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IMPACT OF SEASONAL CHANGES ON GROUNDWATER QUALITY IN SANITATION-INFLUENCED AREAS OF VILLAGE SHEIKHPURA, PATNA, BIHAR

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ABSTRACT

Groundwater quality is crucial for rural communities, especially in regions where sanitation practices directly influence aquifer health. This study evaluates the impact of seasonal changes on the physico-chemical characteristics of groundwater in Sheikhpura village, Patna, Bihar, India, with particular attention to the role of onsite sanitation systems. Water samples were systematically collected from hand pumps and shallow wells over three distinct seasons—pre-monsoon, monsoon, and post-monsoon. Each sample was analyzed for pH, temperature, electrical conductivity (EC), total dissolved solids (TDS), total hardness, alkalinity, nitrate, chloride, phosphate phosphorus, and major ions (Na^+, K^+, Ca^{2+}), adopting standard APHA (1998) protocols.

The results reveal pronounced seasonal variations in water quality, with contamination levels peaking during the monsoon, attributed to increased surface runoff and leaching from sanitation sources. Greater fluctuations in parameters were observed in summer and rainy seasons, indicating vulnerability of groundwater sources to contamination due to dynamic recharge and dilution patterns. The study demonstrates the need for regulated distances between drinking water sources and sanitation structures, enhanced sanitation design and routine monitoring to mitigate risks to safe drinking water.

The aim of this research is to inform policy decisions and guide local interventions for safe water supply by highlighting seasonal vulnerabilities in sanitation-influenced rural aquifers.

KEYWORDS: *Groundwater Quality, Seasonal Variation, Physico-Chemical Parameters, Sanitation Impact, Sheikhpura, Bihar, India.*

INTRODUCTION

Groundwater serves as the cornerstone of rural water supply across the Indo-Gangetic Plains, providing drinking water to millions of households that depend on shallow aquifers for their daily needs. In the absence of reliable piped-water networks, hand pumps and dug wells become fundamental lifelines that sustain communities. These aquifers, however, are increasingly threatened by growing anthropogenic pressures, especially from onsite sanitation systems situated near water abstraction points. As rural settlements expand in population and density, the distance between sanitation structures and household wells has progressively reduced, inadvertently creating a direct pathway for chemical and microbial contaminants to seep into groundwater (Graham & Polizzotto, 2013; Howard et al., 2003). This issue is of particular concern in regions where hydrogeological properties favour rapid infiltration, weak natural attenuation, and shallow water levels, making aquifers highly vulnerable to pollution.

The state of Bihar exemplifies such conditions. Its terrain, perched within the sediment-rich alluvial formations of the Ganga River basin, features permeable sandy to silty soils, fluctuating water tables, and high hydraulic conductivities. These characteristics, while conducive to quick aquifer recharge, also heighten the risk of contamination transport. Seasonal hydrological shifts shape the chemical nature of groundwater, creating distinct patterns during pre-monsoon, monsoon, and post-monsoon periods. Before the monsoon, declining water tables often result in the concentration of dissolved solids, salinity, hardness, and major ions (Rangarajan & Athavale, 2000). When the monsoon arrives, dramatic increases in rainfall and surface infiltration can dilute certain parameters while simultaneously flushing contaminants from sanitation sources, agricultural fields, and waste disposal zones into groundwater. These dynamics underscore the complexity of aquifer behaviour in rural areas (Mukherjee et al., 2011; Lapworth et al., 2017).

Global and regional studies further validate this phenomenon. Research from South Asia, Africa, and Latin America consistently reports that seasonal rainfall patterns influence groundwater chemistry and microbial quality, especially in shallow aquifers exposed to sanitation structures. Increases in nitrate, phosphate, turbidity, iron, and chloride during monsoon months have been documented in India, Bangladesh, Tanzania, and Uganda, with clear evidence linking contamination to pit latrines, unlined septic systems, and domestic wastewater discharge (Islam et al., 2016; Sorensen et al., 2015; Kulabako et al., 2010). In India, several studies in Uttar Pradesh, Bihar, and West Bengal have linked elevated nitrate levels to latrine leaching, often observing concentrations that exceed health-based standards during monsoon and post-monsoon periods (Mahara et al., 2017; Jain et al., 2020). These findings echo WHO's guidance that the effectiveness of sanitation systems depends largely on construction quality, soil conditions, and safe distances from groundwater sources (WHO, 2017).

Despite a growing body of research, significant knowledge gaps persist, particularly in the context of rural groundwater systems in Bihar. First, most studies focus heavily on microbial contamination, while detailed assessments of physico-chemical parameters across multiple seasons remain comparatively limited. Yet parameters such as nitrate, chloride, alkalinity, hardness, major ions, iron, fluoride, and phosphate are equally important indicators of aquifer vulnerability and drinking water safety. Second, village-scale assessments that capture micro-level spatial variability are scarce, even though such environments represent the majority of rural settlements. Third, there is insufficient empirical evidence that examines the combined influence of seasonal hydrology and sanitation proximity on groundwater quality within the same study area. Fourth, although Bihar is recognized as a high-risk state for sanitation-related groundwater contamination, published literature specifically addressing rural settlements like Sheikhpura remains minimal, leaving policy-makers and community institutions with limited locally relevant data.

Given these gaps, a detailed multi-seasonal investigation becomes essential to understand how sanitation practices affect groundwater quality in villages where drinking water sources are shallow and unprotected. Sheikhpura village in Patna district provides a relevant case due to its reliance on hand pumps, close placement of sanitation structures, and seasonal fluctuations in groundwater levels. This study analyzes the groundwater quality across pre-monsoon, monsoon, and post-monsoon seasons, using a wide range of physico-chemical parameters such as pH, EC, TDS, nitrate, chloride, hardness, alkalinity, iron, fluoride, phosphate, and major ions. By comparing seasonal shifts and identifying contamination-sensitive periods, the study aims to contribute evidence for safer water supply planning, improved sanitation siting guidelines, and enhanced monitoring frameworks for rural aquifers.

OBJECTIVES OF THE STUDY

Based on the review of existing literature and identified gaps, the present study aims to:

1. **Assess the seasonal variability** of physico-chemical parameters in groundwater sources of Sheikhpura village during pre-monsoon, monsoon, and post-monsoon periods.
2. **Examine the influence of onsite sanitation systems** on groundwater quality by analyzing contamination-sensitive parameters such as nitrate, chloride, hardness, alkalinity, iron, fluoride, and phosphate.
3. **Identify periods of heightened contamination vulnerability** associated with monsoon-driven recharge and fluctuating groundwater levels.
4. **Provide evidence-based recommendations** for improving sanitation placement, groundwater monitoring, and drinking water safety in rural sanitation-influenced aquifers.

