and green-leaf manuring, leaching the excess salts at the time of land preparation or reviving the traditional practice of trenches along the field bunds, FYM or vermicompost application in treatment with biofertilizers, and crop rotation with grain legumes need to be institutionalized at the farm level. Also, it is worth exploring the possibility of reviving the traditional practice that prevailed in the region for reclaiming saline fields through the use of species like *Calotrophis*, *Theprosia purpurea*, etc. as also proper composting. In addition, the integrated farming system approach is a viable option to create backward and forward linkages to use the resources effectively for soil health management. Apart from enhancing soil health, efforts during the current season are needed to study the hydrological situations and there is a need to focus on evolving an integrated reclamation strategy in order to augment and efficiently utilize groundwater resources.

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A holistic study on mercury pollution in the Ganga River system at Varanasi, India

Mercury is one of the heavy-metal pollutants present in the environment. Since the beginning of the industrial era, anthropogenic activities like increased mining, high rate of fossil-fuel burning, widespread use of raw materials containing mercury in the industries are some important contributors of mercury to the environment. Weathering of mercury-bearing rocks releases about 3500 t/yr, while 25,000–150,000 t of mercury is released in gaseous form during volcanic activities. Besides these natural sources, anthropogenic activities add 2000–4500 t of mercury in the global environment every year. Burning of fossil fuels alone contributes 3000 t of the metal every year[1].

The ultimate sink of mercury, probably as cinnabar ore, is believed to be ocean sediments. Part of the released inorganic mercury is oxidized to Hg^{++} and transformed into organomercurials by methylation or other processes. This transformation takes place primarily in aquatic systems. The intestinal bacterial flora of various animals, including fish, though to a much lower degree, are also able to convert ionic mercury to methyl mercuric compounds[2]. Methyl mercury is avidly accumulated by fish and marine mammals and attains its highest concentration in large predatory species at the top of the aquatic food chain. By this means, it enters the human diet leading to serious health problems. The Minamata disaster of early 1950s in Japan was the first recorded case of mercury poisoning in humans. By 1988, 730 human deaths were reported due to the disease, besides 2209 confirmed cases of mercury poisoning in Japan[3].

The Canadian Global Emission Interpretation Center (CGEIC) has studied the spatial distribution of global emissions of mercury into air and has prepared a map of mercury emitted in different parts of the world. It shows that in India 0.1–0.5 t of mercury is released into the atmosphere every year. Emission rate of the metal in coastal areas is even higher (0.5–2 t/yr). According to the study, anthropogenic emission of mercury is estimated to have increased by 27% during 1990–2000 in the country. Thus India is one of the identified hotspots of mercury pollution in the world[4]. Studies show that the aquatic ecosystem in India has significant amount of mercury[5–8], but limited study on mercury in the aquatic ecosystem has been done in a holistic manner.

The present study was aimed to assess mercury pollution in the Ganga River system at Varanasi. Concentration and accumulation of mercury in the river system, including water, sediment, benthic macroinvertebrates, fish, aquatic macrophytes of the Ganga River, and soil and vegetation of the associated floodplains were worked out during the study.

Varanasi is an ancient and religious city situated on the left bank of the Ganga River in its middle stretch in the northeastern part of India (Figure 1). The city extends from Assi to Varuna, a 7-km long river-face. Over 1.5 million people reside in the city, while the daily floating population is about 0.2 million. Being of religious importance, more than 60,000 pilgrims take a holy dip in the Ganga River at Varanasi every day. The river water is also polluted due to cremation of human dead bodies along its bank. Besides, over 200 MLD effluent is discharged into the river[9]. Up to 1992, there were 2957 small-scale industries, electrical machinery parts and other manufacturing industries in Varanasi, while the number of large and

medium-scale industries in and around the city till 1997 was 23. Saree-printing units numbering around 300 operating in the city without any pollution-control measures, are a major cause of river pollution[10]. Floodplains at the right bank of the river are under intensive cultivation and get flooded every year during the monsoon months of July–September. Annual discharge of the river at Varanasi is 153,000 million cubic metres per annum[11].

