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Comprehensive Analysis Of Heavy Metal Contamination In Groundwater: A Case Study Of Muzaffarnagar And Shamli Districts, Uttar Pradesh, India

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Abstract: Heavy metal contamination in groundwater represents a critical environmental and public health challenge globally. This study assessed the concentrations and spatial distribution of four priority heavy metals—Nickel (Ni), Arsenic (As), Mercury (Hg), and Uranium (U)—in water sources across Muzaffarnagar and Shamli districts of western Uttar Pradesh, India. Water samples were collected from diverse sources including residential borewells, hand pumps in agricultural areas, and surface water bodies during 2025-26. Physicochemical parameters (pH, hardness, dissolved organic carbon, chemical oxygen demand) and heavy metal concentrations were analyzed using standardized methods including EDTA titration, UV-persulfate oxidation, and atomic absorption spectroscopy. Results revealed that Nickel concentrations ranged from 0.12 to 0.35 mg/L (50% exceeding WHO limit of 0.07 mg/L), Arsenic from 0.005 to 0.030 mg/L (75% exceeding 0.01 mg/L limit), Mercury from 0.003 to 0.007 mg/L, and Uranium from 0.01 to 0.05 mg/L (50% exceeding 0.03 mg/L limit). Surface water and urban groundwater showed the highest contamination levels. The findings indicate significant anthropogenic influence from industrial effluents, agricultural runoff, and domestic sewage, compounded by natural geogenic sources. Statistical analysis revealed moderate correlations between metals, suggesting common mobilization mechanisms. This study provides critical baseline data for water resource management and highlights the urgent need for monitoring, treatment infrastructure, and public health interventions in the study region.

Keywords: Heavy metals, Groundwater contamination, Arsenic, Nickel, Uranium, Mercury, Muzaffarnagar, Shamli, Water quality, Public health

I. INTRODUCTION

A. Background

Water is fundamental to life, yet freshwater scarcity and quality degradation pose mounting global challenges. While water covers 71% of Earth's surface, only 2.5% is freshwater, with less than 1% readily accessible for human use (Gleick, 2014). Rapid population growth, urbanization, and industrialization have intensified both water demand and contamination, particularly in developing nations where regulatory frameworks and treatment infrastructure remain inadequate (UNESCO, 2019).

Heavy metals—metallic elements with high atomic weights (>5 g/cm³)—are of particular concern due to their persistence, non-biodegradability, and propensity for bioaccumulation (Tchounwou et al., 2012). Unlike organic pollutants that undergo microbial degradation, heavy metals accumulate in sediments and biological tissues, posing long-term ecological and human health risks (Ali & Khan, 2018). Common heavy metals in aquatic systems include nickel (Ni), arsenic (As), mercury (Hg), lead (Pb), cadmium (Cd), chromium (Cr), and uranium (U).

B. Heavy Metal Contamination Sources

Heavy metals enter aquatic environments through both natural geogenic processes and anthropogenic activities. Natural sources include weathering and erosion of rocks, volcanic activity, and leaching from mineral deposits (Smedley & Kinniburgh, 2002). However, human activities have dramatically increased heavy metal concentrations beyond natural background levels (Nriagu, 1996).

Figure 1 – Schematic representation of heavy metal contamination pathways into groundwater and surface water in the Muzaffarnagar and Shamli study area.

Industrial effluents from electroplating, battery manufacturing, tanneries, and chemical industries release Ni, Cr, Hg, Pb, and Cd into water bodies (Järup, 2003). Mining operations expose buried geological materials, producing acid mine drainage laden with dissolved metals (Johnson & Hallberg, 2005). Agricultural runoff carries metals from fertilizers, pesticides, and livestock feed additives (Wuana & Okieimen, 2011). Coal combustion releases mercury and arsenic through atmospheric deposition (Pacyna et al., 2010). Improper waste disposal, particularly electronic waste, introduces multiple heavy metals into groundwater through leachate formation (Robinson, 2009).

