

# Comparative studies on trace metal geochemistry in Indian and Chinese rivers

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**The trace metal geochemistry in Indian and Chinese rivers in the Asian region was studied to understand its variation on a global scale in terms of climate, geological conditions and anthropogenic impact. The average particulate trace metal concentration of Indian rivers (~300–1000  $\mu\text{g g}^{-1}$ ) is higher than that of Chinese rivers (~150–300  $\mu\text{g g}^{-1}$ ) and the global average (~170–350  $\mu\text{g g}^{-1}$ ). Molar ratios of alkaline and alkaline earth metals to Fe and Al (i.e. segregation factor, SF) were calculated in Indian bed sediment and in suspended matter of Chinese rivers to determine metal reactivity over the drainage basin. The segregation factors for bed sediments in Indian rivers were generally <1, except for the Tapi (~1.7) and the Godavari (1.4) systems. Regional and watershed differences in segregation factors were observed, reflecting variable weathering rates due to differing mineralogy, preferential removal of alkaline and alkaline-earth metals relative to oxide-forming elements (Fe and Al), and a regional climatic shift north to south from temperate to sub-tropical conditions. Elevated levels of lead in Chinese rivers and of cobalt and zinc in Indian rivers indicated anthropogenic inputs of these heavy metals.**

**Keywords:** Trace metal, geochemistry, Indian rivers, Chinese rivers, anthropogenic impact.

THERE is a major amount of sediment being delivered from the Southeast Asian rivers to the oceans<sup>1</sup>. The amount of sediment input by Indian rivers to the world ocean is  $\sim 3 \times 10^9$  tons  $\text{yr}^{-1}$ , of which a major proportion is supplied by the large rivers in the north. The same input is calculated for Chinese rivers (Table 1). They play a significant role in Southeast Asia, in controlling sediment distribution patterns. The suspended sediment chemistry of Indian rivers is less studied than bed sediments. When compared with major world rivers such as Orinoco<sup>2,3</sup>, Nile and St. Lawrence<sup>3,4</sup>, Mississippi<sup>5-7</sup>, Amazon<sup>8,9</sup>, Zaire<sup>9,10</sup> and Lena<sup>11</sup>, the particulate trace metal concentrations are low in both Indian and Chinese rivers/estuaries.

Concentrations of trace metals, alkaline and alkaline-earth metals in suspended matter from the large Indian rivers and/or estuaries are relatively low in comparison with

those in Western countries (e.g. Europe and North America)<sup>12,13</sup>. The trace metal concentration in suspended particles from Krishna river shows that the input is mainly due to anthropogenic influences rather than natural ones. Krishna river is being polluted by human impact in the south. It has a low amount of sediment load of  $\sim 4 \times 10^6$  tons  $\text{yr}^{-1}$ , due to the predominance of Precambrian hard rocks which cover about 80% of the basin area. Thus geographic variation will clearly define the major elements chemistry due to the differences in climatic and weathering conditions prevailing in the region<sup>9,14,15</sup>. Similar changes are also found in the Chinese rivers covering a wide range of climatic zones from semi-arid temperate (e.g. Daliaohe, Luanhe, Haihe, Huanghe and Shuangtaizihe) to subtropical (e.g. Zhujiang and Hanjiang), with Changjiang, Jiulongjiang, Minjiang and Qiantangjiang in the intermediate positions.

In this study, the role of trace metal chemistry of particulate/bed sediments was investigated in Indian and Chinese river/estuary systems with respect to climate, precipitation, tectonic control, basin geology, size of drainage basin, discharge and human impact.

## Geological settings

The Ganges source waters in the high Himalaya flow through three major geological zones: (i) an outer belt of allochthonous sediments containing carbonates, shales, sandstones, conglomerates and quartzites, (ii) an inner sedimentary belt of thick limestones with shales and slates, and (iii) a zone of metamorphic and igneous rocks, which are primarily granites and augen gneisses, lying between the two zones referred above<sup>16</sup>. Weathering of granites and gneisses rich in radiogenic Sr is highest in the source waters of the Ganga<sup>16</sup>. In the lower reaches, the Ganga drainage basin is characterized by alluvial plains, a large part of which is impregnated with alkaline and saline salts<sup>17</sup>. The Brahmaputra originates in the Tibetan Himalaya and flows along the Indus–Tsangpo suture zone. Geological information on the drainage area of the Brahmaputra in the Tibetan Himalaya is limited<sup>18</sup>. A generalized description reports the presence of lithologies, typical of suture zones. At the syntaxial bend, the Brahmaputra takes a southern turn and flows through a zone of crystalline gneisses and granites and then drains the Siwalik sediments<sup>16,17</sup>. Nar-

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**Table 1.** Drainage basin area, water discharge and sediment load of major rivers in India and China

| River         | Drainage area (km <sup>2</sup> ) | Water discharge ( $\times 10^9$ m <sup>3</sup> yr <sup>-1</sup> ) | Sediment load ( $\times 10^6$ t yr <sup>-1</sup> ) | Yield (t/km <sup>2</sup> /yr) | Reference  |
|---------------|----------------------------------|---|--|-------------------------------|------------|
| Brahmaputra   | 580000                           | 605.5   | 540  | 931                           | 46         |
| Ganges        | 975900                           | 369.7   | 520  | 532.8                         | 46         |
| Narmada       | 89000                            | 47.3  | 70   | 786.5                         | 46, 47     |
| Tapti         | 61145                            | 18.9  | 25   | 408.9                         | 46, 47     |
| Godavari      | 312812                           | 100.9   | 170  | 543.5                         | 46, 48     |
| Krishna       | 258945                           | 54.6  | 4  | 15.4                          | 46, 49     |
| Cauvery       | 90000                            | 20.3  | 1.5  | 16.7                          | 46, 47, 50 |
| Yalujiang     | 63788                            | 37.8  | 4.8  | 75.25                         | 34         |
| Shuangtaizihe | 57104                            | 4.3   | 20   | 350.2                         | 34         |
| Luanhe        | 44945                            | 4.9   | 22.7   | 505.1                         | 34         |
| Huanghe       | 752443                           | 43.1  | 400  | 531.6                         | 34         |
| Jiaojiang     | 6750                             | 6.7   | 8.4  | 1244.44                       | 34         |
| Zhujiang      | 452616                           | 355   | 80.5   | 177.9                         | 34         |
| Daliaohe      | 164104                           | 8.7   | 18.5   | 112.7                         | 34         |
| Chiangjiang   | 1807199                          | 932.3   | 250  | 138.3                         | 34         |

Sources: www.unep-wcmc.org, www.mpgovt.nic.in, www.comptons.com, www.soest.hawaii.edu.

mada and Tapti rise in the plateau and fall into the Arabian Sea. Archaean rocks occur on either side of the Narmada river and include granites and gneisses and several outcrops of Bijawar rocks. Tapti flows initially through the basaltic terrains of the Deccan traps and then through the alluvial deposits of unconsolidated fine sand, silt and clay before opening via the Gulf of Cambay into the Arabian Sea. Godavari river basin geology consists of the Tertiary Deccan traps (48%), Archaean granites and hard rocks (39%), Precambrian and Gondwana sedimentary rocks (11%) and recent alluvial cover (2%)<sup>19</sup>. Important human activities in the basin include, mining of coal, limestones, slates, manganese and iron ore. These activities are of special interest in river-basin studies, because they create localized imbalances in sedimentation and erosion processes. Krishna river basin area consists of Archaean and younger crystalline rocks (78%), the Tertiary Deccan Traps (20%) and recent alluvial (2%) cover<sup>20</sup>. The upper reaches of the Cauvery river basin drain predominantly the Precambrian shield rocks; the downstream regions lie on the Tertiary sedimentary rocks and Plio-Pleistocene sediments<sup>21</sup>. Cauvery drains metamorphic rocks composed of quartz and feldspar, which are relatively resistant to weathering and poor in transition metals. Bulk of fine clay minerals (kaolinite and montmorillonite) formed through feldspar weathering are being removed by the river flux to the ocean.

