RESEARCH PAPER

ASSESSMENT OF PRE-MONSOON GROUNDWATER QUALITY OF GABHANA TEHSIL, DISTRICT ALIGARH, UTTAR PRADESH, WITH SPECIAL REFERENCE TO PHYSICOCHEMICAL PARAMETERS

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Abstract

Background: Groundwater supplies the greater part of rural India's drinking and irrigation water, and in the Indo-Gangetic alluvial plain it is withdrawn almost entirely through hand pumps and tube wells. Gabhana Tehsil, a predominantly rural and agricultural subdivision of Aligarh district, Uttar Pradesh, depends on this resource almost completely for potable supply, yet no season-specific chemical baseline has previously been published for the tehsil. Because solute concentrations reach their annual maximum in the dry pre-monsoon months, this period represents the most conservative window in which to test the aquifer against drinking-water standards.

Objective: The study was undertaken (i) to determine the pre-monsoon physicochemical and trace-element composition of groundwater in Gabhana Tehsil, (ii) to evaluate each parameter explicitly against the desirable and permissible limits of Indian Standard IS 10500:2012, and (iii) to identify by name the individual sites and parameters at which those limits are exceeded, so that monitoring and remedial effort can be directed precisely.

Methods: Fourteen groundwater samples (S1–S14) were collected during the pre-monsoon season from functioning hand pumps (S1–S8) and tube wells (S9–S14) in regular domestic and irrigation use across representative villages of the tehsil. Fifteen physical and major-ion parameters — pH, electrical conductivity, total dissolved solids, total hardness, total alkalinity, calcium, magnesium, chloride, sulphate, nitrate, nitrite, fluoride, sulphide, phenolic compounds and anionic detergents (as MBAS) — were determined following the Bureau of Indian Standards IS 3025 series and Standard Methods for the Examination of Water and Wastewater (APHA, 24th edition, 2023). Twenty trace and toxic elements were quantified on 0.45 µm-filtered, nitric-acid-preserved aliquots using an Agilent Technologies 7800 Inductively Coupled Plasma Mass Spectrometer (ICP-MS).

Results: The groundwater was consistently slightly alkaline (pH 7.49–8.05) and fresh, with electrical conductivity of 295–1,025 µS/cm, total dissolved solids of 103–422 mg/L and total hardness of 10.16–28.44 mg/L; every one of these parameters lay within the BIS permissible limit at all fourteen sites, with the single exception of electrical conductivity at S9 (1,025 µS/cm), which exceeded the desirable value of 1,000 µS/cm only marginally. Four parameters showed defined, site-specific exceedances. Total alkalinity exceeded the desirable limit of 200 mg/L at S9 (267.08 mg/L), S11 (269.18 mg/L) and S14 (203.99 mg/L), while remaining below the permissible limit of 600 mg/L. Nitrate exceeded the permissible limit of 45 mg/L at S10 (46.16 mg/L), a limit for which no relaxation is allowed. Fluoride exceeded the desirable limit of 1.0 mg/L at S6, S9 and S12, reaching a maximum of 1.5 mg/L, which is the permissible limit itself. Manganese exceeded the permissible limit of 0.1 mg/L at S3 (0.12 mg/L) and S8 (0.23 mg/L). All remaining toxic elements — lead, cadmium, mercury, arsenic, chromium, nickel, silver, tin and antimony — were at or below the limit of detection at effectively every site and were within permissible limits everywhere.

Conclusion: Pre-monsoon groundwater in Gabhana Tehsil is, on the whole, chemically suitable for drinking and irrigation. The exceedances that were recorded are localised rather than aquifer-wide and are attributable to two distinct causes: nitrogenous fertiliser leaching and dry-season evapoconcentration in the case of alkalinity and nitrate, and geogenic dissolution of fluoride-bearing minerals under alkaline conditions in the case of fluoride. Eight sites — S3, S6, S8, S9, S10, S11, S12 and S14 — require continued seasonal monitoring, and household-level treatment is advisable at S8 and S10 before the water is consumed. The dataset provides the first published pre-monsoon baseline for the tehsil and is intended to be read alongside the corresponding post-monsoon survey.

Keywords: *Groundwater quality; Physicochemical parameters; Trace metals; ICP-MS; Gabhana Tehsil; Aligarh; Pre-monsoon; IS 10500:2012*

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1. Introduction

Groundwater underpins human health, agriculture and economic activity across the developing world, and nowhere more so than in India. Its wide distribution, its relative freedom from the microbiological contamination that affects surface water, and the low cost of abstracting it have made it the default drinking-water source for the majority of the rural population. It

supplies drinking water to roughly 85 per cent of rural households and satisfies more than 60 per cent of the country's irrigation demand.[1] In the Indo-Gangetic alluvial plain, where thick and productive Quaternary aquifers are within easy reach of a hand pump, this dependence is close to total: a single village may draw its entire domestic supply from a handful of shallow abstraction points, with no treatment of any kind between the aquifer and the drinking vessel.

That dependence carries an obvious corollary. Whatever is dissolved in the aquifer is consumed directly, and the chemical composition of the groundwater becomes, in effect, the chemical composition of the community's drinking water. Rising population, expanding irrigation and intensifying land use have placed this resource under growing pressure. Water percolating through soil and rock is filtered naturally, but that filtration is partial and it is being outpaced by the loading imposed on it — industrial effluent, indiscriminate solid-waste disposal, unplanned peri-urban development, leakage from septic tanks and soak pits, and the sustained over-application of nitrogenous fertilisers and pesticides.[2,3] The consequences are difficult to reverse. Groundwater moves slowly, is poorly aerated and has limited capacity for self-purification, so a contaminant that enters an aquifer may persist for years or decades after the source has been removed. Detecting such contamination before it becomes entrenched therefore requires analytical techniques capable of resolving trace and toxic elements at sub-microgram-per-litre concentrations, and it is for precisely this reason that Inductively Coupled Plasma Mass Spectrometry (ICP-MS) has become the reference method for water-quality surveillance.

Whether a given groundwater is fit for drinking or irrigation is decided by a well-defined set of physicochemical characteristics: pH, electrical conductivity, total dissolved solids, hardness, alkalinity and the concentrations of the major cations and anions. When these move outside prescribed ranges, the effects are felt in three separate domains — the palatability and safety of the water itself, the structure and fertility of irrigated soil, and human health. The health consequences are specific rather than diffuse. Nitrate above the permissible limit is a recognised cause of infantile methaemoglobinaemia, in which nitrite formed from ingested nitrate oxidises haemoglobin and impairs oxygen transport.[4] Sustained ingestion of fluoride above about 1.0 mg/L produces dental fluorosis, and above 1.5 mg/L the risk extends to skeletal fluorosis.[5] Elevated salinity and alkalinity degrade soil structure, reduce infiltration and depress crop yield. Toxic metals present a different order of problem again: lead, cadmium, arsenic, chromium, manganese and mercury are non-biodegradable, they accumulate in bone, liver and kidney over years of low-level exposure, and chronic intake has been linked to neurological impairment, renal damage, cardiovascular disease and several cancers.[6] Reliable quantification of these elements is therefore not an optional refinement of a water-quality survey but its central requirement.

