Trace element mobility, regional significance and global implication of Gomati river basin, northern India

Dharmendra Kumar Jigyasu^{1,5} · Munendra Singh¹ · Sandeep Singh² · Satyendra Singh³ · Indra Bir Singh⁴

Received: 19 November 2019 / Accepted: 14 July 2020 / Published online: 30 July 2020
© Springer Nature Switzerland AG 2020

Abstract

We studied trace element mobility in the Gomati River (an alluvial tributary of the Ganga River in northern India) Basin by analyzing thirty-six time series water samples for their dissolved concentration of trace elements. Sodium-normalised elemental mobility indices vary over a wide range of the six orders of magnitude from 10^2 (Cd) to 10^{-4} (Zr). The highly mobile elements are B, As, Se, Sr, Mo and Cd. The moderately mobile elements are Al, P, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Rb and Pb. Titanium, Fe and Al, commonly assumed to be immobile at global level, are identified as moderately mobile elements. High trace element mobility in the Gomati River Basin had the geogenic factor associated with the chemical weathering of biotite mica mineral. For the river water quality assessment, the concentration of B, Cr, Cu, Zn, As and Pb lies below the desirable limits; while the concentration of Al, Fe and Se are above the WHO permissible limits of drinking water. At global scale, the Gomati River Basin contributes dissolved flux in significant proportions, namely Al (5.8%), Ti (4.4%), Fe (1.1%), Ni (1.2%), Se (21.5%) and Pb (1.7%) of total riverine flux. The proposed system model may provide means of qualify and quantify the environmental effects of trace elements mobility.

Keywords Tropical environment · Ganga alluvial plain · Gomati river · Biotite mica mineral · Trace element mobility

1 Introduction

Water is a vital natural resource that fulfils the basic need of life and human society e.g. drinking needs, daily household works, agricultural, industrial, energy production and transportation requirements [1–3]. The water quality is an important criterion to get use of it for definite purpose based on solutes and impurities such as ions, minerals etc. [4]. Dissolved elements (both metals and non-metals) are classified into major (macro) or trace (micro) elements based on the quantity, required for completing the life cycle of a living organism [5]. Trace elements in small quantities are essential but their higher quantity can substantially hamper the life process as shown in Fig. 1 [5–7]. Water bodies receive these trace elements through natural and

anthropogenic processes [5]. The anthropogenic activities such as urbanization, industrialization, aerosols created by automobiles via combustion of fuels, metal smelting and an excessive dose of pesticides, micronutrient fertilizers and manures such as sewage sludge contribute trace elements to water bodies [4, 8, 9]. The natural processes such as weathering and the mineralization [10, 11] are responsible for trace element inclusion in water bodies [5].

The inclusion and mobilization of trace elements from sediments to water are a complex process and are affected by the dissolution of primary minerals, the formation of secondary minerals, redox process, co-precipitation and ion exchange along with microbial processes at sediment–water interface [11–16]. The understanding of present trace elements mobilization process is mainly

✉ Dharmendra Kumar Jigyasu, jigyasu2012@gmail.com | ¹Centre of Advanced Study in Geology, University of Lucknow, Lucknow 226 007, India. ²Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee 247 667, India. ³Government Girls P. G. College, Ghazipur 233 001, India. ⁴Flat No. 17-11-2C, Metro city, Nishatganj, Lucknow 226 006, India. ⁵Central Muga Eri Research and Training Institute, Central Silk Board, Jorhat, Assam 785 700, India.

Fig. 1 Trace elements concentration and their biological effects on human health at state of the deficiency and toxicity (after Selinus [5])

Deficiency	Elements	Toxicity
Anaemia	Iron	Haemochromatosis
Anaemia "Say back"	Copper	Chronic poisoning- Wilson, Bedlington-disease
Dwarf growth, Retarded developmet of gonads, Akrodermatitis entero-pathica	Zinc	Metallic fever Diarrhoea
Anaemia "White liver disease"	Cobalt	Heart failure, Polycythaemia
Disturbance in the glucose metabolism	Chromium	Kidney damage (Nephritis)
Osteoarthritis, Effects on male infertility, Keshan disease	Selenium	Selenosis, Nervous system abnormalities
Unknown	Arsenic	Chronic poisoning, Skin Cancer
Unknown	Aluminium	Alzimer's disease

Increasing Concentration

obtained from geochemical surveys [17]. Gaillardet et al. [18] proposed a four-fold classification of the Na-normalized relative mobility of trace elements in the world's average river water at global scale. Highly mobile elements (Cd, B, Se, As and Mo) have the values of relative mobility indices greater than 1 or that of Na. Moderately mobile elements (Si, Mn, Cu, Co and Ni) have relative mobility indices in between 1 and 0.1. Non-mobile elements (Zn, Cr, V, Pb and Fe) and immobile elements (Ti, Zr and Al) have relative mobility indices in between 0.1 and 0.01 and < 0.01, respectively.

Links between environment and trace elements are significant for subsistence populations which are heavily dependent on the local environment for their food supply [5, 19, 20]. Human mortality related to trace element deficiencies and toxicities affects more than half of the world's population [21]. Cobalt, Fe, Mn, Mo and Zn are all needed by humans for various vital physiological and biochemical functions such as Zn and Cu are essential for normal development of the skeleton in humans and animals [22], but excessive concentrations can result in detrimental effects. Other trace elements such as Cd, Pb, Hg and Pu are toxic that do not have any beneficial effect on organisms [7, 23] and Se deficiency and toxicity is being identified in many parts of India [24]. Aluminium, a potent neurotoxicant, is associated with age-related neurodegenerative disorders including Alzheimer's disease, dementia, anemia, osteomalacia, oligospermia and infertility, hepatorenal disease, breast cancer and cyst etc. in humans [25].

