Heavy Metal Contamination on Surface Water from Pharmaceutical Effluents in Industrial Zones: Pollution Levels and Health Risk Assessment

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A Thesis submitted to the School of Pharmacy in partial fulfillment of the requirements for the degree of Bachelor of Pharmacy (Hons.)

School of Pharmacy
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Declaration

It is hereby declared that

1. The thesis submitted is our own original work while completing degree at BRAC University.
2. The thesis does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The thesis does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.
4. We have acknowledged all main sources of help.

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Approval

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Ethics Statement

This study did not involve any human participants, animal experiments, or identifiable personal data, and therefore did not require formal ethical approval. All procedures related to environmental sampling and laboratory analysis were conducted in compliance with national regulations and institutional guidelines. Water samples were collected from public water bodies with no disturbance to local ecosystems or communities. The study adhered to ethical principles of integrity, transparency, and environmental responsibility throughout its design, data collection, analysis, and reporting.

Abstract

Industrial effluents from pharmaceutical facilities are introducing toxic metals into rivers and lakes, creating persistent pollution that bioaccumulates in aquatic life and threatens human health. Employing ICP-MS, ten heavy metals were quantified in river water collected adjacent to pharmaceutical manufacturing areas, enabling precise detection of trace-level contaminants. Contamination severity was evaluated using multiple indices: Nemerow Pollution Index, Heavy Metal Evaluation Index, and Heavy Metal Pollution Index, etc. Analysis showed that lead (Pb), iron (Fe), and mercury (Hg) often exceeded WHO permissible limits, with the Up-stream (Turag River) showing higher levels of contamination than the Down-stream (Shitalakshya River). HPI and HEI values indicated severe pollution, while NPI and Cd also reflected serious water quality deterioration. The evaluation revealed notable health hazards, with both non-cancer and cancer-associated risks markedly higher for children compared to adults. This integrative approach, combining advanced ICP-MS analysis with multimetric pollution indices and health risk evaluation, highlights an urgent call for more rigorous effluent regulation, continuous water quality surveillance, and mitigation strategies to preserve ecological integrity and public well-being.

Keywords: Heavy metals; Surface water pollution; Health risk assessment; Heavy metal toxicity indices; Non-carcinogenic risks; Carcinogenic risks

Dedication

I dedicate this thesis to my beloved parents for their unconditional love and support, my friends for their encouragement and companionship, and my project supervisor, for her exceptional guidance. This work would not have been possible without you.

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List of Acronyms

BWDB	Bangladesh Water Development Board
PTE	Potentially Toxic Element
HM	Heavy Metal
NCR	Non-carcinogenic Risk
CR	Carcinogenic Risk
HQ	Hazard Quotient
CSF	Conversion Slope Factor
R_fD	Reference Dose
ATSDR	Agency for Toxic Substances and Disease Registry

Chapter 1

Introduction

1.1 Background

Water is the lifeblood of Bangladesh, sustaining its people, feeding its agricultural backbone, and silently shaping its very geography. In a nation interlaced with over 700 rivers, making it the most riverine nation in the world (Bangladesh Water Development Board [BWDB], 2021). From the waterlogged rice fields to the groundwater wells in rural areas, water governs the very foundation of survival and economic sustenance. Around 70% of the population in the country depends on agriculture where water plays a crucial role in growing high-demand crops like jute, rice, etc. making Bangladesh one of the highest water consumers per capital in South Asia (FAO, 2020), over 80% rely on groundwater for drinking vital for carrying out the daily activities (UNICEF, 2021).

The purity and quantity of water play important roles in assessing its suitability for people to consume. Nevertheless, the country grapples with major obstacles in securing safe drinking water, which poses a substantial risk to public health. In its 2019 publication, the World health Organization states nearly a third of humanity lacks access to properly managed drinking water, highlighting a major public health gap. Inadequate water quality drives waterborne diseases in rural areas of Bangladesh, accounting for roughly one out of every three fatalities due to poor sanitation and hygiene (Banerjee et al., 2019). Based on Agenda 21 standards, contaminated water accounts for more than 80% of health issues and about one in three deaths in developing regions (*United Nations Division for Sustainable Development-National Information-Indicators of Sustainable Development*, n.d.).

Countries like Bangladesh are witnessing rapid urban expansion, growing industrialization, and surging population- each significantly fueling its economic progress. Although industrial development is essential for economic progress, it often comes with severe environmental consequences. Regardless, rapid urbanization is causing megacities like Dhaka to grow geographically and demographically as part of the trend of development. According to the UN World Urbanization Prospects 2024, with nearly 24 million residents crammed into just over 300 km^2, Dhaka ranks among the world's most densely inhabited cities.

Over the past decade, industrial activity is booming in the city's outskirts, with existing factories and manufacturing units steadily increasing (G. M. M. A. Hasan et al., 2025). The Department of Environment has found 450 industrial units polluting the Dhaka Division, and they are mostly in Dhaka and the nearby satellite regions of Gazipur and Narayanganj. These zones host a range of industries, which manufacture textiles, pharmaceuticals, and dyes, among others. Among the key contributors is the pharmaceutical industry, which has transformed health-care through the production of lifesaving medicines and therapies (Dichtel, 2023). These industries consume enormous amounts of water in their manufacturing operations, either as a raw material or for process control. However, only a small portion is absorbed; the remaining water is discharged as waste or effluent.

Effluents are the industrial waste products of various manufacturing processes. Rapid industrialization has led to the discharge of industrial effluents, including PTEs, often exceeding permitted levels (Ruba et al., 2021). These effluents are generally complicated and can be a mix of biologically active substances, organic solvents, and heavy metals, and are discharged directly into surface water with little or no treatment (Olatunde et al., 2013). As a result, the water in the rivers has become black and has a foul odor. The Buriganga River and its tributaries (Turag, Tongi Khal, Balu, Sitalakkhya, and Dhaleswari) in Bangladesh are getting about 60,000 m^3 of hazardous waste per day from nine big industrial clusters in areas such as Tongi, Hazaribagh, Tejgaon, Tarabo, Narayanganj, Savar, Gazipur, and Ghorashal, as reported in a study published in a PMC article (Uddin & Jeong, 2021)**.**

Among all the issues, the contamination of natural water reservoirs by effluents containing various potentially toxic elements has become a serious global concern. The majority of the freshwater resources of Bangladesh, including city rivers and lakes, aquatic foods, dairy, crops (e.g., cereals and vegetables), and agricultural soils, are highly infected with heavy metals (HM) (Islam et al., 2018). For instance, an analysis of frequently consumed fruits and vegetables from 30 agro-ecological areas in Bangladesh found that lead (Pb) levels in mangoes and cadmium (Cd) levels in tomatoes surpassed the WHO and UN Food and Agriculture Organization (FAO) safety thresholds, creating concerns about human consumption safety (Shaheen et al., 2016). In Bangladesh, HMs were found in most places, polluting agricultural soil around industries (Proshad et al., 2019); groundwater of different sampling sites (Shamsudduha et al., 2019); and everyday foods, e.g., vegetables, fruits, cereals, raw materials (Ahmed et al., 2015; A. S. S. Ahmed et al., 2019), freshwater streams and fish inhabiting them (Hasan et al., 2021).

The most frequently detected hazardous component in groundwater samples from Dhaka was lead (Pb), followed by arsenic (As). The investigation revealed that the water quality in Dhaka falls short of WHO guidelines, with arsenic and lead exceeding the 0.01 mg/L acceptable limit. (Sharmin et al., 2020). A recent research study exposed the severe consequences of lead consumption across the trophic levels, affecting everything from primary producers to apex predators. Similarly, on the same note, He et al. (2020) assessed surface contamination of chromium (Cr^{6+}) in the Chinese Loess Plateau and assessed corresponding health risks to inform public and government decision-making.

Toxic effects can be distant from the source of pollution, where heavy metals mix with natural water, defining their intensity and concentration (Yin et al., 2018). Wastewater tends to have high concentrations of toxic heavy metals that contaminate land and compromise food quality and safety (Briffa et al., 2020). Toxic elements, including PTEs such as As, Pb, Cr, Co, Cu, Ni, Cd etc. These elements are typically associated with pollution and potential toxicity or ecotoxicity, they are metallic elements that have densities higher than water and are found in the middle portion of the periodic table between Group 3 and 4.

In recent years, global attention has been intensified over the contamination of industrial wastewater and its significant impact on ecosystems and the environment. A large-scale survey conducted in 104 countries found that over one-quarter of river sites worldwide are contaminated with pollutants, endangering both human well-being and aquatic life (Wilkinson et al., 2022). Industrial effluents have a substantial adverse effect on the local marine ecosystem (Bashir et al., 2020). A recent analysis investigates the build-up of PTEs in common freshwater fish species (Pangas anodon hypophthalmus) and evaluates the potential health implications of long-term human exposure. Even though the detected heavy metal levels in the fish were sub-lethal, consistent intake over time can induce a wide spectrum of chronic conditions both carcinogenic and otherwise (Hasan et al., 2020).

Earlier research identifies pollutant-heavy discharges from industries as a growing source of heavy metals in Bangladesh’s groundwater, marking an emerging threat which impacts millions of lives (Kumar et al., 2020). When the concentration of these metals exceeds safe levels, it becomes harmful to the environment. Effluent discharge negatively affects the environment by impacting the physical, structural and chemical balance of water systems as well as the nearby soils. It also impacts soil morphology, causing significant harm to both biotic and abiotic components of the ecosystem (Wyszkowska et al., 2015; Bamidele, 2010). Once released into water bodies or the surrounding environment, heavy metals can accumulate, contaminating soil, water, and the food chain. They also degrade water quality and are highly toxic and persistent due to their resistance to degradation (Tchounwou et al., 2012). This situation has significant long-term risks to ecosystems as well as to human wellness (Münzel et al., 2022).

