.1	2669.4	3621.3
Mean	618.4	964.5	963.7	772.6	714.7	559.7	

C.D. (p = 0.05).

Land use = 77.6; Precipitation = 66.2; Land use × Precipitation = 162.5.

FUTURE STRATEGIES

The aggravated pollution of freshwater resources in the northeastern region of India, along with the progressive encroachment of incompatible activities, demand integrated water resources planning and management. Such integration must cover all types of interrelated freshwater bodies and duly consider water quality and quantity aspects. There is a need for water resources assessment, including identification of potential sources of freshwater and study of the potential impact of climate change in areas prone to droughts and floods. The region has to develop and apply techniques and methodologies for assessing the potential adverse effect of climate change on freshwater ecosystem. There is a need for the establishment and strengthening of technical and institutional capacities to identify and protect sources of water supply within all sectors of society.

The encouragement of development and management of water resources based on a participatory approach, involving users, planners and policy makers at all levels, is required. Proper drinking water supply and sanitation is important since safe water supplies and environmental sanitation are vital for protecting the environment, improving health and alleviating poverty in the region. Rehabilitation of polluted and degraded water bodies to restore aquatic habitats and ecosystems is necessary. Achieving enduring food security in the region through judicious use of water is also a priority. The challenge is to develop and apply water-saving techniques, and through capacity building, enable communities to introduce institutions and incentives for the rural population to adopt new approaches. Human resource development is necessary in order to improve awareness of river problems and to take measures to counter the adverse effects of climate change. The practice of shifting cultivation needs to be replaced by sustainable, eco-friendly and socially acceptable land-use systems.

CONCLUSIONS

Both, natural and anthropogenic factors prevailing in the northeastern region have increased vulnerability to flooding, land and environmental degradation and pollution of freshwater resources. The practice of shifting cultivation as a method of food production is no longer economic and sustainable and has become a resource-depleting practice, causing excessive soil erosion from the hill slopes, which has substantially increased the river sediments. Transport of soil and sediment-associated nutrient load in the runoff, its deposition in rivers and streams and pollution of the freshwater bodies in the northeastern region, is a matter of concern. Unabated deforestation and denudation of hill slopes has led to water scarcity in the region because the natural water cycle has been upset. There is an urgent need to replace the age-old practice of shifting cultivation with eco-friendly, sustainable and socially acceptable land use systems so as to reduce the sediment load in runoff. The present land tenure system requires modification by the enactment of suitable laws by the government and giving of ownership rights to the cultivators so that they may feel a sense of belonging and responsibility for judicious management of water resources. Judicious management of rainwater is necessary so that maximum quantity of rainwater could be retained *in situ* in order to reduce runoff and associated sediment loss.

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