

Integrated Hydrochemical and Microbiological Assessment of Shallow Groundwater Vulnerability to Sanitation-Related Contamination in Patna City, Bihar, India

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Abstract:

Groundwater in densely populated alluvial cities is increasingly vulnerable to chemical and microbiological contamination associated with urban activities and inadequate sanitation. This study evaluated the hydrochemical and microbiological quality of shallow groundwater in Patna City, Bihar, India, with particular emphasis on indicators of potential sanitation-related contamination. Ten groundwater samples were assessed for pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, nitrate, chloride, potassium, phosphate, iron, fluoride, arsenic and total hardness, together with total and faecal coliforms using the Most Probable Number (MPN) method. Descriptive statistics and Pearson correlation analysis were used to examine groundwater-quality variability and relationships between hydrochemical and microbiological indicators. The results showed predominantly near-neutral groundwater (pH 6.8–7.6), while elevated TDS, nitrate, iron, arsenic and hardness were observed at several locations. TDS exceeded 500 mg/L in 80% of samples, nitrate exceeded 45 mg/L in 40%, arsenic exceeded 0.01 mg/L in 80%, and iron exceeded 0.3 mg/L in all samples. Microbiological contamination was widespread, with total coliform concentrations ranging from 60 to 1200 MPN/100 mL and faecal coliforms from 18 to 360 MPN/100 mL. GW8 exhibited the highest concentrations of both chemical and microbiological indicators, followed by GW4 and GW6. Faecal coliforms showed strong positive associations with nitrate ($r = 0.991$), chloride ($r = 0.991$), phosphate ($r = 0.986$), turbidity ($r = 0.945$), EC ($r = 0.982$) and TDS ($r = 0.981$). The concurrent occurrence of elevated nitrate, chloride, phosphate and faecal indicators suggests potential sanitation-related influence on shallow groundwater quality, whereas arsenic and iron require consideration of their established geogenic controls in Bihar. The findings demonstrate the importance of integrating hydrochemical and microbiological indicators for assessing groundwater vulnerability and support improved sanitation management, routine groundwater monitoring and appropriate treatment before domestic consumption in vulnerable areas of Patna City.

Keywords: groundwater quality, Patna City, shallow alluvial aquifer, sanitation contamination, hydrochemistry, faecal coliform, MPN, nitrate, arsenic, Bihar.

1. Introduction

Groundwater is one of the most important components of the global freshwater system and provides a major source of drinking water, domestic supply, agriculture and industrial production. Its importance is particularly pronounced in densely populated regions where surface-water resources are insufficient, seasonally variable or increasingly affected by anthropogenic pollution. The Indo-Gangetic Basin (IGB) contains one of the world's most extensive alluvial aquifer systems and supports hundreds of millions of people across South Asia. Groundwater abstraction from the basin accounts for approximately one-quarter of global groundwater withdrawals, demonstrating its central importance to regional water and food security [1]. The alluvial aquifers of the basin are predominantly composed of unconsolidated sediments deposited by the Indus, Ganga and Brahmaputra river systems, with considerable spatial variation in groundwater recharge, permeability, storage and chemical composition [2].

Despite its importance, groundwater quality in the Indo-Gangetic region is increasingly influenced by both geogenic and anthropogenic processes. Natural geochemical processes can introduce elements such as arsenic, fluoride and iron into groundwater, whereas human activities contribute nutrients, salts, organic matter, microorganisms and other contaminants. MacDonald et al. (2016) demonstrated that groundwater quality represents a major constraint on the availability of potable groundwater within the Indo-Gangetic Basin, with extensive areas affected by salinity and arsenic. Similarly, investigations of alluvial aquifers in northern India have shown that shallow groundwater is particularly vulnerable to anthropogenic loading, with elevated nitrate, chloride and salinity associated with urban and agricultural activities [3]. These findings emphasize that groundwater assessment should not be restricted to individual chemical parameters but should consider the combined influence of hydrochemical and microbiological contamination.

Shallow groundwater is particularly susceptible to contamination from sanitation-related activities. In densely populated settlements, wastewater leakage, septic systems, pit latrines, open drains, solid-waste disposal and inadequate sanitation infrastructure can introduce dissolved nutrients and microorganisms into the subsurface. The potential for sanitation-derived contaminants to reach groundwater depends on several factors, including groundwater depth, soil and sediment characteristics, hydraulic conductivity, groundwater flow, recharge conditions and the distance between sanitation structures and water points. Graham and Polizzotto (2013), in a systematic review of pit-latrines impacts, demonstrated that both chemical and microbial contaminants can migrate from on-site sanitation systems into groundwater, with shallow groundwater systems being particularly vulnerable under favourable hydrogeological conditions [4].

Chemical indicators can provide important evidence of anthropogenic influence on groundwater. Nitrate, chloride, potassium and phosphate are particularly useful in evaluating possible contributions from sewage, domestic wastewater and other human-derived sources. Nitrate may originate from human excreta, wastewater, agricultural fertilizers and decomposing organic matter, while chloride behaves relatively conservatively in many groundwater systems and can therefore act as an indicator of anthropogenic inputs. The simultaneous enrichment of nitrate and chloride may provide stronger evidence of contamination than either parameter considered independently. Research from alluvial aquifers of northern India has demonstrated that shallow groundwater commonly exhibits greater concentrations of nitrate, chloride and salinity where urban and agricultural contaminant loading is significant [3]. Consequently, hydrochemical relationships among nutrients, major ions and general water-quality parameters can help identify potential contamination pathways.

