Dissolved Loads of Rivers and Surface Water Quantity/Quality Relationships
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Factors controlling the chemical composition of river waters of India

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ABSTRACT Extensive analysis of a large number of water samples from rivers draining the Indian sub-continent indicates hydrological, temporal and downstream variations. The chemistry of river waters is partly controlled by chemical weathering, significantly by monsoon precipitation and qualitatively by anthropogenic effects. TDS concentration exhibits an inverse relationship with annual runoff. Compared to Chinese and other Asian rivers, Indian rivers are less alkaline but have more Na and Cl. On a global scale, rivers from India carry greater solute flux than the Amazon or Zaire and have a solute yield twice that of the global average.

Factors conditionnels de la composition chimique des rivières indiennes
RESUME L'analyse d'un grand nombre d'échantillons d'eau des rivières drainant le sous-continent indien met en évidence des variations hydrologiques, des variations dans le temps et des variations spatiales. La chimie des eaux des rivières est fonction en partie du lessivage des sols, mais est affectée significativement par les précipitations dues à la mousson et qualitativement par l'action de l'homme. La hauteur totale de précipitations annuelles et la surface du bassin versant varient en sens inverse de la charge totale dissoute. En comparaison avec des rivières de Chine ou plus généralement d'Asie, les rivières indiennes sont moins calcaire, mais sont plus chargées en sodium et chlore. D'une manière générale les rivières indiennes charrient des flux de matières dissoutes plus grandes que ceux de l'Amazone et du Zaïre et présentent un taux de matières dissoutes dû à l'érosion de la moyenne générale.

INTRODUCTION

Chemical quality of river waters has been the subject of study by several groups of workers. Recently an attempt has been made to derive an average composition of world rivers, based on extensive data from selected Asian and South American rivers (Meybeck, 1979). While this has improved upon the earlier, but most frequently cited, average values of Livingstone (1963), lack of data for rivers draining the Indian sub-continent makes these values at best an approximation. Although the Indian rivers discharge together only about one third of the runoff from the River Amazon, they are important on a global scale because of their extensive drainage areas and their intensive utilization by man. Preliminary and broad investigations of Indian rivers have been periodically reported (Subramanian, 1979; Bikshamaih & Subramanian, 1980). Recently, a similar study has been made of some large Chinese rivers including the basin of the Brahmaputra located in Tibet (Hu Ming-Hui *et al.*, 1982).

HYDROLOGY AND GEOLOGY OF INDIAN RIVERS

The Indian rivers together discharge approximately 16 x $10^{11} m^3 year^{-1}$, which is about 5% of global runoff to world oceans (Rao, 1975). Among the large and median Indian rivers, the mean annual discharge varies from 16 000 $m^3 s^{-1}$ for the Brahmaputra to 600 $m^3 s^{-1}$ for the Tapti. The combined drainage area of these rivers equals that of the Zaire (Congo). However, due to the influence of the monsoon, Indian rivers have a markedly seasonal flow regime. Many of them carry 90% of their annual discharge during the three-month monsoon period, but even the large rivers, such as the Ganges, may dwindle at certain stations to no more than a few metres in width in the rest of the year.

Since the nine rivers under discussion (Ganges, Brahmaputra, Indus, Narmada, Tapti, Mahanadi, Godavari, Krishna and Cauvery) cover the entire sub-continent, practically all rock types are exposed in their drainage basins. The headwaters of the Indus-Ganges-Brahmaputra basin rise in the Tertiary Siwalik rocks of the Himalayas, whereas downstream reaches flow over recent alluvium. The Narmada-Tapti system traverses the Vindhyan (Pre-Cambrian) mountains, whereas the Godavari-Krishna-Mahanadi basin is underlain by the Deccan Traps (Tertiary volcanics), and the Cauvery drains the South Indian Shield (Pre-Cambrian).