METHODOLOGY

Study Design and Sampling Framework

This study was conducted in Sheikhpura village of Patna district, Bihar, a densely populated rural settlement where groundwater extracted from hand pumps and shallow wells serves as the primary source of drinking water. To assess the seasonal influence of sanitation systems on groundwater quality, systematic sampling was performed during three hydrological seasons:

1. **Pre-monsoon (April–May)** representing the lowest groundwater levels,
2. **Monsoon (July–August)** characterized by intense recharge and high infiltration, and
3. **Post-monsoon (October–November)** depicting aquifer stabilization after rainfall recession.

A total of 20 groundwater sampling locations (S1–S20) were selected to capture spatial variability. These sites were chosen based on:
(a) Proximity to onsite sanitation systems (pit latrines, septic tanks, soak pits)
(b) Representative coverage of household hand pumps and shallow wells
(c) local hydrogeological setting, including soil type, depth to water table, and settlement density.
Sampling points were geo-referenced using a handheld GPS unit.
At each location, separate samples were collected during all three seasons, generating a total of 60 samples for physico-chemical analysis.

Sample Collection and Preservation

Groundwater samples were collected following standard procedures recommended by the American Public Health Association (APHA, 2017) and BIS IS:3025 series.

Before sampling, hand pumps were purged for 3–5 minutes to remove stagnant water. Pre-cleaned high-density polyethylene (HDPE) bottles (500 mL) were rinsed three times with sample water prior to final collection.

For parameters prone to oxidation or volatilization (iron, nitrate, phosphate, and major ions), samples were preserved as follows:

- **Iron and metals**: acidified to pH < 2 using ultrapure nitric acid.

- **Nutrients (NO_3^-, PO_4^{3-})**: stored at 4°C in iceboxes.
- **Unacidified samples**: used for pH, EC, TDS, alkalinity, and hardness.

All samples were transported to the laboratory and analyzed within 24 hours to minimize physico-chemical changes.

Sample No.	Site	Latitude	Longitude	Depth of ground water source(feet)	Depth of Soakpit(feet)	Distance between source & Soakpit(feet)
1	Sheikhpura	25.466754°	84.999677°	145	9	3
2	Sheikhpura	25.466474°	84.999697°	160	10	3
3	Sheikhpura	25.466234°	84.999583°	165	12	4
4	Sheikhpura	25.466238°	84.999887°	150	10	6
5	Sheikhpura	25.466466°	85.000543°	160	10	3
6	Sheikhpura	25.4670794°	84.999952°	155	7	1.5
7	Sheikhpura	25.467108°	84.999866°	136	9	1
8	Sheikhpura	25.467660°	85.000777°	155	9	8
9	Sheikhpura	25.466552°	85.001265°	160	10	2
10	Sheikhpura	25.466553°	85.001264°	165	9	3
11	Parsotimpur	25.466646º	85.000958º	140	10	4
12	Sheikhpura	25.464751º	84.995892º	160	12	3
13	Dihra	25.46436º	84.995242º	155	9	2
14	Sheikhpura	25.466683º	84.99936º	140	10	4
15	Sheikhpura	25.466683º	84.99936º	170	12	5
16	Sheikhpura	25.466239º	84.996217º	165	10	6
17	Dihra	25.46655º	84.995634º	150	13	3
18	Sheikhpura	25.466239º	84.996217º	160	11	2
19	Sheikhpura	25.467335 º	84.996215 º	170	10	4
20	Sheikhpura	25.467535 º	84.996515 º	165	12	5

Physico-Chemical Analysis:All analytical procedures adhered to APHA Standard Methods for the Examination of Water and Wastewater (23rd Edition, 2017). The following parameters were analyzed:

S. No.	Parameter	Method Used (APHA / Standard Method)	Unit
1	pH	Electrometric Method	—
2	Electrical Conductivity	Conductivity Meter	µS/cm
3	Total Dissolved Solids	Conductivity–TDS Conversion / Gravimetric	mg/L
4	Turbidity	Nephelometric Method	NTU
5	Salinity	Conductivity-based Estimation	ppt / %
6	Nitrate (NO_3^-)	UV Spectrophotometric Method	mg/L
7	Chloride (Cl^-)	Argentometric Titration	mg/L
8	Total Hardness	EDTA Titrimetric Method	mg/L
9	Calcium Hardness	EDTA Titration with Murexide Indicator	mg/L
10	Magnesium Hardness	Derived from Total Hardness & Calcium Hardness	mg/L
11	Alkalinity	Titration Method	mg/L
12	Iron (Fe)	Phenanthroline Colorimetric Method	mg/L
13	Fluoride (F^-)	Ions-Selective Electrode method	mg/L
14	Sodium (Na^+)	Flame Photometry	mg/L
15	Potassium (K^+)	Flame Photometry	mg/L
16	Phosphate (PO_4^{3-})	Ascorbic Acid Method	mg/L
17	Arsenic (As)	SDDC / AAS Method	mg/L

Table 1- Method used for Analysing Parameters

pH

pH represents the intensity of acidity or alkalinity in water and governs several chemical equilibria. It influences the solubility of metals, corrosion potential of pipes, biological activity, and the buffering capacity of groundwater. Deviations from the permissible limits may indicate contamination from sanitation sources, mineral dissolution, or chemical reactions within the aquifer.

Electrical Conductivity (EC)

EC reflects the total ionic content of water and is an indicator of mineralization, salinity, and anthropogenic inputs. Higher EC values often signal increased dissolved salts, leachate infiltration, or contamination from wastewater and sanitation systems.

Total Dissolved Solids (TDS)
TDS measures the combined concentration of all dissolved inorganic and organic substances. Elevated TDS affects taste, palatability,
scaling, and may indicate sewage mixing, salt intrusion, or extensive mineral dissolution.

Turbidity
Turbidity expresses the clarity of water and reflects the presence of suspended particles such as clay, silt, organic debris, and microorganisms. High turbidity can impair disinfection efficiency and may indicate surface runoff, infiltration of contaminants, or poor well protection.

Salinity
Salinity describes the amount of dissolved salts, mainly chlorides, sulfates, and bicarbonates. In rural aquifers, higher salinity may originate from domestic wastewater, agricultural return flow, or geogenic sources, and influences both potability and irrigation suitability.

Nitrate (NO_3^-)
Nitrate is a sensitive indicator of contamination from human and animal waste, pit latrines, septic tanks, and fertilizers. In groundwater, elevated nitrate levels are particularly associated with sanitation leakage and rapid monsoonal recharge, posing potential health risks such as methemoglobinemia.

Chloride (Cl^-)
Chloride is a conservative ion and a key tracer of sewage contamination, domestic wastewater ingress, and mineral dissolution. High chloride concentrations often signal direct infiltration from sanitation systems or surface runoff.

Total Hardness (TH)
Total hardness indicates the concentration of calcium and magnesium ions. Hardness affects the usability of water for domestic purposes and may reflect geogenic mineral dissolution or anthropogenic influences such as wastewater and detergents.

Calcium Hardness
Calcium hardness corresponds to the fraction of hardness contributed by calcium ions. It originates primarily from limestone, gypsum, and soil leaching. Excessive levels may indicate aquifer–rock interaction or seepage from wastewater sources.