C. Health And Environmental Impacts

Heavy metal exposure occurs primarily through drinking water consumption, contaminated food intake, and dermal contact (Chowdhury et al., 2016). Health impacts vary by metal type, concentration, exposure duration, and individual susceptibility. Arsenic exposure causes skin lesions, cardiovascular diseases, diabetes, and cancers (Naujokas et al., 2013). Mercury, especially methylmercury, severely impacts the nervous system, causing cognitive deficits and developmental disorders (Karagas et al., 2012). Lead affects neurological development in children and cardiovascular function in adults (Lanphear et al., 2005). Nickel causes dermatitis, respiratory problems, and potential carcinogenic effects (Das et al., 2008). Uranium primarily affects kidney function through chemical toxicity (Zamora et al., 2009).

D. Study Area Context

Western Uttar Pradesh, part of the Indo-Gangetic alluvial plain, faces significant groundwater quality challenges. The region's unconsolidated alluvial aquifers are vulnerable to contamination from intensive agriculture, industrial activities, and inadequate wastewater treatment (CGWB, 2017). Muzaffarnagar and Shamli districts, characterized by sugarcane cultivation, sugar mills, distilleries, and metal industries, represent typical semi-urban regions experiencing rapid environmental changes.
Previous studies have documented sporadic arsenic contamination in eastern Uttar Pradesh (Chakraborti et al., 2018), but comprehensive multi-metal assessments in western districts remain limited. This study addresses this knowledge gap by evaluating Ni, As, Hg, and U concentrations alongside physicochemical parameters influencing metal mobility.

Figure 2 – Schematic map of the study area showing Muzaffarnagar and Shamli districts and the four sampling locations (S1–S4) along the Hindon River basin, western Uttar Pradesh

E. Research Objectives

This study aimed to:
1. Assess concentrations of Ni, As, Hg, and U in water sources across Muzaffarnagar and Shamli districts
2. Evaluate physicochemical parameters (pH, hardness, DOC, COD) influencing metal behavior
3. Compare observed levels with BIS and WHO drinking water standards
4. Identify spatial distribution patterns and potential contamination sources
5. Assess potential environmental and human health risks
6. Provide recommendations for water quality management

II. MATERIALS AND METHODS

A. Study Area

Muzaffarnagar (29.47°–29.76°N, 77.7°–77.97°E) and Shamli (29.45°–29.80°N, 77.10°–77.40°E) districts lie in the Hindon River basin within the Indo-Gangetic floodplain. The region experiences a semi-arid subtropical climate with 600-1000 mm annual rainfall concentrated during monsoon months (July–September). The hydrogeology consists of unconsolidated alluvium—alternating layers of sand, silt, and clay deposited by the Ganga and tributaries—forming a multi-layered aquifer system.

Shallow unconfined aquifers (0–50 m depth) are highly vulnerable to surface contamination, while semi-confined deeper aquifers (50–150 m) offer partial protection but may contain naturally elevated arsenic and uranium due to reducing geochemical conditions. Groundwater flow is generally southeastward, influenced by rainfall infiltration, canal seepage, and irrigation return flow.

B. Sampling Strategy

WATER SAMPLES WERE COLLECTED FROM FOUR STRATEGICALLY SELECTED LOCATIONS REPRESENTING DIVERSE LAND-USE PATTERNS:

- S1: Residential borewell, Muzaffarnagar (deep aquifer, domestic use)
- S2: Hand pump in agricultural area, Muzaffarnagar (shallow groundwater, agricultural influence)
- S3: Hand pump near residential area, Shamli (urban-peripheral domestic water)
- S4: Pond/reservoir, Shamli (surface water, runoff influence)

Sampling was conducted during the pre-monsoon season (dry period) when contaminant concentrations are typically elevated due to reduced dilution. Pre-cleaned high-density polyethylene (HDPE) bottles were used following rigorous acid-washing protocols. Field parameters (pH, temperature, electrical conductivity, dissolved oxygen) were measured in situ using calibrated portable instruments. Samples for heavy metal analysis were acidified to pH <2 with ultrapure nitric acid and stored at 4°C until analysis.