Aligarh district lies in western Uttar Pradesh and is significant both agriculturally and industrially. Metal finishing, electroplating and lock manufacture are concentrated in and around Aligarh city, and the groundwater consequences of these activities have been documented in a number of earlier studies.[3,7,8] That body of work is, however, almost entirely urban in focus. The rural aquifers that supply the surrounding tehsils — where the dominant pressure is agrochemical rather than industrial, and where the population has least access to alternative supply or to treatment — remain comparatively unexamined, and this asymmetry constitutes a real gap in the regional literature. Gabhana Tehsil illustrates the point. It is predominantly rural and agricultural, it is underlain by a multi-layered Quaternary alluvial aquifer system that yields water readily, and the same permeability that makes the aquifer productive also makes it vulnerable to downward migration of surface-applied contaminants. To the authors' knowledge, no season-specific physicochemical and trace-element baseline has previously been published for the tehsil.

The present study was designed to address that gap explicitly. Its objectives were twofold: (i) to analyse the physical, chemical and trace-element composition of pre-monsoon groundwater at fourteen representative sites in Gabhana Tehsil using the standard methods prescribed by APHA (24th edition, 2023) and the Bureau of Indian Standards, and to compare every result directly against drinking-water specification IS 10500:2012; and (ii) to identify, parameter by parameter and site by site, where the desirable and permissible limits are exceeded, and to interpret those exceedances in terms of the hydrogeological setting and the anthropogenic activity of the surrounding land. The pre-monsoon season was chosen deliberately, since minimal recharge and high evapotranspiration make it the period of maximum solute concentration and therefore the most demanding test of the aquifer. The resulting dataset is intended to serve as a reference baseline for groundwater monitoring, for sustainable resource management and for public awareness in the region.

2. Materials and Methods

2.1 Study Area and Hydrogeological Setting

The investigation was carried out in Gabhana Tehsil, Aligarh district, Uttar Pradesh, which lies within the central Indo-Gangetic alluvial plain — one of the most extensive and productive groundwater provinces in northern India. The tehsil covers approximately 473 km² and is bounded by the Karwan River to the west and the Senger River to the east; both rivers influence local recharge and shallow flow direction. The climate is humid warm-temperate, with hot summers, cool winters and strongly monsoon-dominated rainfall. Mean annual precipitation is about 760 mm, of which close to 80 per cent falls during the south-west monsoon between July and September. Temperatures range from roughly 2 °C in winter to 47 °C in summer, so that the pre-monsoon months combine negligible recharge with very high evapotranspiration — the specific combination under which dissolved-solute

concentrations reach their annual peak, and the reason this season was selected for sampling.

Hydrogeologically, the area is underlain by Quaternary alluvial deposits consisting of interbedded silt, fine to medium sand, clay and calcareous kankar. These form a multi-layered aquifer system in which the shallow and deeper horizons are frequently in hydraulic continuity, since the intervening clay beds are laterally discontinuous rather than forming a single confining layer. Two consequences follow, and they pull in opposite directions. Yields are good and abstraction is easy, which is why hand pumps and tube wells are so widely used for drinking, domestic and irrigation purposes throughout the tehsil. At the same time, the absence of a continuous aquitard leaves the aquifer open to downward migration of surface-derived solutes, so that contaminants applied at the land surface — principally agrochemicals in this setting — can reach the abstraction depth without effective attenuation. The quality of the water in this system is therefore directly consequential for both public health and agricultural productivity.

2.2 Sampling Design and Site Selection

Fourteen sampling locations, coded S1 to S14, were distributed across the tehsil so as to capture its spatial variability rather than to characterise any single village. Sites were chosen by a stratified approach against five explicit criteria: population density and the degree of local dependence on groundwater for potable use; the type of abstraction structure, so that both shallow hand pumps and deeper tube wells were represented; the dominant land use surrounding the source, whether agricultural, residential or roadside; proximity to identifiable contamination sources, in particular fertiliser-intensive farmland and dense habitation; and position relative to the regional drainage and recharge pattern established by the Karwan and Senger rivers.

The resulting set divides cleanly by source type. Sites S1 to S8 are hand pumps drawing on the shallower aquifer horizon and are situated within or immediately adjacent to habitation — beside temples, schools and road junctions. Sites S9 to S14 are tube wells set in open farmland and drawing from greater depth. This division was intentional, because it allows the influence of shallow, habitation-proximate conditions to be separated from that of deeper, farmland-proximate conditions, and it proves to be the single most informative distinction in the results reported below. Each location was assigned a unique site code to maintain consistency across analytical interpretation and spatial comparison; full details are given in Table 1 and the distribution of sites is shown in Figure 1.

Table 1. *Details of the groundwater sampling locations, Gabhana Tehsil, Aligarh district*

S. No.	Site Name	Site Code	Source	Location Description
1	Bhojpur Garhia	S1	Hand pump	Near T-junction on Anupshahr–Barauli Road, Jawan
2	Dabthala	S2	Hand pump	Opposite Langotia Baba Temple
3	Nagla Banjara	S3	Hand pump	Opposite the first temple in Baazgarhi
4	Barauli Khas	S4	Hand pump	Opposite Shanti Dham Ashram
5	Songra	S5	Hand pump	At the Y-junction on entry to Songra
6	Ponkargarhi	S6	Hand pump	Near the Gaushala, Ponkargarhi
7	Rigaspuri	S7	Hand pump	Within the premises of the primary school
8	Barauli By-pass	S8	Hand pump	Opposite Shri Hotilal Maheshwari Inter College
9	Hursaina	S9	Tube well	Farmland on the Hursaina–Barauli road, Gabhana
10	Pratappur	S10	Tube well	Farmland on the Pratappur–Barauli road, Gabhana
11	Madangarhi	S11	Tube well	Farmland on the Madangarhi–Barauli road, beyond a sharp bend
12	Shyampur	S12	Tube well	Farmland at Shyampur, opposite the Ponkargarhi entry gate
13	Ramnagar	S13	Tube well	Opposite Navjyoti Higher Secondary School
14	Barauli	S14	Tube well	Opposite Dev Drashti Mahavidyalaya

Sites S1–S8 are hand pumps abstracting from the shallow aquifer horizon; sites S9–S14 are tube wells abstracting from greater depth in open farmland.

