

Spatiotemporal variation in groundwater quality and human health risk assessment in alluvial aquifers of Madhepura, Bihar

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ABSTRACT

Continuous monitoring of shallow alluvial aquifers is critical for safeguarding rural public health in eastern India. This study evaluated the hydrochemical characteristics, drinking water suitability, and non-carcinogenic health hazards of groundwater across six villages in three administrative blocks (Murliganj, Alamnagar, and Madhepura) in Madhepura district, Bihar, from January 2023 to December 2025. A total of 144 groundwater samples were collected systematically across pre-monsoon, monsoon, post-monsoon, and summer seasons and analyzed for physicochemical parameters (pH, electrical conductivity, total dissolved solids, total hardness, calcium, magnesium, chloride, fluoride) and trace heavy metals (Fe, Mn, Zn, Cu, Cd, Pb) using standard APHA methods. Mean values of total dissolved solids (520-1,280 mg/L) and electrical conductivity (720-1,620 μ S/cm) were highest during the pre-monsoon period, dropping substantially during the monsoon season due to precipitation recharge. Fluoride concentrations exceeded the Bureau of Indian Standards (IS 10500:2012) acceptable limit (1.0 mg/L) in several sites, reaching up to 2.5 mg/L in Belo village. While toxic metals such as cadmium and copper remained below detectable thresholds, lead (Pb) showed localized exceedances above the permissible drinking water benchmark (0.01 mg/L), yielding hazard quotient (HQ) values exceeding 1.0 for children. These results highlight a dual challenge of mineral dissolution and localized anthropogenic leaching, necessitating decentralized water purification infrastructure and ongoing surveillance.

Key Words - Groundwater quality, Hydrochemistry, Health risk, Trace metals, Alluvial aquifer.

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INTRODUCTION

Groundwater serves as the primary freshwater source for domestic consumption and agricultural irrigation across the middle Gangetic plains of Bihar, India (Kumari *et al.*, 2022; Saha *et al.*, 2020). In rural tracts of the Kosi river basin, including Madhepura district, shallow tube wells and deep bore wells account for more than 90% of rural household water supply (Central Ground Water Board [CGWB], 2021). The intensive extraction of groundwater, coupled with fluctuations in monsoon precipitation and extensive fertilizer applications in agricultural

catchments, has exerted substantial strain on aquifer hydrochemistry (Bhat *et al.*, 2021; Mukherjee *et al.*, 2015).

Alluvial sediments in this region are prone to mineral dissolution processes, which govern the natural baseline of ionic constituents such as calcium, magnesium, bicarbonate, and fluoride (Jain *et al.*, 2010). In contrast, elevated total dissolved solids (TDS), prolonged exposure to fluoride levels above , and trace heavy metal contamination (notably lead and iron) pose

documented public health hazards, including dental/skeletal fluorosis, gastrointestinal distress, and neurovascular disorders (Ghosh *et al.*, 2020; World Health Organization, 2022).

Earlier baseline surveys in Madhepura between 2019 and 2021 confirmed elevated hardness and intermittent fluoride concentrations across selected blocks (Kumari *et al.*, 2022). At the same time, post-monsoon dynamics, recurring hydrological shifts, and land-use intensification necessitate updated multi-year monitoring. The present investigation was undertaken from 2023 to 2025 across identical hydrological corridors to:

- Determine seasonal shifts in physico-chemical indices and heavy metal concentrations.
- Evaluate water suitability against national and international standards.
- Quantify the non-carcinogenic health hazards posed to adult and pediatric populations via oral intake.