C. Physicochemical Analysis

pH: Measured using a calibrated pH meter (accuracy ±0.01 units).
Total Hardness: Determined by EDTA titration method. 50 mL sample was titrated with 0.01 M EDTA using Eriochrome Black T indicator. Color change from wine-red to blue indicated the endpoint. Results expressed as mg/L CaCO.
Dissolved Organic Carbon (DOC): Samples were filtered (0.45 μm), treated with persulfate oxidizing agent, and exposed to UV light. Organic carbon was converted to CO and quantified spectrophotometrically. Results expressed as mg/L.

Chemical Oxygen Demand (COD): Determined by closed reflux dichromate method. Sample (20–50 mL) was mixed with potassium dichromate and sulfuric acid, with silver sulfate (catalyst) and mercury sulfate (chloride interference eliminator). The mixture was refluxed at 150°C for 2 hours. Remaining dichromate was measured by back-titration with ferrous ammonium sulfate using ferroin indicator. Results expressed as mg Om/L.

D. Heavy Metal Analysis

Nickel (Ni): Analyzed by Atomic Absorption Spectrophotometry (AAS) at 232 nm wavelength following acid digestion with HNO3-HCl mixture (aqua regia). Standards: 0.05, 0.1, 0.5, 1.0 mg/L.
Mercury (Hg): Determined by Cold Vapor AAS at 253.7 nm. Mercury was reduced with SnCl2 to elementalmercury, which was then volatilized and measured.

Arsenic (As) and Uranium (U): Analyzed by AAS or Inductively Coupled Plasma Mass Spectrometry (ICP-MS) following appropriate sample preparation. Standards ranged from 0.05–1.0 mg/L.

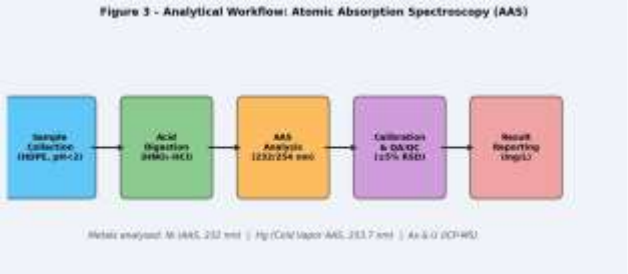

Figure 3 – Analytical workflow employed for heavy metal quantification, from sample collection through AAS/ICP-MS analysis to quality-assured reporting.

E. Quality Assurance

All analyses were performed in triplicate. Reagent blanks were used to account for contamination. Instrument calibration was verified before and after sample analysis using certified reference materials. Detection limits met WHO/BIS standards. Relative standard deviation was maintained below 5%.

F. Data Analysis

Results were analyzed using descriptive statistics (mean, median, standard deviation, range). Spatial distribution patterns were evaluated. Concentrations were compared with BIS (IS 10500:2012) and WHO drinking water standards. Statistical significance was assessed at $p<0.05$ level.

III. RESULTS

A. Physicochemical Characteristics

Table 1: Physicochemical Parameters of Water Samples

Sample	Water Source	pH	Hardness (mg/L CaCO■)	DOC (mg/L)	COD (mg/L)
S1	Residential borewell, Muzaffarnagar	7.1	180	2.5	25
S2	Agricultural handpump, Muzaffarnagar	6.9	220	3.2	38
S3	Urban handpump, Shamli	6.8	300	2.8	30
S4	Surface water, Shamli	7.0	250	5.0	75

pH values ranged from 6.8–7.1, indicating neutral to slightly acidic conditions typical of alluvial aquifer systems. Total hardness varied from 180–300 mg/L CaCO, with highest values in urban groundwater (S3), reflecting elevated Ca^2/Mg^2 from mineral dissolution and potential anthropogenic inputs.