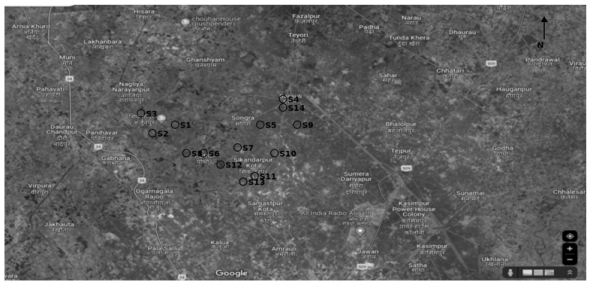

Figure 1. *Location map of the groundwater sampling sites (S1–S14) in Gabhana Tehsil, Aligarh district, Uttar Pradesh. Base imagery: Google Maps / Google Earth; sampling points overlaid by the authors.*

2.3 Sample Collection, Handling and Preservation

Sampling was carried out during the pre-monsoon season, which is recognised as the period of maximum solute concentration because rainfall recharge is negligible and evaporative loss is high. Samples were taken directly from hand pumps and tube wells that were operational and in regular local use, on the reasoning that a source in daily use yields water representative of what the community actually drinks. Before collection, each source was purged continuously for five to ten minutes in order to flush out water that had been standing in the column and casing, so that the sample drawn represented the aquifer rather than the borehole.

Samples were collected in baked, acid-washed 10 L polyethylene bottles. Filling was carried out slowly and with the bottle neck submerged where practicable, to avoid aeration and the formation of headspace — a precaution that matters particularly for pH, alkalinity and sulphide, all of which shift on contact with atmospheric oxygen and carbon dioxide. Each container was sealed immediately, labelled with its site code and the date of sampling, and transported to the laboratory under controlled conditions. For trace and toxic element determination, a separate aliquot was filtered through a 0.45 µm membrane filter to remove particulate matter and colloids, and then preserved by acidification with ultrapure nitric acid to below pH 2, which keeps the metals in solution and prevents adsorptive loss to the container wall during storage.

2.4 Analytical Methods

All physicochemical parameters — pH, electrical conductivity, total dissolved solids, total alkalinity, total hardness, calcium, magnesium, chloride, sulphate, nitrate, nitrite, fluoride, sulphide, phenolic compounds and anionic detergents (as MBAS) — were determined using the procedures specified in the Bureau of Indian Standards IS 3025 series and in Standard Methods for the Examination of Water and Wastewater (APHA, 24th edition, 2023).[13] Twenty trace and toxic elements (Na, K, Cr, Mn, Fe, Ni, Cu, Zn, As, Se, Mo, Ag, Cd, Sn, Sb, Ba, Hg, Pb, Al and B) were measured on an Agilent Technologies 7800 Inductively Coupled Plasma Mass Spectrometer. The instrument was calibrated with certified multi-element reference standards prepared in 1 per cent nitric acid, matching the matrix of the preserved samples. Every result was subsequently compared against the desirable and permissible limits prescribed by IS 10500:2012.[14] The complete set of parameters, together with the method or reference and the instrument used for each, is set out in Table 2.

Table 2. *Parameters analysed, with the corresponding analytical methods and instruments*

S. No.	Parameter	Method / Reference	Instrument
1	pH	IS 3025 (Part 11)	pH meter
2	Electrical conductivity	Electrometric method	Conductivity meter
3	Total dissolved solids	IS 3025 (Part 16)	Gravimetric determination
4	Total alkalinity (as $CaCO_3$)	IS 3025 (Part 23)	Standard titration
5	Total hardness (as $CaCO_3$)	IS 3025 (Part 21)	EDTA titration
6	Calcium (as Ca)	IS 3025 (Part 40)	EDTA titration
7	Magnesium (as Mg)	IS 3025 (Part 2)	Calculated from titration
8	Chloride (as Cl)	IS 3025 (Part 32)	Argentometric titration
9	Sulphate (as SO_4)	IS 3025 (Part 24)	UV–Vis spectrophotometer
10	Nitrate (as NO_3)	APHA 4500-NO_3, 2017	UV–Vis spectrophotometer
11	Nitrite (as NO_2)	IS 3025 (Part 34)	UV–Vis spectrophotometer
12	Sulphide (as S^{2-})	IS 3025 (Part 29):1986, methylene blue method	UV–Vis spectrophotometer
13	Fluoride (as F)	APHA 4500-F^- D, 23rd ed., 2017	UV–Vis spectrophotometer
14	Phenolic compounds (as C_6H_5OH)	IS 3025 (Part 43):1992, 4-aminoantipyrine method with chloroform extraction	UV–Vis spectrophotometer
15	Anionic detergents (as MBAS)	IS 3025 (Part 68):2019	UV–Vis spectrophotometer

S. No.	Parameter	Method / Reference	Instrument
16	Trace and toxic elements (Na, K, Cr, Mn, Fe, Ni, Cu, Zn, As, Se, Mo, Ag, Cd, Sn, Sb, Ba, Hg, Pb, Al, B)	IS 3025 (Part 65):2014	ICP-MS (Agilent Technologies 7800)

2.5 Quality Assurance and Quality Control

Analytical reliability was maintained through a defined set of controls applied throughout the work. All laboratory glassware and sampling containers were acid-cleaned before use and rinsed with deionised water. Calibration standards were prepared fresh each day from certified stock, and calibration accuracy was verified against an independently sourced quality-control standard before any sample was analysed; agreement within the accepted tolerance was a precondition for proceeding. Instrument response was rechecked at intervals during each analytical run to detect drift. Relative standard deviations for replicate determinations remained within acceptable analytical limits for every parameter reported. Concentrations falling below the instrumental limit of detection are reported throughout as "< LOD" rather than as zero, since a non-detect indicates only that the analyte was not measurable at the working sensitivity of the method and does not establish its absence.

2.6 Data Treatment and Interpretation

For each parameter the fourteen site values were tabulated, and the minimum, maximum and range were determined; the coefficient of variation was used as an index of spatial heterogeneity, with a low value taken to indicate uniform lithological control across the tehsil and a high value to indicate discrete, localised inputs. Every value was then classified against IS 10500:2012 in three categories: at or below the desirable limit, between the desirable and permissible limits, and above the permissible limit. This three-way classification is applied consistently in the sections that follow, because the distinction carries real practical weight — a value between the two limits indicates water that remains acceptable where no alternative source exists, whereas a value above the permissible limit indicates water that should not be used for drinking without treatment. Site-wise variation for each parameter is presented graphically in Figures 2 to 15, in which the horizontal axis in every case denotes the sampling site (S1–S14).

3. Results

3.1 General Hydrochemical Character

Groundwater across the study area was consistently slightly alkaline. pH values fell between 7.49 at S7 and 8.05 at S1, a spread of barely half a unit across fourteen sites separated by several kilometres (Figure 2). Such a narrow range is itself informative: it indicates a chemically stable, well-buffered aquifer in which the carbonate–bicarbonate system controls pH, and it is consistent with the pH ranges reported previously for alluvial groundwater elsewhere in Aligarh district.[6,7] Every site lay comfortably within the BIS acceptable range of 6.5 to 8.5, for which no relaxation is permitted.