Magnesium Hardness
Magnesium hardness arises from magnesium-bearing minerals and contributes to the total hardness of water. Elevated values may result from geological sources or from interaction with wastewater and sanitation effluents.

Alkalinity
Alkalinity represents the buffering capacity of groundwater, mainly attributed to bicarbonates, carbonates, and hydroxides. It regulates pH stability and reflects the influence of carbonate weathering, organic matter degradation, and wastewater seepage.

Iron (Fe)
Iron is commonly found in alluvial aquifers due to natural reductive dissolution of iron-bearing minerals. However, excessive concentrations can also indicate infiltration of organic-rich wastewater. High iron affects taste, staining, and aesthetic quality.

Fluoride (F^-)
Fluoride occurs naturally in groundwater through the dissolution of fluoride-bearing minerals. While trace amounts are beneficial, higher levels can cause dental and skeletal fluorosis. Its concentration varies seasonally with recharge and aquifer chemistry.

Sodium (Na^+)
Sodium is a major cation originating from weathering of minerals, domestic wastewater, and sewage intrusion. Elevated sodium levels influence salinity, water taste, and suitability for drinking and irrigation.

Potassium (K^+)
Potassium is typically low in groundwater due to its strong fixation by clay minerals. Elevated levels may indicate contamination from sewage, detergents, fertilizers, or oxidation of organic matter.

Phosphate (PO_4^{3-})
Phosphate is a strong indicator of contamination from domestic sewage, detergents, and human waste. Due to its low mobility, its presence in groundwater often reflects direct leaching from sanitation structures or surface wastewater infiltration.

Arsenic (As)
Arsenic contamination in alluvial aquifers is commonly linked to natural geochemical processes under reducing conditions. However, changes in redox potential caused by organic-rich sanitation effluents can enhance arsenic mobilization. Its presence poses significant long-term health risks.

RESULT

The seasonal analysis of 60 groundwater samples revealed distinct hydrochemical transitions across the pre-monsoon, monsoon, and post-monsoon periods. These transitions reflect the complex interactions between rainfall-driven recharge, aquifer geochemistry, and the influence of nearby sanitation structures, which are known to significantly reshape groundwater chemistry in densely populated rural environments (Lapworth et al., 2017; Graham & Polizzotto, 2013).

Parameters	pH	Conductivity (µmhos/cm)	Salinity	Turbidity (NTU)	TDS (mg/l)	Nitrate (mg/l)	Chloride (mg/l)	Total Hardness (mg/l)	Calcium Hardness (mg/l)	Magnesium Hardness (mg/l)	Fluoride (mg/l)	Alkalinity (mg/l)	Iron (mg/l)	Sodium	Potassium	Arsenic (mg/l)	Phosphate
BIS:10500 :	**6.5-8.5**	-----		**1-5**	**500-2000**	**0-45**	**250-1000**	**200-600**	**75-200**	**30-100**	**1-1.5**	**200-600**	**0.3**	----	----	**0.01**	---
S-1	6.73	580	0.39	0.2	388	24.50	145	598	187.2	31.28	0.15	396	0.25	28.92	12.06	0.006	0.3
S-2	6.37	367	0.25	0.1	247	8.12	211	560	140.8	80.04	0.12	336	0.12	22.11	10.20	0.002	0.7
S-3	6.79	415	0.29	0.8	279	5.87	213	434	104	9.2	0.18	392	0.06	36.17	11.93	0.010	0.4
S-4	6.96	394	0.20	0.6	265	30.30	214	392	188	10.12	0.19	378	0.30	31.28	21.98	0.015	0.3
S-5	7.65	439	0.30	0.8	294	45.80	214	306	196.8	78.2	0.10	372	0.80	16.46	10.19	0.001	0.3
S-6	6.43	375	0.26	0.6	251	12.40	113	424	196	27.6	0.22	394	0.14	20.62	10.48	0.008	0.7
S-7	7.01	436	0.31	0.9	293	6.53	214	440	144	59.8	0.12	316	0.05	36.75	11.69	0.020	0.9
S-8	6.23	586	0.40	0.1	392	61.25	127	460	191.2	34.46	0.15	422	0.95	45.74	11.02	0.030	1.0
S-9	6.20	401	0.28	0.4	269	7.90	227	486	127	76.36	0.28	310	0.42	43.47	14.74	0.007	1.3
S-10	6.19	324	0.22	0.9	217	3.60	210	514	119.2	91.4	0.17	410	0.02	26.39	10.61	0.000	0.7
S-11	6.44	433	0.29	0.2	291	18.00	214	480	119.2	95.8	0.12	440	0.60	34.03	11.90	0.005	1.7
S-12	6.71	375	0.26	0.4	252	9.75	212	396	140	55.2	0.13	420	0.08	25.85	10.77	0.012	0.8
S-13	6.20	643	0.44	0.2	435	70.15	149	480	136.8	84.64	0.25	560	1.20	98.41	11.04	0.045	0.5
S-14	6.18	1020	0.35	0.5	684	43.00	138	720	170.4	99.64	0.28	470	1.60	58.07	16.31	0.032	0.6
S-15	7.06	388	0.26	0.7	260	12.25	212	340	170.4	43.24	0.19	460	0.18	98.41	11.9	0.009	0.2
S-16	7.11	387	0.26	0.4	260	6.00	112	480	170.4	84.64	0.11	600	0.05	58.07	16.31	0.011	1.5
S-17	6.55	432	0.26	0.5	291	28.50	112	340	136.8	84.64	0.24	460	0.40	14.08	10.02	0.004	1.2
S-18	6.64	392	0.26	0.7	260	4.55	242	480	170.4	84.64	0.17	600	0.06	58.07	16.31	0.001	0.5
S-19	6.57	390	0.26	0.9	260	7.12	127	480	170.4	43.24	0.29	460	0.03	14.08	10.02	0.003	1.8
S-20	6.79	437	0.26	0.5	291	10.50	179	396	140	55.20	0.13	420	0.09	25.85	10.77	0.008	1.3

