Assessment of Heavy Metal Contamination in Yamuna River water in the Mathura Region Using an Index-Based Analytical Approach

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***Abstract*—Heavy metal pollution in the Yamuna River water in the Mathura region was assessed during the summer season at five sampling sites, namely M1, M2, M3, M4 and M5. The mean concentrations of heavy metals followed the order: Zn (1860 µg L^{-1}) > Fe (1222 µg L^{-1}) > Pb (656 µg L^{-1}) > Cd (254 µg L^{-1}) ≥ Mn (158 µg L^{-1}) > Cu (116 µg L^{-1}) > Ni (96 µg L^{-1}) > Cr (70 µg L^{-1}). Among these, Fe, Pb, Ni, and Cr were found to be within the permissible limits for irrigation water at all sites, whereas Cd, Zn, Cu, and Mn exceeded the permissible limits at certain locations. The mean Heavy Metal Pollution Index (HPI) indicated that site S4 exhibited the highest level of contamination. The overall mean HPI value for the Yamuna River during summer was 2035, which is significantly higher than the critical limit of 100, indicating severe pollution. Similarly, the Metal Quality Index (MQI) was highest at site M4 (75), while the average MQI for the river was recorded as 30. Pearson's correlation analysis revealed a significant positive correlation among all the studied heavy metals, suggesting a common point source of pollution.**

***Keywords*—Heavy metal pollution index (HPI), Heavy metals, Metal quality index (MQI), Pearson's correlation, Yamuna**

I. INTRODUCTION

Rapid urbanization and industrialization in expanding cities have led to the deterioration of both surface and groundwater quality, which critically affects agriculture, as well as animal and human health worldwide, including in the Indian subcontinent (Paul, 2017; Kumar et al., 2026) [18, 11]. Indian agriculture largely fulfills its water demand from surface sources such as rivers, reservoirs, and dams. However, many Indian rivers are increasingly becoming polluted due to the discharge of large quantities of untreated wastewater from urban and industrial sources (CPCB, 2012) [7].

Contamination of rivers by heavy metals represents a serious ecological concern and requires continuous monitoring, as these metals are toxic, non-biodegradable, and tend to bioaccumulate through the food chain. In several regions across the world, polluted river water is being used for irrigation without proper assessment of its suitability, leading to the degradation of both soil quality and crop productivity (Furhan et al., 2004; Gholami & Srikantaswamy, 2009) [8, 9].

The Heavy Metal Pollution Index (HPI) is a useful tool for identifying and quantifying trends in water quality, particularly with respect to the spatial variation of heavy metal concentrations. Similarly, the Metal Quality Index (MQI) is employed to evaluate the suitability of water resources for drinking and irrigation purposes based on metal contamination (Ojekunle et al., 2016) [17]. Furthermore, Pearson's correlation analysis serves as an effective statistical tool for identifying potential sources of pollution (Yalcin et al., 2010; Manoj et al., 2012) [20, 13].

The Yamuna River serves as the primary freshwater resource in the Mathura district of Uttar Pradesh, fulfilling domestic, industrial, and irrigation water demands. The catchment area of the Yamuna in Mathura is highly urbanized and interconnected by numerous drainage channels. The heavy metal status of the Yamuna River has been investigated by various water resource authorities in the past (Kaur & Mehra, 2012; Malik et al., 2014) [10, 12]. However, in the present study, an attempt has been made for the first time to comprehensively evaluate the water quality of the Yamuna River stretch in Mathura with respect to heavy metals (Fe, Pb, Cd, Cr, Cu, Ni, and Mn) using indices such as the Heavy Metal Pollution Index (HPI), Metal Quality Index (MQI) (Abdel-Satar et al., 2017) [1], along with Pearson's correlation analysis to assess its suitability for irrigation purposes.

II. MATERIALS AND METHODS

A. Sampling Sites

A total of five sampling sites were selected along the stretch of the Yamuna River in the Mathura district, designated as M1, M2, M3, M4, and M5 (Fig. 1). Among these, sites M2, M3, and M4 were located within the municipal limits of Mathura, whereas S1 and S5 were situated outside the municipal boundary, approximately 5 km upstream and downstream, respectively.

B. Analysis of Heavy Metals

Water samples were collected from all five sites during the summer season (May 2025). At each site, three composite samples were obtained from a depth of approximately 1 foot below the water surface using pre-sterilized 500 mL high-density polyethylene (HDPE) bottles to prevent contamination and unpredictable changes in water characteristics.

The collected samples were immediately preserved in an ice jacket at 4 °C and transported to the laboratory for further analysis. Upon arrival, the samples were acidified with concentrated nitric acid to maintain a pH below 2.0, thereby minimizing metal precipitation and adsorption onto the container walls, as recommended by standard procedures.

Heavy metal concentrations were determined using Atomic Absorption Spectrometry (AAS) (PerkinElmer 3300/96, MHS-10) following an acid digestion procedure in accordance with APHA (2012) [3]. All analyses were conducted in triplicate, and the results were expressed as mean values.