Electrical conductivity ranged from 295 µS/cm at S1 to 1,025 µS/cm at S9 (Figure 3). Thirteen of the fourteen sites — approximately 93 per cent — remained within the desirable limit of 1,000 µS/cm; S9 exceeded it by 25 µS/cm, an excess of 2.5 per cent that is marginal in analytical terms but consistent in direction with the other findings at that site. The distribution of conductivity is not random. The five northern hand-pump sites S1 to S5 form a tight low-mineralisation group below 360 µS/cm, the remaining hand pumps S6 to S8 occupy an intermediate band, and the six farmland tube wells S9 to S14 are consistently the most mineralised, running between roughly 605 and 1,025 µS/cm. This progressive increase from shallow habitation-proximate sources to deeper farmland-proximate sources is the clearest single spatial trend in the dataset, and it points to fertiliser-derived solute loading combined with dry-season evapoconcentration beneath irrigated land.

Figure 2. *Site-wise pH values. All fourteen sites lie within the BIS acceptable range of 6.5–8.5, for which no relaxation is permitted.*

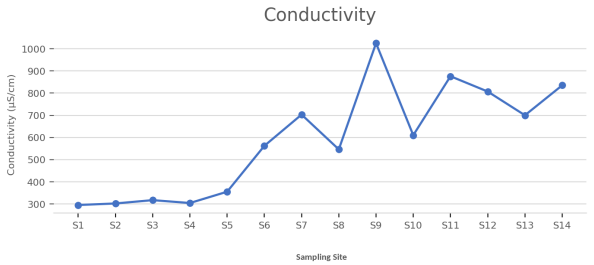

Figure 3. *Site-wise electrical conductivity (µS/cm). Site S9 (1,025 µS/cm) marginally exceeds the BIS desirable limit of 1,000 µS/cm; note the step increase from the hand-pump sites (S1–S8) to the farmland tube wells (S9–S14).*

3.2 Total Dissolved Solids, Hardness and the Major Ions

Total dissolved solids ranged from 103 mg/L to 422 mg/L (Figure 4), the lowest values occurring at the shallow northern hand pumps and the maximum at S9, which places every site well within the desirable limit of 500 mg/L and far below the permissible limit of 2,000 mg/L. The coefficient of variation was low (below 25 per cent), indicating that a common lithology exerts broadly uniform control on mineralisation across the tehsil, with local enrichment

superimposed on that background rather than replacing it.

Total hardness ranged from 10.16 to 28.44 mg/L as $CaCO_3$ (Figure 5), classifying the water as soft by any conventional scheme and leaving it an order of magnitude below the desirable limit of 200 mg/L. The corresponding cation concentrations are correspondingly low: calcium ranged from 2.44 to 6.51 mg/L against a desirable limit of 75 mg/L (Figure 6), and magnesium from not detected to 2.9 mg/L against a desirable limit of 30 mg/L (Figure 7). Water this soft has a practical implication worth stating directly — it is non-scaling and pleasant for domestic use, but it also has limited capacity to precipitate or complex trace metals, so a dissolved metal entering this aquifer tends to stay dissolved.

Total alkalinity showed the widest proportional spread of any major parameter, from 71.5 mg/L to 269.18 mg/L (Figure 8). Three sites exceeded the desirable limit of 200 mg/L: S9 at 267.08 mg/L, S11 at 269.18 mg/L and S14 at 203.99 mg/L. All three nonetheless remained well within the permissible limit of 600 mg/L, so the water at these sites is not rendered unfit, but the exceedance is real and all three sites are farmland tube wells. The pattern is consistent with bicarbonate enrichment produced by carbonate dissolution, assisted by the elevated soil carbon dioxide that accompanies cultivation and irrigation.

Chloride and sulphate, by contrast, were uniformly low. Chloride ranged from 5.0 to 42.98 mg/L against a desirable limit of 250 mg/L (Figure 9), and sulphate from 20.80 to 52.80 mg/L against a desirable limit of 200 mg/L (Figure 10). Neither approached its limit at any site. This combination — elevated alkalinity and conductivity but low chloride and sulphate — is diagnostically useful, because sewage ingress, industrial effluent and saline intrusion would all be expected to raise chloride and sulphate alongside the other solutes. Their absence therefore argues against those sources and points instead to a diffuse agricultural origin for the enrichment observed at the tube-well sites.

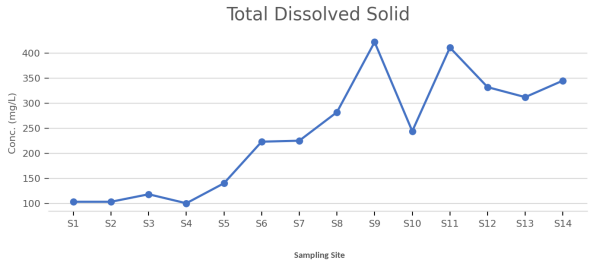

Figure 4. *Site-wise total dissolved solids (mg/L). All values fall within the BIS desirable limit of 500 mg/L and well below the permissible limit of 2,000 mg/L.*

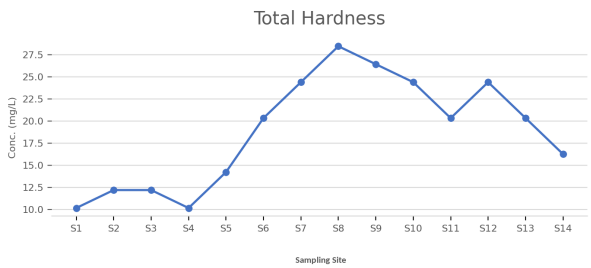

Figure 5. *Site-wise total hardness (mg/L as $CaCO_3$). All values lie far below the BIS desirable limit of 200 mg/L, indicating uniformly soft groundwater.*

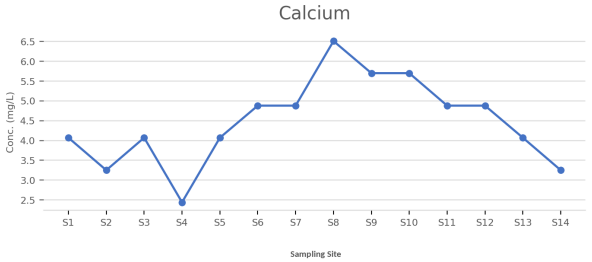

Figure 6. *Site-wise calcium concentration (mg/L). All values are within the BIS desirable limit of 75 mg/L.*

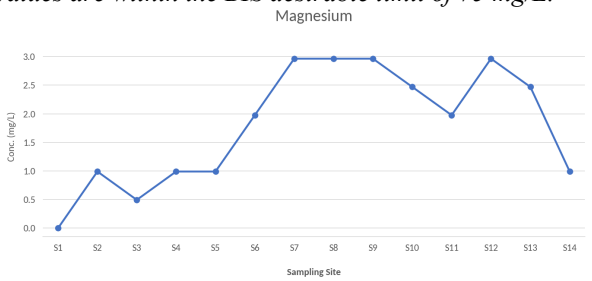

Figure 7. *Site-wise magnesium concentration (mg/L). All values are within the BIS desirable limit of 30 mg/L.*

