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Geochemical characteristics of the major tropical rivers of India

R. RAMESH
Institute for Ocean Management, Centre for Water Resources, Anna University, Madras 600 025, India
V. SUBRAMANIAN
School of Environmental Sciences, Jawaharlal Nehru University, New Delhi 110 067, India

Abstract The tropical rivers, constituting a small part (960 000 km^2) of the great Indian river system are nevertheless important due to the area they drain and the density of population they serve. The annual transport of dissolved and particulate load of the ten major tropical rivers have been estimated to be around 57.5×10^6 t and 342×10^6 t respectively. The Godavari River alone transports nearly 50% of the sediment load of all the major tropical rivers. The rate of chemical erosion among these basins range from 22 t km^{-2} $year^{-1}$ to 199 t km^{-2} $year^{-1}$. Similarly, the rate of physical erosion ranged from 16 t km^{-2} $year^{-1}$ to 793 t km^{-2} $year^{-1}$. The chemistry of river water is partly controlled by chemical weathering and by monsoon precipitation and qualitatively by anthropogenic effects. Sediment chemistry indicates that Cauvery River sediments are most siliceous while those of the Godavari are least siliceous. The geology of the basins is one of the main controlling factor of the sediment transport of the tropical rivers. Sediment erosion in the basins reflect man's interference with natural processes.

INTRODUCTION

River particulate matter and dissolved salts play a significant role in geochemical cycles. The river sediment fluxes represent about three-quarters of the total denudation of the continents under present-day conditions. River sediments also adsorb and transport a number of aqueous ionic constituents. Recent compilations of the available data have estimated that the total annual discharge of river particulate and dissolved load to the coastal zones of the world under present-day conditions are 13.5×10^9 t and 3.87×10^9 t respectively (Milliman & Meade, 1983; Meybeck, 1979). The estimates for the individual continents are listed in Table 1. The suspended/ dissolved ratio reaches a maximum value of 10.45 for Oceanic and 4.04 for Asia, which mainly reflects the high suspended loads transported by rivers drawing such countries particularly Taiwan, New Guinea and New Zealand. The dissolved load exceed suspended sediment load only in Europe (Table 1).

The tropical rivers constituting a small part of the great Indian river system are nevertheless important due to the area they cover and density of population they serve.

Table 1 Dissolved and particulate loads carried by rivers to the ocean from individual continents.

Continent	Drainage area (km^2)	Dissolved load ($t \times 10^6$ $year^{-1}$)	Suspended load ($t \times 10^6$ $year^{-1}$)	Sediment yield ($t\ km^{-2}\ year^{-1}$)	Ratio of suspended /dissolved	Mean continental elevation (km)
Asia	16.88	1592	6433[a]	380	4.04	0.96
Oceania[b]	5.2	293	3062	~1000	10.45	~1.0
North America	17.5	758	1462	66	1.93	0.72
South America	17.9	603	1788	97	2.97	0.59
Africa	15.34	201	530	35	2.64	0.75
Europe	4.61	425	230	50	0.54	0.34

[a]Including value for Eurasian Arctic.
[b]Includes Pacific and Indian Ocean Islands – Japan, Indonesia, Taiwan, Philippines, New Guinea and New Zealand.
Sources: Meybeck (1979); Milliman & Meade (1983).

Major tropical rivers in India exist on the east coast, where the rivers discharge into the Bay of Bengal (Fig. 1). The present study of the major tropical rivers of India is an attempt to understand the dissolved and sediment fluxes and controlling factors involved. The general characteristics of water quality and suspended sediment for all the major tropical river basins, based on data generated in the last few years, are discussed together with some selected data from unpublished or published reports of the agencies.

