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Spatial Variations of Heavy Metal Content in the Surface Water of Yamuna River, India

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Abstract Fast-growing urbanization, industrialization, and encroachment of the river banks have increased the pollution load in the rivers. The concentrations of heavy metals like Cadmium (Cd), Chromium (Cr), Copper (Cu), Iron (Fe), Lead (Pb), Magnesium (Mn), Nickel (Ni) and Zinc (Zn) in the waters of river Yamuna were studied. Sampling was done at 41 sites from upstream in the mountainous region to confluence point with River Ganga near the city of Prayagraj. It was found that the samples from the upstream sites in the mountainous region (falling in the state of Himachal Pradesh) were less polluted than those of Delhi stretch of the river suggesting huge influence of the anthropogenic activities along the Delhi stretch of the river. Fe, Pb, Ni, Cu, Cd and Mn concentration surpassed the prescribed maximum permissible limits for drinking water all along the river, while Cr, and Zn concentration remained within the permissible limit throughout. The peak concentration of Fe, Ni, Mn and Cd were recorded along Delhi stretch and downstream from Delhi suggesting contributions from the industrial effluents of various industries such as nut-bolt industry, electroplating, and Galvanizing and cycle industries in the region. The status of various heavy metals in the water of the Yamuna River has been discussed in the present study with respect to the heavy metal pollution index (HPI). HPI for Yamuna water was found highest along the Delhi-stretch. The mean concentrations of heavy metals in sampled water of Yamuna followed the order as stated here Fe>Zn>Cu>Ni>Mn>Pb>Cr>Cd in water.

Keywords: *Heavy Yamuna River, heavy metals, water, contamination, HPI*

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1. Introduction

All life forms depend upon water for their existence. As there is a general lack of a well-planned sewage and treatment system, the various industries directly discharge their untreated effluents into the open drains, ponds, streams and rivers. [1] If water gets polluted, lives get endangered as most of the human habitat and activities developed nearby the rivers from ancient times to the present day. Yamuna is one of the very important rivers among Indian rivers. Ganga, Yamuna and Saraswati (there is no evidence of Saraswati river in modern times; however, one finds its name mentioned in the ancient Indian scriptures) have been the source of inspiration for the Indian culture and spiritual traditions. The city of Prayagraj (formerly known as Allahabad) is situated on the banks of the confluence of the three rivers, viz., Ganga, Yamuna and Saraswati and hence considered a sacred spot in India. The Yamuna originates from Yamunotri glacier near Bandarpunch peak of the lower Himalaya (38^{o}59´N 78^{o}27´E) at an elevation of about 6320 meter above sea level. Yamuna's total scratch is about 1367 km; from origin to its confluence at Prayagraj, spread over the catchment area of about 3.5X10^{5} km^{2} covering many states of India. [2] The river flows over a distance of 224 km within the state of Haryana starting from Hathnikund up to Pala then, enters the Union Territory of Delhi, traversing a total distance of about 22 km and then again passes through Haryana near Faridabad and again covers about 100km before entering Uttar Pradesh. [3] Thus, it traverses a total distance of 324 km in Haryana. This river has faced the brunt of the anthropogenic activities happening along its banks. Fast-growing urbanization, industrialization and encroachment of the river banks have increased the pollution load in the rivers. [2] The anthropogenic activities (sewage, industry, mining, agriculture, deforestation) far exceed the natural causes (erosion, decay, etc.) of pollution. The catchment area of Yamuna River has a large number of industries and big urban conglomerations right from its mountain region to confluence except for a small stretch before entering into the State of Haryana. The National Capital Territory of Delhi, although is only one percent of the total catchment area of Yamuna but it contributes for more than 50 % of total heavy metals pollutants found in the river Yamuna. [4] Delhi state depends on the Yamuna for all types of water needs, but increasing industrial activities and sustained increases in population have put tremendous pressure on water supply and sanitation resulting in the pollution load in the river. [5] The Haryana stretch of the river is also polluted by the industries at places such as Yamunanagar (distillery, sugar, paper mill, and utensils), Panipat (sugar, textile, paper, drain no. 2) and Sonipat-Gohana (cycle, sugar, distillery, tannery, drain no. 8). [3] The Uttar Pradesh stretch of the river Yamuna gets heavy pollution load in Mathura and Agra since this part is highly urbanized and networked by many drains. [6,7] The heavy metal pollution in rivers results in a severe ecological and health problem because heavy metals are not biodegradable and get accumulated both in plants and soil resulting in serious threats to biota including human health. [8] When the contaminated water of the river is directly used for irrigation without using any treatment it may lead to deterioration of soil and human health via the contaminated agricultural products. [9,10] The study of pollution load for the river is helpful in indicating and appraising the trends in water quality with respect to the variations in heavy metal concentrations at different parts of the river. The heavy metal enters the river mainly through anthropogenic activities such as disposal of untreated industrial effluents and sewage containing toxic metals. Other channels of heavy metals entry into river are chemical reactivity, mineralogy and land use pattern etc.