The overall quality of river water with respect to heavy metal contamination was evaluated using the Heavy Metal Pollution Index (HPI). The critical value of HPI is 100. The index was calculated using the weighted

C. *Analysis of Heavy Metals*

The Heavy Metal Pollution Index (HPI) was calculated using the weighted arithmetic mean method as follows:

$$HPI=\Sigma Wini=1Qi\Sigma Wini=1$$

where $Wi$is the unit weight of the ith parameter, defined as the reciprocal of the corresponding standard permissible value (Si) for irrigation water as prescribed by FAO (Ayers and Westcot, 1994), and $n$is the number of parameters considered. Qirepresents the sub-index of the ith parameter.

The sub-index (Qi) was computed using the following equation:

$$Qi=(MiSi)\times 100$$

where $Mi$is the monitored concentration of the i th heavy metal, and $Si$is its corresponding standard permissible limit (expressed in µg L-1).

Higher values of Mirelative to Siindicate poorer water quality, reflecting increased contamination levels.

The Metal Quality Index (MQI) was calculated according to Tamasi and Cini (2004) [19] as follows:

$$MQI=\Sigma MiSini=1$$

An MQI value greater than 1 indicates a threshold of concern or warning level for water quality (Bakan et al., 2010) [6].

D. *Statistical Analysis*

The data were statistically analyzed using SPSS version 20.0. Descriptive statistics, including mean and standard deviation, were calculated. Pearson’s correlation coefficient was used to determine the relationships among heavy metals, and the level of significance was tested at $p<0.05$.

III. RESULTS AND DISCUSSION

The concentrations of eight heavy metals analyzed during the summer season, along with basic statistical parameters, are presented in Table 1. The mean concentration of heavy metals in Yamuna River water followed the order: Zn (1860 µg L^{-1}) > Fe (1222 µg L^{-1}) > Pb (656 µg L^{-1}) > Cd (254 µg L^{-1}) ≥ Mn (158 µg L^{-1}) > Cu (116 µg L^{-1}) > Ni (96 µg L^{-1}) > Cr (70 µg L^{-1}). A continuous increase in the concentration of all heavy metals was observed from site M1 to M4, followed by a considerable decrease at site M5. This decline at M5 may be attributed to its location approximately 5 km downstream of the municipal boundary, which provides sufficient residence time for heavy metals to undergo precipitation and sorption, resulting in their transfer from the dissolved phase to riverbed sediments (Abdel-Ghani & Elchaghaby, 2007) [2]. The highest concentrations of all heavy metals were recorded at site M4, as it is located downstream of multiple municipal drains in Mathura. These drains carry untreated or partially treated wastewater from fertilizer and chemical industries, as well as residential areas, thereby significantly increasing the pollution load. Heavy metals such as Fe, Pb, Ni, and Cr were found to be within the maximum permissible limits for irrigation water quality at all sites. In contrast, other metals exceeded permissible limits at specific locations. Cadmium (Cd) exceeded the permissible limits at all sites, with concentrations ranging from 3 to 68 times higher than the standard limits, indicating severe contamination. The primary source of Cd is likely wastewater discharged from painting and electroplating industries within the city. Zinc (Zn) concentrations were found to be 1.05 to 1.2 times higher than the permissible limits at sites M3 and M4, which can be attributed to effluents from municipal and fertilizer industries. Similarly, copper (Cu) and manganese (Mn) concentrations exceeded permissible limits at site M4 by 1.17 and 1.25 times, respectively, reflecting localized industrial and urban discharge inputs.

Heavy Metal	M1	M2	M3	M4	M5	Mean	SD
Fe	460	670	1890	2580	510	1222	959
Pb	320	450	670	1120	720	656	306
Cd	30	50	460	680	50	254	298
Zn	1700	1900	2100	2400	1200	1860	450
Cr	40	50	80	120	60	70	31
Cu	50	75	130	235	90	116	72
Ni	85	95	110	115	75	96	16
Mn	80	160	180	250	120	158	64

Table 1: Heavy metal concentrations in river water at different sampling sites and statistical values for mean concentration of various heavy metals.

The HPI values were determined using the mean concentrations of eight heavy metals (Fe, Pb, Cd, Zn, Cr, Cu, Ni, and Mn). Table 2 presents the detailed calculation of HPI, including the unit weights (Wi) and sub-index values (Qi) for all sampling sites. The critical value of the Heavy Metal Pollution Index is 100 (Milivojević, 2016) [14].

The mean HPI value for the Yamuna River in Mathura during the summer season was found to be extremely high (2035), indicating severe heavy metal pollution. Such elevated HPI values can be primarily attributed to the discharge of untreated industrial effluents and domestic wastewater into the river.