To assess mercury pollution in the river system, water (n = 18), sediment (n = 18), benthic macro-invertebrate (n = 28), fish (n = 67), soil (n = 12) and flora (n = 61) samples were collected from the river and adjoining floodplains from both banks at Ramnagar bridge (25°16.39′ N and 83°01.04′ E), upstream at Varanasi and at the Varuna–Ganga confluence (25°20.51′ N and 83°03.37′ E), downstream of the city in January (winter), June (summer) and November (post-monsoon) 2001. The seasonal river velocity at the upstream and downstream locations ranged from 0.26 to 0.30 and 0.17 to 0.46 m/s respectively. Water depth was in the range of 1.28–2.44 and 1.58–2.31 m at sampling sites at upstream and downstream locations respectively. The sampling stations were about 11 km apart. Water and sediment samples were collected from one-fourth (left bank), half (mid-stream) and three-fourth (right bank) of the river width. Water samples were collected at a depth of about 40 cm in 500 ml glass bottles properly acid-washed in HNO_3 prior to collection. Seasonally collected floodplain soil samples were taken after removing the top-soil of about 2 cm thick. Due care was taken to keep the samples free from any contact contamination.

Water samples were chemically preserved (2 ml HNO_3 + 5 ml of 2.5% $K_2Cr_2O_7$ in 250 ml sample), while other samples were stored and preserved[12] at 5°C for further processing as described by de Zwart and Trivedi[13]. In case of benthic macro-invertebrates, mercury was analysed in composite soft tissues and exo-skeleton of gastropods and pelecypods. Processed samples were analysed by the cold-vapour method using ECIL Mercury Analyzer, Model MA-5840. The concentrations were calculated with the help of standard curve prepared before analysis of the samples.

In this exploratory study, mercury was found in all types of samples in different magnitudes. Summary statistics of mercury concentration in the Ganga River system is presented in Table 1. It shows a wide range of variation in mercury concentration within the samples. Table 2 depicts seasonal variation of mercury in the river system at Varanasi during the study period. Detection frequency (%) of the metal in the samples is shown in Figure 2. Seasonal detection of mercury in physical samples (water, sediment and floodplain soil) of the river system varied greatly. Among different samples, detection frequency was maximum for fish (96%), while it was minimum for river-water samples (28%).

Annual mean concentration of mercury in the river water was 0.00023 ppm (SD = 0.00048, SE = 0.00011). The concentration ranged from NT (not traceable) to 0.00191 ppm (November 2001, upstream left bank). During winter, mercury could not be traced in the water samples, while in summer its concentration was marginally higher than during post-monsoon. There was no significant difference in the mean concentration of mercury at upstream and downstream locations (t_{stat} = 1.002, $t_{(0.05,16)}$ = 2.119). Except during winter and summer months (t_{stat} = 3.105, $t_{(0.05,10)}$ = 2.228), no significant difference in seasonal mean concentration of the metal was observed. A study by Indian Toxicological Research Centre (ITRC), Lucknow during 1986–92 showed maximum annual concentration of mercury in the Ganga River water at Rishikesh, Allahabad district and Dakshineswar as 0.081, 0.043 and 0.012 ppb respectively[5], lower than the metal concentration found in the present study. Mercury in the Ganga River water at Varanasi is lesser than that in the Cauvery River (range: 0.001–0.0136 ppm) polluted by chlor-alkali industry discharge[5], and the Damodar River polluted by coal mines and coal-based industries. Mondal *et al.*[14] and Mittal *et al.*[15] have reported mercury concentration from below detection limit to 0.0009 ppm and below detection limit to 7.2 ppm respectively, in the Damodar River water. Dall'Aglio[16] and Stock and Cucuel[17] have reported mercury (0.01–0.05 ppb) in river waters of Italy without any pollution source and natural waters of Germany respectively, which is lower than the present mercury level found in the Ganga River. Though the mean concentration of mercury in the water of the