Improper management of industrial and agricultural activities results in addition of many contaminants such as heavy metals and pesticides in the river waters. The drains carry sewage, agricultural runoff and domestic wastes. The assessment of heavy metal contamination in river water is critical as the presence of these metals above a certain threshold value is harmful to human and environmental health, as many of these metals accumulate in soil and enters into the food chain overtime. In the present study, the contamination of water by Fe, Cu, Cd, Cr, Ni, Mn, Zn and Pb are estimated over the whole stretch of the Yamuna River.

2. Materials and Methods

2.1. Sampling

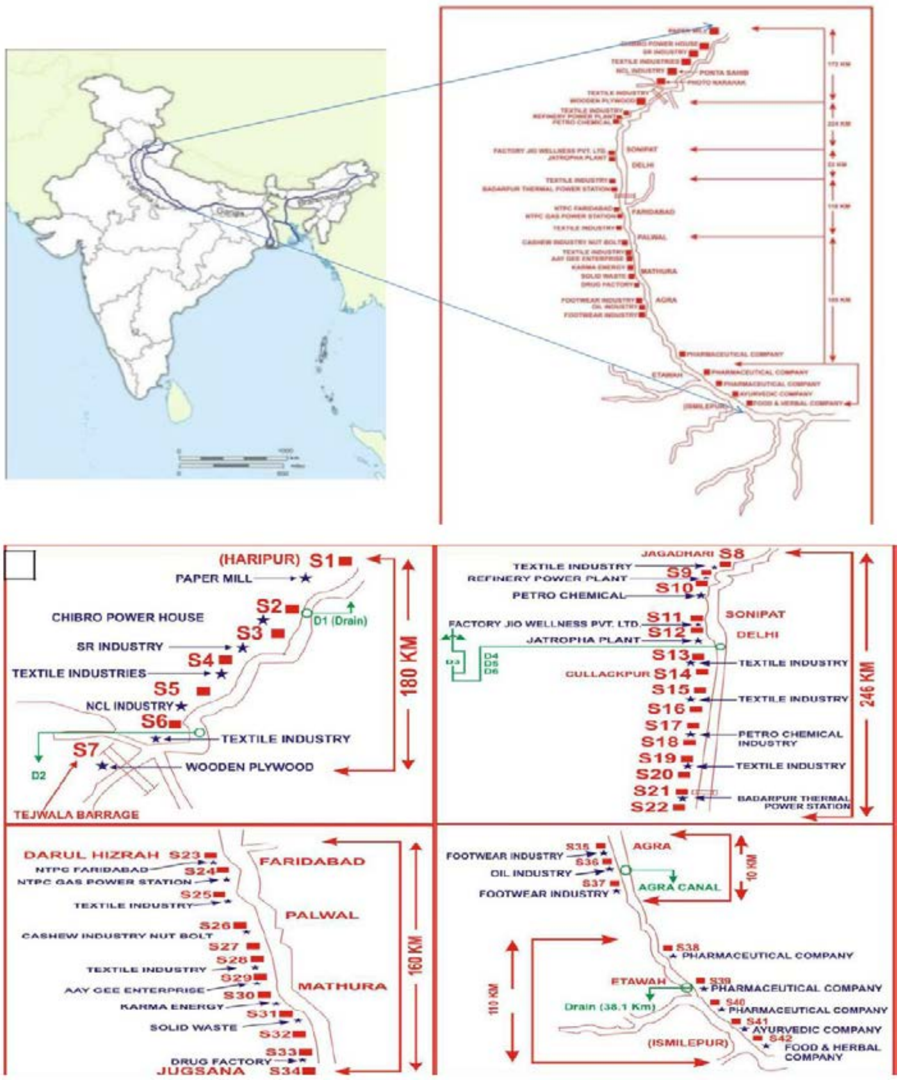

Figure 1. Geographical map showing various sampling sites

Sampling of water samples was done along the Yamuna river stretch from Haripur (Uttrakhand) to Confluence with Ganga River near Prayagraj in May 2017. The sampling was conducted at 41 study sites (Figure 1). The physical parameters were examined on the spot using portable kit (Ferrotek). For determination of heavy metals concentration, the samples were stored in pre-cleaned and pre acid washed polypropylene bottles in an ice boxes at less than 4°C and transferred to laboratory for further analysis. The samples were filtered through whatmann 42 glass filter paper and were further digested using nitric acid.

Quality assurance was maintained using blank and performing duplicate sample analysis on approximately 10% sample. The instrument was calibrated using standard solutions of Merck and precision was better than 2% for all heavy metals analyzed. The standard solutions of different concentration were prepared using serial dilution method and after every ten water samples, a blank solution was run.

2.2. Heavy Metal Analysis

For digestion of water samples for heavy metals detection was done by taking 250ml of water sample in a beaker. [11] To this 5ml of concentrated Nitric acid (HNO_3) was added along with few boiling chips and glass beads. The sample was allowed to evaporate on a hot plate with temperature range 80-90°C avoiding boiling of the sample until the volume of sample remained 10-20ml. After this, again 5ml concentrated HNO_3 was added and the samples were again reduced to 10-20ml. This step was repeated till the colorless sample solution obtained. The