## Study area

Major Indian rivers like Brahmaputra, Ganges, Narmada, Tapti, Godavari, Krishna and Cauvery are compared with Chinese riverine and estuarine systems of Yalujiang, Shuangtaizihe, Luanhe, Huanghe, Jiaojiang, Zhujiang, Daliaohe and Changiang in this study (Figure 1). The river systems in both the regions reflect changes in water discharge and sediment yield, with significant variation in rainfall and vegetation coverage in the drainage areas (Tables 1 and

2). North China has relatively limited water discharge (Table 1) and elevated sediment loads compared to South China. There are higher water discharges in the Indian rivers Brahmaputra and Ganges in the north than those in the south.

## Results and discussion

The chemical composition of elements in sediments, suspended particulate matter (SPM) and soil on a world basis (Table 3) and the riverine composition of metals in SPM of Indian, Chinese and world rivers are shown in Tables 3 and 4 respectively. There are significant variations in chemical composition and concentration for some trace metals in the rivers of both India and China. For example, the average concentration of Fe, Mn, Cr, Ni and Zn in suspended matter in Indian rivers is higher than the world average. The trace metal content of suspended matter in Chinese rivers is in the same range as the Indian rivers and the world average, except Pb<sup>12,22,23</sup>. The average trace metal concentrations (sum of Mn, Co, Cr, Cu, Ni and Pb/number of trace metals) of Indian rivers lie in the range of  $\sim 300$ – $1000 \mu\text{g g}^{-1}$ , whereas Chinese rivers lie in the range of  $\sim 150$ – $300 \mu\text{g g}^{-1}$  and world rivers  $\sim 170$ – $350 \mu\text{g g}^{-1}$  (Figure 2).

## Indian rivers

The world average is calculated from data of fine suspended sediments and the Indian average is calculated from coarse bed sediments. The world surface rock (WSR) represents the average lithology subjected to weathering in the hydrosphere<sup>9</sup>. Indian rivers, including Brahmaputra have high rates of chemical weathering<sup>24</sup>. The difference in Indian average sediments and WSR is markedly in mobile and reactive elements. Due to highly active carbonate equilibria in the Indian river waters<sup>25</sup>, Ca, Mg, Ba and Sr

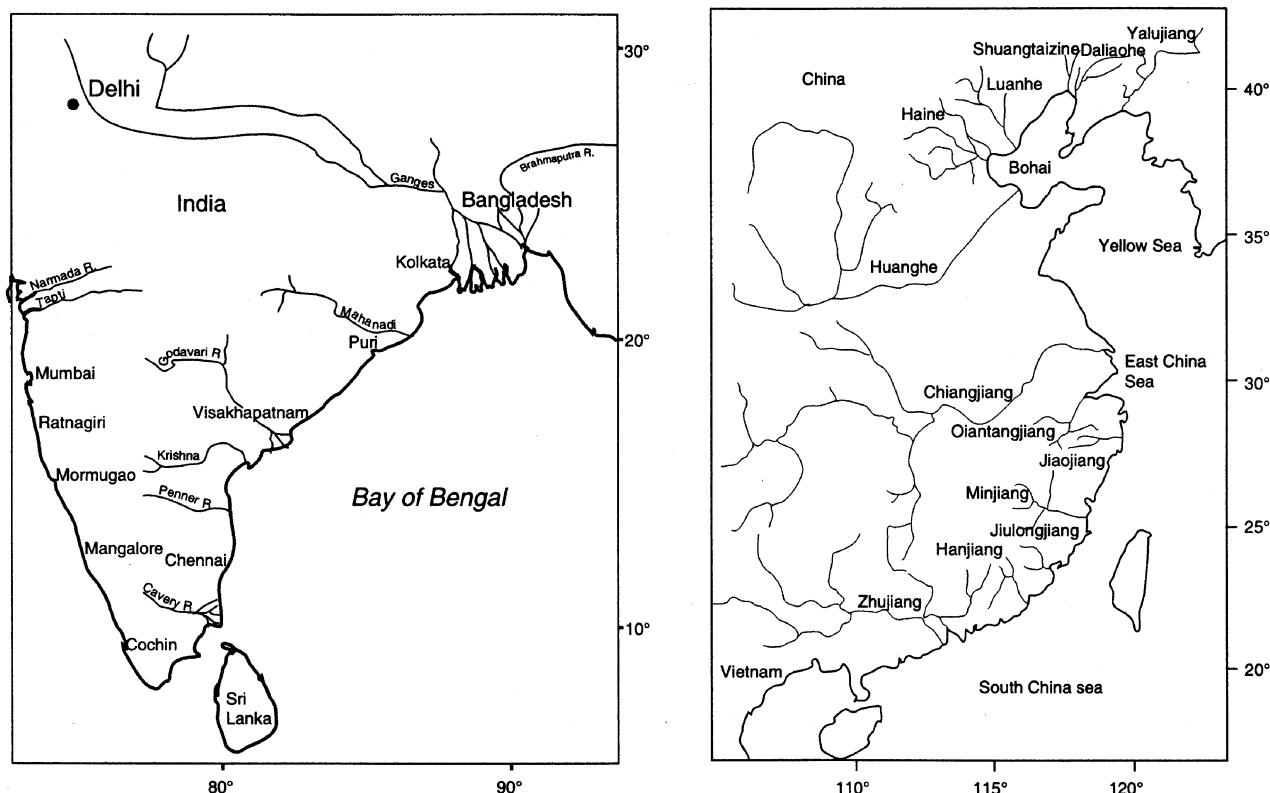


Figure 1. Map showing the locations of various river basins in India and China.

Table 2. Specific run-off, and rainfall of major rivers in India and China

| River         | Specific run-off (mm/km <sup>2</sup> /yr) | Rain fall (mm) | Height <i>H</i> (m) | Length <i>L</i> (km) | ( <i>H/L</i> ) | Molar ratio (SF) |
|---------------|---|----------------|---------------------|----------------------|----------------|------------------|
| Brahmaputra   | 992.6                                     | 2220           | 5200                | 2900                 | 1.29           | 0.57             |
| Ganges        | 378.8                                     | 2030           | 7000                | 2480                 | 2.8            | 0.62             |
| Narmada       | 531.5                                     | 1000           | 760                 | 1312                 | 0.58           | 0.71             |
| Tapti         | 309.5                                     | 800            | 740                 | 724                  | 1.02           | 1.7              |
| Godavari      | 174.4                                     | 1185           | 420                 | 1465                 | 0.29           | 1.41             |
| Krishna       | 389.7                                     | 500            | 1337                | 1400                 | 0.96           | 0.67             |
| Cauvery       | 225.6                                     | 1318           | 457                 | 756                  | 0.61           | 0.49             |
| Yalujiang     | 592.6                                     | 1099           | 1445                | 795                  | 1.82           | 0.61             |
| Shuangtaizihe | 75.3                                      | 677.4          | 2039                | 116                  | 17.58          | 0.78             |
| Luanhe        | 109.0                                     | 608.6          | 2293                | 888                  | 2.58           | 0.58             |
| Huanghe       | 57.3                                      | 534            | 5242                | 5464                 | 0.96           | 0.76             |
| Jiaojiang     | 992.6                                     | 1434           | 1184                | 197.7                | 5.99           | 0.59             |
| Zhujiang      | 784.3                                     | 1944           | 2136                | 2216                 | 0.96           | 0.23             |
| Daliaohe      | 53.0                                      | 677.4          | 2039                | 512                  | 3.98           | 0.75             |
| Chiangjiang   | 515.9                                     | 1068           | 6621                | 6300                 | 1.05           | 0.65             |