However, chemical measurements alone cannot adequately establish microbiological safety of groundwater. Groundwater may appear chemically acceptable while still containing faecal indicator organisms originating from human or animal waste. Total coliforms and faecal coliforms are therefore widely used as indicators of microbiological contamination and sanitary quality. The detection of these organisms can provide evidence of faecal pollution and possible contamination pathways associated with sanitation infrastructure. In particular, the Most Probable Number (MPN) technique provides a conventional approach for estimating the density of coliform organisms in water samples. Standard microbiological procedures for water examination have long incorporated culture-based approaches for assessing indicator organisms, providing an established basis for microbiological water-quality assessment [5].

The importance of microbiological assessment is particularly relevant in Patna City, where groundwater is widely used for domestic purposes and the urban environment is characterized by high population density, extensive settlement and substantial dependence on groundwater resources. Previous investigations of groundwater quality in Patna have documented variations in physicochemical characteristics and have also demonstrated the occurrence of total and faecal coliforms in groundwater samples. A study of groundwater quality in Patna reported physicochemical parameters including pH, TDS, electrical conductivity, chloride, nitrate, fluoride and hardness, while microbiological analysis detected total and faecal coliforms through the MPN method. The study highlighted the importance of microbiological contamination even where an overall water-quality index suggested relatively acceptable chemical quality [6].

Patna's location within the middle Ganga alluvial plain further increases the relevance of shallow-aquifer vulnerability. The unconsolidated alluvial setting permits relatively rapid interaction between surface-derived contaminants and shallow groundwater under suitable recharge conditions. Investigations around Patna have demonstrated the presence of anthropogenic contaminants in groundwater and identified urban inputs as important influences on groundwater quality. Sorensen et al. (2015), working in Bihar, also demonstrated that sanitation interventions and subsurface sanitation systems can create pathways through which excreta-derived contaminants reach groundwater. Such findings are important for Patna because sanitation-related contamination may not always be apparent from conventional physicochemical measurements alone [7].

The seasonal hydrological cycle is another important factor controlling groundwater contamination in the region. During the monsoon, enhanced recharge can increase the downward transport of contaminants from the land surface and sanitation structures into shallow aquifers. At the same time, increased recharge may dilute certain dissolved constituents, producing apparently lower concentrations despite continued contaminant loading. Therefore, the interpretation of groundwater quality requires consideration of both contaminant sources and hydrogeological processes. In shallow alluvial systems, seasonal recharge, groundwater movement and local sanitation conditions may jointly control the distribution of nitrate, chloride, nutrients and microbial indicators.

In this context, an integrated assessment combining physicochemical and microbiological indicators provides a more comprehensive understanding of groundwater contamination than either approach alone. Relationships among turbidity, electrical conductivity, total dissolved solids, nitrate, chloride, potassium, phosphate, iron, arsenic, fluoride and total hardness can be examined alongside total and faecal coliform concentrations to identify possible contamination patterns. Particularly, the co-occurrence of elevated nutrients and major ions with increased coliform densities may provide evidence consistent with

sanitation-derived contamination, although source attribution should be interpreted cautiously because individual chemical constituents can have multiple natural and anthropogenic sources.

Research rationale and knowledge gap

Although groundwater-quality studies have been conducted in Patna and other parts of Bihar, many assessments have primarily emphasized physicochemical parameters or water-quality indices. Previous Patna research has demonstrated the presence of microbiological contamination, but an integrated assessment explicitly combining hydrochemical indicators with quantitative MPN-based microbial indicators can provide additional insight into sanitation-related groundwater vulnerability. This is especially relevant for shallow alluvial aquifers where the proximity of groundwater to surface-derived contamination sources can facilitate contaminant transport. Existing evidence from the broader Indo-Gangetic Basin confirms the vulnerability of shallow groundwater to anthropogenic contamination, while Bihar-specific studies demonstrate the relevance of sanitation-related pathways.

Therefore, the present study evaluates the hydrochemical and microbiological characteristics of shallow groundwater in Patna City, Bihar, with particular emphasis on indicators associated with sanitation-driven contamination. The study considers major physicochemical parameters together with total coliform and faecal coliform concentrations expressed as MPN/100 mL. The combined dataset is used to examine spatial differences in groundwater quality and the relationships between microbial contamination and selected hydrochemical indicators. The study ultimately aims to provide an integrated perspective on the vulnerability of shallow urban alluvial groundwater to sanitation-related contamination and its implications for drinking-water safety.

2. Materials and Methods

2.1 Study Area

The study was conducted in Patna City, Bihar, India, located on the southern bank of the River Ganga within the Middle Gangetic Plain. The area is underlain predominantly by unconsolidated alluvial deposits and is characterized by extensive urban development and widespread dependence on groundwater for domestic purposes. The combination of shallow alluvial aquifers, dense settlement and sanitation infrastructure makes groundwater susceptible to contamination from both natural and anthropogenic sources.