Across the vast majority of cities and industrial zones worldwide, people living near industries are increasingly exposed to the impacts of untreated or inadequately treated waste water (Kayode-Afolayan et al., 2022). When industrial effluents go untreated, they introduce persistent pollutants within the ecosystem and ultimately posing risks to human health. Medical and physiological effects of PTE exposure rely on the metal's properties, their concentrations, and the duration of exposure, making each scenario unique in its risk profile. However, metals like Copper (Cu), Zinc (Zn), and Iron (Fe) are essential for normal growth and development. Nonetheless, these vital metals are detrimental when they excessively contaminate the water. For example, excessive iron can corrode plumbing systems, stain clothing, and give water a metallic taste. High levels of zinc can impair aquatic organisms by blocking essential copper absorption; concurrently, an overabundance of copper intake in humans is linked to gastrointestinal issues and liver and renal damage. Extensive research has established that exposure to toxic metals and pharmaceutical contaminants can cause serious physiological and developmental issues—from DNA damage, oxidative stress, and reproductive dysfunction to behavioral alterations in wildlife and increased disease risk in humans (Walker et al., 2021; Ayilara et al., 2020).

The main concern with pharmaceuticals lies not in their immediate toxic effects but in their long-term toxicity. Additionally, the poisonous compounds cadmium, arsenic, nickel, chromium, lead, and zinc have been found to have elimination half-lives of several decades, which makes them extremely toxic because they can accumulate in body tissues and cause several diseases, like cancer, kidney damage, and neurological disorders (Water, Sanitation, Hygiene and Health (WSH), 2011). Pregnant women and children especially face heightened risks from exposure to heavy metals.

To assess contamination levels, several water quality indices have been developed, relying on the consistent monitoring of various river water quality parameters. A health risk assessment strategy helps identify potential health hazards to residents caused by contaminated drinking water. Understanding these risks is essential for developing long-term management strategies and guiding decision-makers on the most effective methods for pollution prevention. Ecological and pollution indices are valuable tools for delivering accurate environmental information to both authorities and the public, thereby enhancing awareness and promoting informed action. Comparing toxic elements to reference levels alone is insufficient for assessing health risks from contaminated water; health risk assessment models are needed to evaluate the implications of heavy metal exposure (Alidadi et al., 2019). Distinct from prior studies, the current research employs a multi-index framework alongside evaluations of cancer and non-cancer health risks for both adults and children, explicitly analyzing the impacts of water ingestion and skin exposure.

1.2 Aim of the Study

This study seeks to evaluate the degree of contamination in surface runoff waters sampled from rivers bodies near pharmaceutical industries in the Dhaka region of Narayanganj and Gazipur by measuring the concentrations of various heavy metals.

1.2 Objective of the Study

The objectives of the study are-

- evaluating the extent of pollution using multiple indices: Heavy Metal Evaluation Index (HEI), NPI, Degree of Contamination (Cd), Single Factor Pollution Index (Pi), Heavy Metal Pollution Index (HPI), Heavy Metal Toxicity Load (HMTL), Water Pollution Index (WPI).
- addressing the health risk assessment for both children and adults by assessing non-carcinogenic and carcinogenic exposures.

Chapter 2

Materials and methods

2.1 Site Selection and Sample Collection

Across the central part of Bangladesh, Gazipur and Narayanganj are two of the most intensely industrialized zones, home to textiles, dyeing, chemical, and pharmaceutical industries, among others, which makes them high-priority regions with unregulated industrial effluent discharge. Gazipur and Narayanganj both are experiencing rapid urbanization and industrial growth, making them relevant for understanding the pollution load of these environmental stress zones.

The industries majorly release their effluents directly or indirectly into the adjacent rivers, specifically the Turag and Shitalaksya which are two of the major rivers flowing through Gazipur and Narayanganj, respectively. Both are an integral part of the riverine network in the central region of Bangladesh, notably in Dhaka. These rivers are the key tributaries of the Dhaka watershed, where the Turag River originates from the Bangshi River, flowing through Gazipur district, while merging into the Buriganga River, whereas the Shitalakshya River, a distributary of the old Brahmaputra River, flows into the Meghna River system.

These areas are located in a region characterized by a humid tropical monsoon climate with significant seasonal fluctuations in temperature and precipitation, which poses a notable influence over the water quality of the rivers. During the monsoon season (June to early October) intense rainfall averages annually 2200 mm of which 80-90% rain occurs during this season which results in heavy surface runoff that causes the release of industrial effluents, domestic wastes and other contaminants directly into the adjacent water bodies leading to a surge in pollution load (Kabir et al., 2015). Alternatively, in the dry season (November to February) with temperatures hitting 10 to 20℃, there is a considerable decline in the river discharge, thereby limiting the self-purification capacity of the river and amplifying the concentration of pollution (Das et al., 2021).

Additionally, during the higher temperatures of pre-monsoon season (March to May) exceeding 30°C, the concentration of contaminants in the rivers increases due to increased evaporation rate and reduced flow rate of the rivers. Turag and Shitalaksya rivers are relied on by local communities for various day-to-day activities, agricultural purposes, and small-scale fisheries, eventually leading to broader socioeconomic consequences due to the degraded water quality in the rivers. Pollution has not only degraded water quality but also increased the risk of waterborne diseases, affecting overall public health (Rahman et al., 2020).

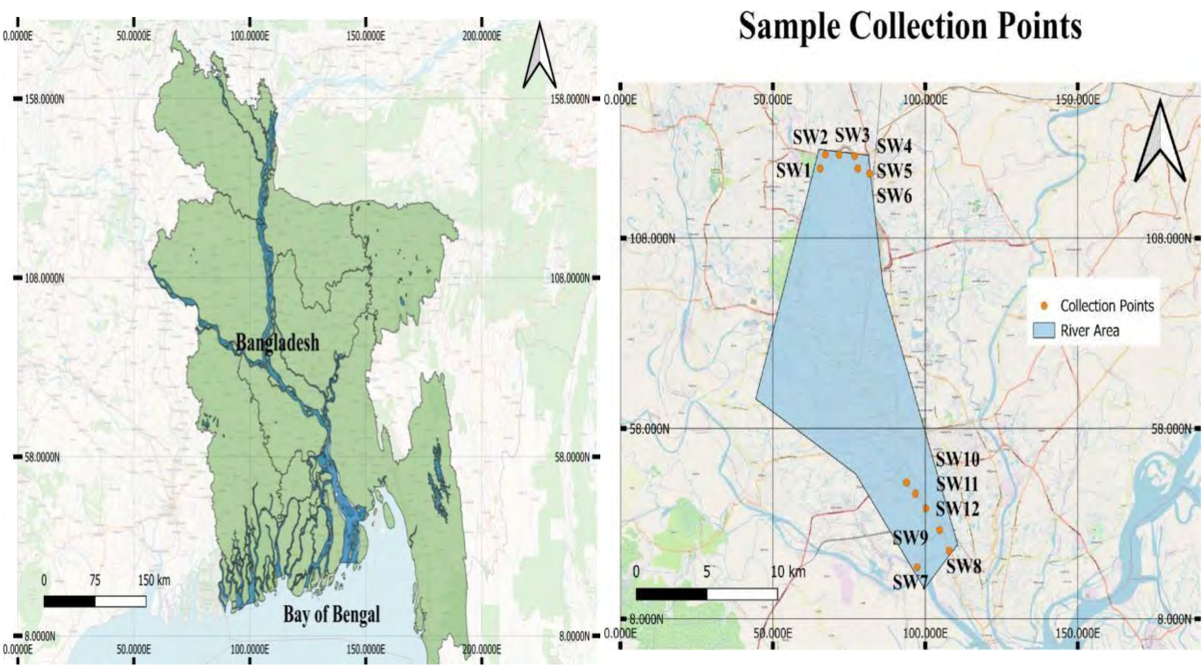


Figure 1: Location of the Study Area

Water samples were collected from 12 points of water bodies as shown in Figure 1 near the industrial zones in Tongi, Gazipur, and Narayanganj, namely the Turag River and Shitalaksya River, where the industrial effluents are released mainly. The duration of sample collection being from late November 2024 to early January 2025. The locations of sampling sites are shown in Figure 1. From each point of the study area, water sample was collected in one pair of bottles, the first point being at the closest proximity to the industries, and the rest of the points going further along towards the possible industrial discharge area in the river. To ensure accurate identification, the samples were promptly labeled with unique identifiers, including time, date, and GPS coordinates, after collection. They were sealed in airtight bags and stored at 2–3°C in a refrigerator before being submitted to the Bangladesh Council of Scientific and Industrial Research (BCSIR), where they were stored at 4–8°C.