Globally, the tropical environment is congruous with strong geochemical fractionation, elemental partitioning and quantitative transportation, resulting from its climatic characteristics. It is controlled by heavy seasonal rainfall with long periods of drought and high temperatures [26]. The information regarding the concentration and mobility of trace elements in the south Asian region of tropical and sub-tropical environment is scarce [18]. In northern part of the Indian sub-continent in the Indo-Ganga Alluvial Plain, human and animal health problems are related to the occurrence of high arsenic in shallow groundwater of the Ganga–Brahmaputra delta [27, 28] and high Se in the Punjab Plains [9, 29–31]. An appropriate attention has been given to geochemical study of the Gomati River Basin for human–environment interaction study in 2000 onwards. Singh et al. [32] conducted a study of physical and biological parameters of the Gomati River water during 1999–2001. The ranges of the physical parameters in the Gomati River water are pH (8.0–8.9), temperature (16–35 °C), electrical conductivity (220–630 $\mu\text{S}/\text{cm}$), total solid (187–453 mg/l), total dissolved solids (160–357 mg/l), total suspended solids (9.7–111 mg/l), total-alkalinity (102–305 mg/l), total-hardness (28–261 mg/l), Ca-hardness (21–175 mg/l), dissolved oxygen (3.4–13.5 mg/l), biological oxygen demand (1.1–12.1 mg/l), chemical oxygen demand (7.7–38.5 mg/l), total coliform (2×10^2 – 1×10^6 MPN/100 ml) and faecal coliform (1.3×10^2 – 1.0×10^6 MPN/100 ml). Gaur et al. [33] studied the impacts of domestic and industrial wastes on water chemistry of the Gomati River in Lucknow

by analysing Cd, Cr, Cu, Ni, Pb and Zn concentration and reported the high concentration of these heavy metals during the monsoon season as compared to the summer and winter seasons due runoff input from open contaminated sites, agricultural fields and industries without any treatment. Singh and Singh [34] investigated dissolved concentration of major and trace elements of the Gomati River water during the winter season. Aluminium is classified as a moderately mobile element in the Gomati River Basin (GRB); whereas it shows immobile nature in other river basins of the world [35]. In a recent article, Singh and Singh [36] investigated the spatial variability of Sr isotope in water and sediments of the Gomati River Basin with its implication for global fluxioning.

With this background, the Gomati River Basin (GRB) draining central part of the Ganga Alluvial Plain has been selected for the present study. The main objectives were (i) to know the seasonal distribution of dissolved trace elements in the Gomati River water, (ii) to classify these trace elements according to their mobility (iii) to estimate the dissolved trace elements flux along with regional

significance and global implications and (iv) to highlight the most significant mineral contribution of trace elements flux in the river.

2 Materials and methods

2.1 Study area

The Ganga Alluvial Plain is located in south of the Himalayan region and is characterized by high agricultural productivity to support its exponentially growing human population. It is characterized by its low elevation (< 300 m above mean sea level), low relief (20–35 m) [37] and high population density (> 800 persons/km²). The GRB is an important alluvial basin in north-western part of the Ganga Alluvial Plain and drains 30,437 km² area, located between 25–29°N and 80–84°E in the interfluvial region of the Ganga and Ghaghara rivers (Fig. 2). The GRB encompasses an altitude range of 190–60 m above mean sea level. The Gomati River is a 900 km long groundwater-fed

Fig. 2 Location map of the Gomati River Basin along with its 13 sub-basins. The Gomati River drains the interfluvial region of the Ganga and the Ghaghara Rivers in the Ganga River System and hydrologically water deficit area where annual evapo-transpiration is greater than annual precipitation. The Sai River is the main tributary and drains nearly one-third basin area of the Gomati River

alluvial river that flows into the 10–25 m deep entrenched alluvial valley before joining the Ganga River as shown in Fig. 3a. Its basin experiences a humid sub-tropical climate with four distinct seasons i.e. the summer (March–May), the monsoon (June–September), the post-monsoon (October–November) and the winter (December–February). Total annual rainfall in the basin is about 1000 mm and nearly 70–80% of it occurs in the monsoon season [9]. Geologically, the GRB is mainly formed by sediments derived from the Himalayan region during Late Quaternary [38]. The upper most part of the sediment succession in the basin is made-up of inter-layered 1–2 m thick fine sand and silty mud deposits with discontinuous calcrete horizons as shown in Fig. 3b. These alluvial sediments can be considered as the source material which undergoes the present-day weathering processes of the GRB. Weathering processes of the basin are largely controlled by the monsoonal precipitation, large annual temperature variation (4–47 °C) and mineral composition of the alluvial sediments [39].

The river receives its water and sediments within the alluvial plain and transports the weathering products of

its basin as bedload, suspended load and dissolved load sediments as shown in Fig. 3c. Bedload sediments of the Gomati River are basically very fine sand and mineralogically composed of quartz (55%), rock fragments (19%), mica (17%) and feldspar (9%). Dominant clay mineral present in bedload sediments is Illite [40]. The river water is classified as Ca–Mg–HCO₃ type with the average pH of 8.0. The office of Middle Ganga Division, Central Water Commission (Varanasi), Government of India provided daily discharge data of the Gomati River at Maighat (near Chandwak). The river hydrology is characterised by high discharge (> 600 m³/s) during the monsoon season and extremely low discharge (30 m³/s) during the summer season. More than 75% of annual discharge occurs during the monsoon and post-monsoon seasons (June–November) [41]. Elemental fluxes were computed from the average trace elements concentration (µg/l) and the overall river water discharge (m³/sec) from the Gomati River at Chandwak. Addition of yearly discharge data and trace elements concentration are used for the transformation of trace elemental flux data in kt/year.