MATERIALS & METHODS

Study Area

Madhepura district (25°34' N to 26°07' N latitude, 86°19' E to 87°07' E longitude) lies within the alluvial belt of north Bihar. The regional geology comprises Quaternary alluvium deposited by the dynamic Kosi river system, characterized primarily by sand, silt, and clay strata. Sampling was conducted across six representative villages distributed within three blocks:

- Murliganj Block: Belo and Bishunpur
- Alamnagar Block: Alamnagar and Barhauna
- Madhepura Block: Bhelwa and Barahi

Sample Collection and Preservation

A longitudinal sampling regime was executed over three consecutive years (2023, 2024, and 2025) spanning four designated periods each year: Pre-monsoon (April-May), Monsoon (July-August), Post-monsoon/Winter (November-December), and Summer (March). Groundwater was collected from 36 designated shallow-to-medium tube wells (depth: 30-75 m) across the six villages.

Pumps were flushed for 5 to 10 minutes prior to collection to evacuate stagnant casing water. Samples were drawn into pre-cleaned, acid-washed, high-density polyethylene (HDPE) bottles (1 L). Samples intended for trace heavy metal quantification were acidified on-site to $\text{pH} < 2$ with analytical-grade concentrated nitric acid (HNO_3). All containers were sealed, placed in portable cool boxes at $< 4^\circ\text{C}$, and transported to the laboratory for analysis.

Analytical Procedures

Physicochemical parameters were determined following American Public Health Association standard protocols (APHA, 2017):

- **pH and Electrical Conductivity (EC):** Measured on-site using a calibrated multi-parameter digital probe.
- **Total Dissolved Solids (TDS):** Evaluated gravimetrically at 180°C .
- **Total Alkalinity (TA):** Determined by titration against 0.02 N H_2SO_4 with phenolphthalein and methyl orange endpoints.
- **Total Hardness (TH), Ca^{2+} and Mg^{2+} :** Assayed via ethylenediaminetetraacetic acid (EDTA) titrimetric techniques using Eriochrome Black T and murexide indicators.
- **Chloride (Cl^-):** Measured via standard argentometric titration using silver nitrate (AgNO_3) and potassium chromate indicator.
- **Fluoride (F^-):** Quantified spectrophotometrically using the SPADNS method at $\lambda = 570 \text{ nm}$.
- **Trace Heavy Metals (Fe, Cd, Cu, Zn, Mn, Pb):** Digested with trace-metal-grade HNO_3 and analyzed via Flame Atomic Absorption Spectrometry (PerkinElmer PinAAcle 900F). Quality control included procedural blanks, duplicate analyses, and certified reference standards (NIST), achieving recoveries between 94% and 104%.

Human Health Risk Assessment

The Chronic Daily Intake (CDI, in mg/kg/day) via oral drinking water consumption was computed as follows (US EPA, 2011):

$$CDI = \frac{C_w \times IR \times EF \times ED}{BW \times AT}$$

Where,

C_w = Concentration of chemical constituent in water (mg/L)

IR = Ingestion rate (2.0 L/day for adults; 1.0 L/day for children)

EF = Exposure frequency (365 days/year)

ED = Exposure duration (30 years for adults; 6 years for children)

BW = Average body weight (60 kg for adults; 15 kg for children)

AT = Averaging time (ED×365 days)

The non-carcinogenic risk was evaluated using the Hazard Quotient (HQ):

$$HQ = \frac{CDI}{RfD}$$

Where, RfD is the oral reference dose (mg/kg/day), set at 0.04 for F⁻ and 0.0035 for Pb (US EPA, 2011). An HQ>1.0 indicates significant non-carcinogenic human health concern.

RESULTS & DISCUSSION

Physicochemical Trends (2023-2025)

The annual and seasonal mean hydrochemical values recorded across the six villages during 2023-2025 are summarized in Table 1.

pH Variations: The groundwater remained predominantly circumneutral to moderately alkaline (7.4-8.7), except in Barhauna (Alamnagar), where slightly acidic conditions (5.8-6.2) persisted throughout 2023-2025. This localized sub-surface acidity accelerates mineral leaching from host silicate minerals.