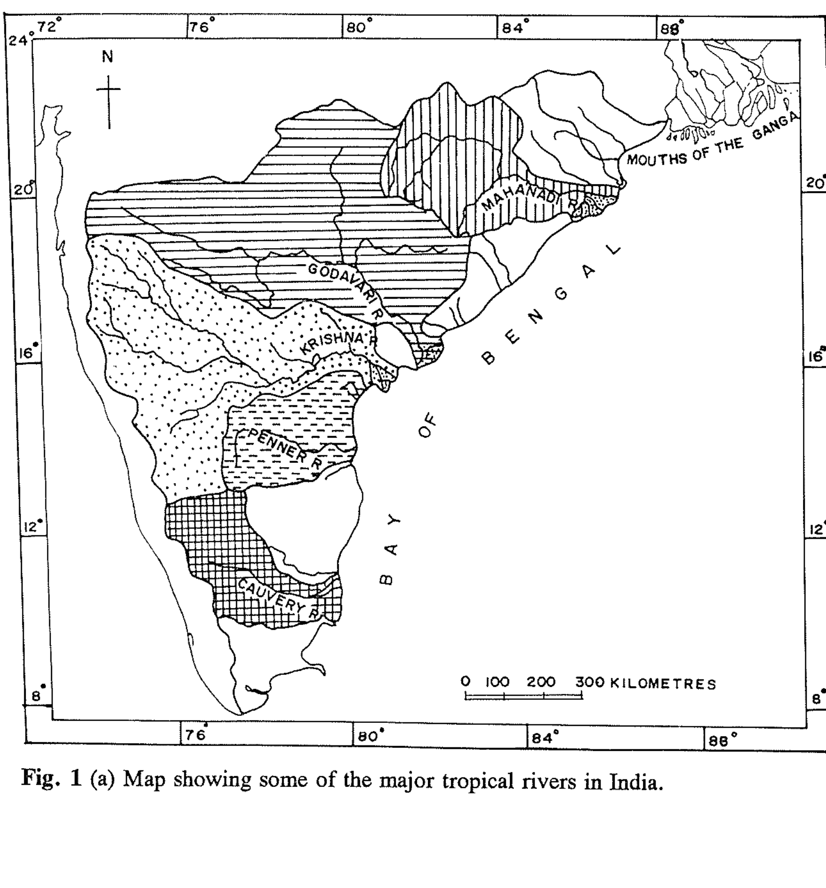

Fig. 1 (a) Map showing some of the major tropical rivers in India.

TROPICAL RIVER BASINS OF INDIA

The hydrological characteristics of major tropical river basins in India are summarized in Table 2. The total fresh-water runoff for the 10 river basins (Table 2) is 281 $\times$ 10^9 km^3 $year^{-1}$, which is about 17% of the water discharge from the Indian sub-continent. Unlike the large river system of the Amazon (water discharge 6340 km^3 $year^{-1}$) representing a single drainage network, the Indian rivers cover different climatological, geographical and geological formations. The Godavari, Krishna and Cauvery river basins together account for over 60% of the tropical Indian river system (Fig. 1). These rivers rise in the Western Ghats and flow about 1000 km before discharging into the Bay of Bengal. The Godavari and Krishna river basins are under the influence of a semiarid climate. The Cauvery crosses different climatic zones. The northwestern side of the basin is bounded by per-humid climate. After passing from northwest to east, the river crosses humid, moist humid, dry sub-humid and semiarid climate zones. Drainage and the geological formation of these rivers as well Pennar and Mahanadi Rivers is provided in Fig. 1(a) and 1(b).