2.2 Sample preparation

The preparation of the sample bottles involved a 24-hour immersion in a 10% nitric acid solution, followed by rinsing with laboratory-grade deionized water maintained at 10°C after the collection. In a fume room, 40 mL of water samples were dispensed into acid-washed, labeled 100 mL (PTFE) Teflon vessel. To each, 5 mL of concentrated Nitric acid (65%) and 2.5 mL of Hydrogen peroxide (30%) was added. After that, the vessels were placed into the microwave carousel for digestion. After digestion, Teflon vessels were cooled and allowed material that had been vaporized to settle. The digested samples were diluted to a final volume of 50 mL in a plastic centrifuge test-tube vial. The prepared final solution served as the basis for measuring heavy metals in the water samples implying ICP-MS/GFAAS. Trace metal quantification was carried out using inductively coupled plasma-mass spectrometry (ICP-MS; PerkinElmer, Model: NexION 2000; USA). The sample, was nebulized at a flow rate of approximately 0.85 mL/min, then injected into the Argon (Ar) plasma core within the ICP-MS system where trace metals were atomized and ionized. A quadrupole mass filter then identified individual ions by analyzing their mass-to-charge (m/z) ratios. To establish a ppb-level calibration curve, a ICP multi-element standard solution XIII (Merck, Germany) was utilized in the study.

Instrument performance was verified beforehand using PerkinElmer's NexION Setup solution (USA). A five-point curve spanning 1.0–100 ppb showed excellent linearity ($R^2 > 0.9995$). Instrument consistency was verified through at least three replicates, ensuring relative standard deviations remained within 5–8%. Detection limits (DL) were established at three times the background noise, and quantification limits (QL) at ten times the noise. The percentage recovery of target elements like As, Pb, Cr, Cu, Ni, Zn, Hg, Cd, Fe, Mn was evaluated using NIST's SRM 1643f trace elements in water reference material. The recovery rates of these elements ranged from 95.97% to 104.21% (Table 1). To reduce analytical error, the procedure included reagent blanks, filter blanks, spiked samples, and SRM recoveries; final metal concentrations were corrected using both blank data and recovery percentages.

Table 1: Concentrations of Standard Reference Material (SRM NIST 1643f: Trace Elements in Water), and recoveries for metals

Metal	Unit	Certified Mass Concentration Value	Recovery Range (%)
As	(µg/L)	57.42 ± 0.38	97.21-102.21
Cr	(µg/L)	18.50 ± 0.10	97.87-100.87
Cu	(µg/L)	21.66 ± 0.71	97.87-102.76
Pb	(µg/L)	18.488 ± 0.084	97.87-101.95
Ni	(µg/L)	59.8 ± 1.4	97.21-102.78
Zn	(µg/L)	74.4 ± 1.7	95.76-102.56
Cd	(µg/L)	5.89 ± 0.13	96.21-102.02
Fe	(µg/L)	93.44 ± 0.78	95.97-100.38
Mn	(µg/L)	37.14 ± 0.60	96.22-102.05

2.3 Single factor pollution index (Pi)

Using the single-factor index approach, the water integrity classification is based on the most critical pollutant, its measured concentration is evaluated relative to the WHO water quality standard, enabling the identification of key contaminants and their hazard levels in a specific water body (Wu et al., 2020). This method is particularly useful for pinpointing which single pollutant most significantly deviates from standard limits. To calculate the pollution index value, its observed concentration is divided by the allowable threshold defined by national or international water quality guidelines. The following Eq. (1) represents the single- factor pollution index.

$$Pi = \frac{Ci}{Si} \qquad (1)$$

Using the relationship above, P_i denotes the pollution index for a specific water quality parameter, C_i is the contaminant concentration (mg/L), and S_i is the guideline value (mg/L), the pollution status is classified into five categories: $P_i<1$ (Type I- unpolluted), 1-2 (Type II- slightly polluted), 2-3 (Type III- lightly polluted), 3-5 (Type IV- moderately polluted), and >5 (Type V- heavily polluted) (Wu et al., 2020).

2.4 Nemerow pollution index (NPI)

A weighted multi-parameter index, the Nemerow method accounts for overall average pollution as well as the maximum contaminant level detected. This approach provides a more comprehensive assessment of water quality by considering both typical and extreme pollutant concentrations (Li et al., 2022). The Eq. (2) expresses the Nemerow pollution index:

$$P_N = \sqrt{\frac{Pi^2 + Pimax^2}{2}} \qquad (2)$$

In the formula, the composite pollution level (PN) at a sampling point is calculated from the maximum (Pi_{max}) and average (Pi) single-factor indices. Interpreting PN yields these classifications: below 1 indicates standard water quality; 1–5 indicates slight contamination; 5–10 indicates moderate pollution; and values above 10 signal severe pollution. (Li et al., 2022).

2.5 Degree of contamination (Cd)

This method applies the contamination factor—determined by the ratio of each heavy metal concentration to their background level—and the degree of contamination, which sums all C_f values, to evaluate HM pollution in environmental water samples. This approach compares the concentration of each HM to a predefined standard or background value, offering a precise understanding of pollution severity (Li et al., 2014). This is expressed through the following equations:

$$Cd = \sum_{i=1}^{n} Cfi \quad (3)$$

$$Cfi = \frac{Mi}{Si} - 1 \quad (4)$$

The contamination factor for the i^{th} heavy metal is given above (Eq 4). Summing these yields the degree of contamination (C_d). Based on Hakanson's criteria, Contamination factor less than 1 indicates minimum contamination $C_d < 1$, C_d factor between 1 and 3 indicate moderate contamination, and $C_d > 3$ signifies high contamination (Li et al., 2014).

2.6 Heavy metal evaluation index (HEI)

HEI is a straightforward metric that gauges overall water quality by adding up each heavy metal's concentration relative to its regulatory threshold, reflecting their combined effects on human health and suitability for drinking water (Edet and Offiong, 2002). To derive the HEI, each heavy metal's concentration in the sample is expressed as a fraction of its corresponding maximum permissible value, and these values are summed, as shown in Eq. (5).

$$HEI = \sum_{i=1}^{n} \frac{Ci}{(MACi)} \quad (5)$$

In the HEI equation, n denotes the total metals analyzed; C_i and MAC_i are the measured concentration and regulatory limit for each metal. Based on HEI values, water quality is divided into low (<10), medium (10–20), and high (>20) contamination categories (Backman et al., 1998).

2.7 Heavy metal pollution index (HPI)

In this approach, overall water quality is assessed based on the presence of contaminated trace metals using the Heavy Metal Pollution Index (HPI). The process calculates HPI by combining weighted sub-indices for each metal (with weights between 0 and 1) using a formula involving both Q_i and W_i, as outlined in Equations (6) and (7) (Mohan et al., 1996).

$$HPI = \frac{\sum_{i=1}^{n} WiQi}{\sum_{i=1}^{n} WiQi} \quad (6)$$

$$Qi = \sum_{i=1}^{n} \frac{|Mi - Ii|}{Si - Ii} \times 100 \quad (7)$$

The variable n represents the total trace elements evaluated; W_i is the unit weight for i^{th} metal, typically calculated inverse to its maximum acceptable concentration, and is used to weight the contribution of each pollutant in the overall HPI (such as As= 0.0372, Pb= 0.0372, Cd= 0.0744, Cr= 0.0074, Ni= 0.0186, Cu= 0.0002, Zn= 0.0007, Hg= 0.3721, Fe= 0.0019, Mn= 0.0074), S_i is the maximum permissible limit of the i^{th} heavy metal, Q_i is the sub-index of the i^{th} metal, and I_i is the maximum desirable limit of the i^{th} metal. The resulting HPI then falls within five quality categories: excellent (<25), good (26--50), poor (51--75), very poor (76--100), and unsafe for drinking (>100) (Prasad and Bose, 2001).

2.8 Heavy metal toxicity load (HMTL)

This metric evaluates health-related metallic pollution levels in surface water and the treatment effort required to render it safe. Using Eq. 8, the concentration of each metal is multiplied by its ATSDR-assigned hazard score (HIS), with all results summed to yield the HMTL.

$$HMTL = \sum_{i=1}^{n} Mi \times HISi \quad (8)$$

Where Mi is the observed concentration of a heavy metal (mg/L), n is total count of trace metals, and HISi is the hazard intensity score of the trace metals. Such scores are: As=1675, Pb=1531, Cd=1317, Cr=892, Ni=994, Cu=807, Zn=916, Hg=1455, Fe= 0, Mn=799 (ATSDR, 2022). The Hazard Intensity Score integrates three components—exposure potential, chemical toxicity, and frequency of occurrence on the National Priorities List (NPL)—to gauge the relative health risk posed by a pollutant.

2.9 Water pollution index (WPI)

Introduced by Horton in 1965, the WPI serves as a tool for assessing, monitoring, and regulating water pollution, with its value computed using Equation (9) (Horton, 1965).

$$WPIi = \frac{(Mi - Mini)}{Ri} \tag{9}$$

The variables M_i, Min_i, and R_i define the metal's average concentration, minimum limit, and acceptable range respectively. Water quality categories according to WPI are: < 0.5 for excellent, 0.5--0.75 good, 0.75--1.0 fairly polluted, and > 1.0 indicating severe pollution and unsuitability for human consumption (WHO, 2017).

2.10 Health risk assessment

To estimate the health implications of groundwater metallic contamination, the study applied Health Risk Assessment (HRA) methods—including calculating hazard quotient (HQ), lifetime average daily dose (LADD), and relevant empirical indices— for both ingestion and dermal exposure pathways, assessing impacts on adults and children.