Ten groundwater sampling locations were considered and designated GW1–GW10. The representative geographic coordinates used for spatial presentation of the sampling locations are provided in Table 1.

Table 1. Geographic coordinates of groundwater sampling locations in Patna City

Sample ID	Latitude (°N)	Longitude (°E)
GW1	25.6205	85.1410
GW2	25.6138	85.1372
GW3	25.6268	85.1515
GW4	25.6065	85.1538
GW5	25.6182	85.1625
GW6	25.6008	85.1658
GW7	25.6325	85.1328

GW8	25.5958	85.1485
GW9	25.6280	85.1640
GW10	25.6085	85.1745

2.2 Groundwater Sampling and Physicochemical Analysis

Samples GW1–GW10 intended for physicochemical analysis were collected in clean sampling containers, while samples for microbiological analysis were collected separately in sterile bottles using aseptic procedures. Samples were transported to the laboratory under appropriate conditions and analyzed using standard analytical procedures.

The physicochemical parameters included pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, nitrate, chloride, potassium, phosphate, iron, fluoride, arsenic and total hardness. The analytical methods used for each parameter are presented in Table 2. The procedures were based principally on *Standard Methods for the Examination of Water and Wastewater* [5]. The resulting dataset for GW1–GW10 included all listed physicochemical parameters.

Table 2. Physicochemical parameters and analytical methods

Parameter	Unit	Analytical method
pH	—	Electrometric method using calibrated pH meter
Electrical conductivity (EC)	$\mu\text{S}/\text{cm}$	Conductivity-meter method
Total dissolved solids (TDS)	mg/L	Gravimetric method / calculated from EC
Turbidity	NTU	Nephelometric method
Nitrate (NO_3^-)	mg/L	UV spectrophotometric method
Chloride (Cl^-)	mg/L	Argentometric titration
Potassium (K^+)	mg/L	Flame photometric method
Phosphate (PO_4^{3-})	mg/L	Ascorbic acid spectrophotometric method
Iron (Fe)	mg/L	Colorimetric/spectrophotometric method
Fluoride (F^-)	mg/L	SPADNS spectrophotometric method
Arsenic (As)	mg/L	Hydride-generation/atomic absorption spectrometric method
Total hardness	mg/L as CaCO_3	EDTA complexometric titration

2.3 Microbiological Analysis

The microbiological quality of groundwater was assessed using the Most Probable Number (MPN) technique. Total coliform and faecal coliform concentrations were determined and expressed as MPN/100 mL. The multiple-tube fermentation procedure, including presumptive and confirmatory stages, was followed using standard microbiological procedures described by APHA, AWWA and WEF (2017) [5].

Table 3. Microbiological parameters and analytical methods

Parameter	Unit	Analytical method
Total coliform	MPN/100 mL	Multiple-tube fermentation/MPN method
Faecal coliform	MPN/100 mL	Multiple-tube fermentation with confirmatory testing

The microbiological results were integrated with the physicochemical dataset to assess the possible association between sanitation-related microbial contamination and hydrochemical characteristics.

2.4 Statistical Analysis

Descriptive statistics were calculated for all physicochemical and microbiological parameters. The mean, standard deviation (SD), and coefficient of variation (CV) were calculated using:

Mean

$$\bar{x} = \frac{\sum_{i=1}^n x_i}{n}$$

where x_i is the observed value and n is the number of observations.

Standard deviation

$$SD = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n - 1}}$$

Coefficient of variation

$$CV(\%) = \frac{SD}{\bar{x}} \times 100$$

Pearson's correlation coefficient was used to evaluate relationships among groundwater-quality parameters:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}}$$

where x_i and y_i represent paired observations of two variables, and $\bar{x}$ and $\bar{y}$ are their respective means. Because microbial concentrations can show a skewed distribution, MPN values were transformed before correlation analysis using:

$$MPN_{log} = \log_{10}(MPN + 1)$$

The transformed total and faecal coliform values were correlated with selected hydrochemical parameters, particularly nitrate, chloride, phosphate, turbidity, EC and TDS, to examine potential associations with sanitation-related contamination. Statistical significance was evaluated at $p < 0.05$.

2.5 Quality Assurance and Quality Control

All analyses were performed following standardized analytical procedures. Instruments were calibrated using appropriate standards before measurements. Clean sampling containers were used for

physicochemical analyses, while sterile containers and aseptic procedures were used for microbiological sampling. Appropriate blanks, standards and procedural controls were employed wherever applicable to minimize contamination and analytical error.

3. Results and Discussion

3.1 Physicochemical characteristics of groundwater

The physicochemical characteristics of the ten groundwater samples (GW1–GW10) from Patna City are presented in Table 4 & 5. The results demonstrate considerable variation among the sampling locations, particularly for electrical conductivity (EC), total dissolved solids (TDS), turbidity, nitrate, chloride, iron, arsenic and total hardness. The pH values remained relatively stable, whereas several parameters showed a progressive increase toward samples exhibiting greater microbial contamination.