Table 2- Pre Monsoon

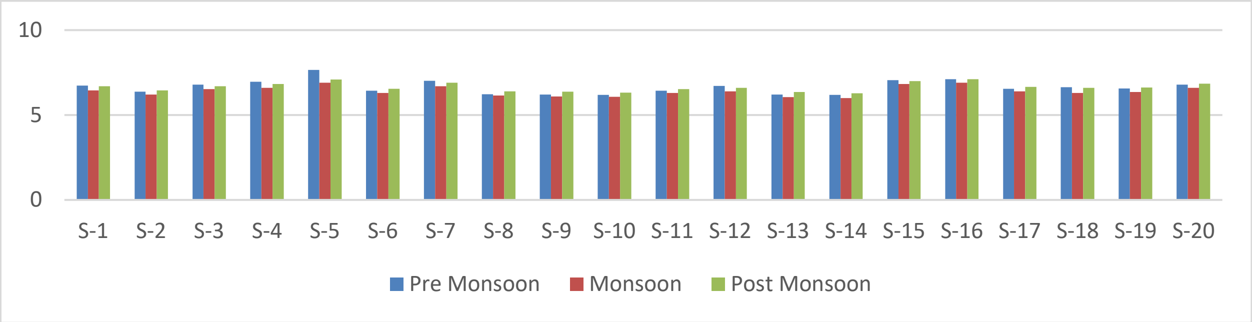
Parameters	pH	Conductivity (µmhos/cm)	Salinity	Turbidity (NTU)	TDS (mg/l)	Nitrate (mg/l)	Chloride (mg/l)	Total Hardness (mg/l)	Calcium Hardness (mg/l)	Magnesium Hardness (mg/l)	Fluoride (mg/l)	Alkalinity (mg/l)	Iron (mg/l)	Sodium	Potassium	Arsenic (mg/l)	Phosphate
BIS:10500: 2012	**6.5-8.5**	**-----**		**1-5**	**500-2000**	**0-45**	**250-1000**	**200-600**	**75-200**	**30-100**	**1-1.5**	**200-600**	**0.3**	**----**	**----**	**0.01**	**---**
S-1	6.45	312	0.29	0.1	210	21.50	135	480	160	20.2	0.038	350	0.30	22.1	11.62	0.004	0.14
S-2	6.21	430	0.18	0.1	290	7.12	201	430	180	60.1	0.010	290	0.15	16.8	10.12	0.001	0.12
S-3	6.52	475	0.21	0.6	320	5.81	203	350	160	6.8	0.030	330	0.08	28.2	11.10	0.006	0.16
S-4	6.60	311	0.20	0.4	210	28.30	210	320	110	8.10	0.007	320	0.42	24.0	21.10	0.009	0.18
S-5	6.90	407	0.22	0.6	240	41.80	200	250	135	52.3	0.096	300	1.10	12.4	10.10	0.001	0.10
S-6	6.30	433	0.21	0.4	297	10.43	111	330	130	20.4	0.018	360	0.20	17.2	10.32	0.006	0.21
S-7	6.70	482	0.23	0.5	330	5.57	203	350	140	41.2	0.025	280	0.09	29.1	11.22	0.014	0.10
S-8	6.15	311	0.28	0.1	210	51.35	121	380	120	26.4	0.069	350	1.20	34.2	17.50	0.022	0.12
S-9	6.10	341	0.24	0.1	230	5.91	220	390	150	62.1	0.014	260	0.50	31.4	12.80	0.005	0.21
S-10	6.08	421	0.14	0.5	280	3.60	211	410	180	95.4	0.005	380	0.05	18.4	10.41	0.000	0.17
S-11	6.30	351	0.19	0.1	240	15.00	213	360	160	92.0	0.011	390	0.42	26.0	11.40	0.004	0.12
S-12	6.40	593	0.18	0.3	398	9.35	211	300	150	46.1	0.018	360	0.12	20.4	10.60	0.010	0.11
S-13	6.05	521	0.34	0.1	350	69.05	150	390	100	70.8	0.088	500	1.42	80.1	85.2	0.028	0.21
S-14	6.00	473	0.30	0.3	320	42.07	139	590	180	150.2	0.052	530	1.85	46.2	12.8	0.021	0.25
S-15	6.82	312	0.22	0.4	210	11.15	202	270	140	31.4	0.007	390	0.22	82.8	87.1	0.006	0.17
S-16	6.90	473	0.21	0.2	320	4.50	113	390	180	72.1	0.009	520	0.08	44.6	12.1	0.008	0.11
S-17	6.40	492	0.21	0.1	340	18.54	115	290	147	70.2	0.016	380	0.50	10.2	10.01	0.002	0.23
S-18	6.30	464	0.19	0.5	310	14.57	240	380	190	68.3	0.005	520	0.11	42.0	12.5	0.001	0.16
S-19	6.35	432	0.20	0.4	293	7.12	120	380	140	36.8	0.007	380	0.06	11.4	10.01	0.002	0.23
S-20	6.60	341	0.20	0.3	230	10.50	173	310	120	45.2	0.011	360	0.12	21.4	10.61	0.005	0.12

Table 3- Monsoon

Parameters	pH	Conductivity (µmhos/cm)	Salinity	Turbidity (NTU)	TDS (mg/l)	Nitrate (mg/l)	Chloride (mg/l)	Total Hardness (mg/l)	Calcium Hardness (mg/l)	Magnesium Hardness (mg/l)	Fluoride (mg/l)	Alkalinity (mg/l)	Iron (mg/l)	Sodium	Potassium	Arsenic (mg/l)	Phosphate
BIS:10500 :	**6.5-8.5**	-----		**1-5**	**500-2000**	**0-45**	**250-1000**	**200-600**	**75-200**	**30-100**	**1-1.5**	**200-600**	**0.3**	----	----	**0.01**	---
S-1	6.70	207	0.31	0.11	140	26.1	257	520	97	25.4	0.41	360	0.22	25.4	11.80	0.005	0.17
S-2	6.45	177	0.20	0.23	120	10.2	281	470	117	65.2	0.11	310	0.12	19.8	10.14	0.001	0.13
S-3	6.70	217	0.24	0.71	150	8.1	293	380	193	8.1	0.32	350	0.05	30.1	11.32	0.007	0.16
S-4	6.82	215	0.23	0.49	140	33.2	307	350	163	9.5	0.08	340	0.30	26.5	21.20	0.011	0.17
S-5	7.10	248	0.25	0.67	170	44.3	291	290	149	60.2	1.00	320	0.90	14.8	10.14	0.001	0.11
S-6	6.55	195	0.23	0.49	130	16.5	211	360	157	25.8	0.20	230	0.12	18.5	10.36	0.007	0.23
S-7	6.90	237	0.25	0.57	160	11.4	313	390	191	48.5	0.28	270	0.06	32.2	11.32	0.015	0.17
S-8	6.40	195	0.30	0.21	130	60.2	371	410	163	31.4	0.75	180	0.80	40.1	19.20	0.024	0.19
S-9	6.38	237	0.27	0.11	160	10.2	220	430	97	70.1	0.16	280	0.38	36.0	13.40	0.006	0.23
S-10	6.32	169	0.18	0.47	110	4.8	291	460	112	102.8	0.06	360	0.03	20.5	10.50	0.000	0.19
S-11	6.52	248	0.21	0.13	170	20.1	313	400	193	98.0	0.13	320	0.35	28.0	11.48	0.005	0.14
S-12	6.61	195	0.20	0.37	130	12.1	311	350	180	50.1	0.22	380	0.10	23.1	10.70	0.014	0.16
S-13	6.35	259	0.36	0.16	180	75.4	250	410	120	76.4	0.92	350	1.10	88.4	95.4	0.032	0.22
S-14	6.28	248	0.33	0.31	170	38.8	199	650	133	170.1	1.60	380	1.50	52.6	14.8	0.024	0.27
S-15	7.00	215	0.24	0.47	140	10.8	272	300	117	35.6	0.08	320	0.16	90.2	96.6	0.006	0.19
S-16	7.12	221	0.23	0.23	150	9.0	213	420	137	79.0	0.10	580	0.06	50.2	14.2	0.009	0.10
S-17	6.65	247	0.24	0.17	170	25.4	215	310	142	76.2	0.18	370	0.32	12.4	10.02	0.003	0.22
S-18	6.60	207	0.22	0.53	140	7.5	293	420	172	72.6	0.06	360	0.08	48.0	14.5	0.001	0.16
S-19	6.62	194	0.23	0.46	130	10.1	227	410	107	40.8	0.09	320	0.04	13.0	10.03	0.003	0.25
S-20	6.85	238	0.23	0.35	160	12.4	251	360	157	52.0	0.12	280	0.08	23.0	10.70	0.006	0.13