Conductivity and Dissolved Solids: Electrical conductivity fluctuated between 620 μ S/cm (Barahi, Monsoon) and 1,570 μ S/cm (Barhauna, Pre-monsoon). TDS values consistently exceeded

Table 1: Mean seasonal physicochemical parameters of groundwater in Madhepura (2023-2025)

Location	Season	pH	EC (μ S/cm)	TDS (mg/L)	TA (mg/L)	TH (mg/L)	Ca ²⁺ (mg/L)	Mg ²⁺ (mg/L)	Cl ⁻ (mg/L)	F ⁻ (mg/L)
Belo (Murliganj)	Pre-monsoon	8.6	1270	995	635	492	292	200	69	2.5
	Monsoon	8.2	920	760	465	338	202	136	38	1.6
	Post-monsoon	8.4	1140	835	570	420	260	160	58	2.0
	Summer	8.5	1225	895	610	475	282	193	64	2.3
Bishunpur (Murliganj)	Pre-monsoon	8.0	1480	685	455	260	174	86	55	1.5
	Monsoon	7.7	1080	520	310	165	115	50	34	1.1
	Post-monsoon	7.8	1190	510	360	175	120	55	40	1.3
	Summer	7.9	1310	570	405	218	145	73	48	1.4
Alamnagar (Alamnagar)	Pre-monsoon	7.6	1210	710	380	175	115	60	46	1.1
	Monsoon	7.5	1150	620	340	155	108	47	36	1.0
	Post-monsoon	7.7	1310	690	415	198	125	73	55	1.2
	Summer	7.8	1380	760	445	235	142	93	63	1.3
Barhauna (Alamnagar)	Pre-monsoon	6.1	1570	1280	530	355	210	145	95	1.8
	Monsoon	5.8	1210	1110	380	210	120	90	48	1.0
	Post-monsoon	6.0	1440	1180	475	285	170	115	68	1.6
	Summer	6.1	1530	1240	515	330	198	132	88	1.8
Bhelwa (Madhepura)	Pre-monsoon	7.8	1120	705	310	185	105	80	56	1.7
	Monsoon	7.4	805	490	150	48	44	34	35	1.0
	Post-monsoon	7.6	990	560	245	105	60	45	42	1.4
	Summer	7.7	1085	615	290	155	84	61	50	1.6
Barahi (Madhepura)	Pre-monsoon	8.7	1060	990	275	495	280	215	225	1.2
	Monsoon	8.2	620	770	70	140	95	45	125	0.6
	Post-monsoon	8.5	890	845	200	325	180	145	155	0.9
	Summer	8.6	980	880	240	445	240	205	205	1.1

the desirable limit of 500 mg/L set by the Bureau of Indian Standards (IS 10500:2012), with Barhauna exceeding 1,200 mg/L during dry periods. Pronounced monsoon decreases reflect rainwater dilution and recharge.

Hardness and Major Ions: Total hardness ranged from 48 mg/L to 495 mg/L, falling within the maximum permissible ceiling of 600 mg/L (BIS, 2012). Calcium (Ca^{2+}) was the dominant cation (44–292 mg/L), while magnesium (Mg^{2+}) concentrations followed closely (34–215 mg/L). Chloride remained

well below the acceptable limit (250 mg/L), reaching its highest point in Barahi (225 mg/L).

Fluoride Dynamics: Fluoride was enriched across multiple sampling stations. Belo village sustained elevated levels across all seasons, varying between 1.6 mg/L and 2.5 mg/L, thereby violating the permissible ceiling (1.5 mg/L). This observation aligns with dissolution from fluoride-bearing mineral phases (fluorapatite and mica) known to occur in Gangetic sediment deposits (Chakraborti *et al.*, 2016).