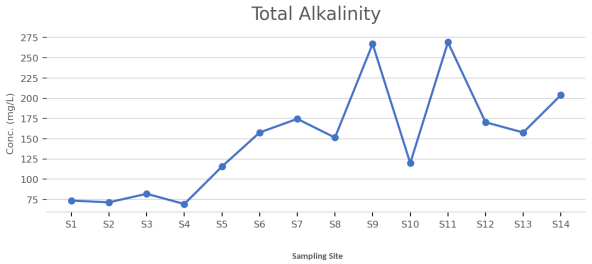

Figure 8. *Site-wise total alkalinity (mg/L as $CaCO_3$). Sites S9, S11 and S14 exceed the BIS desirable limit of 200 mg/L but remain within the permissible limit of 600 mg/L.*

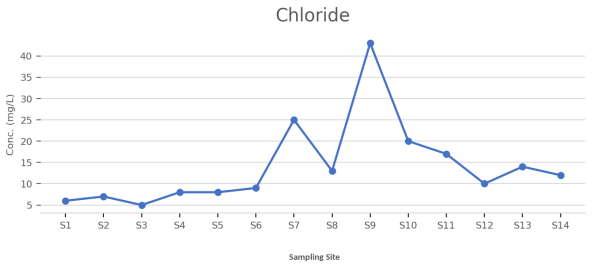

Figure 9. *Site-wise chloride concentration (mg/L). All values are within the BIS desirable limit of 250 mg/L.*

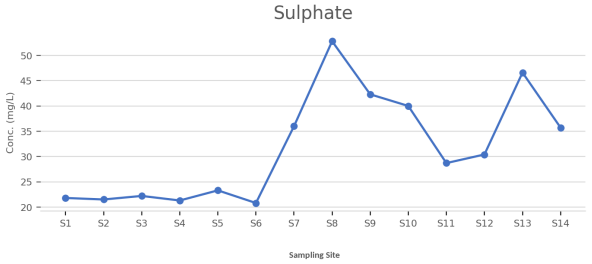

Figure 10. *Site-wise sulphate concentration (mg/L). All values are within the BIS desirable limit of 200 mg/L.*

3.3 Nutrients and Health-Relevant Parameters

Nitrate ranged from 0.13 mg/L to 46.16 mg/L (Figure 11). Thirteen sites remained below the BIS permissible limit of 45 mg/L, but S10 exceeded it at 46.16 mg/L. The exceedance is small in absolute terms — 1.16 mg/L, or about 2.6 per cent above the limit — yet it deserves to be stated plainly rather than minimised, for two reasons. First, IS 10500:2012 allows no relaxation whatever on nitrate, so a value above 45 mg/L is a failure against the standard and not a borderline result. Second, the health endpoint concerned is infantile methaemoglobinaemia, and infants are precisely the group least able to tolerate an exceedance. Site S10 is a tube well set in open farmland on the Pratappur–Barauli road, and the elevated value is consistent with leaching of nitrogenous fertiliser from the adjoining fields. The wider spatial pattern supports that reading: nitrate stays below about 3 mg/L at S1–S5, then rises across the cultivated part of the tehsil to its maximum at S10.

Nitrite was low at all sites, with a marginal exceedance of the permissible limit of 0.02 mg/L recorded at S11. Because nitrite is a short-lived intermediate in the nitrification–denitrification sequence, its presence at measurable concentration indicates a relatively recent nitrogen input or an active transformation of organic matter or fertiliser residue at that location, rather than a long-standing accumulation.

Fluoride ranged from not detected to 1.5 mg/L (Figure 12). Three sites exceeded the desirable limit of 1.0 mg/L — S6, S9 and S12 — with the maximum of 1.5 mg/L recorded at S6, a value that coincides exactly with the permissible limit and therefore sits at the very edge of acceptability. The spatial signature of fluoride differs markedly from that of nitrate: it is discontinuous, with values at or near zero at S2–S5 and again at S14, and sharp isolated peaks at S6, S9 and S12. This scattered, non-agricultural pattern is characteristic of geogenic release from fluoride-bearing minerals rather than of any surface-applied source, and dissolution of such minerals is favoured by exactly the alkaline conditions recorded throughout the study area. Prolonged consumption at these concentrations carries a recognised risk of dental fluorosis and, at the upper end, of skeletal fluorosis.

Sulphide was detectable but negligible, ranging from 0.0071 to 0.0084 mg/L against a desirable limit of 0.05 mg/L (Figure 13), which confirms that the aquifer is not reducing in character. Phenolic compounds (Figure 14) and anionic detergents measured as MBAS (Figure 15) were below the limit of detection at every one of the fourteen sites. Taken together, these three results rule out anaerobic conditions, industrial organic contamination and domestic detergent ingress as factors anywhere in the study area. A summary of all major physicochemical parameters, with the corresponding BIS limits and the sites exceeding them, is presented in Table 3.

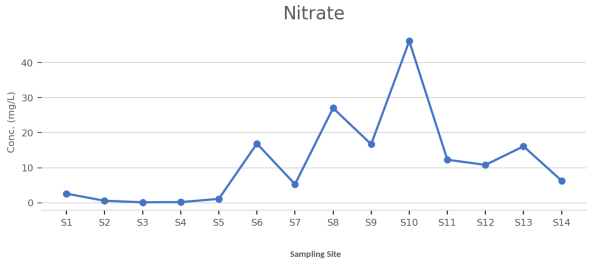

Figure 11. *Site-wise nitrate concentration (mg/L). Site S10 (46.16 mg/L) exceeds the BIS permissible limit of 45 mg/L, for which no relaxation is permitted.*

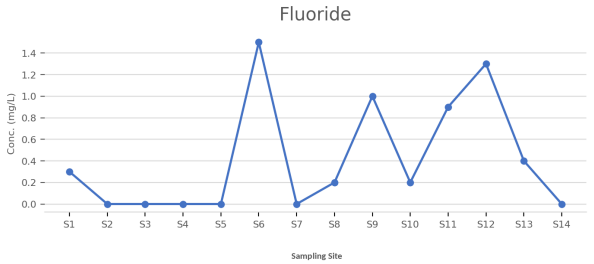

Figure 12. *Site-wise fluoride concentration (mg/L). Sites S6, S9 and S12 exceed the BIS desirable limit of 1.0 mg/L; the maximum of 1.5 mg/L at S6 coincides with the permissible limit.*