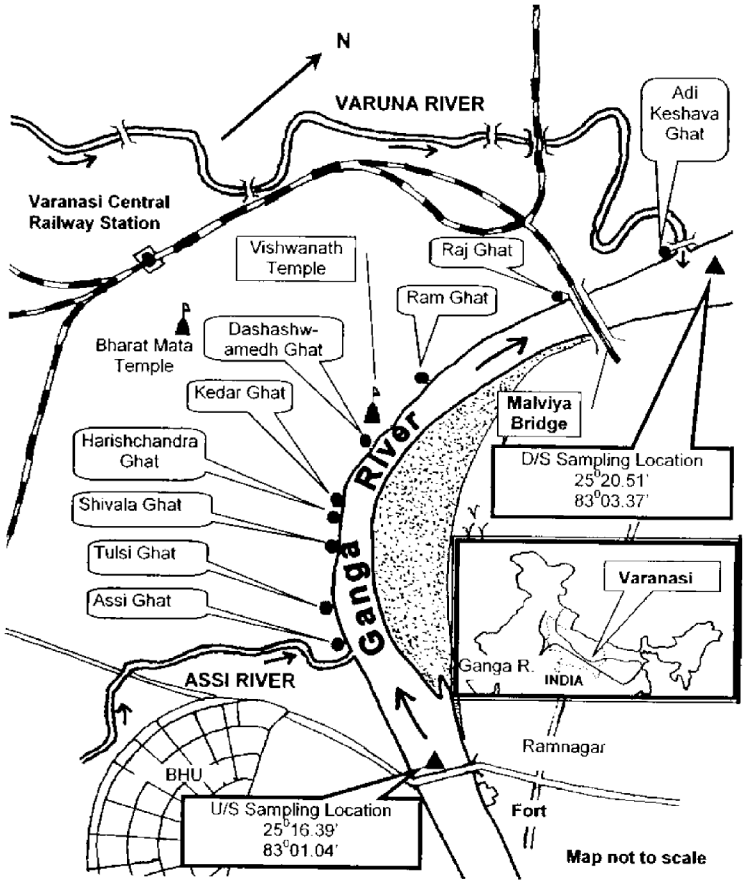

Figure 1. Map showing study site and sampling locations.

Table 1. Summary statistics of mercury concentration in samples of the Ganga River collected at Varanasi

	Water	Sediment	Benthos	Fish	Soil	Vegetation
Number of samples	18	18	28	67	12	61
Annual mean concentration (ppm)	0.00023	0.067	0.118	2.638	0.074	0.200
Minimum concentration (ppm)	NT	NT	NT	NT	NT	NT
Maximum concentration (ppm)	0.00191	0.301	0.748	91.679	0.269	1.674
Standard deviation	0.00048	0.090	0.192	13.714	0.100	0.268
Standard error of mean	0.00011	0.022	0.036	1.675	0.029	0.034
Confidence level (95.0%)	0.00024	0.045	0.074	3.345	0.0635	0.069

NT, Not traceable.

Table 2. Seasonal variation of mercury concentration (ppm) in different samples of the Ganga River collected at Varanasi

Season	Water	Sediment	Benthos	Fish	Soil	Vegetation
Winter	0	0.106 ± 0.113	0.144 ± 0.252	4.048 ± 18.676	0.095 ± 0.114	0.254 ± 0.397
Summer	0.00037 ± 0.00029	0.080 ± 0.087	0.108 ± 0.167	0.205 ± 0.531	0.126 ± 0.111	0.098 ± 0.081
Post-monsoon	0.00032 ± 0.00048	0	0.092 ± 0.129	4.369 ± 16.067	0	0.245 ± 0.127

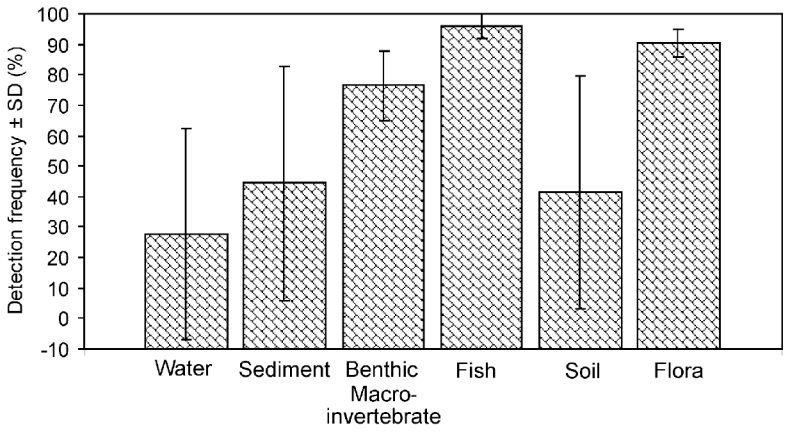

Figure 2. Detection frequency of mercury in samples collected from the Ganga River at Varanasi.

Ganga River at Varanasi was found well within the maximum permissible standard of 0.001 ppm prescribed for drinking water by the World Health Organization[18], the maximum value found in the study exceeded the standard.