2.10.1 Non-Carcinogenic Health Risk

The non-carcinogenic risk assessment is conducted according to the methodology recommended by the United States Environmental Protection Agency (USEPA, 1989). Non-carcinogenic effects are evaluated using the hazard quotient (HQ), which quantifies the estimated exposure relative to a reference dose (R_fD). Exposure can proceed via two primary routes: oral intake and skin contact. The LADD through ingestion is calculated as:

$$LADD\ ingestion = \frac{C \times IR \times EF \times ED}{BW \times AT} \tag{10}$$

Where: C = Concentration of heavy metal (mg/L), IR = Ingestion rate (L/day), EF = Exposure Frequency (365 days/year), ED = Exposure Duration (6years for children, 30 years for adults), BW = Body Weight (16kg for children, 70kg for adults), AT = Averaging Time (ED × 365)

The LADD through dermal contact is calculated as:

$$LADD\ dermal = \frac{C \times ET \times EF \times Kp \times SA \times CF \times ED}{BW \times AT} \quad (11)$$

Where: ET = Exposure Time (1h/day for Children, 0.58h/day for Adults) Kp = Skin permeability coefficient (Cd = 0.001, Cr = 0.002, Cu = 0.001, Fe = 0.001, Mn = 0.001, Ni = 0.0002, Pb = 0.0001, Zn = 0.0006 cm/h), SA = Skin surface area exposed (600 cm^2 for children, 1800 cm^2 for adults), CF = Unit conversion factor (0.001 L/cm^3) Other variables are as previously defined.

The Non-carcinogenic Hazard Quotient (HQ) is then determined using:

$$HQ\ ingestion\ or\ dermal = \frac{LADD\ in\mathrm{Bestion}\ or\ LADD\ dermal}{RfD\ in\mathrm{Bestion}\ or\ RfD\ dermal} \quad (12)$$

Where R_fD is the reference dose for the respective metal (mg/kg-day).

$$NCR = \sum_{i=1}^{n} HQ\ ingestion\ or\ dermal \quad (13)$$

2.10.2 Carcinogenic health risk

For carcinogenic risks (CR), the lifetime probability of cancer development resulting from exposure to heavy metals can be estimated by Equation (14).

$$CR\ ingestion\ or\ dermal = LADD\ ingestion\ or\ dermal \times CSF \quad (14)$$

Where CSF is the cancer slope factor (mg/kg/day), specific to each heavy metal. CR values in the range of 10^{-6} to 10^{-4} are generally considered acceptable or tolerable (USEPA, 2000). The calculations were performed separately for oral intake and dermal pathways in Children and Adults, using corresponding physiological and exposure parameters. Reference values for R_fD and CSF are provided in Table 8.

Chapter 3

Results and Discussion

3.1. Quantitative Measurement

Findings indicate significant heavy metal pollution in the Turag (upstream) and Shitalakshya (downstream) rivers, both of which are heavily exposed to effluents from industrial zones in Gazipur and Narayanganj. Presented in Table 2 are the concentrations of heavy metals such as arsenic, lead, cadmium, chromium, nickel, copper, zinc, mercury, iron, and manganese in the water samples from different points. The measured values, expressed in parts per billion (ppb), are compared to the permissible limits set by the World Health Organization (WHO) in 2011.

Table 2: Observed Concentration Ranges of Heavy Metals Compared to Standard Permissible Limits (n = Number of Observations)

Analyzed heavy metals	Range of concentrations of measured HMs (in ppb)	Standard permissible limit (in ppb) (WHO, 2011)	The number of samples observed exceeding the WHO standard, n
As	2.46-10.45	10	1
Pb	5.68-449.57	10	10
Cd	0.05-2.56	3	0
Cr	4.19-41.13	50	0
Ni	6.71-32.2	70	0
Cu	8.09-140.80	2000	0
Zn	16.07-505.88	3000	0
Hg	0.53-33.70	6	6
Fe	214.4-2284.05	300	10
Mn	103.05-817.84	400	4

Analysis revealed that lead, mercury, and iron levels exceeded WHO (2011) drinking water standards in a significant proportion of the analyzed surface water samples. Pb was shown to be above permissible limits in 10 samples, Hg in 5 samples, and Fe in 10 samples among the 12 samples, underscoring their crucial influence on water pollution in the area. This finding aligns with the nationwide assessment of Bangladesh surface waters by Hossen and Mostafa (2023) on heavy metal pollution in various rivers, including Turag and Shitalakshya, which showed that Fe, and Pb were the most commonly exceeding metals, with them being the primary pollutants in the industrial river system.

Table 3: Results of different pollution indices (Pi, P1, Pimax, NPI, Cd, HEI, HPI, and HMTL) of samples collected from the Turag River (upstream) Shitalakshya River (downstream)

River	Sample No.	P_{As}	P_{Pb}	P_{Cd}	P_{Cr}	P_{ni}	P_{Cu}	P_{Zn}	P_{Hg}	P_{Fe}	P_{Mn}	P_1	P_{max}	NPI	Cd	HEI	HPI	HMTL
Up-stream	SW-1	0.39	2.47	0.17	0.35	0.23	0.01	0.03	1.45	3.17	2.04	1.03	3.17	2.36	0.31	10.3	122.91	853.4
	SW-2	0.27	1.74	0.12	0.23	0.18	0.01	0.04	0.47	3.16	0.78	0.70	3.16	2.28	-3.00	7.00	49.55	432.3
	SW-3	0.25	0.78	0.05	0.11	0.12	0.00	0.02	0.09	1.45	0.37	0.32	1/45	1.05	-6.77	3.23	14.81	223.0
	SW-4	0.74	44.9	0.85	0.82	0.46	0.01	0.17	2.20	7.61	1.18	5.90	44.9	32	49	59.0	470.48	1651.5
	SW-5	0.30	2.53	0.02	0.12	0.22	0.00	0.01	0.21	0.74	0.70	0.49	2.53	1.82	-5.15	4.85	35.49	328.6
	SW-6	0.50	1.76	0.02	0.13	0.20	0.01	0.01	0.21	0.71	0.26	0.38	1.76	1.27	-6.19	3.81	31.06	173.6
Mean		0.41	9.03	0.21	0.29	0.24	0.01	0.05	0.77	2.81	0.89			6.8	4.7	14.7	120.72	610.4
Down-stream	SW-7	1.04	2.87	0.11	0.32	0.2	0.04	0.01	4.51	2.10	0.74	1.19	4.51	3.29	1.94	11.94	331.41	456.09
	SW-8	0.68	1.79	0.13	0.15	0.16	0.03	0.01	1.84	1.48	0.61	0.69	1.84	1.39	-3.11	6.89	143.52	328.61
	SW-9	0.64	0.57	0.08	0.09	0.12	0.02	0.01	1.25	1.38	0.41	0.46	1.38	1.03	-5.43	4.57	94.47	228.07
	SW-10	0.62	1.69	0.4	0.21	0.29	0.07	0.04	5.62	3.29	1.18	1.34	5.62	4.09	3.42	13.4	399.98	716.52
	SW-11	0.86	1.2	0.43	0.19	0.16	0.03	0.05	0.97	4.23	1.37	0.95	4.23	3.07	-0.51	9.49	88.48	688.69
	SW-12	0.66	1.12	0.53	0.08	0.09	0.01	0.01	0.23	1.24	0.28	0.43	1.24	0.93	-5.73	4.27	35.85	187.88
Mean		0.75	1.54	0.28	0.17	0.17	0.03	0.02	2.40	2.29	0.77			2.3	-1.57	8.43	182.3	434.31

With regards to spatial patterns in pollution indices, these indices invariably suggested higher levels of contamination upstream rather than downstream, hence reflecting a higher pollution burden upstream. An analogous outcome was documented in a study examining heavy metal concentrations in the Turag River by Suchi et al (2024), where Turag River was reported to have a high contamination level with a similar spatial pollution gradient.

3.2. Single factor pollution index (Pi)

By applying Equation (1) to derive the Single Factor Pollution Index (Pi), the average levels in the upstream Turag River were determined: Arsenic (As) 0.41, Lead (Pb) 9.03, Cadmium (Cd) 0.21, Chromium (Cr) 0.29, Nickel (Ni) 0.24, Copper (Cu) 0.01, Zinc (Zn) 0.05, Mercury (Hg) 0.77, Iron (Fe) 2.81, and Manganese (Mn) 0.89. Water quality ratings classify mercury as slightly polluted, iron as lightly polluted, and lead as heavily polluted. P_i values for the remaining metals fall below 1, signifying no notable pollution from arsenic, cadmium, chromium, nickel, copper, and zinc.

Transitioning to the examined surface water of Downstream (Shitalakshya river), the mean concentrations of heavy metals exhibited a modest shift reflected in the following data: Arsenic (As) 0.75, Lead (Pb) 1.54, Cadmium (Cd) 0.28, Chromium (Cr) 0.17, Nickel (Ni) 0.17, Copper (Cu) 0.03, Zinc (Zn) 0.02, Mercury (Hg) 2.40, Iron (Fe) 2.29, and Manganese (Mn) 0.77, which under the water quality criteria, the downstream surface water is identified as slightly polluted with lead and exhibits marginally greater contamination levels for mercury and iron, while the P_i values of the rest heavy metals are below 1, suggesting they are within normal limits and therefore the surface water of downstream is unaffected by them.

3.3 Nemerow pollution index (NPI)

The computed NPI values for Upstream (Turag River) surface water using Eq. (2) spanned from 1.05 to 32.0, with a mean of 6.8. (shown in Table 3), which, according to the NPI classification, indicates that the surface water is moderately polluted.

On the contrary, the surface water from Downstream (Shitalakshya River) exhibits NPI values of between 0.93-4.09 with a mean of 2.3 (see Table 3), and according to the Nemerow index criteria, the surface water is lightly contaminated with heavy metals.

3.4 Degree of contamination (Cd)

The Degree of Contamination in surface water Upstream and Downstream was determined using the Equations (3,4). The Cd values for the Upstream (Turag River) range from -6.19 to 49 with a mean of 4.7 (Table 3), which indicates a high degree of contamination in this surface water. The numbers of samples are classified according to Edet et al. 2002, where 4 of them show a low degree of pollution, except for SW1 and SW4, which show moderate pollution and a high degree of pollution, respectively (Table 4).