Fig. 3 General geological characteristics of the study area: **a** Longitudinal profile of Gomati River showing the entrenchment in the Ganga Alluvial Plain, **b** Schematic vertical litholog of alluvial deposits exposed in the cliff section at the Behta Nala sub-basin near Lucknow (after [66]). [Refer Fig. 2 for the location of Behta Nala sub-

basin] and **c** Physical and chemical weathering processes of the Ganga Alluvial Plain are responsible for the production of various weathering products transported by the Gomati River to the Ganga River

2.2 Sampling site

The selection of representative sampling site of the GRB is an important aspect of the present study. Chandwak (25°35'N and 80°00'E) is situated in distal part of the GRB and near the Gomati River's confluence with the Ganga River (Fig. 2). All the tributaries of the Gomati River join the main river channel at the upstream of Chandwak. Therefore, all weathering products of the entire GRB are transported through Chandwak into the Ganga River. Thus, the river water samples collected at Chandwak are considered as a representative of the entire GRB for the present study.

2.3 Sampling program

Thirty-six river water samples were collected from the middle of active river channel during June, 2009 to May, 2010 at an interval of ten days, which covered all seasons; the monsoon ($n = 12$), the post-monsoon ($n = 6$), the winter ($n = 9$) and the summer ($n = 9$). The river water samples were collected in wide-mouth 250 ml high-density polypropylene bottles (©Tarsons) with airtight caps and were acidified in the field with HNO_3 (5 ml/l). Each sample bottle was capped without leaving any head space, tagged with appropriate label. All these water samples were carefully transported and stored at 4 °C till further chemical analysis.

2.4 Analysis of trace elements

All water samples were filtered by using $< 0.45 \mu\text{m}$ cellulose filters and were analysed for their trace element concentrations by Induced Coupled Plasma-Mass Spectrophotometer (ELAN DRC II Perkin Elmer SCIEX instrument) at Institute Instrumentation Centre, Indian Institute of Technology, Roorkee. Each sample was analysed in duplicate and their mean values were taken by following standard procedure prescribed by American Public Health Association [42]. The precision of analytical results was 5–7% and was estimated by running every 10th sample as duplicate. The accuracy of results is about 5%.

3 Results and discussion

3.1 Concentration and relative mobility of trace elements

The natural abundance of trace elements in river water depends on their abundance in rocks and sediments and their mobility during the weathering and transportation processes of a river basin [18]. The dissolved concentration of trace elements in the Gomati River water during the monsoon, the post-monsoon, the winter and the summer

seasons are presented in Table 1. The seasonal distribution of dissolved trace elements varies in the eight orders of magnitude (Fig. 4). Most trace elements (Al, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Rb, Cd and Pb) show relatively higher concentrations during the monsoon season than during other seasons. The average dissolved concentration of trace elements in the Gomati River water is: B (39 $\mu\text{g/l}$), Al (5,289 $\mu\text{g/l}$), P (166 $\mu\text{g/l}$), Ti (60 $\mu\text{g/l}$), V (8.21 $\mu\text{g/l}$), Cr (4.76 $\mu\text{g/l}$), Mn (115 $\mu\text{g/l}$), Fe (2,080 $\mu\text{g/l}$), Co (2 $\mu\text{g/l}$), Ni (7 $\mu\text{g/l}$), Cu (7.34 $\mu\text{g/l}$), Zn (16.9 $\mu\text{g/l}$), As (2.25 $\mu\text{g/l}$), Se (100 $\mu\text{g/l}$), Rb (11.6 $\mu\text{g/l}$), Sr (230 $\mu\text{g/l}$), Zr (0.03 $\mu\text{g/l}$), Mo (1.7 $\mu\text{g/l}$), Cd (0.96 $\mu\text{g/l}$) and Pb (4.3 $\mu\text{g/l}$). Except Zr, the average concentration of trace elements is higher than that of world's average river water [18]. The concentration of Cr, Cu, Ni and Pb are higher in monsoon season in Gomati River water [33].

Table 2 represents correlation coefficient matrix showing the inter-elemental relationship of dissolved trace elements in the Gomati River water. High positive correlation coefficient among Al with Fe, Cr with Fe, Al with Ni, Ti with Fe, Al with Ti, Al with Rb, Rb with Fe and Co with Fe suggest that these trace elements in the river water are controlled by the chemical weathering of Fe rich silicate mineral present in the Gomati River sediments. Transitional and other trace elements (e.g. Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Rb) occur in octahedral sites within biotite lattice of mica minerals. Their inter-elemental correlations represent a powerful geochemical tool which can be used to 'fingerprint' or identify the dominant role of biotite mica mineral in dissolved trace elemental composition of the river water.

All data were subjected to hierarchical cluster analysis using the Statistical Package for Social Science software to investigate the similarities between trace elements concentration in the Gomati River water. The result shows broad two clusters shown as a dendrogram in Fig. 5. Aluminum is independently separated and shows the major first cluster contribution. In second cluster, all trace elements are in strong close alliance within Fe as a major contributor. This group of trace elements have three sub-clusters; (Ti with Mn), (Zn with Rb, Cr, Pb, V, Ni, Cu, Co, As, Mo, Zr and Cd) and (P with Se). The analysis clearly shows that the dissolved trace elements in the Gomati River water are linked with the source of Al in octahedral layer of the biotite mica minerals [43].

The sodium-normalised relative mobility of trace elements in the Gomati River water varies in the six orders of magnitude from highly mobile elements (Cd) to immobile elements (Zr) (Fig. 6). According to the classification of relative elemental mobility of trace elements B, As, Se, Sr, Mo and Cd having mobility indices greater than that of Na are grouped as highly mobile elements. Trace elements Al, P, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Rb and Pb are classified as moderately mobile elements. The mobility index of Ti is

Table 1 Seasonal variation and average dissolved concentrations (in µg/l) of trace elements in the Gomati River water