Sources: Refs 17, 20, 46, www.unep-wcmc.org, www.indiansaga.com, www.mapsofindia.com, www.comptons.com, www.mpgovt.nic.in.

are less in Indian average sediments than WSR. Al, K and Si are likely lower in bed sediments due to formation of illite and kaolinite and their transport in suspension by Indian rivers<sup>26</sup>.

### Ganges and Brahmaputra rivers

Both rivers originate from the Central Himalayas and drain regions of similar geology with similar sediment chemistry.

Suspended sediments of the Ganges–Brahmaputra are coarse relative to other large river systems; at the confluence of the Ganges and Brahmaputra, about 40% is sand (mostly fine–very fine and 60% silty-clay). The mean grain size of river-borne sediments is coarser in the Brahmaputra than the Ganges. As a result, the levels of Al, Si and Ca are less in the Brahmaputra relative to the Ganges. Similarly, higher levels of Fe, Mn and Ni are generally abundant in fine (clay-associated) sediments. Both these

river basins have practically all rock types with a wide range of geological ages. Therefore, it is difficult to identify specific sources individually for each of the elements. The concentration range for individual elements is larger for the southern rivers like Krishna, Godavari and Cauvery.

### Narmada and Tapti

These are the only two major rivers of Central India draining into the Arabian Sea. The number of samples studied is not large enough to generalize, but they differ chemically from the Himalayan as well as the southern rivers. High levels of Ca, Mg, Ti, V, Cu and Zn and deficiency in K and Fe relative to Himalayan system were found in the Tapti river. Narmada river is deficient in Al, Ca, Ti, Mn and Fe relative to Godavari and Krishna. Both Narmada and Tapti do not show significant chemical variations downstream. In contrast to other Indian rivers, the Narmada and Tapti sediments are relatively homogenous and the average reflects the composition of sediments from the entire basin<sup>21,27</sup>.

### Godavari river

Godavari river is the largest among the non-Himalayan rivers and the sediments of this basin differ in chemistry in comparison with the Ganges–Brahmaputra (GB) system. K, Al and Si are depleted relative to the GB system, which

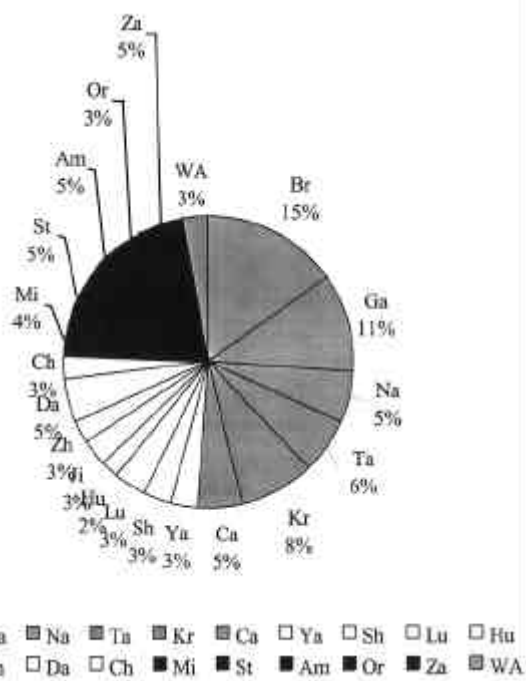
reflects the paucity of illite and other K-micas in Godavari river sediments<sup>28</sup>. Higher levels of Ti, V and Cr reflect the abundance of heavy minerals such as illmenite, chromite and rutile<sup>29</sup> and those of Ca, Ba and Sr reflect the abundance of carbonate minerals. Overall, the system is highly heterogeneous in sediment composition. The transition elements enrichment reflects hydrogenic (authigenic) component generated during the chemical weathering of basaltic Deccan traps in the catchment area. Unlike the GB, the chemistry of the Godavari sediments varies downstream, due to the differing contributions from tributaries draining distinct geological terrains.

### Krishna river

Suspended particles of Krishna river are enriched in heavy metals throughout the basin relative to bed sediments. The river carrying a sediment load of  $<4 \times 10^6$  t/yr may be due to the existence of Precambrian hard rocks of ~80% of the basin area<sup>30</sup>.

### Sediment chemistry of Cauvery river

The chemistry of suspended sediments is different from the bed sediments in the Cauvery basin. The suspended sediments are enriched in Fe, Mn and other transition elements relative to bed sediments. The mean value for heavy metals in the Cauvery particulates exceeds that of world average<sup>9</sup>. The water chemistry of Cauvery river is similar to that of an average river water from the Indian subcontinent. The chemistry of bed sediments differs



**Figure 2.** Variation of average trace metal concentration in suspended particulate matter in Indian, Chinese and world rivers. Ya, Yalujiang; Sh, Shuangtaizihe; Lu, Luanhe; Hu, Huanghe; Ji, Jiaojiang; Zh, Zhujiang; Da, Daliaohe; Ch, Changjiang; Br, Brahmaputra; Ga, Ganges; Na, Narmada; Ta, Tapti; Kr, Krishna; Ca, Cauvery; Mi, Mississippi; St, St. Lawrence; Am, Amazon; Or, Orinoco; Za, Zaire; WA, World average.

**Table 3.** Chemical composition of elements in sediment, SPM and soil on a world basis

| Metal                       | WA   | WSR   | WAS   |
|-----------------------------|------|-------|-------|
| Si (%)                      | 28.5 | 27.50 | 33.00 |
| Al (%)                      | 9.4  | 6.93  | 7.10  |
| Fe (%)                      | 4.8  | 3.59  | 4.00  |
| Mg (%)                      | 1.18 | 1.64  | 0.50  |
| Ca (%)                      | 2.15 | 4.50  | 1.50  |
| Na (%)                      | 0.71 | 1.42  | 0.50  |
| K (%)                       | 1.42 | 2.44  | 1.40  |
| Ti ( $\mu\text{g g}^{-1}$ ) | 4160 | 3800  | 5000  |
| P ( $\mu\text{g g}^{-1}$ )  | 1150 | 610   | 800   |
| Mn ( $\mu\text{g g}^{-1}$ ) | 1050 | 720   | 1000  |
| V ( $\mu\text{g g}^{-1}$ )  | 170  | 97    | 100   |
| Cr ( $\mu\text{g g}^{-1}$ ) | 100  | 97    | 70    |
| Co ( $\mu\text{g g}^{-1}$ ) | 20   | 13    | 8     |
| Ni ( $\mu\text{g g}^{-1}$ ) | 90   | 49    | 50    |
| Cu ( $\mu\text{g g}^{-1}$ ) | 100  | 32    | 30    |
| Zn ( $\mu\text{g g}^{-1}$ ) | 350  | 129   | 90    |
| Pb ( $\mu\text{g g}^{-1}$ ) | 150  | 16    | 12    |
| Sr ( $\mu\text{g g}^{-1}$ ) | 150  | 278   | 250   |
| Ba ( $\mu\text{g g}^{-1}$ ) | 600  | 445   | 500   |

WA, World average suspended sediments<sup>9</sup>; WSR, World surface rock<sup>9</sup>; WAS, World average soils<sup>32</sup>.