The pH ranged from 6.8 to 7.6, with a mean of 7.20 ± 0.26 , indicating predominantly near-neutral groundwater conditions. All samples were therefore within the commonly accepted drinking-water pH range of 6.5–8.5 specified by BIS. The relatively narrow pH range indicates that pH was not a major source of variability among the investigated groundwater sources. Similar near-neutral groundwater conditions have been reported in regional investigations of Bihar groundwater, where pH commonly occurs within a relatively moderate range despite substantial spatial variation in other chemical constituents [8].

EC ranged from 700 to 1085 $\mu\text{S}/\text{cm}$, with a mean of 883.5 $\mu\text{S}/\text{cm}$. The relatively elevated EC values indicate appreciable dissolved ionic content in the groundwater. TDS ranged from 450 to 690 mg/L, with a mean of 560.5 mg/L. Eight of the ten samples exceeded the BIS acceptable value of 500 mg/L for TDS, although none exceeded the permissible limit of 2000 mg/L. The simultaneous increase in EC and TDS suggests that dissolved mineral content contributes substantially to groundwater variability. Similar relationships between EC and dissolved constituents have frequently been reported in Indian groundwater systems, where mineral dissolution, ion exchange and anthropogenic inputs collectively influence groundwater mineralization [9].

Table 4. Original physicochemical and microbiological groundwater dataset

Sample ID	pH	EC (µS/cm)	TDS (mg/L)	Turbidity (NTU)	NO ₃ ⁻ (mg/L)	Cl ⁻ (mg/L)	K ⁺ (mg/L)	PO ₄ ³⁻ (mg/L)	Fe (mg/L)	F ⁻ (mg/L)	As (mg/L)	Total Hardness (mg/L as CaCO ₃)	Total Coliform (MPN/100 mL)	Faecal Coliform (MPN/100 mL)
GW1	7.2	820	520	2.8	38	72	8.5	0.42	0.85	0.62	0.012	310	240	70
GW2	7.5	910	580	3.1	44	85	9.1	0.55	1.02	0.74	0.018	345	460	140
GW3	7.1	760	480	2.4	29	60	7.8	0.36	0.65	0.58	0.009	280	110	30
GW4	6.9	1020	640	4.2	52	110	10.3	0.71	1.45	0.81	0.026	390	920	280
GW5	7.3	870	550	3.6	41	79	8.9	0.49	0.98	0.69	0.015	325	330	100
GW6	7.0	950	600	3.9	47	95	9.8	0.63	1.28	0.77	0.021	360	680	210
GW7	7.4	700	450	2.1	24	55	7.2	0.28	0.54	0.52	0.007	265	60	18
GW8	6.8	1085	690	4.8	58	125	11.0	0.82	1.62	0.88	0.031	420	1200	360
GW9	7.6	790	505	2.7	33	68	8.0	0.39	0.73	0.60	0.011	295	180	50
GW10	7.2	930	590	3.4	46	92	9.5	0.58	1.10	0.76	0.019	350	520	160

Table 5. Descriptive statistics of physicochemical and microbiological parameters of groundwater

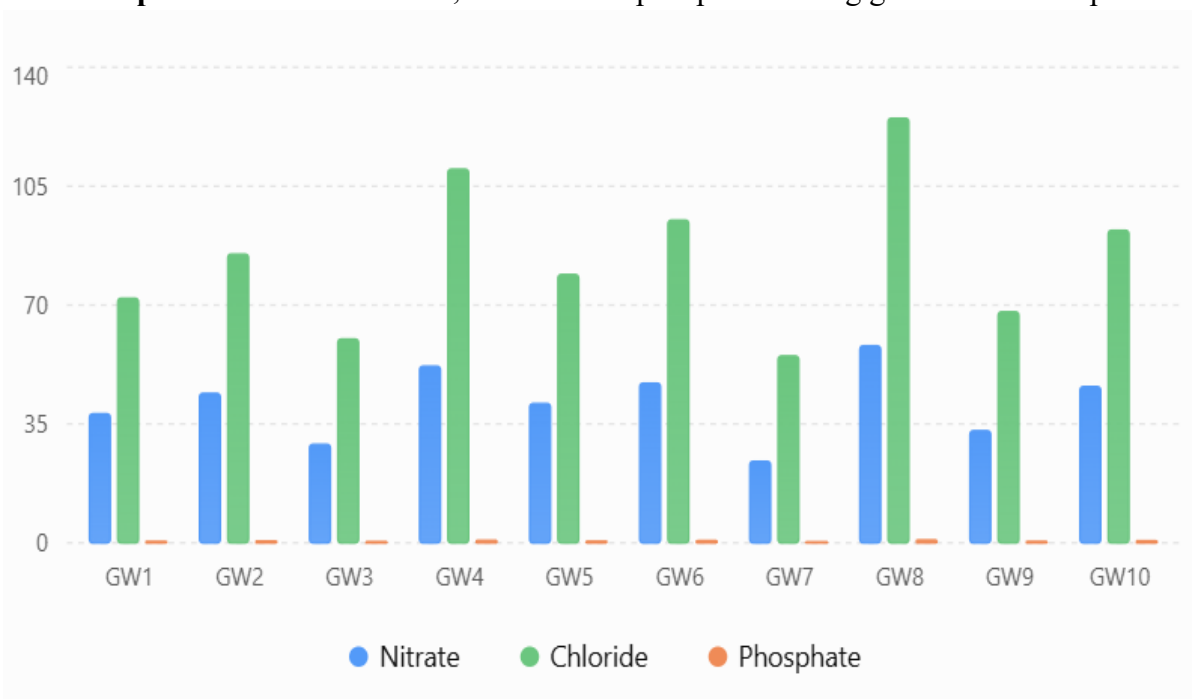
Parameter	Mean ± SD	Minimum	Maximum	CV (%)
pH	7.20 ± 0.26	6.80	7.60	3.58
EC (µS/cm)	883.5 ± 119.44	700	1085	13.52
TDS (mg/L)	560.5 ± 74.10	450	690	13.22
Turbidity (NTU)	3.30 ± 0.85	2.10	4.80	25.61
Nitrate (mg/L)	41.20 ± 10.47	24	58	25.40
Chloride (mg/L)	84.10 ± 22.07	55	125	26.24
Potassium (mg/L)	9.01 ± 1.18	7.20	11.00	13.10
Phosphate (mg/L)	0.523 ± 0.168	0.280	0.820	32.12
Iron (mg/L)	1.022 ± 0.350	0.540	1.620	34.25
Fluoride (mg/L)	0.697 ± 0.114	0.520	0.880	16.36
Arsenic (mg/L)	0.017 ± 0.008	0.007	0.031	47.06
Total hardness (mg/L as CaCO ₃)	334.0 ± 48.81	265	420	14.61
Total coliform (MPN/100 mL)	470.0 ± 370.65	60	1200	78.86
Faecal coliform (MPN/100 mL)	141.8 ± 112.97	18	360	79.66