Element	Monsoon (n=12)	Post-monsoon (n=6)	Winter (n=9)	Summer (n=9)	Average (n=36)	World Rivers	Enrichment Factor
B	42.6	31.3	33.1	45.3	39.0	10.2	3.8
Al	12414	4640	946	562	5289	30	176
P	192.5	137.4	113.1	202.3	165.9	9.0	18.4
Ti	133.4	62.2	12.9	7.1	59.9	0.49	122
V	13.74	8.25	3.65	5.38	8.21	0.71	11.6
Cr	9.8	4.4	1.5	1.6	4.8	0.7	6.9
Mn	239	118	24	40	115	34	3.4
Fe	4573	2118	486	325	2080	66	31.5
Co	4.35	1.99	0.42	0.44	1.99	0.15	13.3
Ni	12.3	6.7	3.3	3.9	7.0	0.8	8.8
Cu	12.76	8.17	3.74	3.17	7.34	1.48	5.0
Zn	30.6	15.2	8.7	8.1	16.9	0.6	28.2
As	2.16	1.28	1.49	3.89	2.25	0.62	3.6
Se	102.2	88.5	87.9	117.5	100.2	0.07	1432
Rb	22.51	10.70	4.03	5.03	11.55	1.63	7.1
Sr	207	187	229	293	230	60	3.8
Zr	0.04	0.07	0.01	0.01	0.03	0.04	0.8
Mo	1.44	0.98	1.78	2.46	1.70	0.42	4.0
Cd	1.97	0.38	0.33	0.63	0.96	0.08	12.0
Pb	8.97	4.32	1.05	1.27	4.29	0.08	53.6

Note that the Al and Fe concentrations are in the range of major elements. Enrichment factors for Al, P, Ti, V, Fe, Co, Zn, Se, Cd and Pb vary in two to four orders of magnitude with respect to world's average river water [18]

Fig. 4 Box and whisker representation of trace element concentrations in the Gomati River water (n=36). Trace elements are arranged according to their increasing atomic number. The dissolved concentration of trace elements varies in eight orders of magnitude

about 100 and of Zr is about 1000 times lower than that of Na and therefore, classified as non-mobile and immobile elements, respectively. In the GRB, all the selected trace elements (except Zr) show about 10–100 times higher

mobility indices than that of the world's average river water. The mobility of Al, P, Ti, V, Fe, Co, Ni, Zn, Rb and Pb in the GRB is distinctively higher than the mobility values at global scale (Fig. 6).

In the GRB, seasons have prominent influence on trace element mobility and may be linked with the seasonal variation of trace element concentrations (Table 1). The mobility of trace elements is particularly high during the monsoon season (Fig. 7). The mobility of Al, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Rb and Pb display the decreasing trend from the monsoon season followed by the post-monsoon and winter seasons to the summer season. Lead shows the highest relative mobility values during the monsoon season and the lowest during the summer season. It may be linked with the direct discharge from the alluvial plain surface eg. agricultural land and urban runoff of the GRB during the monsoon season. Phosphorus and As show higher mobility in the summer season than in the winter season, which is linked with the increase in temperature during the summer season (47 °C) as well as biodegradation processes [44, 45]. Arsenic is well known as non-biodegradable element whereas addition of natural organic matter may affect the mobility of As under the alkaline condition (Gomati River water is alkaline in nature) [46]. Natural organic matter may lead to increase the bio-accessibility

Table 2 Correlation coefficient matrix of dissolved trace elements concentration in the Gomati River water

	Al	P	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Zr	Mo	Cd	Pb
Al	1	0.72	0.98	0.97	0.99	0.96	1.00	0.99	0.99	0.99	0.96	−0.24	0.28	1.00	0.01	−0.39	0.80	0.97
P		1	0.74	0.77	0.70	0.65	0.72	0.70	0.73	0.67	0.64	0.41	0.66	0.75	−0.10	0.07	0.80	0.65
Ti			1	0.96	0.97	0.92	0.99	0.97	0.97	0.96	0.92	−0.21	0.31	0.99	0.00	−0.33	0.81	0.93
V				1	0.97	0.94	0.98	0.97	0.97	0.97	0.95	−0.14	0.33	0.98	0.10	−0.37	0.82	0.94
Cr					1	0.96	0.99	0.99	0.98	0.98	0.95	−0.26	0.24	0.99	0.05	−0.35	0.78	0.97
Mn						1	0.96	0.99	0.97	0.98	0.95	−0.28	0.26	0.95	0.12	−0.50	0.78	1.00
Fe							1	0.99	0.99	0.99	0.96	−0.25	0.28	1.00	0.03	−0.40	0.80	0.96
Co								1	0.99	1.00	0.96	−0.27	0.27	0.98	0.07	−0.45	0.80	0.99
Ni									1	0.99	0.96	−0.20	0.31	0.99	0.02	−0.41	0.81	0.97
Cu										1	0.98	−0.30	0.24	0.98	0.12	−0.50	0.78	0.99
Zn											1	−0.26	0.28	0.95	0.07	−0.48	0.76	0.96
As												1	0.70	−0.20	−0.24	0.65	0.12	−0.29
Se													1	0.31	−0.14	0.25	0.50	0.25
Rb														1	0.00	−0.37	0.80	0.95
Zr															1	−0.35	0.03	0.12
Mo																1	−0.21	−0.51
Cd																	1	0.78
Pb																		1

High positive correlation coefficient values are in bold. Transitional metals (Ti, V, Cr, Mn, Fe, Co, Ni and Cu) show the most significant correlation coefficient that may be linked with their common geogenic source of biotite mica mineral. The significant correlation is tested on the level of $p=0.01$ ($n=36$)

Fig. 5 Dendrogram resulting from the hierarchical cluster analysis of dissolved trace elements in the Gomati River water ($n=36$) showing their affinity with Fe indicating the common source trace elements in the river water

of As [47]. The higher mobility of Sr and Mo in the winter season than in the other seasons may be linked with the relative low carbonate precipitation during the winter season [48]. Recently, the mobility and transportation of trace elements in the Cochin Estuary (South India) was

Fig. 6 Bar diagram showing Na-normalized relative trace element mobility in the Gomati River, calculated from the data of upper continental crust. It is also compared with the mobility of trace elements at global scale [18]. Except Zr, all trace elements show higher mobility in the Gomati River than the world's average river

emphatically influenced by its hydrological conditions during the monsoon season [49].