solution was then made 100 ml in a volumetric flask with the help of double distilled water. The metals in water samples were analyzed using an atomic absorption spectrophotometer (Lab India AA-7000). The wavelength for Cd (228.80), Cr (357.9), Cu (224.8), Fe (248.3), Mn (279.5), Ni (232), Pb (283.31) and Zn (23.9) was found suitable for the heavy metals detection in AAS.

3. Results and Discussion

The concentrations of Fe, Cu, Cd, Cr, Ni, Mn and Pb in the river water of all sampling sites are shown in Table 1. The entire stretch of Yamuna was divided into four segments depending on the states through which it passes to assess the pollution load by different states.

The concentration of heavy metal was found more where ever the river received effluents from various industries and municipal discharge. The segment-III of the river Yamuna i.e. New Delhi stretch was most polluted followed by segment-IV and segment-II. The spatial variations reported in the concentrations of various heavy metals may be due to the vegetation present, the different man-made sources, lithological influences and hydrological phenomenon. [12] Figure 2 shows the concentrations of the heavy metals in the samples.

Cadmium: -

Cadmium concentration was found to be more than permissible limit in the three segments of Yamuna River studied. Maximum Cd enrichment was found in segment-III i.e. New Delhi segment where coal fired thermal power plants, paper mill and municipal waste water may be an apparent source of Cd. The high concentration for the other entire region may be attributed to various industries like engineering and electrical goods, textile and chemicals industries that are situated on both sides of Yamuna River in the entire stretch. [12,13,14] The results indicate that the average concentration of Cd was higher than BIS [15] standards which is a cause of concern for human health given the fact that it creates testicular degeneration and damages the proximal tubules of each nephron of kidney. [16] A significant enrichment of Cd in water and sediment samples of Yamuna in Haryana and Delhi has been showed by Kaushik et al. [3] and Bhardwaj et al. [13]. Yeh et al. [14] has also found high concentration of Cd in industrial affected Houjing River, Taiwan which received wastewater from a complex of plastic and petrochemical manufacturing industries.