The highest EC and TDS values were recorded at GW8 (1085 $\mu\text{S}/\text{cm}$ and 690 mg/L), followed by GW4 and GW6. These samples also exhibited comparatively high nitrate, chloride, phosphate and microbial concentrations. This co-occurrence is important because elevated dissolved-solute concentrations in shallow urban groundwater may reflect a combination of natural water-rock interaction and surface-derived anthropogenic inputs. Therefore, EC and TDS should be interpreted as general indicators of groundwater mineralization rather than as direct indicators of sanitation contamination.

3.2 Turbidity and major nutrient indicators

Turbidity varied from 2.1 to 4.8 NTU, with an average of 3.30 ± 0.85 NTU. GW8 recorded the highest turbidity, followed by GW4 and GW6. All samples exceeded the desirable turbidity value of 1 NTU, although none exceeded 5 NTU. Elevated turbidity in shallow groundwater may result from suspended mineral particles, poorly developed wells, disturbed sediments or infiltration of surface-derived material. More importantly in the present study, turbidity showed a positive relationship with faecal-coliform concentration, suggesting that samples with greater particulate loading also tended to show greater microbial contamination.

Graph 1. Variation of nitrate, chloride and phosphate among groundwater sample



Nitrate concentrations ranged from 24 to 58 mg/L , with a mean of 41.2 ± 10.47 mg/L . Four samples, namely GW2, GW4, GW6 and GW8, exceeded the BIS acceptable concentration of 45 mg/L . GW8 recorded the maximum nitrate concentration of 58 mg/L . Nitrate is particularly useful in evaluating anthropogenic groundwater contamination because elevated concentrations can originate from sewage, septic systems, animal waste and agricultural nitrogen inputs. Studies from the Middle Gangetic Plain have similarly identified anthropogenic sources as important contributors to elevated groundwater nitrate, particularly in densely settled areas [10].

The spatial pattern of nitrate is noteworthy because GW4, GW6 and GW8 also exhibited elevated total and faecal coliform concentrations. This concurrent occurrence strengthens the interpretation that sanitation-related inputs may contribute to groundwater contamination at these locations. However, nitrate alone cannot conclusively identify sewage as its source because fertilizer application and natural nitrogen cycling can also contribute to groundwater nitrate.

Chloride concentrations ranged from 55 to 125 mg/L, averaging 84.1 ± 22.07 mg/L. All samples were below the BIS acceptable limit of 250 mg/L. Nevertheless, chloride displayed a strong positive relationship with microbial indicators in the present dataset. Chloride is relatively conservative in many groundwater systems and is commonly used as a tracer of anthropogenic loading, particularly when interpreted together with nitrate and microbial indicators. Investigations of sanitation-impacted alluvial aquifers have similarly used the combined behaviour of chloride, nitrate and faecal indicators to identify possible contamination from on-site sanitation systems.

Phosphate ranged from 0.28 to 0.82 mg/L, with the highest concentration recorded at GW8. Although phosphate does not have a direct drinking-water guideline comparable with nitrate, its presence at measurable concentrations can provide supporting evidence of anthropogenic nutrient loading when considered alongside nitrate, potassium, chloride and microbial indicators. The relatively high phosphate concentrations at GW4, GW6 and GW8 therefore provide additional support for investigating sanitation-related nutrient inputs.