Table 4: Assessing Upstream (Turag River) Water Quality Using a Pollution-Index Classification

Pollution assessment index	Classification Sources	Categories	Quality of the water samples	Number of Samples	Samples observed in each class
Cd	Edet et al. 2002	<1	Low	4	66.67%
		1-3	Moderate	1	16.67%
		>3	High	1	16.67%
HEI		<10	Low	4	66.67%
		10-20	Medium	1	16.67%
		>20	High	1	16.67%
HPI		<25	Excellent	1	16.67%
		26-50	Good Quality	3	33.33%
		51-75	Poor	0	0%
		76-100	Very poor	0	0%
		>100	Unconsumable	2	50%

The mean Cd estimate for the Downstream (Shitalakshya River) is -1.57, varying between a low of -5.73 to a high of 3.42 (refer to Table 4). All the samples within the research site are in the category of low pollution, except for samples 1 and 4, as indicated by calculated Cd values lower than 1. The sample waters 1 and 4 fall into the moderately and highly polluted categories, respectively, based on Edet et al. (2002). As per these categories, 66.67% of samples fall in low pollution, 16.67% in medium pollution, and 16.67% in high pollution (Table 5).

Table 5: Assessing Downstream (Shitalakshya River) Water Quality Using a Pollution-Index Classification

Pollution assessment index	Classification Sources	Categories	Quality of the water samples	Number of Samples	Samples observed in each class
Cd	Edet et al. 2002	<1	Low	4	66.67%
		1-3	Moderate	1	16.67%
		>3	High	1	16.67%
HEI		<10	Low	4	66.67%
		10-20	Medium	2	33.33%
		>20	High	0	0%
HPI		<25	Excellent	0	0%
		26-50	Good Quality	1	16.67%
		51-75	Poor	2	33.33%
		76-100	Very poor	1	16.67%
		>100	Unconsumable	2	33.33%

3.5 Heavy metal evaluation index (HEI)

Using equation (5), we calculated the Heavy Metal Index (HEI) for surface water from both the upstream and downstream sections. In the upstream segment of the Turag River, the HEI ranged from 3.23 to 59, averaging 14.7 (Table 3). The number of samples grouped under the categories according to Edet et al. 2002, where 4 samples, ie, 66.7% fall under low and 2 ie. 33.33% fall under the medium pollution class (Table 4).

For the Shitalakshya River (downstream), the calculated HEI for this region averaged 8.43, exhibiting a minimum of 4.27 and a maximum of 13.42 (Table 3). According to Edet et al.'s (2002) method, around 65.5 % of sampling points fell under the low pollution category, 34.5 % were considered moderately polluted, and notably, none of them were rated as high pollution (Table 5).

3.6 Heavy metal pollution index (HPI)

In the upstream segment of the Turag River, the Heavy Metal Pollution Index (HPI)— derived via Equations 6 and 7—averaged 120.717, spanning from a minimum of 14.8 to a maximum of 470.5 across sampled sites, as detailed in Table 3. Among these, 2 samples exceeded the threshold of 100, indicating the water is not suitable for consumption. Based on HPI categories, 16.67% fall within <25, 16.67% of samples fall within 26–50, showing good quality, while 0% indicate low pollution, 0% medium pollution, and 50% fall under high pollution (Table 4), suggesting that parts of the area are heavily polluted and unfit for use.

Equations (6) and (7) yielded HPI values downstream of the Shitalakshya River with an average of 100.22 (range: 49.71–179.63) (Table 3). Since two samples had HPI > 100—a threshold typically indicating unsuitability for consumption—those water samples are considered unsafe for drinking. According to the HPI categories, 16.67% of the samples are in the range of 26-50, indicating that these samples are in good quality. Of the total samples, 33.33% exhibited low pollution levels, 16.67% showed medium pollution, and 33.33% were classified under high pollution (Table 5), which reveals that the areas are highly polluted and not suitable for consumption.

3.7 Heavy metal toxicity load (HMTL)

To estimate the toxic heavy-metal load across the study region, HMTL values were derived for each sample in accordance with Equation 8. The Heavy Metal Toxicity Load (HMTL) of samples collected from the upstream Turag River ranges between 173.6 and 1651.5, with a mean value of 610.4 (Table 3). Two samples, SW1 and SW4, surpassed the risk threshold of 500, indicating elevated toxicity. The HMTL values across the sampling sites are ranked as follows: SW-4 > SW-1 > SW-2 > SW-5 > SW-3 > SW-6.

Correspondingly, the Heavy Metal Toxicity Load (HMTL) in the study area (Shitalakshya River) is from 187.88 and 716.52 and has a mean of HMTL 434.31 (Table 3). Two of the values, SW 10 and SW 11 are greater than 500. The results could point to possible hazards from ingestion for humans and adverse effects on the local ecosystem. HMTL order based on sampling stations is: SW-10 > SW-11 > SW- 7 > SW-8 > SW-9 > SW-12.

In brief, both upstream and downstream water samples recorded HPI scores above 100—the accepted boundary for safe heavy-metal levels—signifying that the water is unsafe for consumption. Furthermore, the HTML values suggested that the toxicity load of both rivers was elevated, with some of the sample points being identified as pollution hotspots. A parallel study was reported where the outcomes from Rahman et al. (2022) indicated high HPI, HEI, and Cd values in water sources neighboring ship-breaking sites. Though they are different water types, both studies align in their findings that industrial effluents can cause toxic heavy metal burdens that transform the water sources into unfit for consumption.

3.8 Water pollution index (WPI)

Water Pollution Index (WPI) of the study area water was assessed using equation (9). In the case of Upstream data (Table 6) the results indicate that most of the elements have WPI values below 0.5, reflecting insignificant pollution and safe concentration levels except for a few heavy metals like Manganese (Mn) and Mercury (Hg) that fall under the moderately polluted category, indicating elevated levels that may require monitoring. In contrast, lead (Pb) and Iron (Fe) are classified as highly polluted, suggesting serious contamination that could pose risks to both ecological and human health.

Table 6: Evaluation of the water quality in the Upstream section of Turag River using Water Pollution Index (WPI)

Heavy Metals	Mean, Mi(μg/L)	Range, Ri (μg/L)	WPI	Class
As	4.41	10	0.44	Not Polluted
Pb	90.37	10	9.04	Very Polluted
Cd	0.2	3	0.07	Not Polluted
Cr	15.09	50	0.30	Not Polluted
Ni	14.83	70	0.21	Not Polluted
Cu	14.52	2000	0.01	Not Polluted
Zn	144.13	3000	0.05	Not Polluted
Hg	4.47	6	0.05	Moderately Polluted
Fe	842.15	300	2.81	Very Polluted
Mn	354.13	400	0.89	Moderately Polluted

Conversely, the heavy metal pollution analysis of downstream water, as indicated by the Water Pollution Index (WPI), reveals that the concentrations of these metals are below 0.5, suggesting minimal contribution to overall pollution and concentrations were within safe limits (shown in Table 7).

Table 7: Evaluation of the water quality in the Downstream of Shitalakshya River using Water Pollution Index (WPI)

Heavy Metals	Mean, Mi (μg/L)	Range, Ri (μg/L)	WPI	Class
As	0.75	10	0.08	Not Polluted
Pb	1.54	10	0.15	Not Polluted
Cd	0.28	3	0.09	Not Polluted
Cr	0.17	50	0	Not Polluted
Ni	0.17	70	0	Not Polluted
Cu	0.03	2000	0	Not Polluted
Zn	0.02	3000	0	Not Polluted
Hg	2.40	6	0.4	Not Polluted
Fe	2.29	300	0.008	Not Polluted
Mn	0.77	400	0.002	Not Polluted

Accordingly, the water pollution index confirmed the contamination upstream, with Pb and Fe classified as “Very polluted” and Hg and Mn as “Moderately polluted”. However, the Downstream WPI values were subsequently below 0.5, implying no significant pollution. This indicates possible dilution or sedimentation, or in-situ natural treatment occurring between the two rivers, Turag (Up-stream) and Shitalaksya (Down-stream). Emphasizing the same conclusion, Rahman et al. (2014) reported high-level WPI values for Fe and Hg in the

Upstream and low WPI values in the Downstream. In both the Rupsha River (Islam & Mostafa, 2023) and the Pasur estuary (Haque et al., 2023), seasonal sampling revealed a downstream decrease in the Water Pollution Index (WPI) in estuarine mixing zones. These findings underscore the role of adequate hydrological flow in maintaining the presence of heavy metals in the environment.

3.9 Health Risk Assessment

Within specific zones of the study region, households utilize surface water from multiple water bodies for domestic purposes, which includes direct drinking, highlighting the reliance on available water sources despite potential quality concern. This generates potential health risks through ingestion and dermal contact as the primary avenues through which humans encounter pollutants are inhalation, ingestion, and dermal absorption, each presenting distinct health risks.