Though mercury contamination of the river water has not reached an alarming extent, its presence in the river system is worrisome. In the present study, annual mean concentration of the metal in the sediments was 0.067 ppm (SD = 0.090, SE = 0.022). Maximum mercury concentration in the sediments was 0.301 ppm during January (downstream left-bank). Fuska[19] suggested that sediments, biofilms and benthic organisms were the most suitable components for monitoring mercury in the ecosystem. Sediments constitute a major pool of mercury in freshwater. In rivers, sediments control the turnover and retention of the metal, acting either as a sink or secondary source depending on the physical and chemical conditions[20].

The metal was detected only in 45% of the collected sediment samples (Figure 2) and was not traceable during the post-monsoon season (Table 2). No significant differences in the mean concentrations of mercury at upstream and downstream locations were observed ($t_{stat} = 1.074$, $t_{(0.05,16)} = 2.119$), while mercury concentration during winter–post-monsoon ($t_{stat} = 2.302$, $t_{(0.05,10)} = 2.228$) and summer–post-monsoon ($t_{stat} = 2.321$, $t_{(0.05,10)} = 2.228$) differed significantly. As the mercury species is adsorbed in the particulate matter and subsequently deposited on the riverbed as fine sediment[21], mercury could not be traced in the post-monsoon samples when the riverbed has freshly deposited sediment. During comparatively low river flow in winter, mercury concentration was maximum (mean = 0.106, SD = 0.113 ppm). Low flow rate allows sufficient time for sedimentation of the driven particles[22], and hence more mercury deposition in sediments during winter. In contrast, the river gets fresh monsoon rains in June resulting in more flow and thus fresher sediments compared to winter. During the onset of monsoon the river sediment can be supposed to be a mix of old as well as fresh deposition, which is replenished with completely fresher sediment during post-monsoon and hence less deposition of mercury in June. This phenomenon justifies the seasonal variation of the metal (Table 2). Concentration of mercury in the sediments of the Ganga River at Varanasi is much lower than the Cauvery River (range: 0.01–4.36 ppm) polluted by chlor-alkali industrial efficient discharge[5].

Annual mean concentration of mercury in the benthic macro-invertebrate biota was 0.118 ppm (SD = 0.192, SE = 0.036). Maximum and minimum mercury concentration was found during winter and post-monsoon seasons respectively (Table 2). Mercury was found below detectable limit in 25% of the samples. Pelecypod shells contained mercury in the range of NT to 0.546 ppm (annual mean = 0.074, SD = 0.1712 ppm), while in gastropod shells the range was NT to 0.366 ppm (annual mean = 0.089, SD = 0.1102 ppm). Higher concentration of mercury in gas-

tropod samples than in bivalves was reported from Mumbai[4]. The pelecypod group of molluscs is a filter feeder and depends mainly on suspended particles for food, while the gastropods are mainly detritivores. This may be the reason for higher accumulation of mercury in gastropods feeding on bottom sediments containing the metal. Parkman[23] studied mercury accumulation in zoobenthos and reported high concentration in detritivorous species in comparison to predators. During minimum flow in the river, mercury in suspended solid particles is increased[22]. This might be the reason for higher accumulation of mercury in pelecypods during comparatively low-water seasons, i.e. winter. In the composite soft tissue of the benthic macro-invertebrates, mercury ranged from 0.012 to 0.748 ppm (annual mean = 0.227, SD = 0.2887 ppm); maximum during winter. Mean concentration of mercury in the soft tissues is higher than that in the exoskeleton of molluscs. In gastropod and pelecypod shells, maximum concentrations were recorded during post-monsoon and summer respectively (Figure 3).

Mercury concentration in fish of the Ganga River ranged from NT to 91.679 ppm (annual mean = 2.638 ppm, SD = 13.714, SE = 1.675). Mercury level in fish in this study was higher than that of mercury in fish collected from the western coast, Mumbai (0.03 to 0.82 ppm)[4]. Kannan *et al.*[24] have reported higher mercury (range = 0.03–2.22 mg/kg and mean = 0.31 mg/kg on wet weight basis) in Florida estuaries. Minimum concentration in fish samples was found during summer (Table 2). Concentration of mercury in different fish species is given in Table 3. Maximum mercury concentration (91.679 ppm) was found in mud dweller, *Macrognathus pancalus*. Effect of such a high concentration of the metal in this species has not been studied, but a concentration of this magnitude (32–114 ppm) has been reported to cause decreased appetite and activity, a mortality behaviour, in sub-adult rainbow trout, *Oncorhynchus mykiss*[25]. Food of *M. pancalus* is dominated by insect larvae and annelids with high feeding intensity during June–September[26]. Food and dwelling habit might be exposing the fish to mercury through ingestion of bottom-dweller food organisms as well as the sediments. Habitual intense feeding during June–September explains high mean mercury concentration during post-monsoon and winter seasons, due to cumulative exposure and accumulation of more mercury in the species. Uryu *et al.*[27] have explained feeding habit of a fish as the most important determinant of its mercury concentration. Barak and Mason[28,29] have emphasized the importance of sediments as a source of contamination in eels (*Anguilla anguilla*), which spend much of their lives in intimate contact with sediments. However, Barbosa *et al.*[30] have reported lesser mercury content in most of the detritivorous and omnivorous