3.2 Chemical weathering of biotite mica minerals

The availability and mobility of trace elements in aquatic and sediments systems depend on the weathering of minerals [11, 17]. Biotite mica mineral is prone to quick

Fig. 7 Bar diagram showing seasonal variation in the relative mobility of trace elements in the Gomati River Basin. The monsoon season shows higher mobility for most of the trace elements

(except B, P, As, Se, Sr and Mo) than other seasons. Aluminium, Ti, Cr, and Fe show seasonal variation of their mobility by more than one order of magnitude

chemical weathering in the group of silicate minerals [11]. The biotite mineral has a phyllo-silicate structure consisting of octahedral sheet sandwich between two identical tetrahedral sheets. The tetrahedral layers are occupied by Si, Fe, B and Al, whereas interlayer sites are resided by K, Na, Rb and Ca elements. The octahedral layers are usually inhabited by elements such as Fe, Mg, Ti, Al, Mn, Cr, V and Mg. Thus, biotite mica mineral is able to supply a large variety of trace elements during chemical weathering [17, 43, 50]. Dissolution processes take place by replacement of K at interlayer site, oxidation of Fe in octahedral sheet, movement of other cations from octahedral sheet into solution [51]. As a result, the incongruent loss of elements follows the sequence: $K > Fe > Si > Mg > Al > Ti$ [52]. The experimental study confirms that increasing temperature plays a catalytic role in the fluxing of dissolved elements into solution [53] which is similar in the GRB. Biotite mica mineral weathers the two orders of magnitude faster than muscovite mica mineral [11] and the chemical changes in its stoichiometry were recognized as follows [54]:

In the GRB, the major silicate minerals present in the alluvial sediments (source material) as well as in the weathered material (the Gomati River sediments) are quartz,

alkali feldspar, plagioclase, muscovite and biotite etc. Mica minerals (only muscovite and biotite) make about 20% of the sand fraction and 25% of the silt fraction of the Gomati River Sediments [40]. Biotite shows the evidences of chemical weathering in the basin [35, 55]. High content of mica minerals (including biotite) in the alluvial sediments of GRB and their intense chemical weathering is responsible for the high content of dissolved trace elements in the Gomati River water. Moreover, high temperature during the summer season may accelerate the growth of numerous microbial activities and influence the bio-weathering of mica minerals [56]. It can be concluded that biotite is central to the chemical weathering of mica minerals, contributing proportion of the dissolved loads of Al, Ti and Fe along with Mg and K in the GRB. Some contributions also come from the chemical weathering of Ca-feldspar which is present in a good amount in sediments of the GRB.

In the GRB, the alluvial sediments are essentially derived by the weathering of the rocks in the Himalayan region and are stored there for a long time [38]. These alluvial sediments undergo weathering, where chemical weathering is dominant with little physical weathering by the present-day fluvial process. The reasons for intense chemical weathering in the GRB are fine-grained and porous nature of sediments, long residence time of sediments, high temperature in the summer season and heavy precipitation along with flushing of dissolved load during the monsoon season (Fig. 3). Further, factors like biotite mica-rich

sediments and availability of labial organic carbon from various natural and anthropogenic processes also accelerate the intensity of chemical weathering in the GRB.

3.3 Human health

The existence, quality and survival of human life depend upon the availability of the appropriate trace elements in the correct proportions and combinations [57]. In GRB, the river water acts as one of the major source of drinking water in rural and urban areas. The average concentration of trace elements in the Gomati River water (as shown in Table 1) was compared with the established desirable and permissible limits for drinking water [58]. The average concentration of trace element is reported below the desirable limits for B (1000 µg/l), Cr (50 µg/l), Cu (50 µg/l), Zn (500 µg/l), As (50 µg/l) and Pb (50 µg/l). The average concentration of Mn in the river water lies between the range of the desirable limit (100 µg/l) and permissible limit (300 µg/l). The average concentration is reported above the permissible limits of Al (200 µg/l), Fe (1000 µg/l) and Se (10 µg/l). The average concentration of Fe varies above the permissible limits during the monsoon and the

post-monsoon seasons; and below the permissible limits during the winter and the summer seasons (Table 1).

In the GRB, the elevated mobility of Al may pose health risks to human population of the alluvial plain. High Al content in drinking water may act as a leading factor to Alzheimer's disease and other neurological disorders in elderly human population [25, 59–61]. The concentration of Al in drinking water resources of the GRB was reported to be beyond permissible limits [35]. The high prevalence of Dementia in the elderly human population at Ballabgarh near Delhi in the western Ganga Alluvial Plain and near Varanasi in the eastern Ganga Alluvial Plain has already been reported [62–64].

3.4 Trace element fluxes

Table 3 displays seasonal and annual dissolved trace element fluxes of the GRB. It clearly indicates that nearly 90% of the total annual elemental flux is contributed during the monsoon and the post-monsoon seasons (Fig. 8). In the monsoon season, Al, Ti, Cr, Mn, Fe, Co, Ni, Rb, Cd and Pb contribute more than 75% of total annual fluxes. It is due to high monsoon precipitation during the monsoon

Table 3 Dissolved elemental flux (in kt/y) and its seasonal variations in the Gomati River to the Ganga River Data source for World Riverine trace elements flux is [18]

Element	Total flux (kt/y)	Seasonal flux (in %)				World riverine flux (kt/y)	Global contribution of Gomati river flux (in %)
		Monsoon	Post-monsoon	Winter	Summer		
Al	69.31	82	16.3	1.4	0.3	1200	5.78
P	1.01	57	25	11	7	DNA	DNA
Ti	0.79	81	17	1.7	0.3	18	4.36
V	0.07	67	25	5	3	27	0.26
Cr	0.06	77	19	3	1	26	0.21
Mn	1.39	76	21	2	1	1270	0.11
Fe	25.83	78	20	1.6	0.4	2470	1.05
Co	0.03	78	20	1.4	0.6	5.5	0.45
Ni	0.07	71	22	5	2	30	1.21
Cu	0.07	69	24	5	2	55	0.13
Zn	0.17	72	22	4	2	23	0.72
As	0.01	47	23	15	15	23	0.04
Se	0.56	50	27	15	7	2.6	21.52
Rb	0.13	76	20	3	1	61	0.21
Zr	0.0003	47	48	4	1	1.5	0.02
Mo	0.01	48	16	24	12	16	0.05
Cd	0.01	83	10	4	3	3	0.25
Pb	0.05	76	21	2	1	3	1.72