METHODOLOGY

Over the last 6 years samples have been collected on a seasonal basis from nine major Indian rivers, and the location of sampling stations (except those for the Indus and Mahanadi) are shown in Fig.1. Water samples were collected in polyethylene bottles, and pH and alkalinity were measured in the field. Preservation of samples, laboratory processing and analytical methods were based on standard techniques and details have already been reported (Subramanian, 1979). Discharge data for these locations were obtained from several published or unpublished reports of the Indian Government.

RESULTS AND DISCUSSION

All the rivers studied show erratic downstream variation in water chemistry. As an example, Fig.2 illustrates the downstream profile for the Ganges and the Krishna. In general, minima and maxima in the downstream profile are related to the diluting and concentrating effects of tributary inflows, with respectively low and high TDS content. This influence is particularly clear for the Ganges since some tributaries, such as the Yamuna which meets the mainstream at

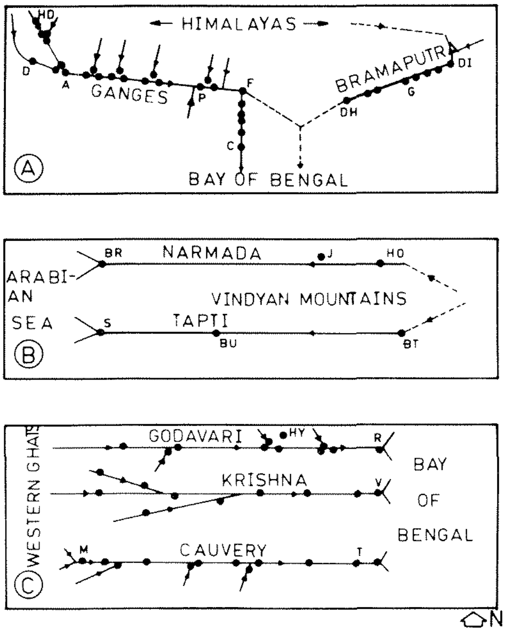

FIG.1 Flow chart of large river basins in India.

Allahabed 1200 km downstream, carry a large dissolved load, whereas others, such as the Ghagra (confluence at 1500 km downstream), have a low dissolved load. In contrast, the Brahmaputra exhibits an increase of TDS downstream although no major tributary joins it in the Indian part of the basin. However, the plains of northeast India are extensively cultivated with tea and other plantations, and addition of agricultural waste to the Brahmaputra is a common feature in this region. Similarly, the Cauvery flows through an area of high population density and the river has generally high TDS levels in its downstream reaches.

Figure 3 shows the general control of TDS concentration by annual discharge. There are two types of relationship contained in the scatter. Most of the high discharge-low TDS samples are from the Ganges-Brahmaputra-Indus system, whereas low/medium discharge-high

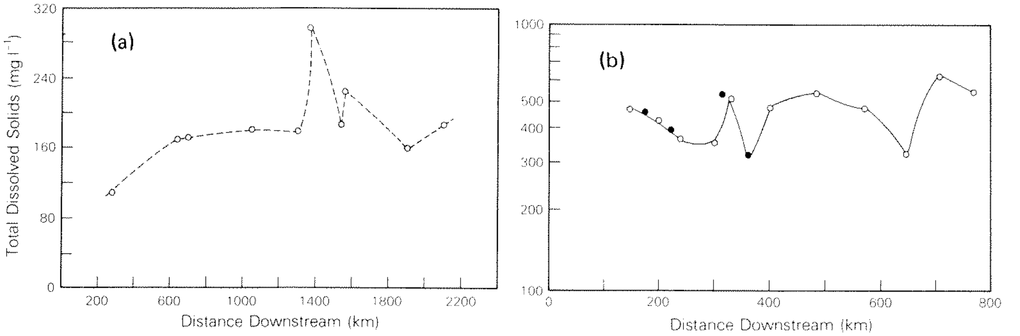

FIG.2 Downstream variation in the TDS concentration of the Rivers Ganges (a) and Krishna (b).