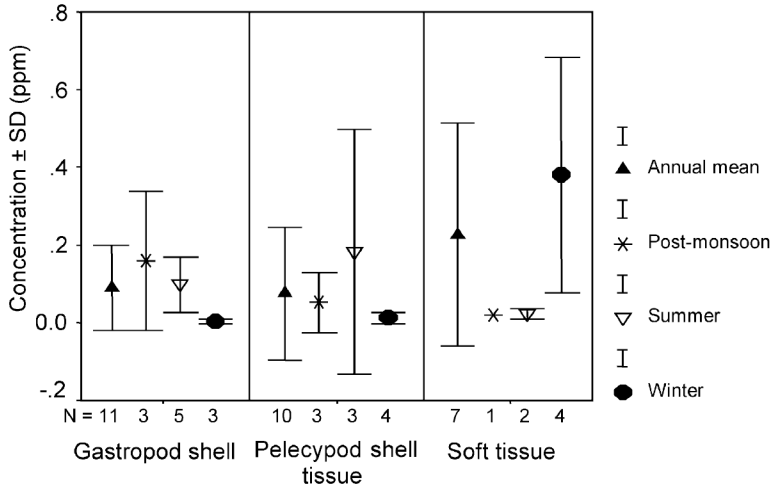

Figure 3. Seasonal variation of mercury concentration in benthic macroinvertebrate tissues collected from the Ganga River at Varanasi.

Table 3. Mercury concentration in fish samples at Varanasi

Species	Range (ppm)	Concentration ± SD (ppm)
Sicamugil cascasia (*n* = 3)	0.126–3.191	1.154 ± 1.764
Mystus tengara (*n* = 4)	0.033–0.205	0.101 ± 0.075
Gudusia chapra (*n* = 1)		0.083 ± 0
Eutropiichthys vacha (*n* = 4)	0.026–1.508	0.422 ± 0.725
Hypophthalmichthys molitrix (*n* = 1)		0.705 ± 0
Rita rita (*n* = 2)	0.048–0.091	0.070 ± 0.030
Puntius sophore (*n* = 5)	0.064–0.162	0.097 ± 0.049
Setipinna phasa (*n* = 1)		0.062 ± 0
Barilius tileo (*n* = 1)		0.953 ± 0
Mystus cavasius (*n* = 1)		0.133 ± 0
Cirrhinus mrigala mrigala (*n* = 1)		0.098 ± 0
Matra* (*n* = 1)		0.026 ± 0
Gudusia chapra (*n* = 3)	0.062–0.298	0.184 ± 0.118
Aspidoparia morar (*n* = 2)	0.033–0.191	0.112 ± 0.112
Nangra viridescens (*n* = 1)		0.019 ± 0
Osteobrama cotio cotio (*n* = 2)	0.012–0.098	0.055 ± 0.061
Clupisoma garua (*n* = 4)	NT–0.119	0.039 ± 0.054
Crossocheilus latius latius (*n* = 1)		0
Garra gotyla gotyla (*n* = 1)		0.054 ± 0
Channa punctatus (*n* = 2)	0.103–0.169	0.136 ± 0.0467
Macrognathus pancalus (*n* = 5)	0.112–91.679	32.347 ± 43.668
Securicula gora (*n* = 3)	0.083–0.405	0.235 ± 0.162
Charkhi* (*n* = 1)		0.334 ± 0
Raiamas bola (*n* = 5)	NT–0.362	0.101 ± 0.149
Labeo bata (*n* = 3)	0.012–0.155	0.081 ± 0.072
Ailia coila (*n* = 1)		0.191 ± 0
Mastacembelus armatus (*n* = 2)	0.105–2.048	1.077 ± 1.374
Baldhoshwa* (*n* = 2)	0.091–0.212	0.152 ± 0.086
Botia dario (*n* = 1)		0.041 ± 0
Bagarius bagarius (*n* = 1)		0.012 ± 0
Rhinomugil corsula (*n* = 2)	0.141–0.762	0.452 ± 0.439

*Vernacular name.

than piscivorous species. However, there are a number of factors, e.g. age of individuals or other criteria directly linked to age such as size or weight, which may influence mercury bioaccumulation in fish either directly or indirectly[31]. The varying mercury concentration in fishes of the Ganga River needs thorough investigation.