Chromium - The concentration of Cr was low and varied widely across all four segments studied. About 22% of the total samples showed high Cr concentrations, exceeding its s permissible limit of 50 µg/l. Most of such samples were found in III & IV segments downstream from Delhi. Cr is considered as a specific pollutant which provides evidence of polluted effluents from industries such as electroplating, semiconductor packaging and metal surface processing. [14,17] High concentration of Cr in river Yamuna due to anthropogenic activities has been shown by Bhardwaj et al. [13] Similar findings have been reported in Ganga river water also by Siddique and Pandey [12]. They found that nearly 56% of sample had Cr concentration above permissible limit. The higher concentration of Cr in Ganga water has caused carcinoma of gall bladder in human beings residing along this river. [16]

Copper: - Copper concentration showed wide fluctuations. The highest concentration of Cu was found to be in segment-I which may be due to paper industries, textile industries and shoe industries operating from the region. Bhardwaj et al. [13], have also found high concentration of Cu in Yamuna River which has been attributed to the discharges from electroplating, steel and pulp industries. In Mahanadi river (a major river in the Eastern part of India), concentration of Cu was within permissible limit of WHO [18] whereas in Ganga river basin nearly 55% samples showed Cu concentration exceeding the permissible limits of BIS [12,15,19]. A low concentration of Cu in Halda river of Bangladesh and Salado river of Argentina has been found by Bhuyan and Baker [20] and Gallo et al. [21] respectively whereas high concentrations of Cu in Liuyang River, and Dongting lake in China have been reported by Jia et al. [22] and Bi et al. [23] respectively. Cu is although an essential metal required by almost all living organism but a high concentration is considered as pollutant. [24]

Lead: - The range for Pb in different segments studied varied from 14 µg/l to 798 µg/l which is higher than the permissible limits of BIS. [15] An exceptionally high concentration of Pb in segment-I and segment-IV may be due to effluents of lead battery based units, tannery effluents and various industries like pharmacy, footwear, and diesel engine manufacturing industries situated in the region. [12,13,19,25] Similar studies of high concentration of lead in Yamuna river have been reported by Sehgal et al. [4] and Bhardwaj et al. [13] High concentrations of Pb, exceeding the prescribed limits of WHO and BIS, have also been reported by Siddiqui & Pandey [12] in nearly 67 percent of samples from the Ganga river basin.

Table 1. Segment wise description for heavy metal concentration in µg/L of River Yamuna water

	Ni	Cu	Cd	Cr	Zn	Fe	Mn	Pb
Range Whole stretch	32-664	190-980	2-9	11.6-97.6	70-1782	93.4-3826	6.3-1134	14-798
Segment-I	118±50.8	443±325	2.48±0.31	26.6±7.8	854±526	580±304	8.3±1.2	312.8±117.6
Segment-II	402±172	445.4±226.3	4.42 ±1.13	36.7±17.2	533±153	1007±895	35.5±21.3	344.7±213.6
Segment-III	454±159	616.9±175.7	7.4±0.86	32.7±15.8	664±140	1101±653	682±329	184±107.9
Segment-IV	385.4±168.8	574.7±143	7.02±1.24	48.2±23.2	458.2±248.7	1118±869.7	196.2±287.1	357.7±238.5
WHO 2011	20	2000	3	50	5000	300	400	10
BIS 2012	20	50	3	50	5000	300	300	10

Figure 2. The concentrations of various heavy metal contaminants along the monitored sites

Bhuyan and Baker [20] and Bi. et al. [23] have reported high concentration of Pb in Halda river of Bangladesh and at the confluence point of Yangtze river in China respectively.

Managanese:- Concentration of Mn in surface water of river Yamuna showed a significant variation. The downstream segments, viz., segment-III and segment-IV showed considerably high concentration of Mn as compared to those of segment-I and segment-II. The higher concentration in downstream segments may be due to various industries, tannery effluents and municipal discharges from commercial and small industrial units operating in the region. [26,27] Mn has also been found to be more than permissible limit in nearly 44.44% of water samples collected from Ganga river basin [12] and in slightly high concentration in water samples of Mahanadi river. [19] Significant accumulation of Mn was reported in the river water of Delice River, Turkey and Halda River, Bangladesh by Akbulunt and Tunner, [28] and Bhuyan and Baker [20] respectively.