3.3 Iron, fluoride, arsenic and total hardness

Iron concentrations ranged from 0.54 to 1.62 mg/L, with a mean of 1.02 ± 0.35 mg/L. All ten samples exceeded the BIS acceptable concentration of 0.3 mg/L. The highest iron concentration occurred at GW8, followed by GW4 and GW6. Elevated iron is common in groundwater systems of Bihar and may have a strong geogenic component associated with aquifer sediments and groundwater redox conditions. A statewide investigation of Bihar groundwater reported substantial spatial variability in iron and demonstrated that groundwater geochemistry in the region is strongly influenced by redox conditions and sedimentary aquifer characteristics [8]. Therefore, the elevated iron concentrations observed in the present study should not be attributed solely to sanitation-derived contamination.

Fluoride concentrations ranged from 0.52 to 0.88 mg/L, with a mean of 0.697 ± 0.114 mg/L. All samples remained below the WHO guideline value of 1.5 mg/L. The relatively narrow range indicates that fluoride was not a major drinking-water-quality constraint within the present dataset. Similar regional investigations have reported considerable spatial variation in fluoride in Bihar, although elevated fluoride is generally more prominent in specific hydrogeological settings south of the Ganga rather than being uniformly distributed throughout the state.

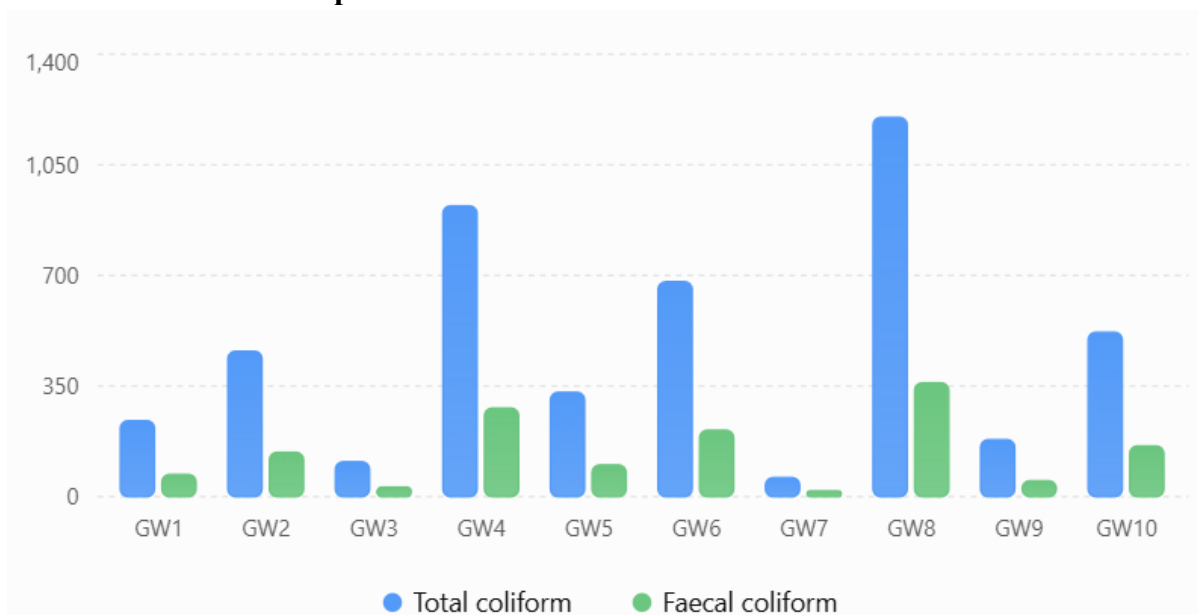
Arsenic concentrations ranged from 0.007 to 0.031 mg/L, with a mean of 0.017 ± 0.008 mg/L. Eight of the ten samples exceeded the WHO guideline value of 0.01 mg/L, although none exceeded 0.05 mg/L. The highest arsenic concentration was observed at GW8 (0.031 mg/L), followed by GW4 (0.026 mg/L). This finding is particularly relevant because arsenic is a well-established geogenic groundwater contaminant in the Middle Gangetic Plain. Richards et al. (2020) reported substantial spatial heterogeneity of arsenic in Bihar groundwater and identified associations with iron, redox conditions and groundwater depth. Consequently, the arsenic concentrations observed here should be interpreted primarily within a geogenic hydrogeochemical framework, rather than being automatically attributed to sanitation [8].

Total hardness ranged from 265 to 420 mg/L as CaCO_3 , with a mean of 334 ± 48.81 mg/L. All samples exceeded the BIS desirable value of 200 mg/L but remained below the permissible limit of 600 mg/L. The observed hardness indicates moderately to highly hard groundwater and may primarily reflect dissolution of calcium- and magnesium-bearing minerals within the alluvial aquifer. Hardness therefore represents an important hydrochemical characteristic but is not, by itself, evidence of sanitation-derived contamination.

3.4 Microbiological quality of groundwater

The microbiological results reveal a clear sanitary-quality concern. Total coliform concentrations ranged from 60 to 1200 MPN/100 mL, with a mean of 470 MPN/100 mL, whereas faecal coliform concentrations ranged from 18 to 360 MPN/100 mL, with a mean of 141.8 MPN/100 mL.

Graph 2. Distribution of total and faecal coliforms.