DOC and COD showed highest values in surface water (S4: 5.0 mg/L DOC, 75 mg/L COD), indicating organic pollution from agricultural runoff, domestic sewage, and decaying organic matter. Agricultural groundwater (S2) also showed elevated organic parameters (3.2 mg/L DOC, 38 mg/L COD), likely from fertilizer application and irrigation return flow.

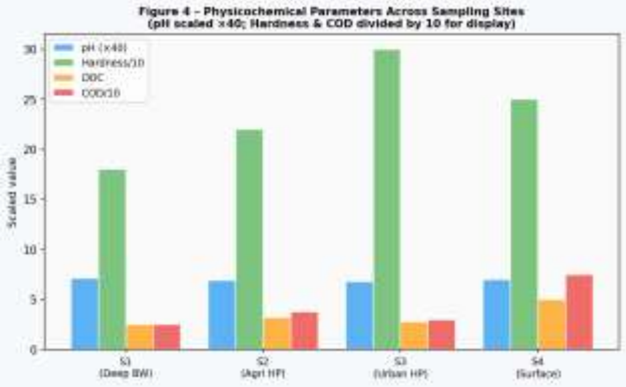

Figure 4 – Grouped bar chart of physicochemical parameters (pH scaled ×40; Hardness and COD divided by 10 for display) across the four sampling sites.

IV. HEAVY METAL CONCENTRATIONS

Table 2 summarizes heavy metal concentrations in all samples.

Table 2: Heavy Metal Concentrations in Water Samples

Sample	Ni (mg/L)	As (mg/L)	Hg (mg/L)	U (mg/L)
S1	0.12	0.005	0.003	0.01
S2	0.18	0.012	0.004	0.02
S3	0.28	0.020	0.005	0.04
S4	0.35	0.030	0.007	0.05
WHO/BIS Limit	0.07	0.01	0.006	0.03

Nickel: Concentrations ranged from 0.12–0.35 mg/L. All samples except S1 exceeded the WHO limit of 0.07 mg/L. Highest concentration (0.35 mg/L, 5× WHO limit) was observed in surface water (S4), followed by urban groundwater (S3: 0.28 mg/L, 4× limit). The elevated nickel suggests anthropogenic sources including industrial effluents from metal industries and electroplating units.

Arsenic: Concentrations ranged from 0.005–0.030 mg/L. Samples S2, S3, and S4 exceeded the WHO guideline of 0.01 mg/L. Surface water showed the highest concentration (0.030 mg/L, 3× limit). The arsenic distribution suggests both geogenic sources (reductive dissolution from alluvial sediments) and anthropogenic contributions (agricultural pesticides, fertilizers).

Mercury: Concentrations ranged from 0.003–0.007 mg/L. Only surface water (S4: 0.007 mg/L) slightly exceeded the WHO limit of 0.006 mg/L. The relatively low mercury levels indicate limited contamination, though surface water shows influence from diffuse sources including agricultural chemicals and atmospheric deposition.

Uranium: Concentrations ranged from 0.01–0.05 mg/L. Samples S3 and S4 exceeded the WHO limit of 0.03 mg/L. The highest concentration (0.05 mg/L) in surface water likely reflects natural geogenic sources from uranium-bearing minerals in Himalayan-derived alluvial sediments, potentially enhanced by phosphate fertilizer application.

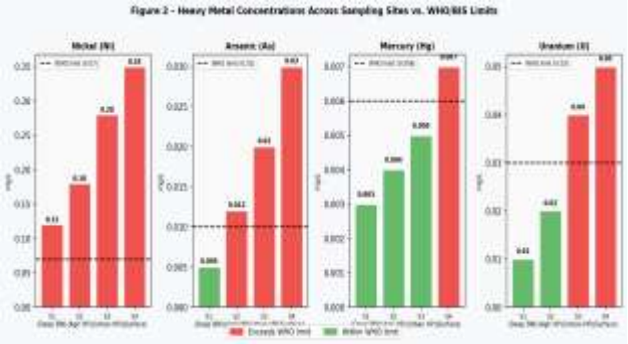

Figure 5 – Heavy metal concentrations (mg/L) at all four sampling sites compared with WHO/BIS permissible limits (dashed black lines). Red bars indicate exceedance; green bars indicate compliance.