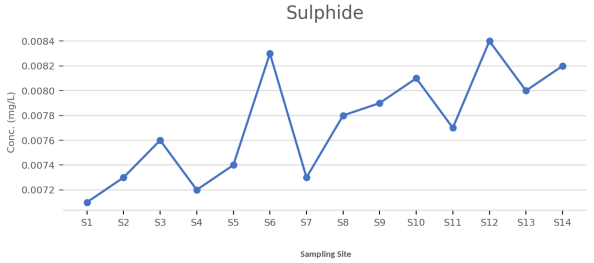

Figure 13. *Site-wise sulphide concentration (mg/L). All values are far below the BIS desirable limit of 0.05 mg/L.*

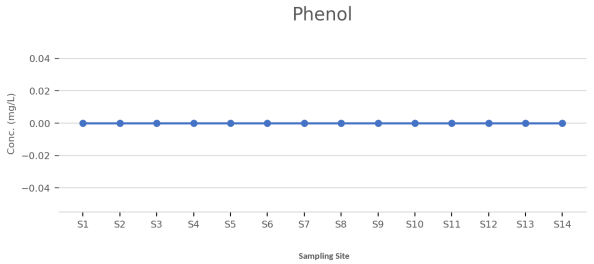

Figure 14. *Site-wise phenolic compounds (as C_6H_5OH). Concentrations were below the limit of detection at all fourteen sites.*

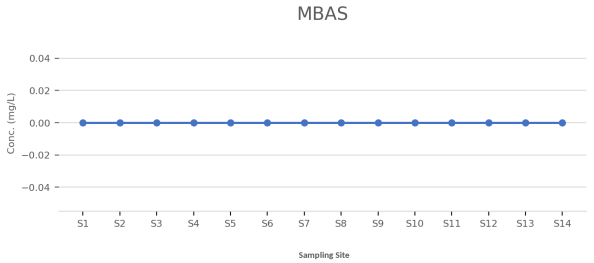

Figure 15. *Site-wise anionic detergents (as MBAS). Concentrations were below the limit of detection at all fourteen sites.*

Table 3. *Summary of the major physicochemical parameters of pre-monsoon groundwater, Gabhana Tehsil, with reference to IS 10500:2012*

Parameter	Range (all sites)	BIS desirable limit	BIS permissible limit	Sites exceeding
pH	7.49 – 8.05	6.5 – 8.5	No relaxation	None
Electrical conductivity (µS/cm)	295 – 1025	1000	No relaxation	S9 (marginal)
Total dissolved solids (mg/L)	103 – 422	500	2000	None
Total hardness (mg/L)	10.16 – 28.44	200	600	None
Calcium (mg/L)	2.44 – 6.51	75	200	None
Magnesium (mg/L)	ND – 2.9	30	100	None
Total alkalinity (mg/L)	71.5 – 269.18	200	600	S9, S11, S14
Chloride (mg/L)	5.0 – 42.98	250	1000	None
Sulphate (mg/L)	20.80 – 52.80	200	400	None
Nitrate (mg/L)	0.13 – 46.16	45 (no relaxation)	—	S10
Nitrite (mg/L)	Trace levels	0.02	No relaxation	S11 (marginal)
Fluoride (mg/L)	ND – 1.5	1.0	1.5	S6, S9, S12
Sulphide (mg/L)	0.0071 – 0.0084	0.05	No relaxation	None
Phenolic compounds (mg/L)	< LOD	0.001	0.002	None
Anionic detergents as MBAS (mg/L)	< LOD	0.2	1.0	None

ND = not detected; LOD = limit of detection. "No relaxation" indicates a parameter for which IS 10500:2012 specifies no permissible limit in the absence of an alternative source.

3.4 Trace and Toxic Element Distribution

Twenty trace and toxic elements were quantified by ICP-MS at all fourteen sites; the complete results are given in Table 4a for sites S1 to S7 and in Table 4b for sites S8 to S14. The dominant feature of the dataset is how much of it consists of non-detects. Chromium, iron, nickel, silver, cadmium, tin, antimony, mercury and lead were at or below the limit of detection at effectively every site, with only a handful of exceptions at trace level — chromium at S9, S10 and S13 (maximum 0.00057 mg/L against a limit of 0.05 mg/L), iron and nickel at S6 alone, and cadmium at S6 at 0.00004 mg/L against a limit of 0.003 mg/L. Lead and mercury were never detected at any site. For an area lying within the same district as a substantial metal-finishing and electroplating industry, this is a significant negative result and it deserves to be stated explicitly: the rural aquifer of Gabhana Tehsil shows no measurable industrial metal signature.

Sodium was within the desirable limit of 200 mg/L at every site but varied by a factor of more than thirty-five, from 4.269 mg/L at S1 to 151.106 mg/L at S11. The division follows the same boundary seen in conductivity: sodium remains below 15 mg/L at six of the eight hand-pump sites and rises to between 22.486 and 151.106 mg/L across the farmland tube wells. Potassium was similarly low throughout, between 2.309 and 7.884 mg/L, with the single exception of S13 at 31.421 mg/L — an isolated value roughly four times the next highest, most plausibly reflecting localised potassic fertiliser input. Arsenic, the element of greatest regional concern across the wider Gangetic plain, ranged from 0.00005 to 0.00432 mg/L, the maximum being less than half the permissible limit of 0.01 mg/L. Barium (0.01540–0.21205 mg/L against 0.7 max), boron (0.00466–0.11699 mg/L against 5.0 max), aluminium (0.00087–0.00561 mg/L against 0.03 max), zinc, copper, selenium and molybdenum were all comfortably within their respective limits.

Manganese was the sole trace element to exceed its permissible limit, and it did so at two sites: S3 at 0.12340 mg/L and S8 at 0.23077 mg/L, against a limit of 0.1 mg/L. The exceedance at S8 is the larger of the two by a considerable margin, at more than twice the permissible value, and it is the most substantial single exceedance recorded anywhere in this study. A third site, S4, reached 0.09907 mg/L, which falls just below the limit and should be treated as effectively at it. All three of these sites are shallow hand pumps located within habitation, and manganese is negligible at every one of the six deeper tube wells. The likely mechanism is reductive dissolution of manganese oxides in localised low-oxygen microenvironments within the shallow horizon, possibly with a contribution from agricultural inputs; chronic exposure to elevated manganese has been associated with neurological effects, which makes continued monitoring at S3 and S8 a specific rather than a general recommendation.