**Table 4.** Chemical composition of suspended particulate matter in the world rivers (Fe in %; all others in  $\mu\text{g g}^{-1}$ )

| River         | Fe   | Mn   | Co   | Cr    | Cu   | Ni    | Pb   | Zn    | Reference |
|---------------|------|------|------|-------|------|-------|------|-------|-----------|
| Brahmaputra   | 10.9 | 4450 | 168  | 222   | 108  | 179   | –    | 916   | 49        |
| Ganges        | 9    | 3450 | 223  | 264   | 252  | 137   | 37   | 643   | 49        |
| Narmada       | 7.6  | 1125 | –    | –     | 128  | 70    | –    | 125   | 28        |
| Tapti         | 7.9  | 1304 | –    | –     | 136  | 68    | –    | 150   | 28        |
| Krishna       | 13.2 | 2540 | 300  | 300   | 220  | 180   | 45   | 270   | 49        |
| Cauvery       | 6.2  | 1300 | 100  | 150   | 60   | 150   | 40   | 500   | 49        |
| Yalujiang     | 3.88 | 972  | 13.7 | 83.5  | 39.3 | 36.9  | 56.5 | 141   | 34        |
| Shuangtaizihe | 4.38 | 1025 | 20.7 | 98.4  | 38.1 | 50.2  | 82   | 114   | 34        |
| Luanhe        | 5.00 | 1081 | 16.8 | 84.4  | 54.9 | 51.7  | 68.7 | 256   | 34        |
| Huanghe       | 3.72 | 767  | 14.0 | 76.9  | 26.7 | 40.3  | 16.5 | 69.8  | 34        |
| Jiaojiang     | 3.62 | 878  | 16.9 | 90.7  | 36.5 | 46.1  | 54.8 | 105   | 34        |
| Zhujiang      | 4.89 | 677  | 17.8 | 70.6  | 51   | 61.8  | 75.2 | 212   | 34        |
| Daliaohe      | 5.17 | 1470 | 83.8 | 93    | 50.7 | 171   | 144  | 177   | 34        |
| Chiangjiang   | 5.2  | 811  | 19.0 | 122   | 62.3 | 64.2  | 39.9 | 97.7  | 34        |
| Mississippi   | 4.43 | 1260 | 21   | 77    | 38.5 | 50.5  | 39   | 193   | 5, 6      |
| St. Lawrence  | 5.07 | 1311 | 14.3 | 84.9  | 40.2 | –     | –    | 342.7 | 3, 51     |
| Amazon        | 5.55 | 1033 | 41.4 | 193.7 | 266  | 105.1 | –    | –     | 8, 9      |
| Orinoco       | 7.4  | 588  | –    | 83.5  | 60.8 | 34    | –    | 76.5  | 2, 3      |
| Zaire         | 7.1  | 1400 | 29.6 | 211   | 100  | 54    | 220  | 300   | 9, 10     |

from the world average river sediments due to the dominance of high silica minerals (quartz) in the bed load. On the other hand, the very fine particulates show enrichment of heavy metals relative to the world average. Transition elements correlate well with each other in suspended as well as bed sediments. Cauvery river suspended matter is depleted in Al and Si, and enriched in Ca, Mn, Cr, Ni, Cu, Zn and Sr relative to the world average river suspended matter. High rates of chemical weathering and human activity (irrigation, deforestation, construction of dams and reservoirs, industrial waste release) throughout the Cauvery basin led to a disbalanced transport of elements mainly in dissolved phase<sup>31</sup>.

### Comparison of Indian and Chinese river systems

Earlier studies showed a wide range of variation between Indian and Chinese rivers in comparison with world rivers. The Indian rivers studied included Brahmaputra, Ganges, Narmada, Tapti, Godavari, Krishna and Cauvery and the Chinese rivers Yalujiang, Shuangtaizihe, Luanhe, Huanghe, Jiaojiang, Zhujiang, Daliaohe and Chiangjiang.

In general, water discharge is higher in Indian rivers in comparison with Chinese rivers, except the Chiangjiang, which is in the range of 1.5–45 times higher than the Indian rivers. Water discharge is higher in the Himalayan rivers (Brahmaputra and Ganges) compared to the southern rivers (Krishna and Cauvery). In contrast to Indian rivers, Chinese rivers have a higher water discharge in the case of the southern rivers; for example, the Zhujiang (Pearl river:  $355 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$ ) and Chiangjiang (Yangtze river:  $932.3 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$ ) in comparison to the northern rivers. In general, the sediment load of Chinese rivers is lower than the Indian rivers, with the exception of Huanghe (Yellow

river) and Chiangjiang rivers. With the exception of the loess-imparted Yellow river, the high sediment yield in Asia is restricted to rivers draining the Himalayan mountains in southern Asia<sup>1</sup>. These loads and yields are substantially higher than all other mountainous rivers of the world (save Oceania).

### Discharge of sediments by Indian and Chinese rivers

The segregation factor (SF) is defined as the molar ratio of alkaline and alkaline-earth metals to Fe and Al in suspended matter/sediment:

$$\text{SF} = (\text{Ca} + \text{K} + \text{Na} + \text{Mg})/(\text{Fe} + \text{Al}). \quad (1)$$

Equation (1) shows the numerator, with the most active metals subjected to weathering condition and the denominator with the inert elements in weathering crust. We compared (SF) Indian bed sediment and SPM in Chinese rivers (Figure 3), because there is lack of data for Indian suspended matter.

The trend of Indian and Chinese rivers from north to south showed a value of less than 1, except Tapti (~1.7) and Godavari (1.4) in India. This may be due to the higher levels of Ca, Mg, Ti, V, Cu and Zn and deficiency in K and Fe in the Tapti river relative to those from the Himalaya. In Godavari river, there are abundant carbonate minerals and a deficit in Al relative to the GB system. The depletion of K, Al and Si reflects the paucity of illite and other K-micas in Godavari river sediments<sup>28</sup>. Tapti and Godavari have the same source in the area in the middle of India.

Areas with high rainfall generally have high rates of erosion, although heavy floods in arid climates periodically also can carry huge amounts of sediment, which is observed for Indian rivers receiving high rainfall (Table 2). The heavy metals normalized against the world surface rock are plotted from north to south for India and China. It is observed that lead concentration in Chinese river/estuarine systems was higher than those for the other metals (Figure 4 a–h), suggesting higher anthropogenic activities (e.g. fuel use) in the drainage basin. The concentrations of cobalt and zinc in Indian suspended matter are also higher than those for the other metals with respect to world surface rock. This is mainly due to industrial activities<sup>31,32</sup>.