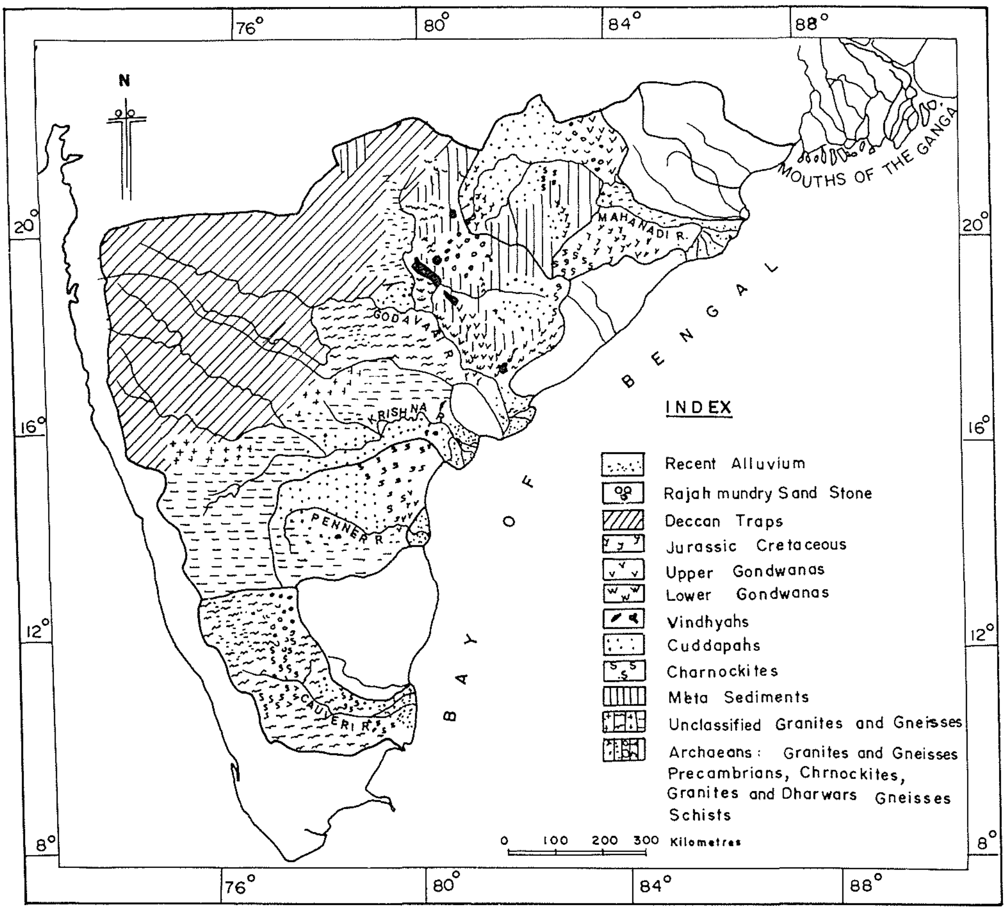

Fig. 1 (b) Map showing geological formations in some of the major tropical rivers in India.

Table 2 Mean discharge, transport and erosion rates of the major tropical rivers of India.

River	Station	Drainage area (km^2)	Annual runoff (10^6 m^3)	TDS (mg l^{-1})	TSM (mg l^{-1})	Chemical load (10^6 t year^{-1})	Sediment load (10^6 t year^{-1})	Total load (10^6 t year^{-1})	Chemical erosion rate (t km^{-2} year^{-1})	Sediment erosion rate (t km^{-2} year^{-1})	Total erosion rate (t km^{-2} year^{-1})	Ratio of sediment/ chemical loads
Godavari	Rajhamundry	313 147	92 245	181	1845	16.7	170	186.7	53.3	543	596	10.2
Krishna	Vijayawada	251 360	32 397	360	122	11.7	4	15.7	46.4	16	62	0.34
Cauvery	Musiri	87 990	11 510	172	120	2.0	1.4	3.4	22.5	16	39	0.71
Mahanadi	Tikarapara	88 320	54 431	149	563	8.1	30.6	38.7	91.8	347	439	3.8
Narmada	Garudeshwar	87 892	46 673	224	1494	10.5	69.7	80.2	119.0	793	912	6.7
Tapti	Savkheoa	49 136	9 713	294	2546	2.9	24.7	27.6	58.1	503	561	8.7
Pennar	Somasila	48 660	5 203	210	1322	1.1	6.9	8.0	22.5	142	165	6.3
Brahmani	Samal	28 200	16 340	72	1241	1.2	20.3	21.5	41.7	720	762	17.3
Mahi	Kadana	25 501	10 817	260	895	2.8	9.7	12.5	110.3	380	490	3.5
Sabarmathi	Valasana	14 176	1 450	352	3143	0.5	4.6	5.1	36	325	361	9.03
Total		994 292	280 779	-	-	57.5	341.9	399.4	58	344	402	5.9

TDS = total dissolved solids (discharge weighted average); TSM = total suspended matter.