A. Spatial Distribution Patterns

Heavy metal concentrations showed distinct spatial patterns:

1. Surface water (S4) exhibited the highest concentrations for all metals, indicating vulnerability to multiple contamination sources including agricultural runoff, domestic sewage, and atmospheric deposition.
2. Urban groundwater (S3) showed elevated levels, particularly for nickel (0.28 mg/L) and uranium (0.04 mg/L), suggesting industrial and domestic pollution sources.
3. Agricultural groundwater (S2) displayed moderate contamination, with arsenic (0.012 mg/L) exceeding WHO limits, likely from pesticide/fertilizer application and natural mobilization under reducing conditions.
4. Deep residential borewell (S1) showed the lowest concentrations for all metals, benefiting from greater depth and longer residence time allowing natural attenuation processes.

B. Comparison With Water Quality Standards

Table 3 summarizes compliance with drinking water standards.

Table 3: Compliance with WHO/BIS Standards

Metal	WHO Limit (mg/L)	Samples Exceeding Limit	Percentage	Maximum Concentration (mg/L)
Ni	0.07	3 of 4	75%	0.35 (5× limit)
As	0.01	3 of 4	75%	0.030 (3× limit)
Hg	0.006	1 of 4	25%	0.007 (1.2× limit)
U	0.03	2 of 4	50%	0.05 (1.7× limit)

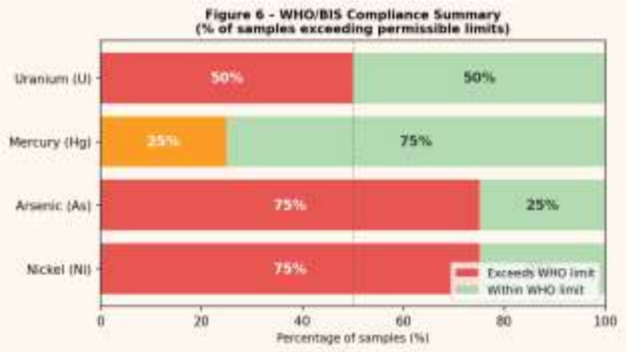

Figure 6 – WHO/BIS compliance summary: percentage of samples exceeding permissible limits for each heavy metal.

Nickel and arsenic showed the most widespread non-compliance (75% of samples).

V. DISCUSSION

A. Physicochemical Controls On Metal Mobility

The neutral to slightly acidic pH (6.8–7.1) observed across samples influences heavy metal speciation and mobility. Under these conditions, nickel remains largely soluble as Ni^2, while arsenic mobility dependsprimarily on redox conditions rather than pH. The elevated hardness indicates high Ca^2/ Mg^2 concentrations, which can compete with toxic metal cations for adsorption sites, potentially enhancing metalmobility (Appelo & Postma, 2005).

Elevated DOC and COD, particularly in surface water and agricultural groundwater, reflect organic matter that can complex with metals, affecting their transport and bioavailability. Dissolved organic matter can either enhance metal mobility through soluble complex formation or reduce bioavailability through binding (Tipping, 2002). The observed correlation between high organic parameters and elevated metal concentrations suggests that organic matter may be facilitating metal transport in the study area.

B. Source Identification And Contamination Mechanisms

Nickel: The progressive increase from deep borewell (0.12 mg/L) to surface water (0.35 mg/L) strongly indicates anthropogenic sources. Industrial activities including electroplating, stainless steel manufacturing, and battery production are probable contributors. Sugar mills and distilleries prevalent in Muzaffarnagar may release nickel-containing effluents. Agricultural areas show intermediate levels, possibly from nickel-containing pesticides and fertilizers.