Table 4-Post Monsoon

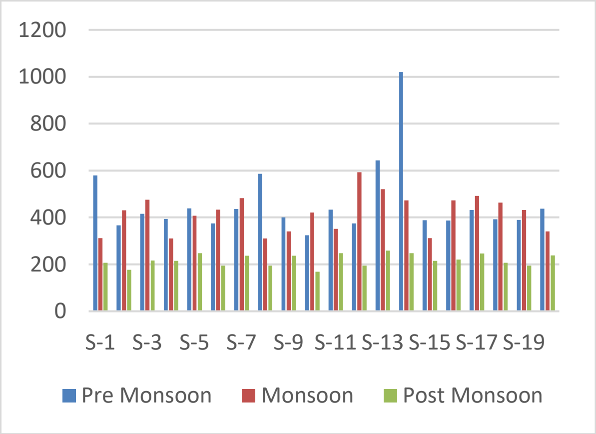
pH



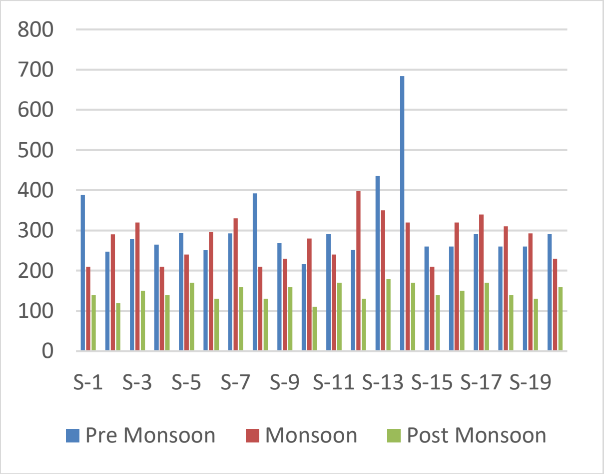
Graph 1: pH

Groundwater pH values ranged from 6.00 to 7.65 across all seasons. Slightly acidic conditions were dominant during the pre-monsoon and monsoon periods, with several samples falling marginally below the BIS desirable limit of 6.5 (Tables 2 and 3). Post-monsoon samples exhibited a shift toward near-neutral conditions (Table 4), indicating improved buffering following recharge. Such seasonal pH moderation is characteristic of carbonate-rich alluvial aquifers (Sharma et al., 2016; Mukherjee et al., 2011).

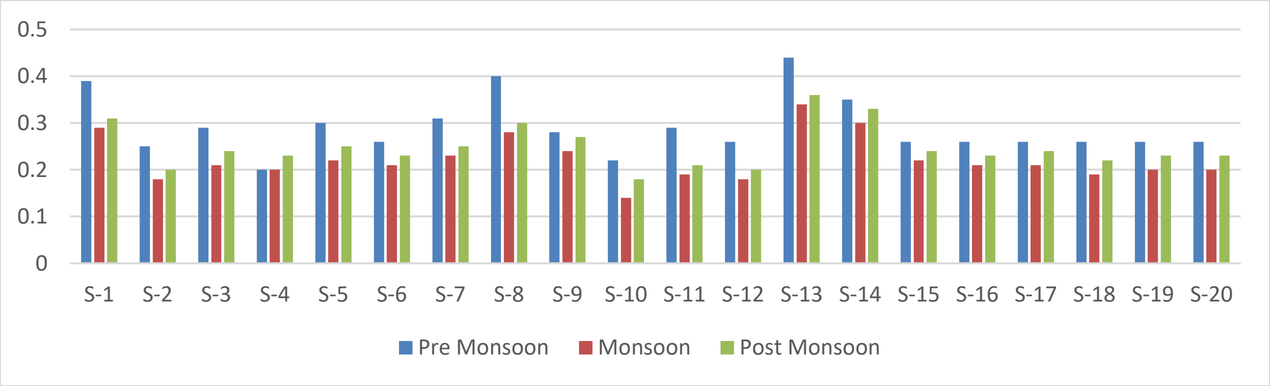
Electrical Conductivity, Salinity, and Total Dissolved Solids



Graph 2: EC



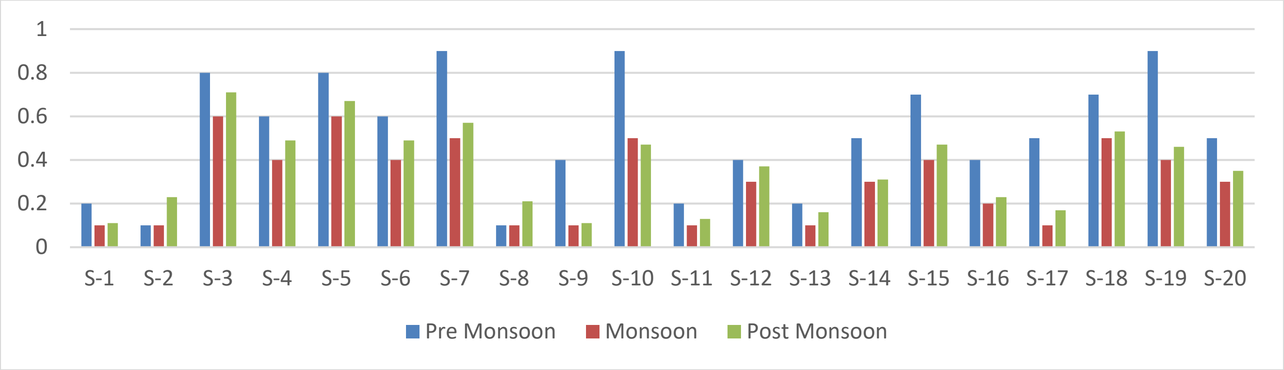
Graph 3: TDS



Graph 4: pH

Electrical conductivity varied widely from 169 to 1020 µS/cm, with the highest values recorded during the pre-monsoon season (Table 2). TDS concentrations ranged between 110 and 684 mg/L, showing minimum values during the monsoon due to dilution effects (Table 3). Post-monsoon samples displayed moderate enrichment, suggesting increased solute mobilisation following aquifer saturation. Similar seasonal dilution and post-monsoon concentration trends have been widely reported in alluvial groundwater systems of northern India (Rao et al., 2015; Lapworth et al., 2017).