Table 4a. *Trace and toxic element concentrations (mg/L) in groundwater samples, sites S1–S7 (Agilent Technologies 7800 ICP-MS)*

S. No.	Parameter	BIS limit (mg/L)	S1	S2	S3	S4	S5	S6	S7
1	Sodium (as Na)	200.0 max	4.269	4.976	7.9122	4.535	5.864	36.844	14.466
2	Potassium (as K)	—	2.680	2.849	2.309	3.328	3.431	5.672	4.738
3	Total chromium (as Cr)	0.05 max	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD
4	Manganese (as Mn)	0.1 max	0.01134	0.03226	0.12340*	0.09907	0.00149	0.00689	0.04366
5	Iron (as Fe)	0.1 max	< LOD	< LOD	< LOD	< LOD	< LOD	0.00306	< LOD
6	Nickel (as Ni)	0.02 max	< LOD	< LOD	< LOD	< LOD	< LOD	0.00186	< LOD
7	Copper (as Cu)	0.05 max	0.00007	< LOD	0.0004	< LOD	< LOD	0.00361	0.00170
8	Zinc (as Zn)	5.0 max	< LOD	0.05636	0.00665	0.02995	0.00555	0.38647	0.06762
9	Total arsenic (as As)	0.01 max	0.00256	< LOD	0.00019	0.00432	0.00085	0.00111	0.00028
10	Selenium (as Se)	0.01 max	< LOD	0.00012	0.00013	< LOD	0.00044	0.00006	0.00013
11	Molybdenum (as Mo)	0.07 max	0.00190	0.00182	0.00287	0.00156	0.00179	0.00167	0.00103
12	Silver (as Ag)	0.01 max	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD
13	Cadmium (as Cd)	0.003 max	< LOD	< LOD	< LOD	< LOD	< LOD	0.00004	< LOD
14	Tin (as Sn)	—	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD
15	Antimony (as Sb)	0.005 max	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD
16	Barium (as Ba)	0.7 max	0.04763	0.01540	0.08473	0.03837	0.00644	0.00728	0.01417
17	Mercury (as Hg)	0.001 max	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD
18	Lead (as Pb)	0.01 max	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD
19	Aluminium (as Al)	0.03 max	0.00248	0.00248	0.00112	0.00477	0.00176	0.00110	0.00155
20	Boron (as B)	5.0 max	0.00632	0.00466	0.01158	0.00809	0.00701	0.00360	0.00251

** Exceeds the BIS permissible limit. < LOD = below the limit of detection of the method.*

Table 4b. *Trace and toxic element concentrations (mg/L) in groundwater samples, sites S8–S14 (Agilent Technologies 7800 ICP-MS)*

S. No.	Parameter	BIS limit (mg/L)	S8	S9	S10	S11	S12	S13	S14
1	Sodium (as Na)	200.0 max	46.484	107.037	22.486	151.106	108.661	71.729	129.994
2	Potassium (as K)	—	5.951	6.906	5.359	7.884	6.977	31.421	6.261

S. No.	Parameter	BIS limit (mg/L)	S8	S9	S10	S11	S12	S13	S14
3	Total chromium (as Cr)	0.05 max	< LOD	0.00008	0.00057	< LOD	< LOD	0.00027	< LOD
4	Manganese (as Mn)	0.1 max	0.23077*	0.00778	< LOD	0.01350	0.00578	0.00056	0.01342
5	Iron (as Fe)	0.1 max	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD
6	Nickel (as Ni)	0.02 max	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD
7	Copper (as Cu)	0.05 max	0.00045	< LOD	< LOD	< LOD	< LOD	< LOD	0.00102
8	Zinc (as Zn)	5.0 max	0.00921 0	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD
9	Total arsenic (as As)	0.01 max	0.00005	0.00057	0.00061	0.00099	0.00084	0.00169	0.00144
10	Selenium (as Se)	0.01 max	0.00006	0.00129	0.00197	0.00107	0.00191	0.00219	0.00177
11	Molybdenum (as Mo)	0.07 max	0.00153	0.00324	0.00048	0.00480	0.00288	0.00226	0.00278
12	Silver (as Ag)	0.01 max	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD
13	Cadmium (as Cd)	0.003 max	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD
14	Tin (as Sn)	—	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD
15	Antimony (as Sb)	0.005 max	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD
16	Barium (as Ba)	0.7 max	0.18568	0.19308	0.17399	0.21205	0.19741	0.19923	0.14719
17	Mercury (as Hg)	0.001 max	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD
18	Lead (as Pb)	0.01 max	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD
19	Aluminium (as Al)	0.03 max	0.00087	0.00148	0.00126	0.00113	0.00152	0.00177	0.00561
20	Boron (as B)	5.0 max	0.03954	0.08215	0.02320	0.11699	0.07595	0.11579	0.09313

** Exceeds the BIS permissible limit. < LOD = below the limit of detection of the method.*

4. Discussion

4.1 Overall Character of the Aquifer

The physicochemical profile obtained for pre-monsoon groundwater in Gabhana Tehsil describes an aquifer in generally sound condition. pH is near-neutral to mildly alkaline, hardness is uniformly soft, and chloride, sulphate and sulphide are low at every one of the fourteen sites. Phenolic compounds and anionic detergents were not detected anywhere. Taken as a whole, this indicates that the aquifer is not subject to widespread geochemical degradation, industrial discharge or sewage ingress, and the finding is broadly consistent with earlier physicochemical investigations of groundwater in Aligarh district, which have likewise reported the major ions to lie within BIS limits while identifying localised exceedances of individual parameters.[3,6,7,8]

It is worth being explicit about what the low chloride and sulphate values exclude, since a negative finding of this kind is often passed over. Sewage infiltration, industrial effluent and saline intrusion each raise chloride and sulphate along with conductivity and alkalinity. At Gabhana, conductivity and alkalinity rise at the tube-well sites while chloride and sulphate do not, and this decoupling is the strongest available evidence that the enrichment observed there is agricultural and diffuse in origin rather than urban,

industrial or saline. The interpretation offered below rests on that distinction.

4.2 Two Distinct Contamination Signatures

The site-specific exceedances recorded in this study do not form a single pattern; they form two, with different spatial distributions and different underlying causes. Recognising this matters, because the two require different responses.

The first signature is agricultural and progressive. Total alkalinity exceeded the desirable limit at S9, S11 and S14, nitrate exceeded the permissible limit at S10, and nitrite was marginally elevated at S11. All four of these sites are tube wells set in open farmland, and all four lie within the group that also shows the highest conductivity, the highest total dissolved solids and by far the highest sodium concentrations. The convergence of five independent parameters on the same set of locations is unlikely to be coincidental. It is consistent with the leaching of nitrogenous fertiliser residues through the unsaturated zone, reinforced by the evapoconcentration of solutes that occurs during a dry season in which recharge is negligible and evapotranspiration is at its maximum. Comparable associations between intensive fertiliser use and elevated nitrate and alkalinity have been reported from the central Ganga plain and from adjoining districts of western Uttar Pradesh, including Agra, Hathras and Sikandra Rao.[9,10,11,12]

The second signature is geogenic and discontinuous. Fluoride exceeded the desirable limit at S6, S9 and S12, reaching 1.5 mg/L at S6. These sites do not form a coherent geographic group, they do not coincide with the highest-nitrate locations, and the intervening sites return values at or near zero. Such an isolated, patchy distribution is characteristic of mineral dissolution controlled by local aquifer mineralogy rather than of a surface-applied input, which would be expected to produce a smoother spatial gradient. The alkaline conditions prevailing throughout the study area actively favour this release, since fluoride substitutes for hydroxide in weathering reactions and its mobility increases as pH rises. The practical implication follows directly: fluoride at these sites cannot be reduced by changing agricultural practice, and mitigation must instead take the form of treatment at the point of use or of switching to an alternative source.