Arsenic: The detection of arsenic exceeding WHO limits in 75% of samples reflects both geogenic and anthropogenic contributions. The Indo-Gangetic alluvial plain is known for naturally elevated arsenic due to reductive dissolution of iron oxyhydroxides under anaerobic conditions (Chakraborti et al., 2018; Smedley & Kinniburgh, 2002). Microbially-mediated reduction of Fe(III) and Mn(IV) oxides releases adsorbed arsenic into groundwater. Agricultural groundwater showed elevated arsenic (0.012 mg/L), suggesting additional input from arsenic-containing pesticides and phosphate fertilizers historically used in the region.

Mercury: The relatively low mercury concentrations (0.003–0.007 mg/L) with only surface water slightly exceeding limits suggest diffuse rather than point-source contamination. Possible sources include agricultural fungicides, atmospheric deposition from industrial emissions and coal combustion, and improper disposal of mercury-containing devices (fluorescent lamps, thermometers). The surface water elevation indicates sensitivity to atmospheric and runoff inputs.

Uranium: Uranium occurrence is predominantly geogenic, originating from uranium-bearing minerals in Himalayan-derived alluvial sediments (Rajmohan et al., 2019). The higher concentrations in surface water (0.05 mg/L) and urban groundwater (0.04 mg/L) may reflect enhanced mobilization under oxidizing conditions and neutral to alkaline pH, which favor soluble uranyl-carbonate complex formation. Phosphate fertilizer application may contribute additional uranium, as phosphate rocks contain trace uranium as a natural contaminant.

C. Health Risk Implications

The exceedance of drinking water standards for multiple metals poses significant public health concerns. Chronic exposure to nickel at observed levels (up to 5× WHO limit) can cause allergic dermatitis, respiratory problems, and potential carcinogenic effects (Das et al., 2008). Populations using surface water and urban groundwater face the highest risk.

Arsenic contamination exceeding WHO limits in 75% of samples is particularly alarming. Long-term arsenic exposure, even at concentrations slightly above 0.01 mg/L, is associated with skin lesions, cardiovascular diseases, diabetes, neurological impairments, and cancers of skin, bladder, and lungs (Naujokas et al., 2013). The study area population, particularly in Shamli district where surface water and shallow groundwater show elevated arsenic, faces cumulative health risks.

Mercury, though only slightly exceeding limits in surface water, warrants concern due to its neurotoxicity and bioaccumulation potential. Even low-level chronic exposure can cause neurological damage, particularly affecting children's cognitive development (Karagas et al., 2012).

Uranium's chemical toxicity primarily affects kidney function, causing tubular damage (Zamora et al., 2009). The observed uranium levels approaching or exceeding 0.03 mg/L in 50% of samples suggest potential nephrotoxic risks for populations relying on these sources.

D. Comparative Analysis With Regional Studies

The findings align with previous groundwater studies in western Uttar Pradesh and the broader Indo-Gangetic plain. Chakraborti et al. (2018) reported widespread arsenic contamination in eastern UP districts, with similar geochemical mobilization mechanisms. The present study extends this understanding westward, documenting arsenic presence in Muzaffarnagar and Shamli districts.

Nickel contamination observed in this study (0.12–0.35 mg/L) is comparable to levels reported by Smith & Singh (2015) in Indian industrial zones (0.12–2.45 mg/L). However, the extent of exceedance is concerning given the mixed residential-agricultural-industrial land use in the study area.

The uranium concentrations (0.01–0.05 mg/L) are lower than those reported in South Indian granitic terrains (15–250 µg/L; Rajmohan et al., 2019) but represent a notable concern in alluvial aquifer systems where uranium occurrence is less expected. This suggests that geogenic uranium mobilization may be more widespread in Indo-Gangetic sediments than previously recognized.

E. Limitations And Uncertainties

This study has several limitations. The sample size (n=4) and single-season sampling provide a snapshot rather than comprehensive temporal-spatial coverage. Seasonal variations in metal concentrations due to monsoon dilution, temperature changes, and agricultural activity patterns were not captured. The study focused on four priority metals, potentially missing other significant contaminants (Pb, Cd, Cr, Zn, Fe).