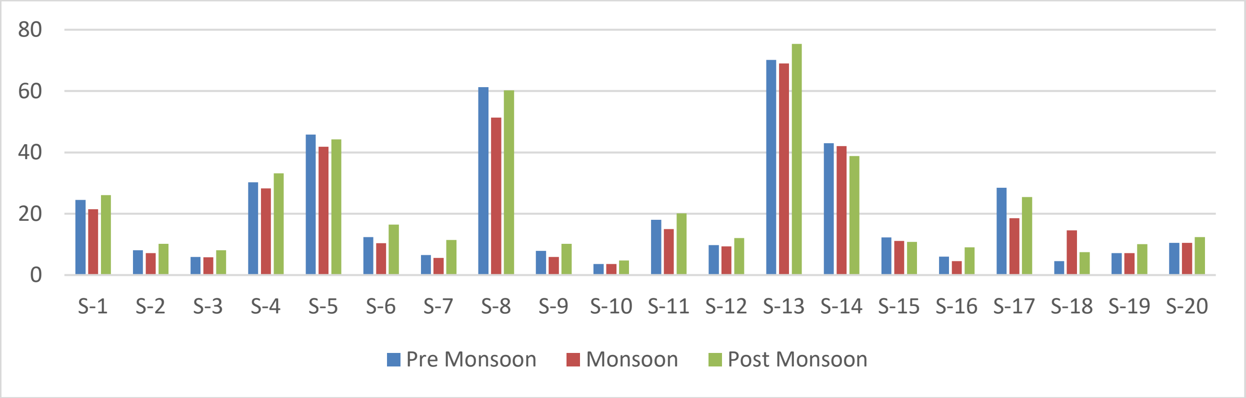
Turbidity



Graph 5: Turbidity

Turbidity remained within BIS permissible limits (0.1–0.9 NTU) throughout the study period. Slight increases during the monsoon season were observed at several locations (Table 3), likely due to infiltration of fine suspended materials and organic matter during rainfall events. Comparable seasonal turbidity patterns have been documented in shallow rural aquifers influenced by surface runoff (Jain et al., 2020).

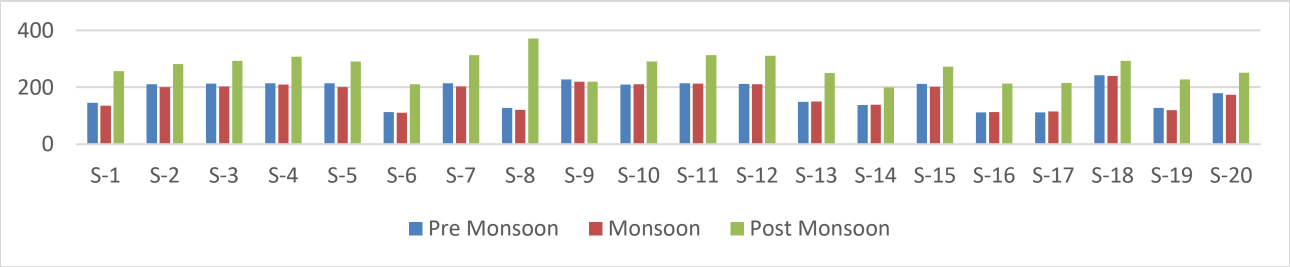
Nitrate (NO_3^-)



Graph 6: Nitrate

Nitrate concentrations ranged from 3.6 to 75.4 mg/L across seasons. Several samples exceeded the BIS guideline value of 45 mg/L, particularly during the monsoon period (Table 3). Elevated nitrate persisted at some locations during pre- and post-monsoon seasons, indicating continuous leaching from onsite sanitation systems. Such nitrate enrichment associated with pit latrines and septic systems has been widely reported in rural groundwater settings (Graham & Polizzotto, 2013; Sorensen et al., 2015; Islam et al., 2016).

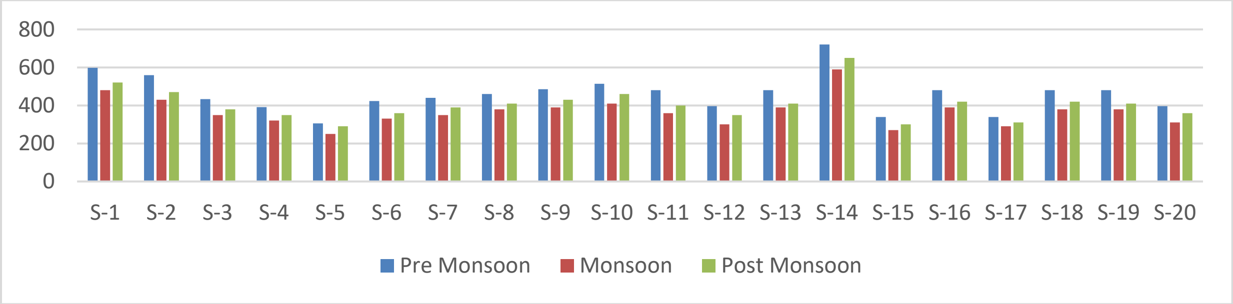
Chloride (Cl^-)



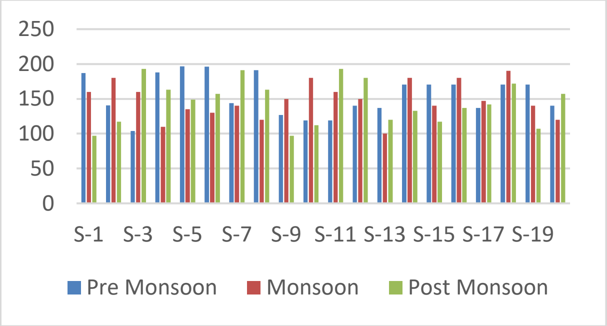
Graph 7: Chloride

Chloride concentrations ranged from 111 to 371 mg/L, with the highest values recorded during the monsoon season (Table 3). As chloride behaves conservatively in groundwater, elevated concentrations suggest infiltration of domestic wastewater during periods of intense recharge. Similar chloride enrichment has been used as a tracer for sanitation-derived contamination in shallow aquifers (Howard et al., 2003; Lapworth et al., 2017).