The highest concentrations of both total and faecal coliforms were recorded at GW8, where total coliform and faecal coliform concentrations reached 1200 and 360 MPN/100 mL, respectively. GW4 and GW6 also showed comparatively high microbial concentrations. GW7 had the lowest microbial concentrations, with 60 MPN/100 mL total coliform and 18 MPN/100 mL faecal coliform.

The detection of faecal coliforms in all ten groundwater samples indicates widespread microbial contamination within the present dataset. This is important because microbiological safety cannot be inferred solely from acceptable physicochemical characteristics. Large-scale systematic reviews have demonstrated that faecal contamination can occur even in improved drinking-water sources, emphasizing the importance of direct microbiological assessment rather than relying exclusively on source type or chemical measurements [11].

The distribution observed here is also consistent with investigations of sanitation-impacted alluvial aquifers in India, where faecal indicators were detected in shallow groundwater associated with on-site

sanitation systems. Such studies have identified nitrate, chloride and faecal indicators as useful complementary parameters for evaluating sanitation-related groundwater contamination.

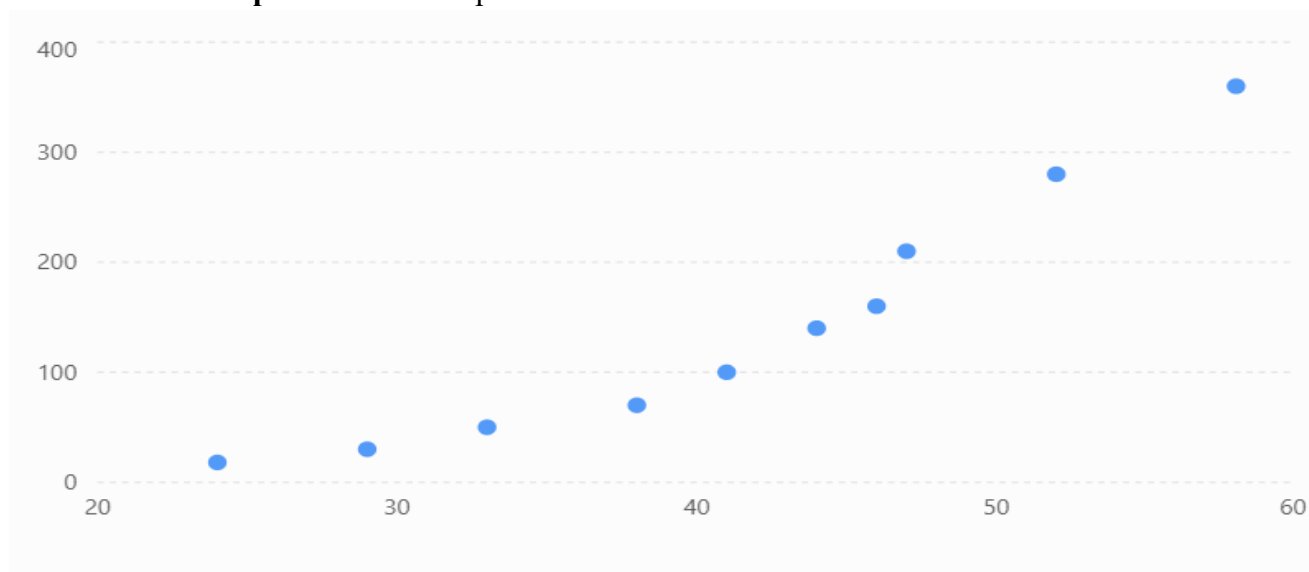
3.5 Relationship between hydrochemical and microbiological indicators

Pearson correlation analysis revealed strong positive associations between microbial indicators and several hydrochemical parameters (Table 6).

Table 6. Pearson correlation coefficients between microbial indicators and selected hydrochemical parameters

Parameter	Total coliform, r	Faecal coliform, r
EC	0.981	0.982
TDS	0.980	0.981
Turbidity	0.940	0.945
Nitrate	0.991	0.991
Chloride	0.984	0.991
Phosphate	0.973	0.986
Iron	0.980	0.987
Arsenic	0.992	0.994
Total hardness	0.982	0.984

Graph 3. Relationship between nitrate and faecal coliform concentration



The strongest association with faecal coliform was observed for arsenic ($r = 0.994$), chloride ($r = 0.991$), nitrate ($r = 0.991$) and phosphate ($r = 0.986$), followed by iron, hardness, EC, TDS and turbidity. Nitrate and chloride are particularly important because both can increase through anthropogenic inputs, while phosphate can provide additional evidence of nutrient enrichment.

The strong association between nitrate and faecal coliform is consistent with the conceptual expectation that sanitation-derived nitrogen and microbial indicators may enter shallow groundwater through related contamination pathways. Similar relationships have been observed in Indian alluvial settings where nitrate and faecal contamination were evaluated together as indicators of on-site sanitation impacts.

However, correlation does not establish a direct causal relationship. In particular, the strong association between arsenic and coliform concentrations should not be interpreted as evidence that sanitation caused arsenic contamination. Arsenic in Bihar groundwater has well-established geogenic controls involving sediment composition and redox processes [8]. The correlation observed in the present dataset is therefore better interpreted as a statistical co-occurrence requiring further hydrogeological investigation.