TDS points relate to the central and southern rivers. In these rivers, discharge is very low during non-monsoon months and ground/ spring waters are the source for runoff during this period. The ground water influence is reflected in high TDS concentrations at low discharges. Table 1 summarizes the average chemical composition of river waters of India. For each river, the average has been calculated based on all the samples in that basin. Variation in TDS concentration is reflected in changes in the proportion of selected individual chemical components. All the southern rivers, except the Mahanadi, show very high carbonate alkalinity relative to the Himalayan rivers. K does not show much variation throughout the sub-continent, suggesting conservative behaviour in river systems (Garrels & Mackenzie, 1971). The high carbonate alkalinity may not reflect intensive chemical weathering, rather it may indicate the extent of mixing with groundwater rich in HCO_3. Also, atmospherically regulated PCO_2-water reactions, especially in the monsoon period, may further enhance the carbonate alkalinity. None of these river basins are

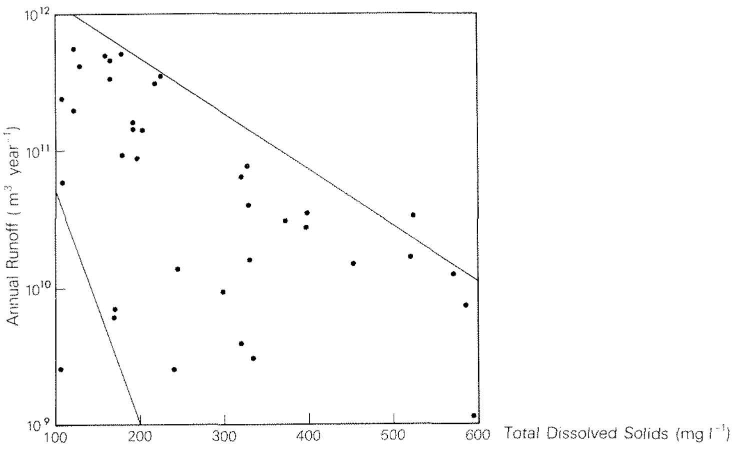

FIG. 3 Runoff/TDS relationship for the Indian sub-continent.

known to drain rich carbonate deposits.

In addition to weathering, atmospheric contributions provide a major source of certain constituents, such as SO_4, in Indian rivers. For example, in the Godavari River basin nearly 60% of the dissolved load is atmospherically recycled (Bikshamiah & Subramanian, 1980). Numerous analyses of rain water at Delhi, located on the Yamuna which is a tributary of the Ganges, indicate that monsoon rain is heavily charged with Na, Cl, Ca and SO_4 (Subramanian & Saxena, 1980).

Table 2 gives the discharge-weighed average composition of runoff from the Indian sub-continent. Also given for comparison are the average composition of Chinese, Zaire and Amazon rivers, and the world average composition of Livingstone (1963). The Chinese rivers are more alkaline than the Indian rivers while their Na levels are lower. Other constituents in both these systems are present in similar concentrations. In spite of their large discharge, Zaire and

TABLE 1 Average chemical composition (mg l^{-1}) of study basins

River	Discharge ($10^6 m^3 year^{-1}$)	Alkalinity	Cl	SO_4	SiO_2	Ca	Mg	Na	K	TDS
Ganges	493 400	81	8	7	3.5	36.5	5	9	4	154
Narmada	40 705	225	20	5	9	14	20	27	2	322
Tapti	17 982	150	65	0.6	16	19	22	47.5	3	322
Brahmaputra	510 450	37.5	15	9.5	6.7	29	7.4	12	2.5	148
Krishna	67 675	125	37	63	5	27.5	13.5	42.5	3	318
Indus	207 800	64	9.2	15	5.3	26.8	0.72	1.25	2.1	122
Godavari	105 000	114	14	10	21	30	2.4	8.0	2.2	200
Cauvery	20 950	177	55	32	19	28	24	60	5.5	400
Mahanadi	66 640	61	31	15	9	10.4	9.5	10.2	1.5	155