METHODOLOGY

Water samples were collected mid-river from the Godavari, Krishna and Cauvery rivers and its major tributaries at least four times since 1982 to broadly cover the seasonal and annual variations. Suspended sediments were separated by 0.45 μm millepore filtration in the laboratory. Preservation of samples, laboratory processing and analytical methods were based on standard techniques and details have already been reported (Subramanian, 1979). Additional data on discharge chemistry and sediment load for other river basins (Tables 2, 3 and 4) obtained from several published/unpublished reports of government agencies in India.

Table 3 Chemical composition, fluxes and erosion rates of the dissolved constituents in the major tropical rivers of India.

River	HCO_3	Cl	SiO_2	SO_4	Ca	Mg	Na	K
Godavari	105[a]	17	8	16	22	5	12	3
	9.69[b]	1.57	0.74	1.48	2.03	0.46	1.11	0.28
	30.93[c]	5.01	2.36	4.71	6.48	1.47	3.53	0.88
Krishna	178	38	49	24	29	8.1	30	2.4
	5.77	1.23	1.58	0.78	0.94	0.26	0.97	0.08
	22.94	4.90	6.32	3.09	3.74	1.04	3.87	0.31
Cauvery	53.3	18	39	8.4	15.4	16	30	2.6
	0.61	0.21	0.45	0.10	0.18	0.18	0.35	0.30
	6.98	2.36	5.11	1.10	2.02	2.10	3.93	0.34
Mahanadi	66	11.7	NA	20.5	20	4.3	3.4	2.4
	3.59	0.64	-	1.12	1.09	0.23	0.19	0.13
	40.68	7.21	-	12.63	12.33	2.65	2.10	1.48
Narmada	108.4	30	20	21.4	17	12.4	9.0	6.6
	5.06	1.40	0.93	1.08	0.79	0.58	0.42	0.31
	57.56	15.93	10.62	11.36	9.03	6.58	4.78	3.50
Tapti	173.1	20.3	29.4	31	28.5	13.2	28.5	3.2
	1.68	0.20	0.29	0.30	0.28	0.13	0.28	0.03
	34.22	4.01	5.81	6.13	5.63	2.61	5.63	0.63
Pennar	116	32	NA	35	34.5	6.6	30.3	2.1
	0.60	0.17	-	0.18	0.18	0.03	0.16	0.01
	12.40	3.42	-	3.74	3.69	0.71	3.24	0.22
Brahmani	54	9	NA	28.5	11	3.5	5.7	2.3
	0.88	0.15	-	0.47	0.18	0.06	0.09	0.04
	31.29	5.21	-	16.51	6.37	2.03	3.30	1.33
Mahi	145	23	NA	5.5	39	9.5	12.5	1.7
	1.57	0.25	-	0.06	0.42	0.10	0.14	0.02
	61.51	9.76	-	2.33	16.54	4.03	5.30	0.72
Sabarmathi	1.55	51	NA	10.5	38.9	14	32.5	3.2
	0.22	0.07	-	0.02	0.06	0.02	0.05	0.01
	15.85	5.22	-	1.07	3.98	1.43	3.32	0.33

NA = not available.
[a] Chemical composition in mg l^{-1}.
[b] Dissolved flux in 10^6 t $year^{-1}$.
[c] Erosion rate in t km^{-2} $year^{-1}$.

Source: The values for Godavari, Krishna and Cauvery were measured by the authors and for other rivers from unpublished data of the author and also of the Central Water Commission (CWC).