4.3 Manganese and the Absence of an Industrial Signature

The manganese exceedances at S3 (0.12340 mg/L) and S8 (0.23077 mg/L) stand out against an otherwise clean trace-element profile, and their distribution differs from both signatures described above. Both are shallow hand pumps within habitation, and manganese is negligible at every farmland tube well — the reverse of the nitrate and alkalinity pattern. This inversion argues against a fertiliser origin and in favour of reductive dissolution of manganese oxides within localised low-oxygen microenvironments in the shallow horizon, a process that is well documented in alluvial aquifers where organic-rich lenses occur close to the water table. The soft, poorly buffered character of the water compounds the problem, since it offers little capacity to precipitate the manganese once mobilised. Site S4, at 0.09907 mg/L, sits immediately below the permissible limit and should be regarded as effectively at it for monitoring purposes.

Against this, the trace-element results are otherwise reassuring, and the point is worth stating in its strongest form. Lead and mercury were not detected at any of the fourteen sites. Cadmium was detected at one site at 0.00004 mg/L, roughly seventy-five times below its permissible limit. Chromium reached a maximum of 0.00057 mg/L against a limit of 0.05 mg/L. Arsenic — the element that dominates groundwater concern across much of the Gangetic plain — peaked at 0.00432 mg/L, less than half its permissible limit, and lay below 0.002 mg/L at eleven of the fourteen sites. Given that Aligarh district supports substantial metal-finishing, electroplating and lock-manufacturing activity, and that urban groundwater contamination associated with those industries has been documented previously,[3,7,8] the absence of any comparable signature in this rural tehsil is a meaningful result in its own right. It indicates that industrial influence has not yet extended into the rural aquifer, and it establishes a baseline against which any future encroachment can be detected.

4.4 Practical Implications and Limitations

Reading the results together, groundwater in Gabhana Tehsil is largely suitable for drinking and irrigation during the pre-monsoon season, but eight sites — S3, S6, S8, S9, S10, S11, S12 and S14 — warrant closer attention. Within that group the priorities are not equal. S8, at more than twice the permissible manganese limit, and S10, which fails a no-relaxation nitrate standard, are the two sites at which household-level treatment should be considered before the water is used for drinking. S3 and S6 follow, the first for manganese and the second for fluoride at the permissible limit. The remaining four sites require monitoring rather than intervention, since their exceedances fall between the desirable and permissible limits.

Three limitations should be stated explicitly, since they bound the conclusions that can properly be drawn. First, the dataset represents a single pre-monsoon sampling round; it establishes the condition of the aquifer at its most concentrated, but it cannot by itself distinguish a seasonal maximum from a persistent trend. Second, the fourteen sites, although selected to represent the range of land use and abstraction types across the tehsil, cannot resolve variation at the scale of individual fields or households, and manganese in particular appears to vary over short distances. Third, microbiological quality was outside the scope of this study, and it is an important complement to the chemical picture in a setting where untreated groundwater is consumed directly. Comparison of these pre-monsoon results with the corresponding post-monsoon dataset for the same tehsil will resolve the first of these limitations directly, by establishing whether the exceedances reported here dilute after recharge — which would indicate a seasonal effect — or persist, which would indicate an established contamination trend requiring sustained intervention.

5. Conclusion

This investigation provides the first published pre-monsoon physicochemical and trace-element baseline

for groundwater at fourteen representative sites across Gabhana Tehsil, Aligarh district, Uttar Pradesh. The groundwater is slightly alkaline (pH 7.49–8.05), fresh (total dissolved solids 103–422 mg/L) and consistently soft (total hardness 10.16–28.44 mg/L), confirming its generally good quality within the Indo-Gangetic alluvial plain. Chloride, sulphate and sulphide were low at every site, and phenolic compounds and anionic detergents were below the limit of detection throughout.

Four parameters exceeded their prescribed limits, and each did so at named sites rather than across the aquifer as a whole. Total alkalinity exceeded the desirable limit of 200 mg/L at S9, S11 and S14 while remaining within the permissible limit. Nitrate exceeded the permissible limit of 45 mg/L at S10, a standard that permits no relaxation. Fluoride exceeded the desirable limit of 1.0 mg/L at S6, S9 and S12, reaching the permissible limit of 1.5 mg/L at S6. Manganese exceeded the permissible limit of 0.1 mg/L at S3 and S8, the latter at more than twice that value. Electrical conductivity marginally exceeded its desirable limit at S9 alone. All other parameters, including the toxic metals lead, cadmium, mercury, arsenic and chromium, were within permissible limits at every site, indicating that the industrial activity present elsewhere in Aligarh district has not yet measurably affected this rural aquifer.

The exceedances separate into two causes with two different remedies. Elevated alkalinity, nitrate and nitrite are confined to farmland tube wells and are attributable to fertiliser leaching and dry-season evapoconcentration; they are therefore amenable to changes in agricultural practice. Elevated fluoride is patchily distributed, is geogenic in origin and is favoured by the alkaline conditions of the aquifer; it is not amenable to such changes and requires treatment or substitution of source. Manganese follows a third and separate pattern, confined to shallow hand pumps and consistent with reductive dissolution in the shallow horizon.

On this basis the following measures are recommended. Regular seasonal monitoring should be established for nitrate, fluoride, alkalinity and manganese at the eight affected sites, with S8 and S10 given priority. The application of nitrogenous fertiliser in the vicinity of S9 to S14 should be regulated and matched more closely to crop demand in order to limit leaching. Household-level or community-level treatment should be provided at S8 and S10, and residents at S3, S6, S9 and S12 should be informed of the specific parameter affecting their source. Finally, the data reported here should be read together with the corresponding post-monsoon dataset, so that seasonal variation can be separated from long-term trend. The results fill an identified gap in the groundwater-quality literature for this tehsil and provide a reference point for future monitoring aimed at safeguarding both the sustainability of the resource and the health of the population that depends on it.

Author Contribution Statement

S. No.	Name of author	Contribution
1	Ms. Chhaya Tiwari	Conceptualisation; field sampling; laboratory analysis; data interpretation; preparation of the original draft; plagiarism check
2	Prof. (Dr.) Ravi Kant	Supervision; formal analysis; manuscript drafting and critical revision; review and editing

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Ethical Approval

Ethical approval was not required for this study, as it involved neither human participants nor experimental animals.

Conflict of Interest

The authors declare that they have no conflict of interest associated with this study.

Data Availability

The data generated and analysed during the present study are available from the corresponding author upon reasonable request.

Consent to Publish

All authors have read and approved the final version of the manuscript and consent to its publication.

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