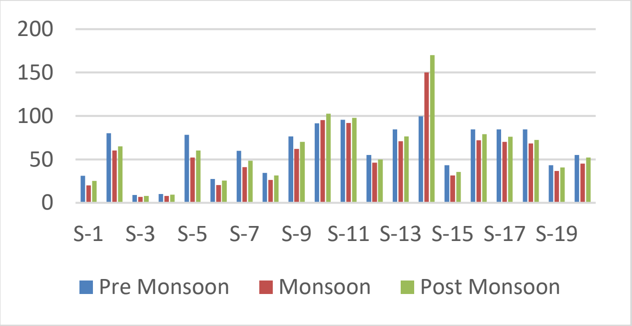
Total Hardness, Calcium, and Magnesium



Graph 8: Total Hardness



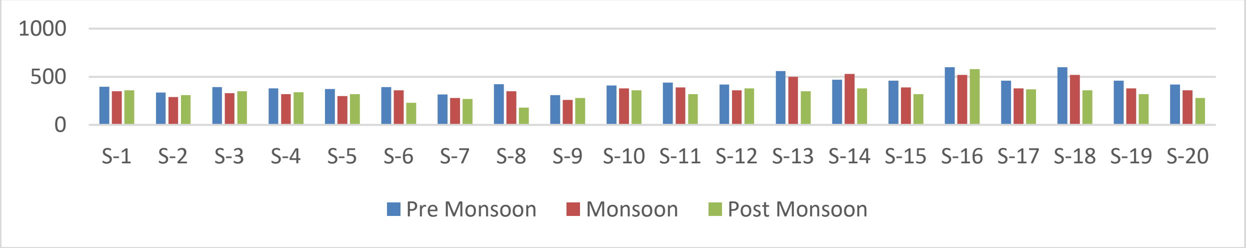
Graph 9: Calcium Hardness



Graph 10: Magnesium Hardness

Total hardness values ranged from 250 to 720 mg/L, classifying groundwater as predominantly hard to very hard. Post-monsoon samples showed comparatively higher hardness at several locations (Table 4). Calcium hardness dominated over magnesium hardness, though magnesium exceeded the BIS desirable limit at selected sites during monsoon and post-monsoon periods. These trends indicate intensified carbonate weathering and water–rock interaction following recharge (Sharma et al., 2016; Rao et al., 2015).

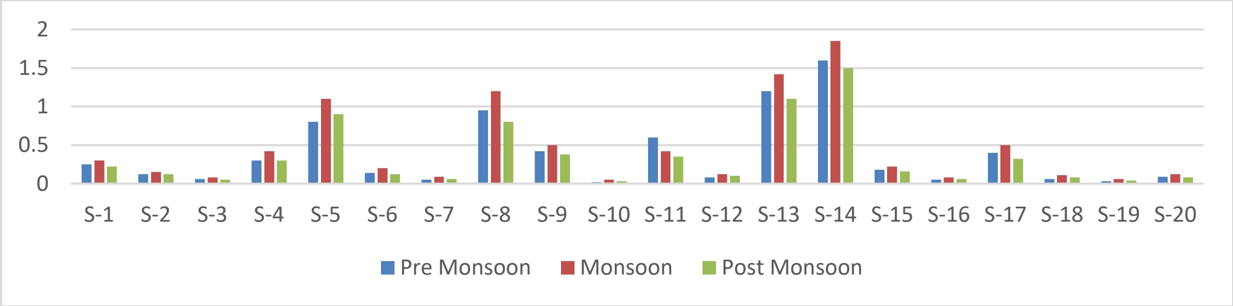
Alkalinity



Graph 11: Alkalinity

Alkalinity values ranged from 180 to 600 mg/L, with higher concentrations generally observed during post-monsoon (Table 4). Elevated alkalinity reflects bicarbonate enrichment due to prolonged groundwater residence time and dissolution of carbonate minerals. Such behaviour is typical of alluvial aquifers influenced by geogenic processes and organic matter degradation (Mukherjee et al., 2011; Lapworth et al., 2017).

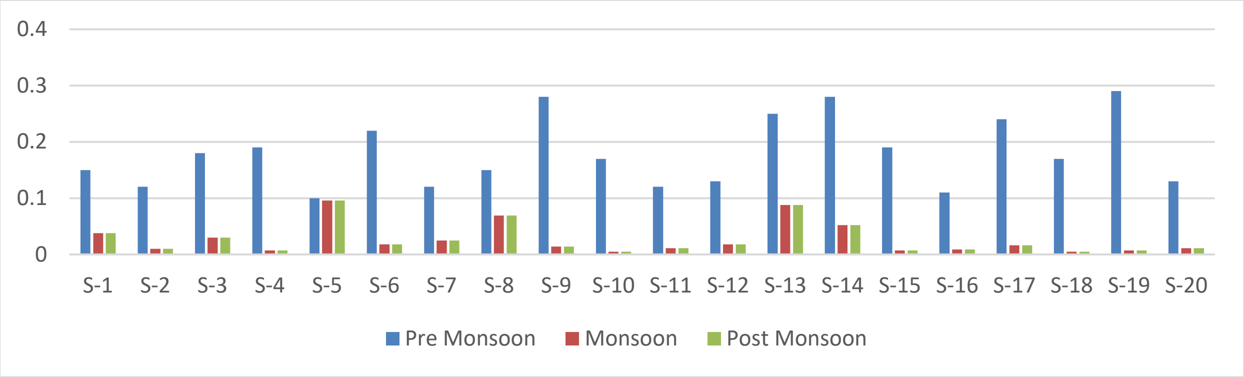
Iron (Fe)



Graph 12: Iron

Iron concentrations varied from 0.02 to 1.85 mg/L. Several samples exceeded the BIS permissible limit of 0.3 mg/L, particularly during monsoon and post-monsoon periods (Tables 3 and 4). Elevated iron levels during these seasons are consistent with reductive dissolution of iron-bearing minerals under organic-rich recharge conditions, a process widely documented in floodplain aquifers of the Ganga basin (Berg et al., 2001; van Geen et al., 2008; Mukherjee et al., 2011).

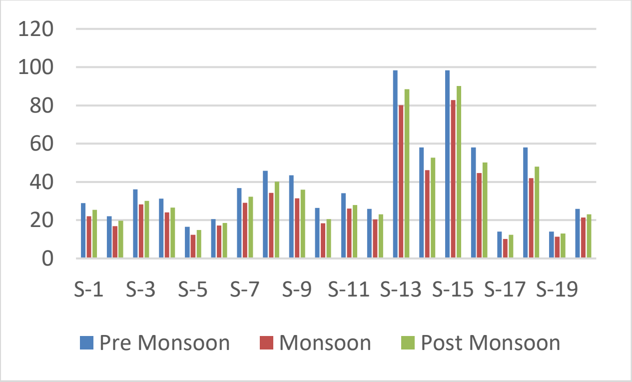
Fluoride (F^-)



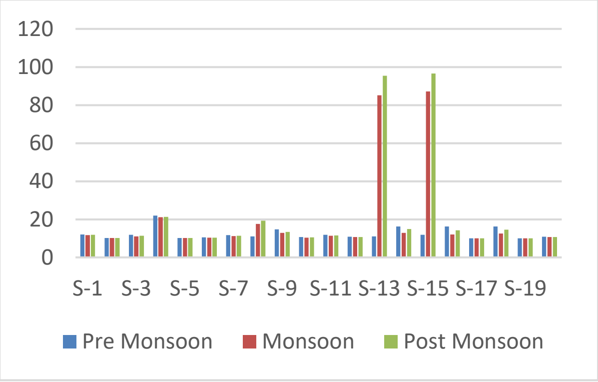
Graph 13: Fluoride

Fluoride concentrations ranged from 0.005 to 1.60 mg/L. While most samples remained within BIS limits, isolated exceedances were observed during the monsoon season (Table 3). Seasonal fluoride enrichment may be attributed to localized dissolution of fluoride-bearing minerals under saturated conditions, as reported in earlier studies from northern India (Sharma et al., 2016).