Table 4 Major elemental composition, fluxes and erosion rates of five major tropical rivers of India.

Element	Godavari	Krishna	Cauvery	Narmada	Tapti
Si	220 000[a] 37.4[b] 119.4[c]	304 300 1.22 4.85	346 000 0.48 5.46	302 000 21.05 239.50	325 000 8.03 163.42
Al	43 100 7.33 23.4	22 500 0.09 0.36	44 400 0.062 0.71	28 900 2.01 22.87	44 400 1.10 22.39
Fe	57 100 9.71 31.0	25 100 0.1 0.4	17 600 0.0246 0.28	31 400 2.19 24.92	109 000 2.69 54.75
Mg	13 720 2.3 7.34	6 500 0.026 0.1	11 000 0.0154 0.18	10 200 0.71 8.08	24 000 0.59 12.01
Ca	45 780 7.78 24.84	24 100 0.096 0.38	15 000 0.021 0.24	20 100 1.40 15.92	81 600 2.02 41.11
Na	NA - -	55 600 0.222 0.88	NA - -	NA - -	NA - -
K	10 340 1.76 5.62	38 200 0.153 0.61	11 020 0.015 0.17	9 300 0.65 7.40	4 200 0.104 2.12
Ti	8 640 1.47 4.69	3 158 0.013 0.052	2 950 0.004 0.05	4 000 0.28 3.19	21 050 0.52 10.58
Mn	1 070 0.18 0.57	906 0.004 0.016	319 0.0005 0.006	514 0.036 0.41	1300 0.032 0.65

[a] Concentration in $\mu g/g^{-1}$.
[b] Flux in 10^6 t $year^{-1}$.
[c] Erosion rate in t km^{-2} $year^{-1}$.

RESULTS AND DISCUSSIONS

River water composition and fluxes

The discharge weighted mean chemical composition of the major ten rivers are presented in Table 3. Also shown are the dissolved flux and erosion rates of individual elements. The HCO_3^- ions are nearly more than 50% of the total dissolved solids (TDS) of the major tropical rivers. High TDS is generally reflected in higher alkalinity and Cl content. The dissolved K content in river water (except Narmada) is uniform for all the basins irrespective of size and location suggesting conservative behaviour in the river system. The high carbonate alkalinity may reflect intensive chemical weathering. Also, atmospherically regulated CO_2-water reactions, especially in the monsoon period, may further enhance the carbonate alkalinity. Gibbs (1970) classified world rivers into three categories: (i) those dominated by rock weathering; (ii) those controlled by precipitation and (iii) those controlled by evaporation. On a diagram developed by him, not shown here, various Indian tropical rivers are plotted and it shows that chemical weathering contributes the bulk of TDS. In addition to weathering, atmospheric contribution provide a major source of certain constituents, such as SO_4, in Indian tropical rivers. For example, in the Godavari river basin nearly 60% of the dissolved load is atmospherically recycled (Biksham & Subramanian, 1980).

The major Indian tropical rivers carry 57.5×10^6 t year^{-1} of solutes which is less than the load transported by the Ganges (76×10^6 t year^{-1} or Brahmaputra (76×10^6 t year^{-1}). It is well known that physical weathering is more dominant in Asian rivers (Gibbs, 1981) than chemical weathering. However, for the Krishna and Cauvery the chemical load is more dominant (Table 2) than sediment load. It should also be noted that the solute yield of Indian tropical rivers is higher than the global average (58 t km^{-2} year^{-1}).