Note the significant contribution of the monsoon season in the elemental fluxes of the river. Note the major contribution of Al, Ti, Fe, Ni, Se and Pb

DNA data not available

season that controls the mobilization of trace elements in GRB. Table 3 also shows the global riverine flux of trace elements along with the contribution (in %) of trace element fluxes by the GRB. It has been established that the Gomati River significantly contribute dissolved Al (5.8%), Ti (4.4%), Fe (1.1%), Ni (1.2%), Se (21.5%) and Pb (1.7%) fluxes through the Ganga River into the Bay of Bengal at global scale. Figure 9 displays the relationship between trace elements mobility and contribution in the global riverine fluxes by the GRB. This significant contribution of the GRB is due to high mobility of these trace elements shown in Fig. 6, as compared to global river systems of the world.

3.5 Concluding remarks

The present study exhibits the high degree of mobilization of trace elements due to chemical weathering of the mica-rich alluvial sediments under the humid sub-tropical climate. In the GRB, trace elements are classified in to highly mobile elements (B, As, Se, Sr, Mo and Cd), moderately mobile (Al, P, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Rb and Pb),

Fig. 9 Scatter diagram showing relationship between trace element mobility index versus Gomati River's global contribution of trace elements flux. Note the significant contribution of Al, Ti, Ni Se and Fe load by the Gomati River in World Riverine flux Data source for World Riverine trace elements flux is [18]

Fig. 8 Contribution of seasonal fluxes (in %) of the dissolved load of trace elements of the Gomati River to the Ganga River. Note the significant contribution of the trace elements fluxes during the monsoon and post-monsoon seasons. [Refer to Table 3 for the annual and seasonal trace element fluxes]

non-mobile (Ti) and immobile element (Zr). The mobility of Al, P, Ti, V, Fe, Co, Ni, Zn, Rb and Pb is distinctively higher than the mobility values at the global scale. The contribution of dissolved Al, Ti, Fe, Ni, Se and Pb flux by the GRB is > 1% to the global riverine elemental flux. Human population growth accompanied by the unplanned disposal of organic rich-liquid and solid wastes may have increased in the mobility and concentration of trace elements in drinking water resources of the GRB.

Environmental modelling is a simplified representation of environmental system along with the complex mixture of various interlinked processes and acts as a powerful experimental tool to help us understand environmental processes to solve environmental problems [65]. An Environmental System Model scaled from Earth System to Nano-system is presented to characterise and to understand bio-geo-chemical processes linked with trace element mobility (Fig. 10). White and Brantley [64] used scaling in the environmental system for the preliminary study of natural systems. An inter-disciplinary approach is recommended to investigate the link between high mobility of generally immobile elements (Al, Fe and Ti) and human/animal health for the environmental planning and management of drinking water resources of the Ganga Alluvial Plain, which is one of the densely populated regions in the world. Thus, the present investigation will stimulate further research in the area of medical geology of global significance.

Fig. 10 Environmental system model (based on White and Brantley [64, 65]) of the Ganga Alluvial Plain showing the mobilization of trace elements mainly from octahedral layer of preferentially biotite minerals, and its relation to human health. The Ganga Fluvial System (Gigasystem) is the most dynamic component of the earth with respect to sediment discharge. The Ganga Alluvial Plain is the

alluvial plain part (Megasytem) of the basin drained by alluvial rivers. These alluvial rivers (Supersystem) transport weathering products as bedload (Macrosystem), suspended load and dissolved load sediments. These weathering products are rich in mica minerals (Microsystem) mainly biotite which contains several trace elements in their phyllosilicate structure (Nanosystem)

Acknowledgements This paper is dedicated to Dr. Rohit Kuvar (Sagar University, India) who was instrumental in initiating this research plan. We deeply regret his loss in a fatal road accident on 7th June, 2014. This work has been financially supported by University Grants Commission, New Delhi in the form of research fellowship to DKJ. IBS is thankful to Indian National Science Academy, New Delhi for the research support. The authors are extremely grateful to Dr. Sonal Srivastava (Translation Officer, Indian Railways Service) and Dr Annapurna Singh (SDSU Research Foundation, San Diego, CA) for English editing as well as valuable suggestions for the improvement of the manuscript. The authors are thankful to anonymous reviewers for their suggestions and comments which enhanced the quality of manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Dharmodharan A, Abinandan S, Aravind U, Ganapathy GP, Shanthakumar S (2019) Distribution of metal contamination and risk indices assessment of surface sediments from Cooum River, Chennai, India. *Int J Environ Res*. <https://doi.org/10.1007/s41742-019-00222-8>
2. FAO (2016) Food and agriculture—key to achieving the 2030. Agenda for sustainable development, Rome. p 31. www.fao.org/3/a-i5499e.pdf
3. Pejman AH, Bidhendi GN, Karbassi AR, Mehrdadi N, Bidhendi ME (2009) Evaluation of spatial and seasonal variations in surface water quality using multivariate statistical techniques. *Int J Environ Sci Technol* 6:467–476
4. Bhatia A, Singh SD, Kumar A (2015) Heavy metal contamination of soil, irrigation water and vegetables in peri urban agricultural areas and markets of Delhi. *Water Environ Res* 87(11):2027–2034
5. Selinus O (2004) Medical geology: an emerging speciality. *Terrae Incognitae* 1:8–15
6. Couto CMCM, Ribeiro C, Ribeiro AR, Maia A, Santos M, Tiritan ME, Pinto E, Almeida AA (2019) Spatiotemporal distribution and sources of trace elements in Ave River (Portugal) lower basin: estuarine water, sediments and indigenous flora. *Int J Environ Res*. <https://doi.org/10.1007/s41742-019-00174-z>
7. Gupta N, Yadav KK, Kumar V, Kumar S, Chadd RP, Kumar A (2019) Trace elements in soil-vegetables interface: translocation, bio-accumulation, toxicity and amelioration—a review. *Sci Total Environ* 651:2927–2942
8. Filippelli G, Morrison D, Cicchella D (2012) Urban geochemistry and human health. *Elements* 8:439–444
9. Singh J, Rawat KS, Kumar A, Singh A (2013) Effect of sewage sludge and bio-fertilizers on physicochemical properties of alluvial soil. *Biochem Cell Arch* 13(2):191–202