Table 8: Parameters utilized in calculating the Hazard Quotient (HQ) and Cancer Risk (CR)

Parameter	**As**	**Pb**	**Cd**	**Cr**	**Ni**	**Cu**	**Zn**	**Hg**	**Fe**	**Mn**	**References**
RfD Ingestion (mg/kg/day)	0.0003	0.0014	0.0005	0.003	0.02	0.04	0.3	0.0004	0.7	0.024	(Phillips & Moya, 2012)
RfD Dermal (mg/kg/day)	0.0001	0.3	0.000025	0.025	0.04	0.30	0.2	0.0001	0.2	0.400	(Document Display | NEPIS | US EPA, n.d.)
CSF Ingestion (mg/kg/day)	1.5	0.0085	6.1	0.5	Not Established	Not Established	Not Established	Not Established	Not Established	Not Established	U.S. EPA IRIS–EPA Cr(VI) U.S. EPA IRIS (1995) – EPA As CSF
CSF Dermal (mg/kg/day)	1.5	Not Carcinogenic	Not Carcinogenic	0.25	Not Carcinogenic	Not Carcinogenic	Not Carcinogenic	Not Carcinogenic	Not Carcinogenic	Not Carcinogenic	Ramos et al., 2016, Environment Research, DOI: 10.1016/j.envres.2016.01.002

3.9.1 Non-carcinogenic health risk

In evaluating non-carcinogenic risks among adults and children, the study considered heavy metals such as arsenic (As), lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), mercury (Hg), iron (Fe), and manganese (Mn). The data from various sampling stations in the study area, as detailed in Tables 9 and 10, highlight the hazardous conditions posed by these individual heavy metals. If the value of Hazard Quotient (HQ) is below 1 then it suggests that the exposure level is within safe limits; whereas an HQ above 1 signals a potential health risk (Li et al., 2018).

In order to estimate health risks via oral, the ingestion hazard quotient (HQ) was computed for both age groups by assessing the concentrations of heavy metals in the study area using equations (10,11,12,13). For the Turag River (upstream), the ingestion hazard quotient (HQ) for both adults and children is summarized in Table 9. In adults, the total HQ values spanned from 0.35 to 6.06, with an average value of 1.62, while in children, the range is notably higher 1.55 to 26.52, with a mean value of 7.10 (Figure 2: a). These outcomes demonstrate that children are at significantly greater risk from ingestion-related exposure to heavy metals.

To determine the possible health hazards associated with dermal exposure to heavy metal-contaminated water, the dermal Hazard Quotient (HQ) was calculated for both adults and children using equations (10,11,12,13). As presented in Table 9, the upstream data consists of the total dermal HQ values in adults ranging from 0.0014 to 0.0122, with a mean of 0.0044, while for children, the values range from 0.0006 to 0.0049, with a mean of 0.0018 (Figure 2: b). Similar to ingestion exposure, the results indicate that children are more vulnerable to dermal absorption of metals such as As, Pb, Cd, Cr, Ni, Cu, Zn, Hg, Fe, and Mn, compared to adults.

Table 9: HQ*i* for adults and children and HQtotal due to ingestion of HMs through drinking water at all the sampling locations of Turag River (Here A= Adult, C=Child)

No	HQ (As)		HQ (Pb)		HQ (Cd)		HQ (Cr)		HQ (Ni)		HQ (Cu)		HQ (Zn)		HQ (Hg)		HQ (Fe)		HQ (Mn)		∑HQ	
	A	C	A	C	A	C	A	C	A	C	A	C	A	C	A	C	A	C	A	C	A	C
1	0.0006	0.0015	0.00	0.00	0.0003	0.0008	0.00	0.0001	0.00	0.00	0.00	0.00	0.00	0.00	0.0013	0.0033	0.0001	0.0002	0.00	0.0001	0.0023	0.0058
2	0.0004	0.0010	0.00	0.00	0.0002	0.0006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0004	0.0011	0.0001	0.0002	0.00	0.00	0.0011	0.0029
3	0.0004	0.0009	0.00	0.00	0.0001	0.0002	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0001	0.0002	0.00	0.0001	0.00	0.00	0.0006	0.0014
4	0.0011	0.0028	0.00	0.00	0.0015	0.0038	0.00	0.0001	0.00	0.00	0.00	0.00	0.00	0.0001	0.0020	0.0050	0.0002	0.0004	0.00	0.00	0.0049	0.0122
5	0.0004	0.0011	0.00	0.00	0.00	0.0001	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0002	0.0005	0.00	0.00	0.00	0.00	0.0007	0.0018
6	0.0007	0.0019	0.0000	0.00	0.00	0.0001	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0002	0.0005	0.00	0.00	0.00	0.00	0.001	0.0025
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.01
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01

(Li et al., 2018b) — Unacceptable (orange) — Acceptable (green)

In the case of the Shitalakshya River (Downstream), for adults and children, the ingestion hazard quotient (HQ) is presented in Table 10. The total HQ of ingestion varies from 0.63-2.13 with a mean of 1.33 in adults and for children, the HQ values are higher, ranging from 2.76 to 9.31, and averaging at 5.81 (Figure 2: c). Based on these HQ values of ingestion, children are more at risk to their health due to exposure to As, Pb, Cd, Cr, Ni, Cu, Zn, Hg, Fe, and Mn through ingestion compared to adults.

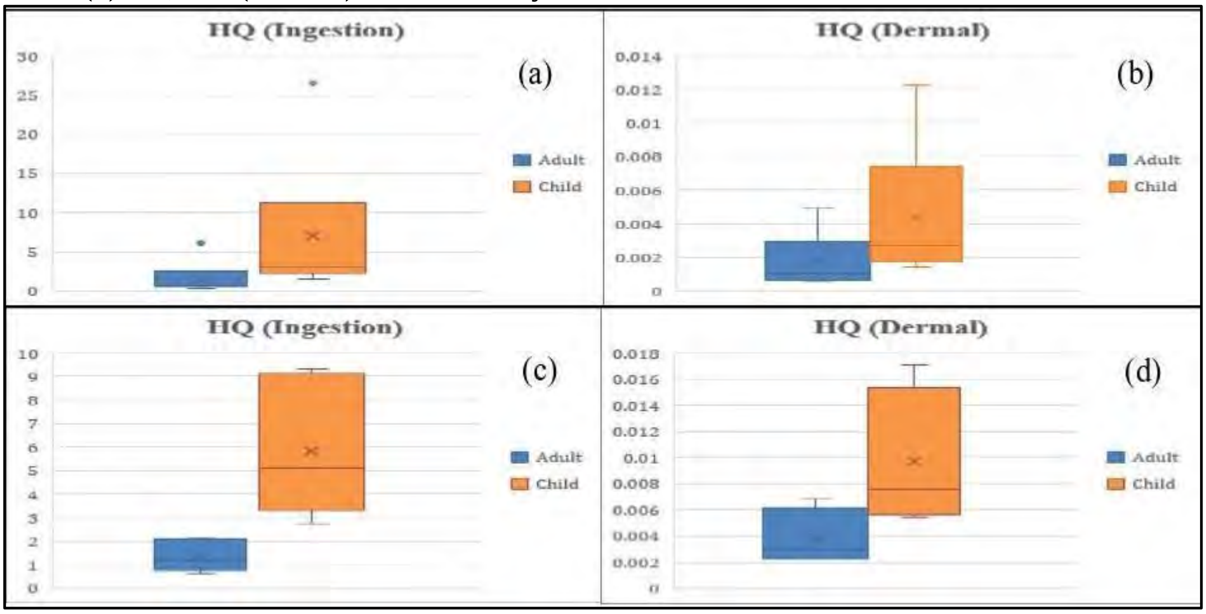
For adults and children, the Downstream dermal hazard quotient data is presented in Table 10. The total HQ dermal concentrations in children range between 0.005 to 0.017 with a mean of 0.0097, and in adults, they range between 0.0021 to 0.0068 with a mean of 0.0039 (Figure 2: d). Based on HQ dermal values, the health risk of the heavy metal exposure through dermal contact is, in general, higher in children compared to adults. All heavy metals have HQ dermal values below 1, indicating low non-carcinogenic risk.

Table 10: HQi for adults and children and HQtotal due to absorption by the skin at all the sampling locations of Shitalakshya River (Here A= Adult, C=Child)

No	HQ (As)		HQ (Pb)		HQ (Cd)		HQ (Cr)		HQ (Ni)		HQ (Cu)		HQ (Zn)		HQ (Hg)		HQ (Fe)		HQ (Mn)		∑HQ	
	A	C	A	C	A	C	A	C	A	C	A	C	A	C	A	C	A	C	A	C	A	C
1	0.19	0.81	0.25	1.10	0.01	0.06	0.08	0.37	0.01	0.05	0.01	0.03	0.00	0.02	0.31	1.35	0.02	0.08	0.49	2.13	1.38	6.02
2	0.13	0.56	0.18	0.78	0.01	0.05	0.06	0.24	0.01	0.04	0.01	0.02	0.01	0.03	0.10	0.44	0.02	0.08	0.19	0.82	0.70	3.06
3	0.12	0.51	0.08	0.35	0.00	0.02	0.03	0.12	0.01	0.03	0.00	0.01	0.00	0.02	0.02	0.08	0.01	0.04	0.09	0.38	0.35	1.55
4	0.35	1.54	4.59	20.1	0.07	0.32	0.20	0.86	0.02	0.10	0.01	0.04	0.02	0.11	0.47	2.07	0.05	0.20	0.28	1.22	6.06	26.52
5	0.14	0.62	0.26	1.13	0.00	0.01	0.03	0.13	0.01	0.05	0.00	0.01	0.00	0.01	0.05	0.20	0.00	0.02	0.17	0.73	0.66	2.90
6	0.24	1.05	0.18	0.79	0.00	0.01	0.03	0.13	0.01	0.04	0.00	0.02	0.00	0.01	0.05	0.20	0.00	0.02	0.06	0.27	0.58	2.53
7	0.49	2.18	0.29	1.28	0.01	0.04	0.08	0.33	0.01	0.04	0.03	0.12	0.00	0.01	0.97	4.22	0.01	0.06	0.18	0.77	2.07	9.05
8	0.33	1.42	0.18	0.79	0.01	0.05	0.04	0.16	0.01	0.04	0.02	0.09	0.00	0.00	0.39	1.73	0.01	0.04	0.15	0.64	1.13	4.96
9	0.30	1.33	0.06	0.25	0.01	0.03	0.02	0.09	0.01	0.03	0.02	0.07	0.00	0.00	0.27	1.18	0.01	0.04	0.09	0.43	0.79	3.46
10	0.29	1.29	0.17	0.76	0.03	0.15	0.05	0.22	0.01	0.06	0.05	0.22	0.01	0.02	1.20	5.27	0.02	0.09	0.28	1.23	2.13	9.31
11	0.41	1.79	0.12	0.54	0.04	0.16	0.04	0.19	0.01	0.03	0.02	0.09	0.01	0.03	0.21	0.91	0.03	0.11	0.33	1.42	1.21	5.29
12	0.31	1.37	0.11	0.50	0.05	0.19	0.02	0.09	0.00	0.02	0.01	0.04	0.00	0.01	0.05	0.22	0.01	0.03	0.07	0.29	0.63	2.76
Li et al., 2018b)							Unacceptable										Acceptable					