Sediment transport and fluxes

The major tropical river basins are transporting about 342 million tonnes of sediments into the Bay of Bengal and the Arabian Sea (Table 2). Only the Godavari River

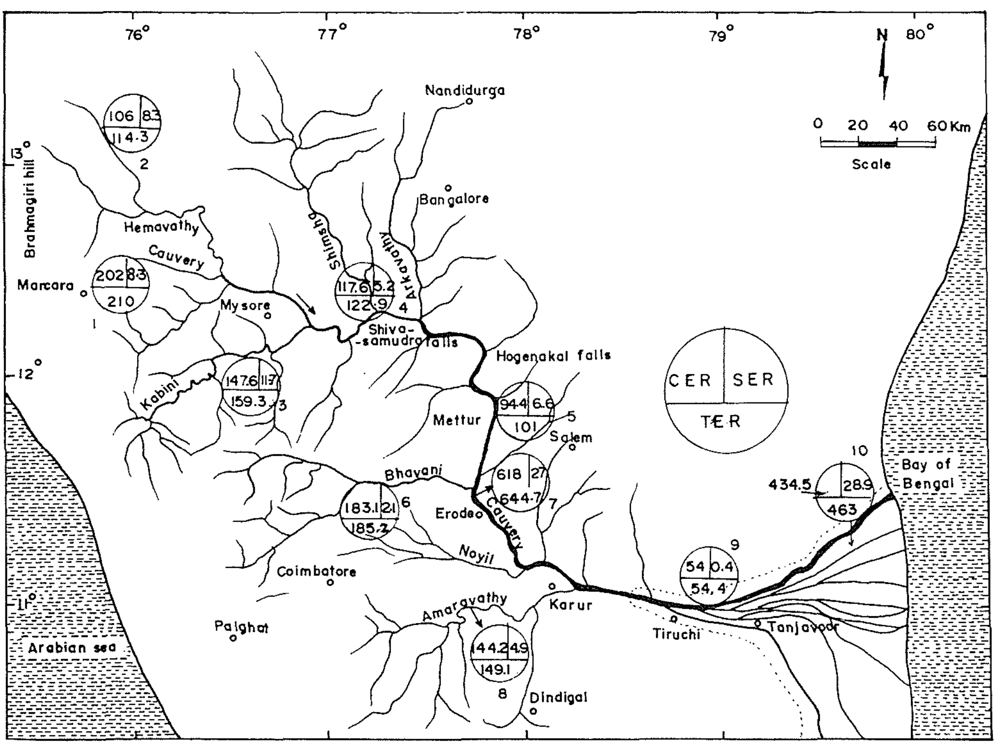

Fig. 2 Erosion rates in the Cauvery River basin (after Subramanian *et al.*, 1993). CER = chemical erosion rate; SER = sediment erosion rate; TER = total erosion rate.

contributes significant sediment load from tropical rivers. Nearly 90% of the sediment load in the Indian sub-continent is derived from the Ganges and Brahmaputra (1226 million t $year^{-1}$). The rivers are eroding at the rate of 344 t km^{-2} $year^{-1}$ which is very high compared to many world rivers (for example Amazon 146 t km^{-2} $year^{-1}$; Mekong 200 t km^{-2} $year^{-1}$; world average 150 t km^{-2} $year^{-1}$) of similar climatic, topographic and geological conditions. In the Krishna and Cauvery river basins, the major portion of the sediment load is being deposited behind dams located at river mouths. For example, Fig. 2 shows the nature of solute and sediment erosion rates prevalent in the entire Cauvery basin (Subramanian *et al.*, 1993). It will be evident from the figure that both the Krishnaraja Sagar Dam region and the Erode Mettur Dam region (locations 4 and 5) show abnormal erosion rates indicating the impact of man on natural rate processes. Similarly, in the estuary region of the river (location 10) involving extensive agricultural activities, the erosion rates are very high. Thus, the Cauvery River system no longer represents natural hydrological process.

Table 4 gives the chemical composition, annual flux of individual elements for the four major tropical rivers together with erosion rates. The annual flux of different elements ranged from 37.4×10^6 t for Si and 0.5×10^3 t for Mn. Fe, Ca and Ti contents in Tapti sediments are abnormally high relative to other tropical rivers. The Cauvery seems to carry highest siliceous materials compared to other rivers.

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