Nickel: - Nickel concentration in Yamuna River water in different segments was found to be ranging from 32µg/l to 664µg/l. It was found that the entire stretch of Yamuna River was having high Ni concentration, above its permissible limit of 20 µg/l as recommended by BIS. [15] The high concentration of Cu, Ni and Cr may be due to waste water from electroplating, metal surface processing industries and municipal discharge. [14] The Yamuna River is highly polluted with Ni especially near Delhi region has also been reported by Kaushik et al. [3] and Bhardwaj et al. [13]. Siddique and Pandey [12] have also found that 33% of water samples collected from Ganga river basin showed Ni concentrations higher than the above-mentioned permissible limit. All these results indicate that Ni may be a metal of concern for human health if Yamuna river water is used for drinking purpose. High concentration of Ni has also been found in Halda River, Bangladesh and Houjing River, Taiwan. [14,20]

Iron- The present study has found that the Iron concentrations exceeded the permissible limit of BIS [15] in all samples. Segment-III and segment-IV showed very high concentration of Fe which might be attributed to iron works in Delhi and Faridabad region. Siddqui and Pandey [12] have also found higher concentration of Fe in nearly 67% of samples in Ganga River basin. Iron is the most abundant metal in the Yamuna river water and its concentration as per the present study was found to be higher than those of the River Ganga, River Mahanadi and River Hindon, India [19,29,30] and Tigris River, Turkey. [31] These high values of Fe could be attributed to high concentration of Fe in soil but anthropogenic sources of Fe due to effluents from industries like metal pipes and steel cannot be ruled out. The high concentration of Fe in water when used for household purpose may release strains of oxides on sanitary wares, laundry, rusting of pipes in supply line. [24]

Zinc: - Various electroplating industries and brass manufacturing industries along with agrochemical industries including fertilizer and pesticides may be the prime source of Zn in the river water. [32] But the concentration of Zn was found to be lower than the permissible limits in the entire stretch of Yamuna River from its origin to confluence point. Similar results in Yamuna River, Mahanadi River and Ganga River basin water have been found by Bhardwaj et al. [13], Sundaray et al. [19] and Siddiqui and Pandey [12] respectively. Bhuyan and Bakar [20] have found average concentration of Zn in Halda River, Bangladesh as 150 µg/l which is below the WHO permissible limit.

Table 2. Comparison of metal concentration of Yamuna River (present study) with other Indian and International rivers

River name	Ni	Cu	Cd	Cr	Zn	Fe	Mn	Pb	Reference
Liuyang,river China(µg/l)	0.80±0.47	2.90±1.78	0.07±0.05	0.73±0.39	101.27±76.75	369.07±212.54	34.51±20.35	1.20±1.11	[22]
Yangtze river, China(µg/l)	-	7.47±10.40	0.16±0.20	-	-	-		6.13±11.47	[38]
Delice river, Turkey(µg/l)	0.04	-	0.287±0.202	-	-	393.53±310.05	43±63.25	-	[28]
Lhasa river, China(µg/l)	-	3.08	.24	3.49	2.16	-	19.4	1.63	[39]
Halda river, Bangladesh(µg/l)	410	100	30	60	350	-	160	70	[20]
Tigris river, Turkey(µg/l)	24.54	17.10	0.044	25.41	12.01	158.16	-	2.82	[21]
Houjing river, Taiwan (µg/l)	33.5	248.7	4.1	27.8	51.2	-	-	64.2	[14]
Mahanadi river,India(µg/l)	10.19	8.39	0.91	3.67	29.28	189.38	19.88	8.04	[19]
Hindon river,India(µg/l)	24	6.6	_	15	58	226	129	37	[30]
Godavari river, India(µg/l)	0.14	0.92	0.07	-	0.66	7.50	-	5.60	[40]
Yamuna river, India(µg/l)	375.5±671.7	2151±3399	47.6±94.6	147.1±413.4	1500.7±4394	10488±10615	-	116.4±229	[13]
Ganga river,India(µg/l)	140	10	5	-	60	800	-	120	[19]
Cauvery river, India(µg/l)	38.3	6	0.43	48.8	81.6	9.90	-	136	[41]
Brahamani river, India (µg/l)	24.78	6.67	-	10.89	31.56	481.78	-	1.67	[42]
Yamuna river, India(µg/l)	378±183	543.7±205.5	6.01±2.02	38.36±19.54	588±275	1022±757	292±370	287.4±189.5	Present study