Mercury in the Ganga River ecosystem at Varanasi followed a trend of: water < sediment < benthic macro-invertebrates < fish (Figure 4 *a*). Duzzin *et al.*[32] have also reported mercury bonds in the order: water < fish < sediment < large aquatic invertebrates of increasing affinity. The bio-concentration factors (ratio between concentration of mercury in biota and that in water) in sediment, benthic macro-invertebrates and fish in the present study have been calculated as 3×10^2, 5×10^2 and 1×10^4, and show successive accumulation and magnification in the bio-physical environment of the river. Masson and Sullivan[33] reported for each trophic level starting with the phytoplankton bio-magnification factor of 3 to 5 for total mercury, while for methyl mercury from water to fish, Stanfford and Haines[34] presented a bio-magnification factor at a level of 5×10^6.

Mercury in floodplain soil of the Ganga River at Varanasi was found in the range of NT to 0.269 ppm (annual mean = 0.074 ppm, SD = 0.10, SE = 0.029). Maximum concentration was found in soil sample at the right bank, upstream location during summer. During post-monsoon season mercury was not found in the soil samples. Deposition of new soil in the floodplains due to monsoon flooding might be the reason for low mercury content in this particular season. The floodplains are under intensive cultivation. However, no authentic information could be collected on the use of organo-mercurial group of pesticides, but there are chances of the use of such compounds on the crops and their successive accumulation in the soil in the latter months, resulting into significant metal concentration during winter and summer (Table 2). There was no significant seasonal difference in the mean concentration of mercury in the soil samples. Difference in mean concentration of the metal at upstream and downstream locations was also not significant ($t_{stat} = 0.634$, $t_{(0.05,10)} = 2.228$). Metal concentration in floodplain soil of the river was higher than that in the river sediments. Floodplain soils around polluted rivers are subject to severe mercury contamination by deposition of river silt during flooding[35].

Annual mean concentration of mercury in the vegetation samples (49 from floodplains and 11 hydrophytes) was 0.200 ppm (SD = 0.268, SE = 0.034). Pooled estimate of mercury in seasonal samples shows maximum concentration in winter, while it is minimum in summer (Table 2). Location-wise pooled estimate of seasonal mercury concentration shows maximum concentration (mean = 0.411, SD = 0.581 ppm) for the downstream right-bank winter sample, while minimum (mean = 0.043, SD = 0.031 ppm) for downstream left-bank summer sample. Significant difference in mean concentration of mercury was not observed in other seasons, except summer and post-monsoon ($t_{stat} = 4.26$, $t_{(0.05,35)} = 2.030$). Radish root (*Raphanus sativus*, $n = 2$) accumulated maximum (1.118 ± 0.7863 ppm) mercury, while linseed (*Linum usitatissium*, $n = 1$) pod and cucumber (*Cucumis utilissimus*, $n = 1$) fruit had minimum concentration (0.048 ppm) of mercury among terrestrial plants (Table 4). Mercury concentration in rice grains collected from different parts of the world[36] ranged from 0.005 to 0.12 ppm. Mean concentration of mercury in radish root was significantly different from that accumulated in seeds, fruits, leaves, pods and entire plant samples collected at Varanasi. Syamala and Rao[37] found comparatively lesser accumulation of mercury in roots than stem and leaf of *Tephrosia purpurea* and *Cassia auriculata*, and higher accumulation in the root of *Arachis hypogea*. They attributed this partly to the plant varieties and their ability to accumulate heavy metals in their tissues. A significant difference in mean concentration of mercury was also

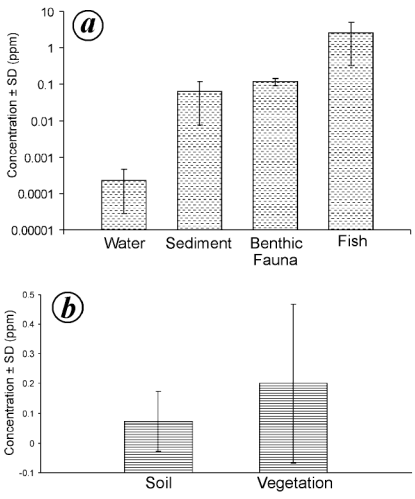

Figure 4. Biomagnification of mercury in aquatic environment (***a***) and floodplain (***b***) of the Ganga River at Varanasi.