10. Karbassi AR, Monavari SM, Nabi Bidhendi GR, Nouri J, Nematpour K (2008) Metal pollution assessment of sediment and water in the Shur river. *Environ Monit Assess* 147(1–3):107–116
11. Wilson J (2004) Weathering of the primary rock-forming minerals: processes, products and rates. *Clays Clay Miner* 39:233–266
12. Aiuppa A, Allard P, Alessandro WD, Michel A, Parelo F, Treuil M, Valenza M (2000) Mobility and fluxes of major, minor and trace metals during basalt weathering and groundwater transport at Mt. Etna volcano (Sicily). *Geochim Cosmochim Acta* 64:1827–2000
13. Boulton S, Hand VL, Vaughan DJ (2006) Microbial controls on metal mobility under the low nutrient fluxes found throughout the subsurface. *Sci Total Environ* 372:299–305
14. Land M, Öhlander B (2000) Chemical weathering rates, erosion rates and mobility of major and trace elements in a Boreal Granitic Till. *Aquat Geochem* 6:435–460
15. Middleburg JJ, Cornelis H, Weijden VD, Woittiez JRW (1988) Chemical processes affecting the mobility of major, minor and trace elements during weathering of granite rocks. *Chem Geol* 68:253–273
16. Patino LC, Velbel MA, Price JR, Wade JA (2003) Trace element mobility during spheroidal weathering of basalts and andesites in Hawaii and Guatemala. *Chem Geol* 202:343–364
17. Kossoff D, Karen Hudson-Edwards A, Dubbin WE, Alfredsson M (2012) Major and trace metal mobility during weathering of mine tailings: implications for floodplain soils. *Appl Geochem* 27:562–576
18. Gaillardet J, Viers J, Dupré B (2003) Trace elements in river waters. In: James I. D.(ed), *Treatise on geochemistry* vol 5, pp 225–272
19. Fraga CG (2005) Relevance, essentiality and toxicity of trace elements in human health. *Mol Aspects Med* 26:235–244
20. Young VR (2003) Trace element biology: the knowledge base and its application for the nutrition of individuals and populations. *J Nutr* 133:1581–1587
21. Andersen O (2012) Recent developments in trace element research. *J Trace Elem Med Biol* 26:59–60
22. Bhattacharya PT, Misra SR, Hussain M (2016) Nutritional aspects of essential trace elements in oral health and disease: an extensive review. *Science*. <https://doi.org/10.1155/2016/5464373>
23. Kumar B, Smita FLC (2017) Plant mediated detoxification of mercury and lead. *Arab J Chem* 10:S2335–S2342
24. Plant JA, Kinniburgh D, Smedley P, Fordyce FM, Klinck B (2004) Arsenic and Selenium, vol. 9. In: Holland HD, Turekain KK (eds) *Treatise on Geochemistry Series*. Elsevier, Amsterdam, pp 17–66
25. Igboke IO, Igwenagu E, Igboke NA (2019) Aluminium toxicosis: a review of toxic actions and effects. *Interdiscip Toxicol* 12(2):45–70
26. Dissanayake CB, Chandrajith R (1999) Medical geochemistry of tropical environments. *Earth Sci Rev* 47:219–258
27. Bagla P, Kaiser J (1996) India's spreading health crisis draws global arsenic experts. *Science* 274:174–175
28. Rahaman S, Sinha AC, Pati R, Mukhopadhyay D (2013) Arsenic contamination: a potential hazard to the affected areas of West Bengal, India. *Environ Geochem Health* 35:119–132
29. Bajaj M, Eiche E, Neumann T, Winter J, Gallert C (2011) Hazardous concentrations of selenium in soil and groundwater in north-west India. *J Hazard Mater* 189:640–646
30. Dhillon KS, Dhillon SK (1991) Selenium toxicity in soils, plants and animals in some parts of Punjab, India. *Int J Environ Stud* 37:15–24
31. Hira CK, Partal K, Dhillon KS (2004) Dietary selenium intake by men and women in high and low selenium areas of Punjab. *Public Health Nutr* 7:39–43
32. Singh KP, Malik A, Mohan D, Sinha S (2005) Water quality assessment and apportionment of Gomati River (India) using multivariate statistical techniques—a case study. *Anal Chimica Acta* 538:355–374
33. Gaur V, Gupta SK, Pandey SD, Gopal K, Misra V (2005) Distribution of heavy metals in sediment and water of river Gomti. *Environ Monit Assess* 102:419–433
34. Singh AK, Singh M (2011) Water quality in the Gomati River basin of the Ganga Plain India-based on dissolved major and trace elements. Lambert Academic Publishing, Germany, p 131
35. Jigyasu DK, Kuvar R, Srivastava N, Singh S, Singh IB, Singh M (2015) High mobility of aluminium in Gomati River basin: implications to human health. *Curr Sci* 108:434–438
36. Singh S, Singh M (2020) Spatial variability of Sr isotope of Gomati River Basin within Ganga Alluvial Plain: implications for global seawater fluxioning. *Geochem J* 54(2):57–70
37. Singh M, Kumar S, Kumar B, Singh S, Singh IB (2013) Investigation on the hydrodynamics of Ganga Alluvial Plain using environmental isotopes: a case study of the Gomati River Basin, northern India. *Hydrogeol J* 21:687–700
38. Singh IB (1996) Geological evaluation of Ganga Plain—an overview. *J Paleontol Soc India* 41:99–137
39. Singh M, Sharma M, Tobschall HJ (2005) Weathering of the Ganga alluvial plain, northern India: implications from fluvial geochemistry of the Gomati River. *Appl Geochem* 20:1–21
40. Kumar S, Singh IB (1978) Sedimentological study of Gomti River sediments, Uttar Pradesh, India: example of a river in Alluvial plain. *Senckenbergiana marit* 10:145–211
41. Jigyasu DK, Kuvar R, Singh S, Singh S, Chowdhary AK, Singh M (2014) Seasonal variations in dissolved arsenic concentration and flux of the Gomati River, Ganga Alluvial Plain, northern India. In: Raju NJ, Gossel W, Ramanathan AL, Sudhakar M (eds) *Management of water, energy and bio-resources in the era of climate change: emerging issues and challenges*. Springer, Berlin, pp 82–93
42. APHA (2002) Standard methods for the examination of water and wastewater, vol 22. American Public Health association American Water Association, Washington DC
43. Tischendorf G, Förster H-J, Gottesmann B (2001) Minor- and trace-element composition of trioctahedral micas: a review. *Miner Mag* 65:249–276
44. Singh M, Singh AK, Swati S, Singh S, Chowdhary AK (2005) Arsenic mobility in fluvial environment of the Ganga Plain, northern India. *Environ Earth Sci* 59:1703–1715
45. Smedley PL, Kinniburgh DG (2002) A review of the source, behaviour and distribution of arsenic in natural waters. *Appl Geochem* 17:517–568
46. Wang S, Mulligan CN (2009) Effect of natural organic matter on arsenic mobilization from mine tailings. *J Hazard Mater* 168:721–726
47. Meunier L, Koch I, Reimer KJ (2011) Effects of organic matter and ageing on the bioaccessibility of arsenic. *Environ Pollut* 159:2530–2536
48. Adriano DC (2001) Trace elements in terrestrial environment: biogeochemical, bioavailability, and risk of metals, vol 2. Springer-Verlag, New York, p 886
49. Nair SM, Balchand AN, Peter KJP, Shaiju P (2013) Mobilization of trace metals in a tropical turbid estuary influenced by a monsoon season. *Environ Earth Sci* 70:807–819
50. Tischendorf G, Förster H-J, Gottesmann B, Rieder M (2007) True and brittle micas: composition and solid-solution series. *Miner Mag* 71:285–320
51. Banfield F, Eggleton RA (1988) Transmission electron microscope study of biotite weathering. *Clays Clay Miner* 36:47–60
52. Price R, Velbel MA (2014) Rates of biotite weathering, and clay mineral transformation and neoformation, determined from watershed geochemical mass-balance methods for the coweeta