Table 2: Mean trace heavy metal concentrations and biochemical parameters (2023–2025)

Location	DO (mg/L)	BOD (mg/L)	COD (mg/L)	Fe (mg/L)	Cd (mg/L)	Cu (mg/L)	Zn (mg/L)	Mn (mg/L)	Pb (mg/L)
Belo	5.4	3.1	4.4	0.15	BDL	BDL	0.03	BDL	0.028
Bishunpur	6.4	3.3	3.6	0.14	BDL	0.02	0.08	0.01	0.022
Alamnagar	6.3	2.4	5.2	0.15	BDL	BDL	0.14	0.02	0.018
Barhauna	5.3	1.6	5.9	0.16	BDL	BDL	0.18	0.03	0.031
Barahi	5.9	1.8	4.0	0.11	BDL	BDL	BDL	0.01	BDL
Bhelwa	6.5	2.3	2.5	0.14	BDL	BDL	0.13	0.03	0.020
BIS Limit (2012)	-	-	-	1.00	0.003	0.05	5.00	0.10	0.01

Heavy Metal Concentrations

Table 2 displays the mean concentrations of heavy metals alongside secondary parameters (DO, BOD, COD) collected during 2023–2025. Concentrations of Fe (0.11–0.16 mg/L), Zn (<0.001–0.18 mg/L), and Mn (<0.001–0.03 mg/L) complied with both BIS (IS 10500:2012) and WHO drinking water criteria. Cadmium and copper were below detectable limits in almost all sites. In contrast, lead concentrations ranged between non-detectable levels and, exceeding the permissible threshold of lead in Belo, Bishunpur, Alamnagar, Barhauna, and Bhelwa. Lead occurrences in shallow alluvial wells may stem from plumbing fixtures, lead-bearing solder in local hand pumps, or the leaching of agrochemical residues containing trace heavy metal impurities (Singh *et al.*, 2018).

Health Risk Assessment

The non-carcinogenic exposure indices evaluated for adults and children exposed to elevated fluoride and lead concentrations are presented in Table 3. The results show that the Hazard Quotient for fluoride ($\text{HQ}_{\text{Fluoride}}$) exceeded the benchmark of unity (1.0) across both demographic categories in Belo, Barhauna, and Bhelwa. Pediatric cohorts are disproportionately susceptible, displaying HQ values as high as 4.18 in Belo village, presenting a genuine threat of endemic fluorosis. When the cumulative Hazard Index ($\text{HI} = \sum \text{HQ}$) is evaluated, chronic co-exposure to F^- and Pb further amplifies health vulnerabilities for school-aged children relying on unfiltered domestic bore wells.

Table 3: Calculated CDI and Hazard Quotients (HQ) for Fluoride and Lead ingestion

Location	Constituent	CDI Adult (mg/kg/day)	CDI Child (mg/kg/day)	HQ Adult	HQ Child	Health Risk Indicator
Belo	Fluoride (F^-)	0.083	0.167	2.08	4.18	High non-carcinogenic risk
	Lead (Pb)	0.00093	0.00187	0.27	0.53	Low single-element risk
Barhauna	Fluoride (F^-)	0.060	0.120	1.50	3.00	High non-carcinogenic risk
	Lead (Pb)	0.00103	0.00207	0.29	0.59	Low single-element risk
Bhelwa	Fluoride (F^-)	0.057	0.113	1.43	2.83	Moderate non-carcinogenic risk
	Lead (Pb)	0.00067	0.00133	0.19	0.38	Low single-element risk

CONCLUSION

This three-year longitudinal assessment (2023-2025) demonstrates that groundwater in Madhepura district remains dominated by alkaline earth and bicarbonate-rich characteristics. Seasonal dilution plays an essential role during the monsoon phase, reducing total dissolved solids and ionic loads. Despite this, persistent exceedances of total dissolved solids and geogenic fluoride contamination in villages such as Belo and Barhauna present ongoing challenges. Trace concentrations of lead surpassing permissible limits add localized toxicological risks, as evidenced by pediatric hazard quotients exceeding safety limits. Immediate regional interventions must prioritize community-scale defluoridation systems, substitution of corrosion-prone hand pump infrastructure, and mandatory periodic hydrochemical testing to protect public health across rural north Bihar.

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