4. Statistical Analysis of Heavy Metals for Drinking Water

4.1. Heavy Metal Pollution Index

The overall quality of river water was evaluated by HPI (Heavy Metal Pollution Index) taking into consideration the concentration of various heavy metals. In order to calculate the HPI values, the weighted average of the heavy metal concentrations were used according to the equation (A). [33]

$$HPI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \quad (A)$$

Where Wi represents the unit weightage and calculated as the reciprocal value of Si, where Si stands for the maximum permissible limit for drinking water given by WHO. [34]
n is the number of heavy metals under study and Q*i* is the lower index which can be calculated by equation (B).

$$Q_i = \sum_{i=1}^{n} \frac{M_i}{S_i} X100 \quad (B)$$

Where Mi is the concentration of the respective heavy metal and, Si is the standard permissible value of respective metal. The quality of water increases in the ratio of heavy metal concentration in terms of the standard permissible limit. In order to assess the water quality of the river with respect to the content of heavy metal, the sampling locations are divided into four different segments i.e., (a) Segment - I (Mountain Segment) (b) Segment - II (Haryana Segment) (c) Segment - III (Delhi Segment) and (d) Segment - IV (Uttar Pradesh Segment). The HPI values were calculated by using mean concentrations of Cu, Zn, Fe, Mn, Ni, and Pb. The values of HPI, Wi and Qi as calculated by using equation A and B have been shown in Table 3.

The primary index for measurement of heavy metal concentration in water is the HPI whose threshold value is below 100 for health and safety reasons. [35] Industrial and municipal wastewater discharges into the river are responsible for the high HPI values. HPI of four different segments were compared to assess pollution load and estimate the water quality for these segments. HPI values for all the segments were found higher than the critical limit. On comparing the different values of HPI for various segments it could be concluded that the pollution load in the Delhi segment was most significant (i.e., 966.45). The Metal Quality Index (MQI) was calculated to measure the total metal contamination in the river water in order to determine the suitability for human consumption. MQI value >1 is a threshold of warning. [36] The MQI is calculated by equation (C). [37]

$$MQI = \sum_{i=1}^{n} \frac{M_i}{S_i} \quad (C)$$

Total metal pollution in the water of River Yamuna for drinking purpose was computed to estimate the MQI as shown in Table 4. All segments were found at high risk with metal pollution for drinking.

Table 3. HPI index calculations for river water (a) Segment-I (b) Segment-II (c) Segment-III (d) Segment-IV

Segment I					
HM	**Mi**	**Si**	**Wi(1/Si)**	**Qi(Mi/Si*100)**	**Wi*Qi**
Cu	443	2000	0.005	22.15	0.11075
Ni	118	20	0.005	590	2.95
Pb	312.8	10	0.0002	3128	0.6256
Zn	854	3000	0.0005	28.46	0.0142
Fe	580	300	0.0002	193.33	0.0386
Mn	8.3	100	0.005	8.3	0.0415
				HPI	237.78

(a)

Segment II					
HM	**Mi**	**Si**	**Wi(1/Si)**	**Qi(Mi/Si*100)**	**Wi*Qi**
Cu	445.4	2000	0.005	22.27	0.11135
Ni	402	20	0.005	2010	10.05
Pb	344.7	10	0.0002	3447	0.6894
Zn	533	3000	0.0005	17.76	0.0088
Fe	1007	300	0.0002	335.66	0.0671
Mn	35.5	100	0.005	35.5	0.1775
				HPI	698.38

(b)

Segment III					
HM	**Mi**	**Si**	**Wi(1/Si)**	**Qi(Mi/Si*100)**	**Wi*Qi**
Cu	616.9	2000	0.005	30.84	0.15
Ni	454	20	0.005	2270	11.35
Pb	184	10	0.0002	1840	0.368
Zn	664	3000	0.0005	22.13	0.0110
Fe	1101	300	0.0002	367	0.0734
Mn	682	100	0.005	682	3.41
			HPI		966.45

(c)