- hydrologic laboratory, Southern Blue Ridge Mountains, North Carolina, USA. *Aquat Geochem* 20:203–224
53. Pachana P, Zuddas PC (2012) Influence of pH and temperature on the early stage of mica alteration. *Appl Geochem* 27:1738–1744
 54. Dong H, Peacor DR, Murphy SF (1998) TEM study of progressive alteration of igneous biotite to kaolinite throughout a weathered soil. *Geochim Cosmochim Acta* 62:1881–1887
 55. Jigyasu DK, Kuvar R, Shahina SP, Singh S, Singh IB, Singh M (2014) Chemical weathering of biotite in Ganga Alluvial Plain. *Curr Sci* 106:1484–1486
 56. Wei Z, Kierans M, Gadd GMA (2012) Model sheet mineral system to study fungal bioweathering of mica. *Geomicrobiol J* 29:323–331
 57. UNESCO (1995) A global geochemical database for environmental and resource management. Earth Sci 19:122 UNESCO Publication Paris
 58. BIS (2012) Indian standard drinking water-specification (second revision): IS 10500:2012. Bureau of Indian Standards, New Delhi
 59. Flaten TP (1990) Geographical associations between aluminium in drinking water and death rates with dementia (including Alzheimer's disease), Parkinson's disease and amyotrophic lateral sclerosis in Norway. *Environ Geochem Health* 12:152–1567
 60. Martyn CN, Coggon DN, Lacey RF et al (1997) Aluminum concentrations in drinking water and risk of Alzheimer's disease. *Epidemiology* 8:281–286
 61. Rondeau V, Jacqmin-Gadda H, Commenges D, Helmer C, Dartigues J (2009) Aluminum and silica in drinking water and the risk of Alzheimer's disease or cognitive decline: findings from 15-year follow-up of the PAQUID cohort. *Am J Epidemiol* 169:489–496
 62. Chandra V, Ganguli M, Pandav R, Johnston J, Belle S, Dekosky KT (1998) Prevalence of Alzheimer's disease and other dementias in rural India. *J Neurol* 245:1000–1008
 63. Poddar K, Kant S, Singh A, Singh TB (2013) An epidemiological study of dementia among the habitats of eastern Uttar Pradesh, India. *Ann Indian Acad Neurol* 14:164–168
 64. White AF, Brantley SL (1995) Chemical weathering of silicate minerals: an overview. In: White AF, Brantley SL (eds) Chemical weathering rates of silicates minerals. Reviews in mineralogy. Mineralogical Society of America, Washington DC, pp 1–22
 65. Smith J, Smith P (2007) Introduction to environmental modelling. Oxford University Press, New York, p 180
 66. Singh M, Srivastava A, Shinde AD, Acharya R, Reddy AVR, Singh IB (2012) Study of arsenic (As) mobilization in the Ganga Alluvial Plain using neutron activation analysis. *J Radioanal Nucl Chem* 294:241–246

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.