In this study we attempted to characterize the metal reactivity using SF. The major element composition in SPM in Indian and Chinese rivers are taken from published reports. The chemical denudation rate is 72 tons km<sup>2</sup> yr<sup>-1</sup> for the Ganges and 105 tons km<sup>2</sup> yr<sup>-1</sup> for the Brahmaputra, which is a factor of 2 to 3 higher than the global average<sup>17</sup>. The high denudation rate, particularly in the Brahmaputra, is attributable to a higher relief and heavier rainfall compared to Chinese rivers (Table 2). An increase in height to length (*H/L*) ratio in the rivers corresponds to reduced elements segregation and as a consequence a low SF (Figure 5). With regard to the Chinese rivers, the estimated SF falls with higher rainfall in the drainage area, which is usually the case from north to the south of the country<sup>33</sup>. Moreover, SF in the watersheds shows an in-

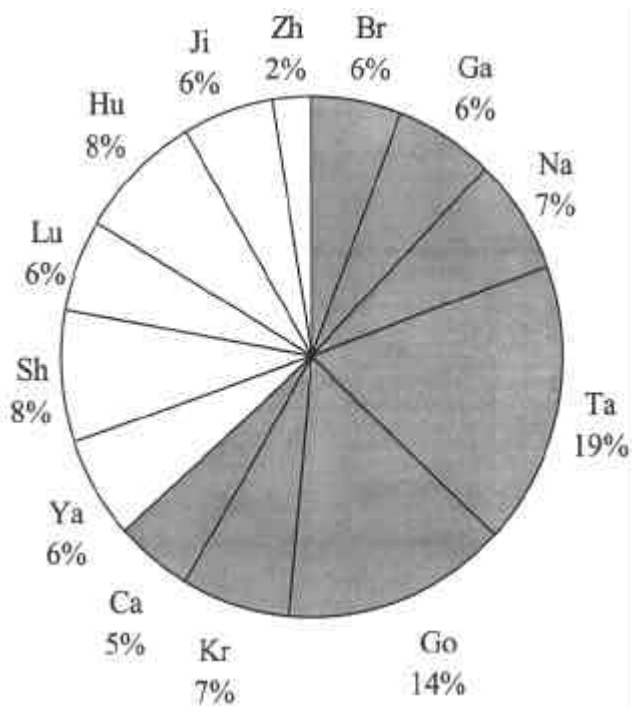
creasing trend with higher sediment yields and *H/L* ratio of the river, indicating that chemical weathering is damped when physical erosion is high. This implies that in the case of short residence time of suspended sediments in the river, as can be approached by examination of *H/L* ratio and sediment yields, the chemical reaction is not allowed to be fully developed, that takes place in the drainage basin to maintain the concentration of dissolved components and deliver seaward flux for dissolved species, like in the Huanghe<sup>34</sup>.

The chemical denudation rate for India ( $8.61 \times 10^4$  kg/km<sup>2</sup>/yr) is nearly 3.5 times higher than the continental earth ( $2.3 \times 10^4$  kg/km<sup>2</sup>/yr). Even though the chemical load of the Amazon is nearly thrice that of the Brahmaputra and many times higher than that of other Indian rivers, the erosion rates in any of the Indian rivers, say even Tapti (small in terms of size and discharge when compared with the Amazon) are much higher. This indicates that the size of the river basin or the discharge has no direct effect on the rate of chemical mass transfer. The chemical rate between the Cauvery and Ganges (Table 5) is not distinctly different, even though the first basin is situated at low latitude, suggesting that the geographical location of a basin, similar to the size, may not be an appropriate chemical rate factor.

On a global scale, except Europe and Australia, chemical erosion rates are similar for all other continents. The high erosion rate in Europe, which is a 'sedimentary carbonate' continent, is expected to be intense, whereas in Australia, which is a mid- to high-latitude desert continent, the predominant eolian weathering is not effective enough for chemical decomposition. The narrow values for Africa, Asia, North and South America suggest that there is a natural uniformity in the chemical mass transfer process from the continental crust to world oceans.

The sediment transport by Cauvery, Godavari, Krishna, Tapti and Narmada is insignificant compared to the Ganges and Brahmaputra, which together account for nearly 90% of the total sediment transfer from the Indian subcontinent. During monsoon, except Cauvery, all the rivers carry TSM in excess of 1000 µg g<sup>-1</sup>; it was observed that Narmada, near Broach<sup>35</sup> carried 3814 µg g<sup>-1</sup>. For most of the rivers in China, particularly those in the north, river sediment load can match about 68–80% of annual discharge in the summer.

The Asian continent dominates the global mass transfer, where ~75% of the sediment transfer takes place. Holeman<sup>36</sup> pointed out that within Asia, the non-Himalayan rivers such as Mekong and Huang Ho contribute larger amount of sediments than the four major Himalayan basins – Indus, Ganges, Brahmaputra and Irrawady, which are however, important for the South Asian region of the continent. The basin area of the Himalayan system is less than half that of Amazon, but its sediment contribution is nearly twice that of the Amazon. The sediment erosion rates show that the Himalayan region is being eroded at a very



**Figure 3.** Segregation factor variation in bed sediments of Indian and suspended matter of Chinese rivers  $\times 10$ .