TABLE 2 Average composition (mg l^{-1}) of Indian, Asian and World rivers

River	Discharge ($10^9 m^3 year^{-1}$)	Area ($10^3 km^2$)	Na	K	Mg	Ca	Cl	SO_4	Si	Alkalinity	TDS	Reference
Chinese rivers*	1 777	3 500	5	1.5	5.5	33	7	14	3	113	181	Hu Ming-Hui et al. (1982)
Zaire	1 230	4 104	1.5	1	1	2	1	1	4	12	24	Meybeck (1979)
Amazon	5 500	6 300	2	1	1	5.5	1	2	0.5	21	34	Meybeck (1979)
Indian rivers	1 700	3 900	12	3	7	30	15	13	7	74	159	Present study
World	31 400	101 000	6	2	4	15	8	11	13	58	120	Livingstone (1963)

* including Mekong River.

TABLE 3 Annual chemical flux (Mt $year^{-1}$) in Indian sub-continent and other environments

River	Na	K	Mg	Ca	Cl	SO_4	Si	Alka-linity	Total annual flux	Solute yield (t $km^{-2} year^{-1}$)
Ganges	4.5	2	2.5	18	4	3.5	1.8	40	76	78
Brahmaputra	4.1	1.3	3.8	14.8	7.7	4.8	3.4	19	76	110
Indus	0.26	0.44	0.15	5.6	1.9	3.1	1.1	14	25	21
India Total	20.4	5.1	11.9	51.0	25.5	20.4	11.9	125.8	270	69
Chinese rivers*	8.8	2.5	9.8	58	12.3	24.7	5.3	200.5	370	80
Zaire	1.7	1.3	1.4	2.6	1.2	1.5	5.0	14.8	35.6	9
Amazon	10.1	5.5	55	3.0	7.1	11.5	2.3	115.1	223	35
World	118.4	62.8	125.6	471	250	345.4	530.6	1821.2	4068	35

* including River Mekong.

Amazon have very low concentrations of all constituents, and the world average of Livingstone, based primarily on Amazon composition, thus needs total revision in the light of the higher loads of Asian rivers.

Table 3 gives the annual flux of individual ions for the large Indian rivers, together with those for the Chinese, Zaire and Amazon rivers, and the global flux. The Indian rivers carry 270 Mt $year^{-1}$ of solutes which is greater than the load transported by the Amazon, despite the considerably greater discharge of the latter. In comparison to Indian rivers, the Zaire has a very low chemical flux and reflects the closed nature of nutrient cycling in the African rainforest environment. The Chinese rivers, which have approximately the same discharge as the Indian rivers, carry a larger solute load primarily due to the higher mean concentration of alkalinity. The Indian rivers are predominantly charged by the monsoon and this is reflected in the very high flux of Na and Cl which is the highest among world rivers. In contrast, the high Ca and SO_4 loads of Chinese rivers is related to the influence of evaporite deposits. Si flux for the Indian basins is higher than for other world rivers and indicates that chemical weathering is active in the sub-continent. It is well known that physical weathering is dominant in Asian rivers (Gibbs, 1981) but it should also be noted that the solute yield of the Indian sub-continent is twice that of global average.

Unlike the Chinese rivers, the Indian rivers are highly regulated by extensive dams, barrages and other structures and are intensively utilized. A large proportion of ions such as SO_4 in the river waters are neither of weathering nor atmospheric origin, since they are strongly influenced by irrigation waters in agricultural areas and discharges from thermal power plants in urban areas. The extent of such influences are at present only qualitatively estimated.

CONCLUSION

Indian rivers are alkaline and carry a greater annual solute load than the Amazon but have a smaller annual solute flux than similar Chinese systems. Na and Cl transport in Indian rivers is higher than in other major river systems of the world, probably due to the influence of the monsoon on continental runoff. Downstream variations in solute concentrations reflect the impact of individual tributaries and for some ions, such as SO_4, the influence of anthropogenic effects. The high solute yield, in comparison with the global average, suggests that the Indian sub-continent is a highly active environment in relation to the North American, South American or African continents.

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