The strength of the correlations should also be interpreted cautiously because the present dataset contains only 10 samples. Larger spatially distributed datasets and repeated seasonal sampling would be necessary to establish robust source relationships.

3.6 Integrated Findings

The integrated hydrochemical and microbiological assessment demonstrates substantial spatial heterogeneity in shallow groundwater quality across Patna City. GW8 represented the most pronounced contamination profile, recording the maximum concentrations of EC (1085 $\mu\text{S}/\text{cm}$), TDS (690 mg/L), turbidity (4.8 NTU), nitrate (58 mg/L), chloride (125 mg/L), phosphate (0.82 mg/L), iron (1.62 mg/L), arsenic (0.031 mg/L), total hardness (420 mg/L), total coliform (1200 MPN/100 mL) and faecal coliform (360 MPN/100 mL). GW4 and GW6 showed the next most pronounced contamination patterns, whereas GW7 generally exhibited the lowest concentrations. This spatial variability indicates that groundwater quality is strongly influenced by local hydrogeological and anthropogenic conditions rather than being uniform throughout the study area [14,15].

The combined occurrence of nitrate, chloride, phosphate and faecal-coliform contamination provides the strongest evidence for potential sanitation-related influence. Nitrate exceeded 45 mg/L in four samples, namely GW4 (52 mg/L), GW6 (47 mg/L), GW8 (58 mg/L) and GW10 (46 mg/L), while these locations also exhibited comparatively elevated faecal-coliform concentrations. The maximum nitrate, chloride, phosphate and microbial concentrations occurred simultaneously at GW8. Such co-occurrence is consistent with observations from other Indian alluvial aquifers where nitrate, chloride and faecal coliforms have been used together to evaluate contamination associated with on-site sanitation systems. Quamar et al. (2017), for example, identified nitrate, chloride and faecal coliforms as critical indicators of sanitation-related groundwater contamination in an alluvial setting and reported the presence of faecal contamination in groundwater affected by on-site sanitation [2].

The microbiological results are particularly significant because faecal coliforms were detected in all ten samples, ranging from 18 to 360 MPN/100 mL. Total coliform concentrations ranged from 60 to 1200 MPN/100 mL. The approximately twenty-fold difference in total and faecal coliform concentrations between GW7 and GW8 demonstrates substantial local variation in sanitary quality. The presence of faecal indicators indicates that the groundwater sources require appropriate treatment before direct drinking-water use. Previous investigations in Indian urban alluvial settings have similarly demonstrated that shallow groundwater can be affected by sanitation-derived microbial contamination, although the degree of contamination depends strongly on local hydrogeological conditions and sanitation infrastructure.

The correlation analysis further supports the observed contamination pattern. Faecal coliforms showed strong positive correlations with nitrate ($r = 0.991$), chloride ($r = 0.991$), phosphate ($r = 0.986$), turbidity

($r = 0.945$), EC ($r = 0.982$) and TDS ($r = 0.981$). The strong relationship between nitrate and faecal coliforms is particularly relevant because nitrate enrichment and faecal contamination may occur through interconnected sanitation pathways in shallow groundwater. However, these correlations should be interpreted as associations rather than definitive evidence of a common contamination source, particularly because nitrate and chloride may also originate from fertilizers, domestic wastewater and other urban sources.

The elevated arsenic and iron concentrations require a separate interpretation. Arsenic exceeded the WHO guideline value of 0.01 mg/L in eight samples, while iron exceeded 0.3 mg/L in all ten samples. These findings are consistent with the well-documented occurrence of geogenic arsenic and associated groundwater geochemistry in Bihar. Richards et al. (2020), based on 273 groundwater samples covering Bihar, demonstrated that arsenic occurrence is highly heterogeneous and is associated with geochemical conditions including iron, manganese, redox status and groundwater depth. Earlier work specifically examining Patna district also documented extensive groundwater arsenic contamination, confirming that arsenic represents an important regional groundwater-quality concern. Therefore, the strong statistical association between arsenic and microbial indicators in the present ten-sample dataset should not be interpreted as evidence that sanitation is responsible for arsenic mobilization. [8,13]

4. Conclusion

Overall, the study demonstrates that shallow groundwater in the investigated areas of Patna City is characterized by localized but substantial hydrochemical and microbiological contamination. The co-occurrence of elevated nitrate, chloride, phosphate, turbidity and faecal-coliform concentrations, particularly at GW4, GW6 and GW8, is consistent with potential sanitation-related influence on shallow groundwater quality. GW8 represents the most pronounced contamination profile in the present dataset. At the same time, arsenic and iron should be interpreted primarily within the context of the established geogenic characteristics of Bihar's alluvial aquifers rather than being attributed directly to sanitation sources.

The findings demonstrate the value of combining hydrochemical parameters with MPN-based microbiological indicators for groundwater-quality assessment. Chemical measurements alone would not have captured the extent of sanitary contamination indicated by the universal detection of faecal coliforms. The results therefore support regular monitoring of both chemical and microbiological parameters, improved protection of shallow groundwater sources, better sanitation management and appropriate treatment of groundwater before domestic consumption. Further investigation using a larger number of sampling locations, seasonal sampling and source-specific tracers would be valuable for confirming contamination pathways and distinguishing sanitation-derived inputs from natural geochemical processes.

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