It can be asserted that through oral exposure, As, Pb, Hg, and Mn are the largest contributors to health risks among adults and children. Children exhibit a higher vulnerability to heavy metals through ingestion of contaminated surface water compared to dermal exposure. Additionally, there is less risk for adults in case of skin contact.

Figure 2: Differences in Non-Carcinogenic Health Risk metrics; (a) HQtotal (Ingestion) of Turag River, (b) HQtotal (Dermal) of Turag River, (c) HQtotal (Ingestion) of Shitalakshya River, (d) HQtotal (Dermal) of Shitalakshya River for various HMs



In short, the non-carcinogenic health risk analysis showed children experience greater risk compared to adults, particularly by ingestion, which is reflected as the dominant exposure route, unlike dermal, which suggested a low non-carcinogenic risk. An analogous study was carried out in India by Naqash et al. (2023), where it was reported that in the health risk assessment, ingestion dominated the risk compared to dermal exposure, which showed minimal threat, even though the study's HQ values were considerably higher, hence indicating significantly greater local exposure. In carcinogenic risk analysis, children exhibited notably higher values compared to adults; however, none of these values surpassed the acceptable limit. Nonetheless, prolonged exposure to these levels suggests a potential risk of developing cancer over a lifetime. For instance, a study in northeast Iran found that the average total carcinogenic risk (TCR) for children was 1.33×10^{-4}, exceeding the U.S. EPA's safety threshold of 1.0×10^{-4} (Alidadi et al., 2019). Similarly, research in Jigjiga City, Ethiopia, reported that children had higher incremental lifetime cancer risk (ILCR) values for heavy metals like cadmium, indicating a greater susceptibility compared to adults (Belew et al., 2024).

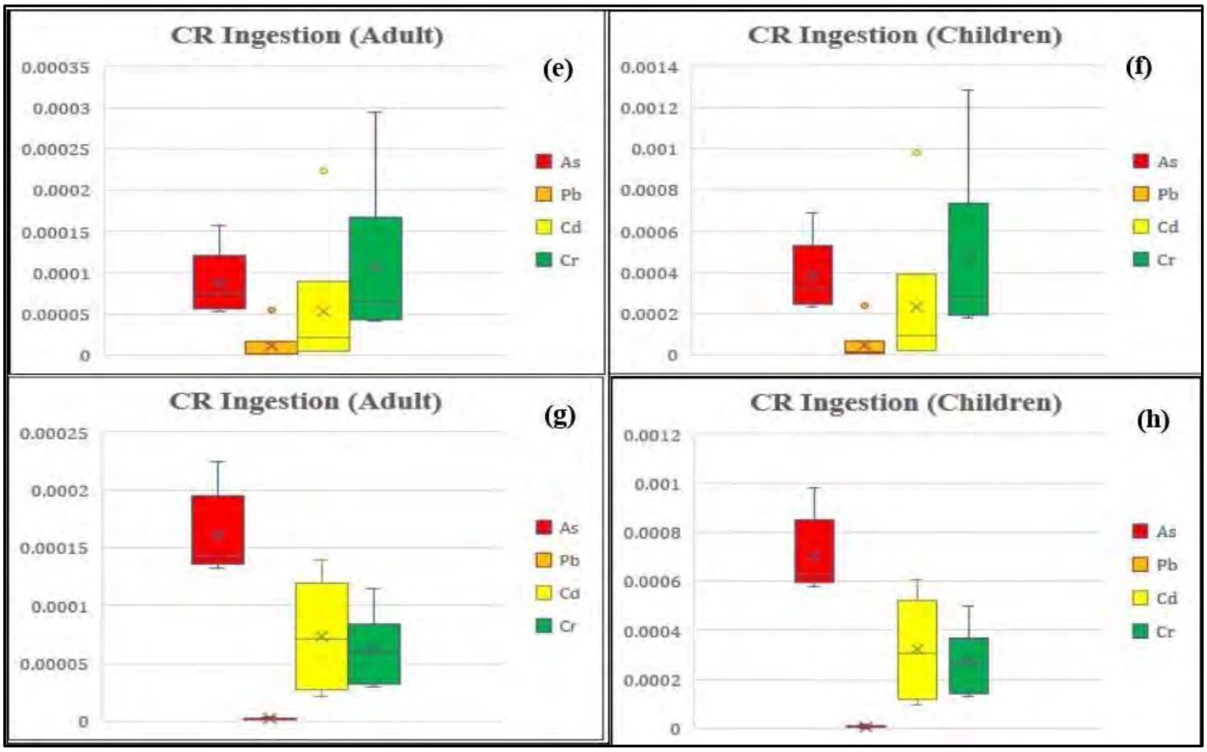
3.9.2 Carcinogenic health risk

Carcinogenic risk was calculated for the intake of heavy metals via contaminated water, based on exposure dose and cancer slope factors to assess potential cancer- related health effects. Carcinogenic risk assessments express the likelihood of cancer from long-term exposure to a contaminant or several contaminants.

Carcinogenic risks from ingestion exposure were assessed for both adults and children in water samples from the Upstream (Turag River), focusing on heavy metals including As, Pb, Cd, and Cr. For children, the ingestion CR for the heavy metals ranged from, As-0.00023 to 0.00069, Pb-0.00000 to 0.00024, Cd-0.00002 to 0.00098, Cr-0.00018 to 0.00129 (Figure 3: f). For adults, CR ingestion values were significantly lower: As: 0.00005 to 0.00016, Pb: 0.00000 to 0.00005, Cd: 0.00000 to 0.00022, Cr: 0.00004 to 0.00029 (Figure: e).

From Downstream (Shitalakshya river) the ingestion carcinogenic risk (CR), of adults for arsenic (As) ranged from 0.00013 to 0.00022, CR values of lead (Pb) were from 6.9×10^{-7} to 3.42×10^{-6}, Cd ingestion carcinogenic risk (CR) ranged from 0.00 to 0.00014, Cr CR values ranged from 0.00 to 0.00014 (Figure 3: g). For children, CR ingestion ranged from 0.00058 to 0.00098, 3.02×10^{-6} to 1.52×10^{-5}, 0.00 to 0.00061, 0.00013 to 0.00049 for As, Pb, Cd, and Cr, respectively (Figure 3:h).

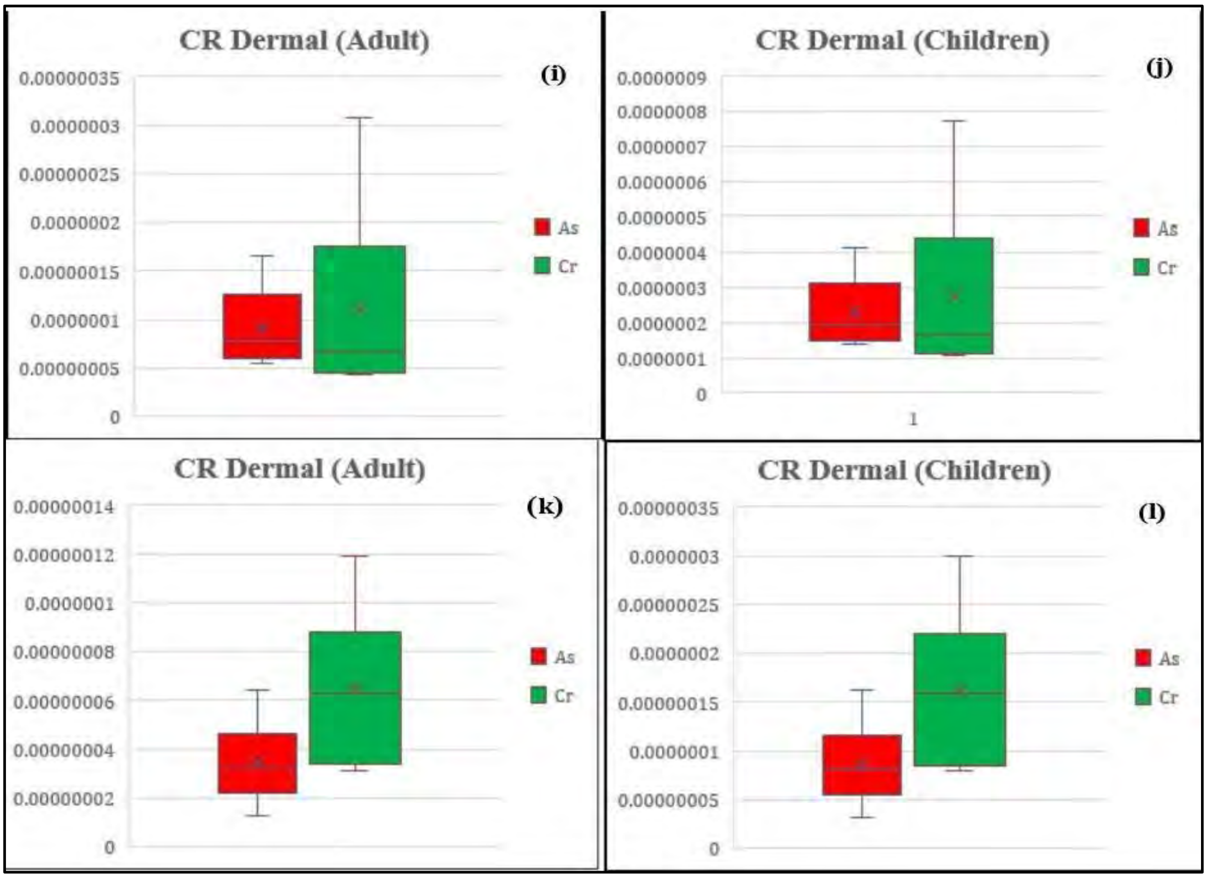
Figure 3: Variation of the Carcinogenic Health Risk Assessment; (e) CR Ingestion (Adult) of the Turag River (f) CR Ingestion (Children) of the Turag River (g) CR Ingestion (Adult) of the Shitalakshya River and (h) CR Ingestion (Children) of the Shitalakshya River for various HMs