Speciation analysis was not performed, limiting understanding of metal bioavailability and toxicity. For instance, distinguishing between As(III) and As(V), or inorganic versus methylmercury, is critical for accurate risk assessment. Future studies should incorporate speciation techniques and isotopic analysis to definitively identify contamination sources.

The hydrogeological characterization, while adequate for context, would benefit from detailed lithological profiling, aquifer testing, and groundwater flow modeling to better understand contaminant transport mechanisms.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. Key Findings

This comprehensive assessment of heavy metal contamination in Muzaffarnagar and Shamli districts reveals:

1. Widespread contamination: 75% of samples exceeded WHO limits for nickel and arsenic, 50% for uranium, and 25% for mercury.
2. Spatial variability: Surface water and urban groundwater showed highest contamination, while deep borewells exhibited lower levels, highlighting depth as a protective factor.

3. Multiple sources: Contamination stems from both anthropogenic activities (industrial effluents, agricultural inputs, domestic sewage) and natural geogenic processes (mineral weathering, reductive dissolution).
4. Public health concern: Significant portions of the population face potential health risks from chronic heavy metal exposure through drinking water.
5. Physicochemical influences: Neutral pH, elevated hardness, and organic matter content influence metal mobility and bioavailability.

B. Immediate Recommendations

Public Health Interventions:

- Issue health advisories for identified high-risk areas
- Provide alternative safe drinking water sources in severely contaminated locations (S3, S4)
- Implement community awareness programs on water quality and health risks
- Establish health surveillance systems to monitor exposure effects

C. Water Treatment:

- Arsenic removal: Activated alumina or iron oxide-based adsorption systems
- Nickel removal: Ion exchange or chemical precipitation
- Uranium removal: Reverse osmosis or ion exchange
- Promote household-level water treatment in affected areas
- Develop community water treatment plants for villages relying on contaminated sources

D. Monitoring Enhancement:

- Establish comprehensive water quality monitoring network covering both districts
- Implement quarterly sampling to capture seasonal variations
- Extend monitoring to include additional metals (Pb, Cd, Cr) and organic contaminants
- Install monitoring wells at strategic locations for early contamination detection

E. Long-Term Strategies

Source Control:

- Enforce strict effluent discharge standards for industries
- Regulate agricultural chemical application through soil testing and integrated nutrient management
- Develop proper industrial and domestic waste management infrastructure
- Create buffer zones around water supply sources

F. Aquifer Management:

- Implement artificial recharge programs to dilute contaminant concentrations
- Regulate groundwater extraction in over-exploited areas
- Promote deeper aquifer utilization where water quality is better
- Conduct detailed hydrogeological investigations to identify safe aquifer zones

G. Policy Development:

- Develop district-specific groundwater protection policies
- Integrate water quality considerations into industrial licensing and land-use planning
- Establish compensation mechanisms for affected communities
- Strengthen inter-departmental coordination (health, agriculture, water resources)

H. Broader Implications

This case study contributes to the growing body of evidence on groundwater contamination in the Indo-Gangetic alluvial plain, highlighting challenges faced by rapidly developing regions with inadequate environmental infrastructure. The findings emphasize that groundwater contamination is not merely an environmental issue but a public health crisis requiring urgent, coordinated action from multiple stakeholders.

The study demonstrates the vulnerability of shallow alluvial aquifers to both surface-derived pollution and natural geogenic contamination. The simultaneous presence of multiple heavy metals from diverse sources necessitates integrated management approaches rather than single-contaminant, single-source interventions.

I. Future Research Directions

Future investigations should:

1. Expand temporal and spatial coverage through multi-season, multi-year monitoring programs
2. Incorporate advanced analytical techniques (metal speciation, isotopic analysis, synchrotron methods)
3. Conduct detailed source characterization studies (industrial effluents, agricultural inputs, sediment geochemistry)
4. Perform quantitative health risk assessments including biomarker studies in exposed populations
5. Develop and pilot-test remediation technologies suited to local conditions and resources
6. Investigate climate change impacts on aquifer geochemistry and contaminant mobilization

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