Segment IV					
HM	**Mi**	**Si**	**Wi(1/Si)**	**Qi(Mi/Si*100)**	**Wi*Qi**
Cu	591.7	2000	0.005	29.585	0.147925
Ni	383.8	20	0.005	1919	9.595
Pb	326.4	10	0.0002	3264	0.6528
Zn	469.8	3000	0.0005	15.66	0.00783
Fe	1158	300	0.0002	386	0.0772
Mn	232	100	0.005	232	1.16
				HPI	732.123

(d)

Table 4. Metal Quality Index (MQI) calculations for river water at each segment

Segments	**MQI**
Segment - I	36.82
Segment - II	44.00
Segment - III	58.84
Segment - IV	50.25

Table 5. Correlation of different heavy metals in the surface water of river Yamuna

	Cu	Ni	Pb	Cd	Cr	Zn	Fe	Mn
Cu	1							
Ni	0.2037276	1						
Pb	0.0218158	-0.079519	1					
Cd	0.3541912	0.3357078	-0.0421705	1				
Cr	-0.2006462	0.0985783	-0.180688	0.0174156	1			
Zn	-0.2858486	-0.2801956	0.1518275	-0.0491117	-0.1447858	1		
Fe	0.1612383	0.1343278	0.0281713	0.3004437	-0.1639115	0.0648273	1	
Mn	0.2087141	0.2312512	-0.2412891	**0.57419**	-0.0255896	0.2717732	0.1082226	1

4.2. Correlation among Heavy Metals

As shown in Table 5, no significant correlation was found among heavy metals except Cd and Mn where a positive correlation was observed between two. Significance level was found at $p < 0.05$. The analysis of the Pearson correlation assessed for the heavy metal content in water reflects that the source of all the heavy metals was different in the Yamuna River. Although the heavy metal concentration was segment specific, taken as a whole, the concentration of heavy metals in Yamuna river was observed in following sequence Fe>Zn>Cu>Ni>Mn>Pb>Cr>Cd. While assessing the concentration of heavy metals with respect to permissible limit prescribed by BIS, [15] it was observed that the upper stretches of the river Yamuna generally had below permissible limit concentrations of heavy metals except for Ni, Cu and Pb. The second segment is region of a developing state where the industrial set up is mostly around the Yamuna River with low population pressure along the banks. The third and fourth segment of Delhi and subsequent downstream are the most polluted stretches of Yamuna. The river in these segments receives large volume of waste water from various small scale industries and the effluents from municipal discharge as large number of cities are situated in this stretch. In this stretch various manufacturing packaging, plastic industry, tannery industries, electroplating industries, thermal power plants as well as refineries are located. The municipal discharge from surrounding commercial and residential areas may be a reason of high heavy metal concentration in this segment. Overall the river water is heavily polluted due to heavy metals in lower reaches. The high concentration of heavy metals as compared to BIS [15] guidelines for drinking water quality indicates that Yamuna River water has high heavy metal concentration due to anthropogenic activities and this may affect the ecological system by entering into the food chain.

5. Conclusions

The river Yamuna is polluted by heavy metals mainly due to the mixing of Industrial effluents with the river water in entire stretch of 712kms. The heavy metal pollution is spread over the entire stretch of the river Yamuna starting from Haripur in Himachal Pradesh up to its confluence point with river Ganga at Prayagraj. The concentration of the various heavy metals varies from location to location depending on the number and type of the industry polluting the river water, dilution and adsorption at barrages. Thus it can be concluded that river water as such is not suitable for drinking although may be suitable for irrigation due to excess of Fe and Mn. Thus great attention is required because the Yamuna river water is used for drinking purpose by a large population living in villages. The present study concludes that the heavy metals pollution from the adjoining industries along the river pose a great threat to it and proper remediation strategies must be implemented to reduce pollution level and to avoid further deterioration of river water quality and thus preventing a human health disaster from occurring.

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Supplementary Material

Table S1. Sites' description and details for the collection of polluted river water samples.