Sodium (Na^+) and Potassium (K^+)



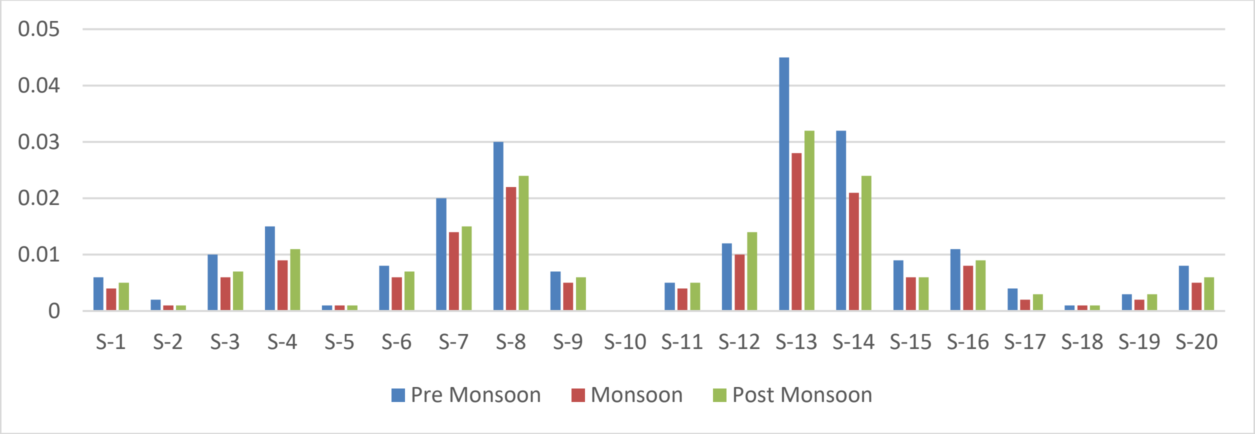
Graph 14: Sodium



Graph 15: Potassium

Sodium concentrations ranged from 10.2 to 98.4 mg/L, with higher values recorded at locations proximal to sanitation systems. Potassium exhibited pronounced enrichment during the monsoon season, reaching up to 95.4 mg/L (Table 3). Given the limited natural mobility of potassium in aquifer materials, elevated concentrations strongly indicate sewage and detergent-derived inputs. Similar Na^+–K^+ enrichment associated with onsite sanitation has been reported by Graham and Polizzotto (2013) and Sorensen et al. (2015).

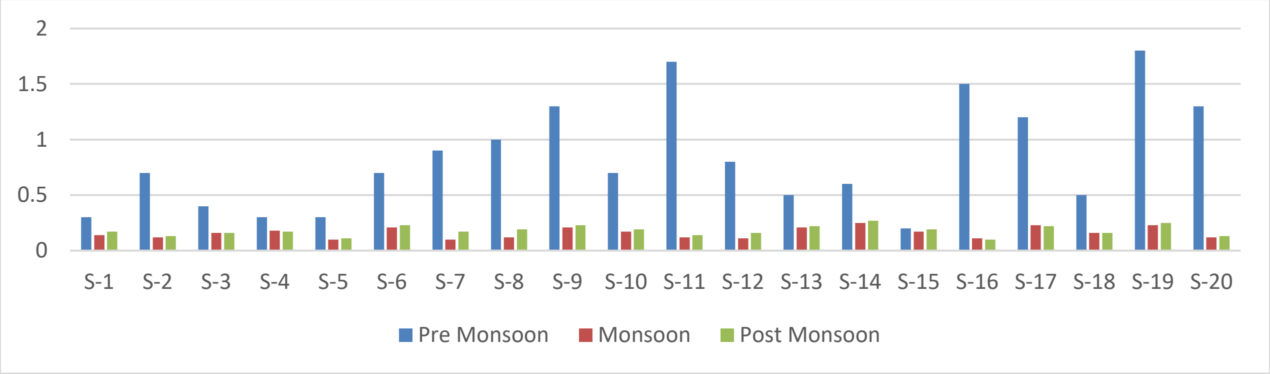
Arsenic (As)



Graph 16: Arsenic

Arsenic concentrations ranged from below detection to 0.045 mg/L. Several samples exceeded the BIS guideline value of 0.01 mg/L, particularly during monsoon and post-monsoon periods. Seasonal increases suggest localized reductive mobilisation associated with organic carbon inputs, a mechanism well established for alluvial sediments of the Ganga basin (Polizzotto et al., 2008; McArthur et al., 2012).

Phosphate (PO_4^{3-})



Graph 17: Phosphate

Phosphate concentrations ranged from 0.10 to 1.80 mg/L, with higher values consistently observed during monsoon and post-monsoon seasons. Given the low natural mobility of phosphate in aquifer systems, elevated concentrations indicate direct infiltration of domestic wastewater and detergent residues. Similar phosphate enrichment patterns have been reported in sanitation-impacted groundwater systems (Graham & Polizzotto, 2013; Nyenje et al., 2013).

CONCLUSION

The present study demonstrates that groundwater quality in the study area is strongly influenced by seasonal hydrological dynamics and persistent anthropogenic pressures, particularly from onsite sanitation systems. Although monsoonal recharge contributes to short-term dilution of dissolved constituents, it simultaneously enhances the vertical transport of contaminants into shallow aquifers. This dual role of recharge highlights the vulnerability of groundwater resources in densely inhabited rural settings under monsoon-dominated climates.

Elevated concentrations of nitrate, chloride, potassium, iron, and phosphate at multiple locations indicate sustained contamination pathways linked to pit latrines and septic systems. The persistence of these contaminants across seasons suggests that natural attenuation processes are insufficient to offset continuous pollutant loading. Similar conclusions have been reported from shallow aquifers in South Asia, Africa, and Southeast Asia, where sanitation infrastructure remains closely coupled with drinking water sources (Taylor et al., 2013; Lapworth et al., 2018).

The occurrence of iron and arsenic enrichment during monsoon and post-monsoon periods further underscores the role of redox-driven geochemical processes triggered by organic carbon inputs. Such processes are increasingly recognized as critical controls on trace metal mobilisation in alluvial floodplain aquifers, with implications for long-term water safety even where contaminant concentrations appear spatially limited (Smedley & Kinniburgh, 2002; Fendorf et al., 2010).

Overall, the findings confirm that groundwater in shallow alluvial settings is highly sensitive to land-use practices and sanitation design. Without adequate separation distances, lining of sanitation systems, and systematic groundwater monitoring, seasonal recharge is likely to exacerbate contaminant migration rather than mitigate it. Integrated management strategies combining improved sanitation planning, protection of wellhead zones, and routine water quality surveillance are therefore essential to ensure sustainable and safe groundwater use.

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