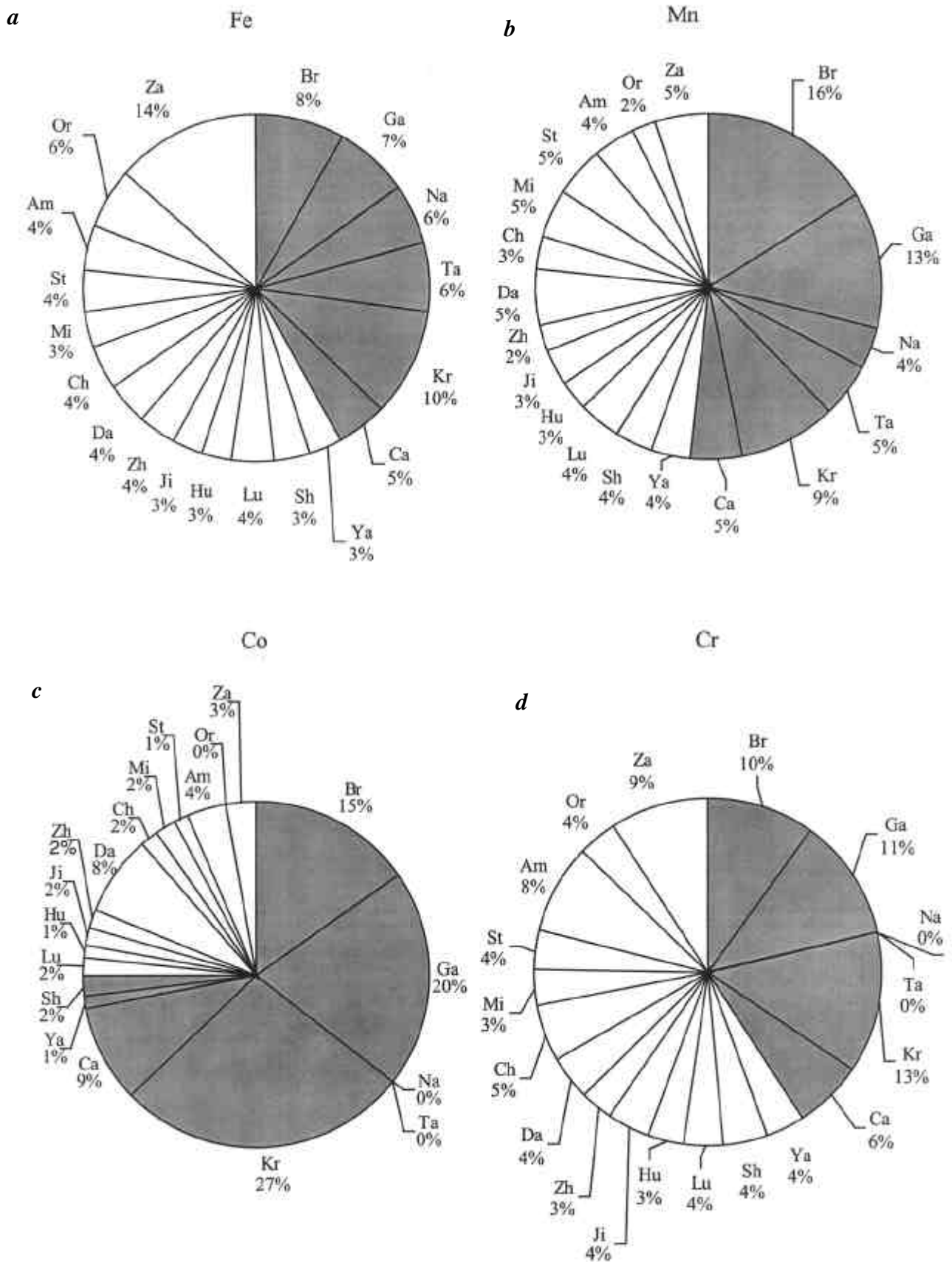


Figure 4. a-d. (Contd...)

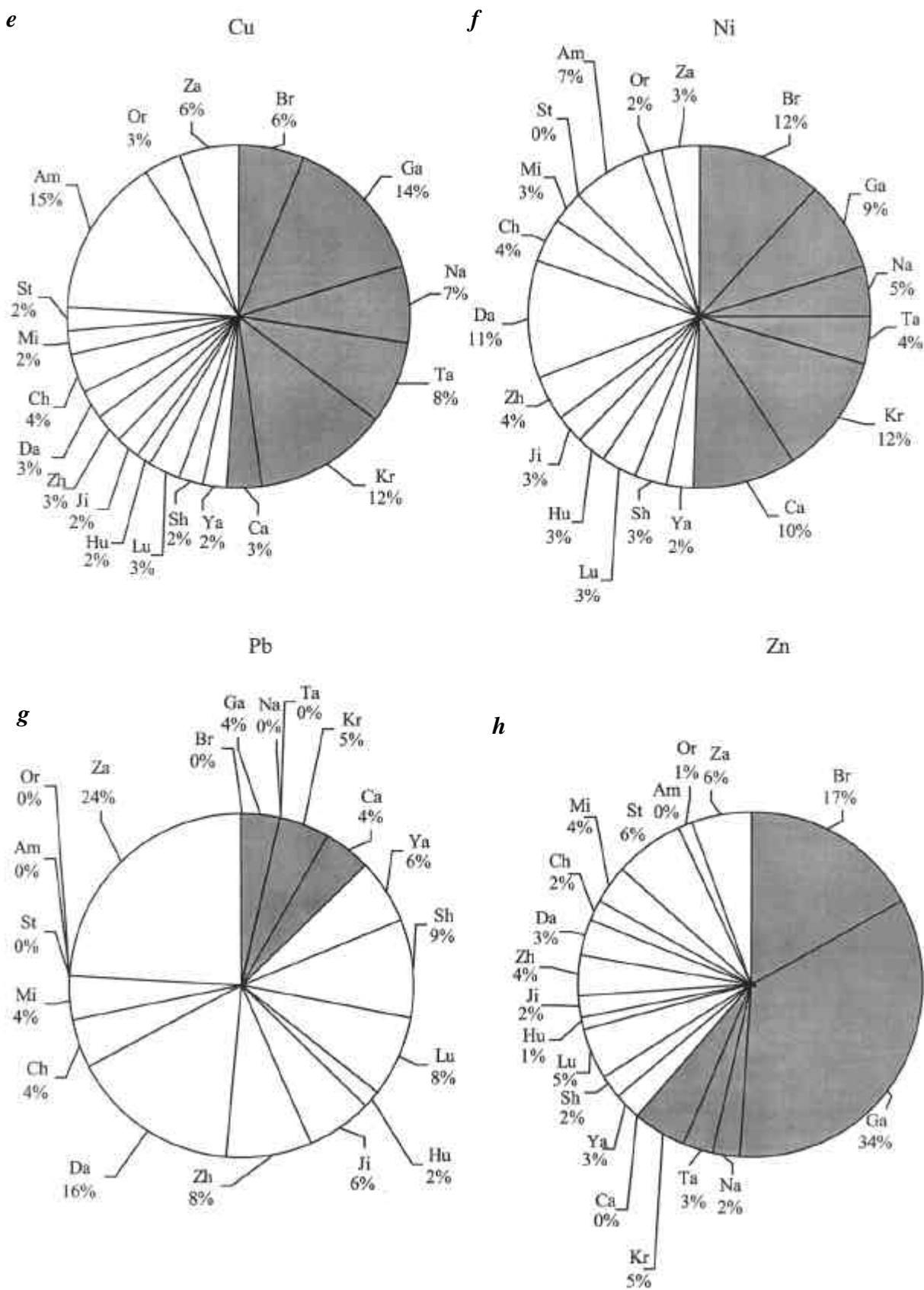


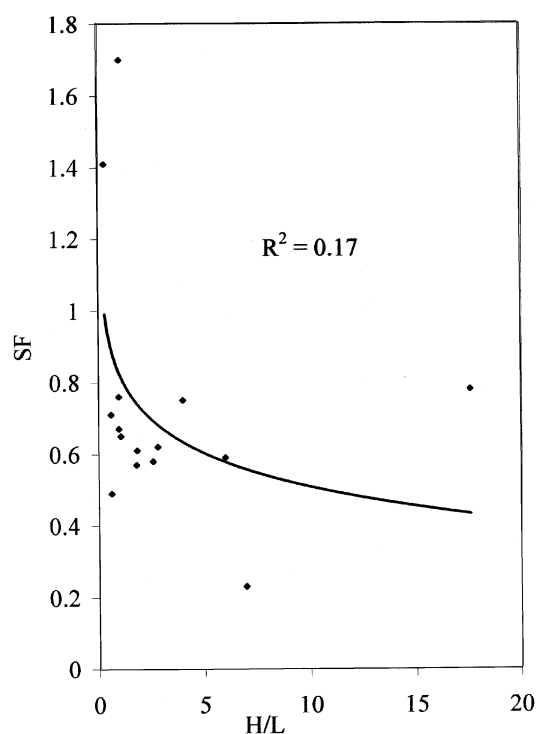
Figure 4. a-h, Distribution of normalized heavy metals against world surface rock in suspended matter of Indian, Chinese and world rivers.