Site No.	Latitude	Longitude
S1	22.93611°	88.23194°
S2	30.5042°	77.7947°
S3	30.4502°	77.269°
S4	29.6800°	77.0597°
S5	30.450001°	77.620003°
S6	30.3142°	77.585°
S7	30.2902°	77.5449°
S8	30.1691566°	77.3033721°
S9	29.3865029°	77.1161561°
S10	37.447052°	77.426581°
S11	29.241600°	77.003300°
S12	28.990160°	77.015580°
S13	28.661516°	77.017829°
S14	28.60189°	77.1485°
S15	28.56°	77.12°
S16	28.67559°	77.26445°
S17	28.3952741°	77.1412922°
S18	28.283625°	77.15496°
S19	28.56375	77.2612
S20	28.5838	77.2947
S21	25.4569°	77.2839
S22	24.47364°	39.610851°
S23	28.64399°	77.091°
S24	22.535313°	88.158114°
S25	28.339252°	77.3165959°
S26	30.1630°	77.7569°
S27	27.9912545°	77.1798565°
S28	26.856°	77.1259°
S29	26.11°	81.19°
S30	24.1222°	77.8912°
S31	23.13°	77.1569°
S32	26.179°	77.89159°
S33	28.36538°	77.75774°
S34	27.174708°	78.042233°
S35	27.1766701°	78.0080745°
S36	23.25°	77.24°
S37	26.38°	77.25°
S38	26.47°	79.02°
S39	26.790513°	79.0237141°
S40	23.6667°	76.1667°
S41	29.1397686°	78.2942569°

Table S2. Heavy metal concentration in water (μg/l) at different sampling sites along the Yamuna River

S.No.	Cu	Ni	Pb	Cd	Cr	Zn	Fe	Mn
S1	290	32	300	2	27.2	534	93.42	6.37
S2	197	124	200	2.4	39.2	1782	678	9.23
S3	230	132	254	2.7	26.5	754	638	8.36
S4	520	136	300	2.5	19.2	548	927	9.46
S5	980	167	510	2.8	21	654	567.2	8.37
S6	245	260	93	3.1	38	438	376.2	8.12
S7	510	304	120	3	56	382	682.9	8.93
S8	238	398	100	4.7	45.6	765	2964	57.2
S9	376	102	300	3.8	37.6	294	367.8	47.28
S10	190	420	500	4.3	22.8	583	192.3	7.38
S11	500	378	530	3.8	67.8	629	543.2	37.94
S12	920	489	320	5.1	21.3	649	1836	57.3
S13	600	652	690	5.6	19.2	629	1276.8	48.2
S14	430	619	450	6.4	22	429	826.8	47.2
S15	670	578	120	7	21.3	489	1362.8	92.6
S16	800	524	210	6.9	60.4	438	1047	573
S17	700	589	120	7	25	482	909.8	328
S18	570	621	310	6.5	43	820	835.6	912
S19	570	652	410	6.7	23.2	792	735.7	983
S20	560	543	190	6.4	34.5	762	692.3	872
S21	670	80	150	7	21.2	538	925.7	91
S22	700	270	160	7.5	23	632	825.7	732
S23	320	460	320	7	66.8	793	688.2	721
S24	230	410	80	9	34.5	839	3028.9	953
S25	780	444	189	8.4	29.2	732	613.2	1134
S26	620	392	120	8	32.4	689	925.6	735
S27	830	340	14	8.8	11.6	632	1724.2	740
S28	830	210	760	8.1	26.7	749	3826.8	328.9
S29	720	176	457	8.6	19.2	489	927.8	293
S30	630	280	130	7.9	66.5	638	528.2	1126.8
S31	430	370	-	7.4	87	520	836.73	126
S32	512	420	282	8	66.8	432	935.7	198.3
S33	570	321	-	7.6	34.5	498	1038.79	125
S34	254	124	798	7.6	25.6	1040	753.67	217.7041
S35	610	278	270	7.2	45.6	473	435.7	9.37
S36	520	356	210	5	97.6	397	589.3	12.6
S37	680	489	280	7	45.6	387	826.2	7.32
S38	510	664	-	8	48.4	401	437.3	9.28
S39	730	589	-	5.3	34.8	70	1253.7	92.5
S40	510	528	210	5.8	50.4	132	1527.2	98
S41	540	598	180	4.9	34.8	189	1735.3	102.5