HM	Mi (µg	Si (µg	Wi (1/Si)	Qi =	Wi × Qi

	L^{-1})	L^{-1})		(Mi/Si × 100)	
Fe	1222	5000	0.0002	24.44	0.004888
Pb	656	5000	0.0002	13.12	0.002624
Cd	254	10	0.1	2540	254
Zn	1860	2000	0.0005	93	0.0465
Cr	70	100	0.01	70	0.7
Cu	232	200	0.005	116	0.58
Ni	192	200	0.005	96	0.48
Mn	158	200	0.005	79	0.395

$\Sigma Wi = 0.1259$, $\Sigma Wi*Qi = 256$, HPI = 2035

Table 2: Heavy metal Pollution Index (HPI) calculations for river water based on mean heavy metal concentration in summer

The HPI values of different sampling sites were compared to evaluate the pollution load and overall water quality (Table 3). The HPI values at all sites were found to be significantly higher than the critical limit of 100, indicating severe contamination across the study area.

Based on the mean HPI values for each sampling site, it can be concluded that the pollution load was highest at site M4, with an HPI value of 5430, highlighting it as the most critically polluted location along the studied stretch of the Yamuna River.

Sampling Site	HPI Value
M1	248
M2	411
M3	3673
M4	5430
M5	411
Mean HPI	**2035**

Table 3: Heavy Metal Pollution Index (HPI) for Yamuna River Water at Different Sampling Sites (Summer)

Sampling Site	MQI Value
M1	6.15
M2	9.17
M3	51.66
M4	75.89
M5	8.69
Mean MQI	**30.31**

Table 4: Metal Quality Index (MQI) for Yamuna River Water at Different Sampling Sites (Summer)

Pearson Correlation Analysis

The Pearson correlation analysis of heavy metal concentrations in Yamuna River water revealed significant and strong positive correlations ($p < 0.05$) among all eight studied heavy metals (Table 5). The observed positive correlations suggest a strong association among the metals, indicating either mutual interaction or a common source of origin.

Such strong correlations imply that the metals are likely introduced into the river system through similar anthropogenic activities, such as industrial effluent discharge, municipal wastewater, and urban runoff (Miller & Miller, 2002) [15]. Furthermore, a high degree of correlation between specific heavy metals indicates their dependence on common causal factors, reinforcing the likelihood of shared pollution sources (Ashraf et al., 2012) [4].

	Fe	**Pb**	**Cd**	**Zn**	**Cr**	**Cu**	**Ni**	**Mn**
Fe	1	0.820	0.998	0.846	0.952	0.942	0.919	0.913
Pb		1	0.833	0.466	0.953	0.949	0.919	0.913
Cd			1	0.820	0.958	0.945	0.896	0.893
Zn				1	0.702	0.716	0.968	0.800
Cr					1	0.997	0.780	0.924
Cu						1	0.776	0.929
Ni							1	0.864
Mn								1

Table 5: Pearson's Correlation Matrix of Heavy Metals in Yamuna River Water

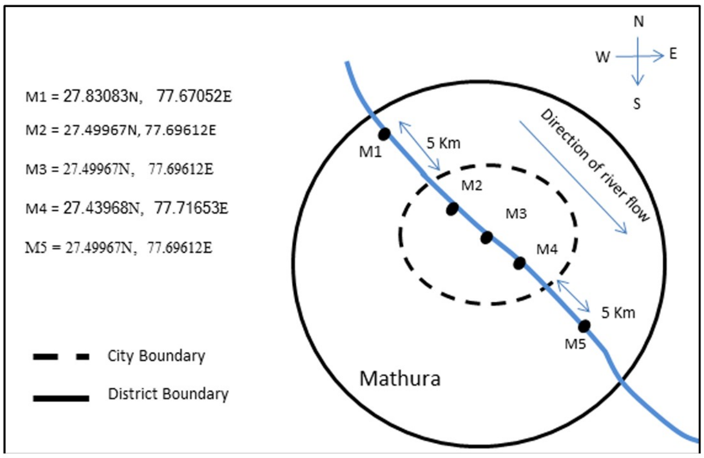

Fig. 1: Schematic representation of five sampling sites along the Yamuna River stretch in Mathura.

Conclusion

The present investigation demonstrates that the Yamuna River along the Mathura stretch is subject to **severe heavy metal contamination**, with site **M4 identified as the most critically impacted location** due to intense anthropogenic pressure. The exceptionally high Heavy Metal Pollution Index (HPI) values confirm that the river water is **heavily polluted and unsuitable for irrigation**, particularly during the summer season when pollutant concentrations are elevated.

The consistently high Metal Quality Index (MQI > 1) across all sampling sites further indicates **widespread and cumulative metal contamination**, reflecting the persistent degradation of water quality throughout the study area. In addition, the strong positive correlations observed among all heavy metals suggest a **common anthropogenic origin**, primarily associated with industrial effluents, municipal wastewater discharge, and urban runoff.

Overall, the study highlights the critical impact of uncontrolled waste disposal on river water quality and underscores the urgent need for **effective wastewater treatment, strict regulatory enforcement, and continuous monitoring programs**. These measures are essential for mitigating heavy metal pollution and restoring the ecological integrity of the Yamuna River.

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