To evaluate cancer risks through skin contact with contaminated water, dermal carcinogenic risks (CR dermal) were determined for both adults and children using equation (14). The analysis focused on Arsenic (As) and Chromium (Cr), as all other assessed metals (Pb, Cd, Ni, Cu, Zn, Hg, Fe, Mn) showed zero carcinogenic potential through dermal exposure. In the Upstream region of the Turag River, among children, CR dermal values for arsenic ranged from 1.0×10^{-7} to 4.0×10^{-7}, while Cr ranged from 1.0×10^{-7} to 8.0×10^{-7} (Figure 4:j). For adults, arsenic values ranged from 6.0×10^{-8} to 2.0×10^{-7}, and Cr from 4.0×10^{-8} to 3.0×10^{-7} (Figure 4:i).

Consequently, in the Downstream region of the Shitalakshya river for adults, the dermal CRs ranged from 1.3×10^{-8} to 6.42×10^{-8} for As and, 1.19×10^{-7} to 7.72×10^{-8} for Cr (Figure 4:k). For children, the CR dermal values ranged from 1.01×10^{-7} to 9.54×10^{-8} for As, and 1.41×10^{-7} to 8.59×10^{-8} for Cr (Figure 4:l).

Figure 4: Variation of the Carcinogenic Health Risk Assessment; (i) CR Dermal (Adult) of the Turag River (j) CR Dermal (Children) of the Turag River (k) CR Dermal (Adult) of the Shitalakshya River and (l) CR Dermal (Children) of the Shitalakshya River for various HMs



Of note, higher carcinogenic risk estimates in children compared to adults are primarily due to their higher per-unit-body-weight ingestion of contaminated food and water (Alidadi et al., 2019b). Wei et al. (2021) cites that the ongoing development of their immune and neurological systems, as well as their inner and outer tissues, renders them vulnerable to both carcinogenic and non-carcinogenic conditions brought about by heavy metals (Wani et al., 2015).

This study presents a comprehensive and site-specific estimation of heavy metal pollution in the surface water of Turag (Upstream) and Shitalakshya (Downstream) rivers, differentiating itself by using a combination of pollution assessment indices (HPI, HEI, NPI, Cd, Pi, HMTL, and WPI) along with Health risk assessment (non- carcinogenic and carcinogenic) for both adults and children via two routes of exposure (ingestion and dermal). Distinct from many other studies, this study incorporates multimetric evaluations to reflect the overall intensity and severity of pollution. Furthermore, by cross-analyzing two hydrologically connected yet industrially contrasting locations, Upstream (Turag) and Downstream (Shitalakshya), the current study offers spatial insight into pollution dynamics. Additionally, the bilateral way of health risk assessment improves the understanding of the impact on public health, particularly in high-risk children's populations. The inclusion of real-time sampling and WHO guideline values assures both applicability and importance of policy making. These findings highlight the urgent need for reinforced policies for more rigorous wastewater discharge control and frequent monitoring of surface water bodies in industrialized urban areas of Bangladesh.

Chapter 4

Conclusion

The comprehensive analysis of heavy metal contamination in the Narayanganj and Gazipur areas indicates a serious environmental concern that impacts public health directly. To analyze ten heavy metals in 23 surface water samples via ICP-MS, a standardized internal standard blend—including 45Sc, 73Ge, 89Y, 115In, 185Re, 193Ir, and 209Bi was accurately added beforehand to mitigate instrumental drift, matrix effects, and inconsistencies in sample delivery. Additionally, various quality control measures, including testing reagent and filter blanks, evaluating spike recoveries, and verifying SRM recoveries were conducted to ensure accuracy and precision while minimizing analytical errors. All experimental glassware was meticulously cleaned with high-grade acid and thoroughly rinsed with ultra-pure water to eliminate potential contaminants prior to use.

Analysis of the concentration indicates that arsenic, cadmium, lead, mercury, nickel, and chromium levels in the samples were found to surpass internationally recognized regulatory thresholds. These, if not checked, can be harmful to our ecosystem. In addition, this can cause harm to living organisms, such as microorganisms in the soil and crops sown on such soil or microorganisms that grow using the effluents as a source of irrigation. This may further have harmful health impacts on the people consuming such crops.

Elements like As, Pb, Cd, Hg, and Cr are classified as carcinogenic, capable of inducing oxidative stress and impairing cellular processes that lead to cancer. Pb exposure chronically is known to result in nervous system damage, such as cognitive function impairment, particularly in children. Arsenic exposure is associated with basal cell and squamous cell carcinoma due to hyperkeratosis. Cases of "Blackfoot disease" accompanied by gangrene of limbs have been found to follow polluted drinking water in Taiwan. Lung and bladder cancers have also been found following exposure to inorganic arsenic (Kuivenhoven & Mason, 2023). Cd is deposited in the kidneys and results in renal impairment and osteoporosis (Satarug, 2024), while Cr exposure has been linked to lung cancer and gastrointestinal irritation (Shin et al., 2023). The excessive level of Pb in surface water bodies is highly toxic to the growth of children, leading to behavioral issues, learning disabilities, and low IQ (*Basic Information About Lead in Drinking Water | US EPA*, 2025). With chronic inhalation, elemental mercury vapor and short-chain alkyl mercury compounds rapidly infiltrate the CNS and inhibits synaptic and neuromuscular function by binding to essential proteins and enzymes—a blockage that ultimately provokes neurodegenerative outcomes. Besides, mercury's passage through the placenta can harm fetal brain development, contributing to lower IQ, motor difficulties, and neurodevelopmental disorders. Due to exposure to Mn and Hg, it is claimed that life in the womb is more vulnerable than life in adulthood (Wu et al., 2024). Manganese (Mn), though a trace element, is neurotoxic in high concentrations, thus presenting a very high risk for memory loss as well as motor dysfunction (Peres et al., 2016). Nickel (Ni) and cadmium (Cd) toxicity cause liver and kidney dysfunction (Apiamu et al., 2023), and overload of iron (Fe) and zinc (Zn) may cause oxidative stress and metabolic disorder. Chronic intake of Fe-contaminated water has been associated with hemochromatosis, causing liver cirrhosis and cardiovascular disease (Porter & Rawla, 2024). Cu and Zn, though needed in small amounts, also turn toxic at excessive concentrations through immunosuppression and endocrine disruption leading to increased vulnerability to infection, thyroid dysfunction, and metabolic impairment (Liu et al., 2023).

The outcomes serve as a clear call to action for regulatory bodies, industrial stakeholders, and nearby populations to curb water pollution and its widespread health impacts. Remediation efforts need to be implemented. The sources of heavy metals within water and sediments must be continuously identified to assess the effectiveness of remediation interventions. People living in the areas should be involved in the planning and implementation of the remediation work. Education programs should be held periodically to teach the public about the risks of heavy metal contamination and prevention. For purposes of regulation, adherence to the guidelines should be observed. The interventions would aim to enhance the quality of the environment, protect public health, and promote sustainable practices in such areas. Sustainable water resource management is not just vital to the well-being of current populations but also essential to ensuring the region's future ecological and socio-economic environment.

4.1 Limitation of the Study

While the study provided valuable insights into surface water contamination near pharmaceutical industrial zones, several limitations should be acknowledged. First, the sampling was limited to two river systems (Turag and Shitalakshya) and a specific timeframe, potentially excluding seasonal variations that could influence pollutant concentrations. Second, the study analyzed only on ten heavy metals, excluding other relevant contaminants such as organic pollutants, pharmaceutical residues, and microbiological indicators, which may also pose significant health risks. Third, while health risk assessments were conducted for ingestion and dermal exposure, they relied on standard assumptions and did not incorporate site-specific exposure behavior or dietary intake patterns of local populations. Moreover, the study did not assess how heavy metals accumulate in aquatic organisms or sediments, which could provide a more comprehensive understanding of ecological risks.

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