**Table 5.** Denudation and erosion rates for major rivers and continental earth<sup>35</sup>

| Basin             | Chemical rate<br>( $\times 10^4$ kg km <sup>-2</sup> yr <sup>-1</sup> ) | Total denudation rate<br>( $\times 10^4$ kg km <sup>-2</sup> yr <sup>-1</sup> ) | Erosion rate<br>( $\times 10^4$ kg km <sup>-2</sup> yr <sup>-1</sup> ) | Sediment load<br>( $10^6$ t yr <sup>-1</sup> ) |
|-------------------|---|---|--|--|
| Brahmaputra       | 12.26   | 122.31  | 122.37   | *  |
| Ganges            | 7.32  | 54.51   | 54.51  | *  |
| Narmada           | 12.11   | 19.10   |  | *  |
| Tapti             | 8.75  | 13.00   |  | *  |
| Godavari          | 7.32  | 12.60   |  | *  |
| Krishna           | 6.11  | 9.42  |  | *  |
| Cauvery           | 8.70  | 9.57  |  | *  |
| Yalujiang         |   |   | 75   | *  |
| Shuangtaizihe     |   |   | 350  | *  |
| Luanhe            |   |   | 505  | *  |
| Huanghe           |   |   | 530  | *  |
| Zhujiang          |   |   | 180  | *  |
| Daliaohe          |   |   | 115  | *  |
| Chiangjiang       |   |   | 140  | *  |
| Mississippi       | 3.66  |   | 10.27  | 213  |
| Amazon            | 3.68  |   | 11.66  | 499  |
| Asia              | 3.2   | 33.44   |  | 14500  |
| Africa            | 2.4   | 4.03  |  | 490  |
| Europe            | 4.2   | 6.47  |  | 250  |
| Australia         | 0.2   | 2.30  |  | 210  |
| North America     | 3.2   | 11.78   |  | 1780   |
| South America     | 2.8   | 8.40  |  | 1100   |
| Continental earth | 2.3   | 13.12   |  | 18300.0  |

\*Source: Table 1.

**Figure 5.** Plot of segregation factor (SF) against height to length ratio (H/L) in the Indian and Chinese rivers.

high rate compared to the rest of the world. In the Amazon basin, only 12% of the area is in a mountain environment, whereas in the Himalayas<sup>37</sup> it is up to 60%.

### Comparison of river suspended matter with oceanic sediments

The chemical composition of river suspended sediment with that of deep-sea clays and oceanic suspended matter is compared to gain insight into marine sedimentation processes. It can be biased due to several factors:

The wide range of particle size fractions in river-borne material can be modified by deposition in estuaries and nearshore areas. More than 90% of river-borne sediment deposited around the Mississippi Delta is less than 1% of the area of the Gulf of Mexico<sup>38</sup>. The input of smaller grain-size particles of river-borne sediment to the open ocean can be enhanced by the above process<sup>39</sup>. Other oceanic processes such as dissolution during settling, diffusion and biological recycling at the sediment-water interface may change the original elemental concentration of river-borne particulates. Elements such as Al, Si, Ti, Fe, P and Co have similar concentrations in river suspended matter and in deep-sea clays. The oceanic distribution of these elements is obviously controlled by river input and associated with 'lattice-held'<sup>40</sup>.

Ca, Sb and Zn are in 'excess' in river suspended sediment, whereas Ca is partly carried to the ocean as CaCO<sub>3</sub>, which can eventually be dissolved below the carbonate compensation layer. For Sb and Zn, two hypotheses may be considered suggesting that the input in river suspended matter that exceeds the output in deep-sea clays, may be due to anthropogenic influences. However, neither Pb nor V, which are typically representative of an anthropogenic

origin, is higher in river suspended sediment than in deep-sea clays.

Under anaerobic conditions occurring in estuarine and nearshore bottom sediments, Mn will be fairly soluble and sulphide compounds are formed subjected to release<sup>41,42</sup>. Under oxic condition, they form insoluble oxides, which might be supplied to the deep-sea sediments. These manganese oxides may be subsequently enriched in various trace metals for which they behave as efficient scavengers. The excess of trace elements results to a large extent from a differential transport of pelagic and non-pelagic particulates to and within the ocean<sup>43,44</sup>. Comparison of elemental concentrations in suspended matter from the euphotic zone<sup>45</sup> is difficult because Al content in these particles is unknown.

## Conclusions

The present status of trace metal geochemistry in the Asian region was compared and assessed, to evaluate their concentrations with respect to climate, precipitation, tectonic control, basin geology, size of drainage basin, discharge and human impact.

- (1) The average trace metal concentrations are higher in Indian rivers compared to those in Chinese and world rivers.
- (2) Due to higher levels of carbonate minerals in the Indian rivers Tapti and Godavari, there is an increase SF.
- (3) Indian rivers have a high SF than Chinese rivers.

1. Milliman, J. D. and Syvitski, J. P. M., Geomorphic/tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers. *J. Geol.*, 1992, **100**, 525–544.
2. Eisma, D., Van der Gaast, S. J., Martin, J. M. and Thomas, A. J., Suspended matter and bottom deposits of the Orinoco Delta: Turbidity, mineralogy and element composition. *Neth. J. Sea Res.*, 1978, **12**, 224–251.
3. Emeis, K., Particulate suspended matter in major world rivers-II; Indus, Waikato, Nile, St. Lawrence, Yangtze, Parana, Orinoco, Caroni and Mackenzie. In *Transport of Carbon and Minerals in Major World Rivers* (eds Degens, E. T. and Herrera, R.), Mitt. Geol. Paläontol Inst. Univ. Hamburg, SCOPE/UNEP, Sonderband, 1985, pp. 593–617.
4. Abdel-Moati, A. R., Behaviour and fluxes of copper and lead in the Nile river estuary. *Est. Coast. Shelf Sci.*, 1990, **30**, 153–165.
5. Presley, B., Trefry, J. H. and Shokes, R. F., Heavy metal input to Mississippi delta sediments, a historical view. *Water Air Soil Pollut.*, 1980, **13**, 481–494.
6. Trefry, J. H., Helsen, T. A., Trocine, R. P., Metz, S. and Vetter, T. W., Trace metal fluxes through the Mississippi river delta system. *Rapp. P.-V. Reun., Cons. Int. Explor. Mer.*, 1986, **186**, 277–288.
7. Shiller, A. M. and Boyle, E., Variability of dissolved trace metals in the Mississippi river. *Geochim. Cosmochim. Acta*, 1987, **51**, 3273–3277.
8. Gibbs, R. J., Transport phases of transition metals in the Amazon and Yukon rivers. *Geol. Soc. Am. Bull.*, 1977, **88**, 829–843.
9. Martin, J. M. and Meybeck, M., Elemental mass-balance of material carried by major world rivers. *Mar. Chem.*, 1979, **7**, 173–206.
10. Martin, J. M., Thomas, A. J. and Van Grieken, R., Trace element compositions of Zaire suspended sediments. *Neth. J. Sea Res.*, 1978, **12**, 414–420.
11. Martin, J. M., Guan, D. M., Elbaz-Poulichet, F., Thomas, A. J. and Gordeev V. V., Preliminary assessment of the distributions of some trace elements (As, Cd, Cu, Fe, Ni, Pb and Zn) in a pristine aquatic environment. The Lena river estuary (Russia). *Mar. Chem.*, 1993, **43**, 185–199.
12. Huang, W. W., Zhang, J. and Zhou, Z. H., Particulate element inventory of the Huanghe (Yellow river): A large, high-turbidity river. *Geochim. Cosmochim. Acta*, 1992, **56**, 3669–3680.
13. Zhang, J., Geochemistry of trace metals from Chinese river/estuary systems: An overview. *Est. Coast. Shelf Sci.*, 1995, **41**, 631–658.
14. Gaillardet, J., Dupré, B. and Allègre, C. J., A global mass budget applied to the Congo basin rivers: Erosion rates and continental crust composition. *Geochim. Cosmochim. Acta*, 1995, **59**, 3469–3485.
15. Allègre, C. J., Dupré, B., Nègre, P. and Gaillardet, J., Sr–Nd–Pb isotope systematics in Amazon and Congo river systems: Constraints about erosion processes. *Chem. Geol.*, 1996, **131**, 93–112.
16. Krishnaswami, S., Trivedi, J. R., Sarin, M. M., Ramesh, R. and Sharma, K. K., Strontium isotopes and rubidium in the Ganga–Brahmaputra river system: Weathering in the Himalaya, fluxes to the Bay of Bengal and contributions to the evolution of oceanic <sup>87</sup>Sr/<sup>86</sup>Sr. *Earth Planet. Sci. Lett.*, 1992, **109**, 243–253.
17. Sarin, M. M., Krishnaswami, S., Dilli, K., Somayajulu, B. L. 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.
18. Galy, A. and France-Lanord, C., Weathering processes in the Ganges–Brahmaputra basin and the riverine alkalinity budget. *Chem. Geol.*, 1999, **159**, 31–60.
19. Biksham, G. and Subramanian, V., Elemental composition of Godavari sediments (central and southern Indian subcontinent). *Chem. Geol.*, 1988, **70**, 275–286.
20. Ramesh, R., Subramanian, V., Van Grieken, R. and Van't Dack L., The elemental chemistry of sediments in the Krishna river basin, India. *Chem. Geol.*, 1989, **74**, 331–341.
21. Subramanian, V., Van't Dack, L. and Van Grieken, R., Preliminary studies on the geochemistry of the Cauvery river basin. *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 1985, **94**, 99–110.
22. Zhang, J., Huang, W. W., Liu, M. G. and Zhou, Q., Drainage basin weathering and major element transport of two large Chinese rivers (Huanghe and Changjiang). *J. Geophys. Res.*, 1990, **95**, 13277–13288.
23. Dekov, V. M., Subramanian, V. and Van Grieken, R., Chemical composition of riverine suspended matter and sediments from the Indian subcontinent. Biogeochemistry of rivers. In *Tropical South and Southeast Asia*, Hamburg: Mitteilugen aus dem Geologisch-Paläontologischen Institut der Universität Hamburg, SCOPE, Sonderband, 1999, pp. 99–109.
24. Milliman, J. D. and Meade, R. H., Worldwide delivery of river sediment to the oceans. *J. Geol.*, 1983, **91**, 1–21.
25. Subramanian, V., Chemical and suspended sediments characteristic of rivers of India. *J. Hydrol.*, 1979, **44**, 37–55.
26. Subramanian, V., Factors controlling chemical composition of rivers of India. *Int. Assoc. Hydrol. Sci.*, 1983, **141**, 145–152.
27. Subramanian, V., Mineralogical input of suspended matter from India to the world ocean. *Mar. Geol.*, 1980, **36**, M1–M6.
28. Borole, D. V., Sarin, M. M. and Somayajulu, B. L. K., Composition of Narbada and Tapti estuarine particles and adjacent Arabian Sea sediments. *Indian J. Mar. Sci.*, 1982, **11**, 51–62.
29. Bikshamaiah, G. and Subramanian, V., Chemical and sediment mass transfer in the Godavari river basin in India. *J. Hydrol.*, 1980, **46**, 331–342.
30. Naidu, A. S., Rao, G. K. and Rao, C. B., Geology of the Godavari Delta. *Bull. Geol. Chem. Soc. India*, 1967, **2**, 20–25.