Table 4. Mercury concentration in vegetation samples in and around the Ganga River at Varanasi

Botanical name	Floral part	Range (ppm)	Concentration ± SD (ppm)
Cajanas cajan ($n = 4$)	Seed	0.133–0.276	0.191 ± 0.0617
Vicia faba ($n = 1$)	Pod	–	0.954 ± 0
Momordica charantia ($n = 1$)	Fruit	–	0.101 ± 0
Coriandrum sativum ($n = 1$)	Leaf	–	0.105 ± 0
Cucumis utilissimus ($n = 1$)	Fruit	–	0.048 ± 0
Cucumis sativus ($n = 2$)	Fruit	0.076–0.076	0.076 ± 0
Cucurbita moschata ($n = 1$)	Fruit	–	0.191 ± 0
Cynodon dactylon ($n = 4$)	Leaf	NT–0.333	0.143 ± 0.1392
Dicanthium sp. ($n = 2$)	Whole plant	0.162–0.248	0.205 ± 0.0608
Eichhornia crassipes ($n = 4$)	Leaf	NT–0.133	0.071 ± 0.0546
Sorghum vulgare ($n = 2$)	Seed	0.191–0.219	0.205 ± 0.0608
Linum usitatissium ($n = 2$)	Pod	0.048–0.048	0.048 ± 0
Luffa cylindrica ($n = 6$)	Fruit	0.048–0.362	0.219 (0.1156)
Pennisetum typhoides ($n = 2$)	Seed	0.219–0.276	0.248 (0.0403)
Cucumis melo ($n = 3$)	Fruit	0.048–0.219	0.114 (0.0917)
Brassica campestris ($n = 4$)	Pod	0.048–0.305	0.137 (0.1148)
Oedogonium sp. ($n = 3$)	Whole plant	NT–0.691	0.313 (0.3501)
Cucurbita pepo ($n = 3$)	Fruit	NT–0.205	0.068 (0.1184)
Raphanus sativus ($n = 2$)	Root	0.562–1.674	1.118 (0.7863)
Lycopersicum esculentum ($n = 7$)	Fruit	0.048–0.276	0.096 (0.0803)
Vallisneria sp. ($n = 2$)	Whole plant	NT–0.048	0.024 ± 0.0803
Citrullus lanatus ($n = 1$)	Fruit	–	0.133 ± 0
Triticum aestivum ($n = 2$)	Fruit	0.048–0.848	0.448 ± 0.5657

observed in leaves and seeds (t_{stat} = 2.555, $t_{(0.05,14)}$ = 2.144). Among hydrophytes, maximum (0.313 ± 0.3501 ppm) mercury concentration was found in *Oedogonium* sp. (n = 3), while a minimum of 0.024 ± 0.0803 ppm mercury was recorded in *Vallisneria* sp. (n = 2). Mean metal concentration in the terrestrial flora was higher (0.206 ± 0.208 ppm) than the aquatic plants (0.168 ± 0.204 ppm), but no statistically significant difference in mean concentration of mercury between these two groups was observed (z_{stat} = 0.508, $z_{(0.05)}$ = 1.959). The trend shows magnification of mercury concentration from soil to vegetation (Figure 4 *b*) but no significant correlation was found between mercury in soil and floral samples (r = 0.229, t_{stat} = 0.7449, $t_{(0.05,7)}$ = 2.306). Total mercury level in plants depends on Hg deposits in the soil, locality, plants species, chemical form of the metal and soil aeration, and thus its concentration range is wide in most common edible plants and food derived from plants[38].

A preliminary study on mercury describes its presence and variation in different biotic and abiotic components of the river system. Though the source of metal in the system could not be clearly traced out, the study provides an overview on the contamination level. Enhanced frequency of sampling and more number of samples, especially water and sediment could have provided a clear picture. Further studies on the dynamics of the metal are required to trace its origin, route and sink in the river system.

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