31. Ramesh, R. and Subramanian, V., Temporal, spatial and size variation in the sediment transport in Krishna river basin, India. *J. Hydrol.*, 1988, **98**, 53–65.
32. Ramanathan, A. L., Vaithiyathan, P., Subramanian, V. and Das, B. K., Geochemistry of the Cauvery estuary, east coast of India. *Estuaries*, 1993, **16**, 459–474.
33. Zhang, J. and Liu, C. L., Riverine composition and estuarine geochemistry of particulate metals in China – Weathering features, anthropogenic impact and chemical fluxes. *Est. Coast. Shelf Sci.*, 2002, **54**, 1051–1070.
34. Zhang, J., Huang, W. W., Letolle, R. and Jusserand, C., Major element chemistry of the Huanghe (Yellow river), China – Weathering processes and chemical fluxes. *J. Hydrol. (AMST)*, 1995, **168**, 173–203.
35. Subramanian, V., Input by Indian rivers into the world oceans. *Proc. Indian Acad. Sci.*, 1978, **87**, 77–88.
36. Holeman, J. N., The sediment yield of major rivers of the world. *Water Resour. Res.*, 1968, **4**, 737–747.
37. Gibbs, R. J., The geochemistry of the Amazon river system. Part I. The factors that control the salinity, the composition and the concentration of the suspended solids. *Geol. Soc. Am. Bull.*, 1967, **78**, 1203–1232.
38. Trefry, J. H. and Presley, B. J., Heavy metal transport from the Mississippi river to the Gulf of Mexico. In *Marine Pollutants Transfer* (eds Windom, H. L. and Duce, R. A.), Lexington, Mass., 1976, pp. 39–76.
39. Postma, H., Sediment transport and sedimentation in the estuarine environment. In *Estuaries* (ed. Lauff, G. H.), Am. Assoc. Adv. Sci. Publ., 1967, vol. 83, pp. 158–179.
40. Chester, R. and Aston, S. R., The geochemistry of deep-sea sediments. In *Chemical Oceanography* (eds Riley, J. P. and Chester, R.), Academic Press, London, 1976, pp. 281–390.
41. Evans, D. W., Cutshall, N. H., Cross, F. A. and Wolfe, D. A., Manganese cycling in the Newport river estuary, North Carolina. *Est. Coast. Mar. Sci.*, 1977, **5**, 71–80.
42. Sundby, B., Manganese-rich particulate matter in coastal marine environment. *Nature*, 1977, **270**, 417–419.
43. Turekian, K. K., Some aspects of the geochemistry of marine sediments. In *Chemical Oceanography* (eds Riley, J. P. and Skirrow, G.), Academic Press, London, 1965, pp. 81–126.
44. Turekian, K. K., Estimates of the average deep-sea clay accumulation rate from material balances calculations. In *Progress in Oceanography* (ed. Sears, H.), Pergamon Press, Oxford, 1967, pp. 227–244.
45. Chester, R. and Stoner, J. H., Trace elements in total particulate material from surface sea water. *Nature*, 1975, **255**, 50–51.
46. Subramanian, V., Van't Dack, L. and Van Grieken, R., Chemical composition of river sediments from the Indian sub-continent. *Chem. Geol.*, 1985, **48**, 271–279.
47. Subramanian, V., Sediment load of Indian rivers. *Curr. Sci.*, 1993, **64**, 928–930.
48. Biksham, G. and Subramanian, V., Sediment transport of Godavari river basin and its controlling factors. *J. Hydrol.*, 1988, **101**, 275–290.
49. Ramesh, R., Subramanian, V. and Van Grieken, R., Heavy metal distribution in sediments of Krishna river basin, India. *Environ. Geol. Water Sci.*, 1990, **15**, 207–216.
50. Dekov, V. M., Araujo, F., Van Grieken, R. and Subramanian, V., Chemical composition of sediments and suspended matter from the Cauvery and Brahmaputra rivers (India). *Sci. Total Environ.*, 1998, **212**, 89–105.
51. Yeats, P. A. and Bowers, J. M., Discharge of metals from the St. Lawrence river. *Can. J. Earth Sci.*, 1982, **19**, 982–992.
52. Bowen, H. J. M., *Environmental Chemistry of the Elements*, Academic Press, New York, 1979, pp. 1–320.

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