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Assessment of Groundwater Quality for Drinking and Irrigation Purposes in Amroha District, Uttar Pradesh, India: A Multi-Seasonal Spatio-Temporal Analysis

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ABSTRACT
In the Indo-Gangetic plains, groundwater is an important resource for home and agricultural usage. The present study assesses the physico-chemical quality of groundwater of 54 locations of six administrative blocks (Gajraula, Joya, Amroha, Gangeshwari, Hasanpur and Dhanaura) of Amroha district, Uttar Pradesh, India for six consecutive seasonal intervals during April 2025 to September 2026. The parameters analysed were pH, electrical conductivity (EC), total dissolved solids (TDS), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), chloride (Cl^{-}), sulphate (SO_4^{2-}), bicarbonate (HCO^{3-}) and total alkalinity (TA). The results revealed that the pH values of all the samples (6.50–8.14) were within the permissible limit of Bureau of Indian Standards (BIS) (6.5–8.5). The mean EC and TDS were highest during the pre-monsoon (April–June) and lowest during post-monsoon (October–December) period due to seasonal effects of dilution and concentration. Around 7.1% of samples had TDS more than BIS approved TDS limit of 500 mg/L and none of the samples were found to be beyond allowable limit of 2000 mg/L. Magnesium exceeded the acceptable level of 30 mg/L in 67% of the samples. All the samples showed low Sodium Adsorption Ratio (SAR) values (mean 0.60) and negative Residual Sodium Carbonate (RSC) values indicating that the water is appropriate for irrigation without any sodium concern. Spatial research showed that salinity was higher in the blocks of Dhanaura and Hasanpur. Secondary data on cropping pattern (mostly sugarcane and wheat), rainfall (annual ~800–960 mm, mainly in July–September) and groundwater levels (pre-monsoon depth usually 4–20 mbgl) were combined. The comparison suggests that the pre-monsoon season has higher EC/TDS, which is related to a higher water level and peak irrigation demand for sugarcane and wheat crops, calling for sustainable management of groundwater. Regular surveillance is recommended especially for overexploited blocks.

Keywords: *Groundwater quality; Electrical conductivity; TDS; SAR; Irrigation suitability; Cropping pattern; Rainfall; Groundwater level; Amroha; Seasonal variation*

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I. Introduction

Groundwater is a major supply of water for drinking, domestic and irrigation use in many parts of India, especially in the densely populated Indo-Gangetic alluvial plains (Central Ground Water Board, 2021; MacDonald et al., 2016). Satellite-based and in situ records show that abstraction in north-western India has exceeded natural recharge (Rodell et al., 2009), whereas across the Indo-Gangetic Basin as a whole, access to potable groundwater is constrained more by salinity and arsenic than by depletion (MacDonald et al., 2016). Groundwater quality is affected by natural geological processes, human activities including the release of agricultural and industrial effluent, and seasonal hydrological changes such as monsoon replenishment and dry-season concentration (Central Ground Water Board, 2021; Umar et al., 2009). Sustainable management of water resources, public health and agricultural production depends on consistent measurement of groundwater quality.

Amroha district is known for intensive agriculture and lies in the Ganga basin in western Uttar Pradesh (Central Ground Water Board, 2018). The area's dependence on groundwater from shallow and deep aquifers is extremely high. The main agricultural commodities are sugarcane, wheat and rice, with more than 98% of the net sown area irrigated (Central Ground Water Board, 2018).

Salinity and hardness are known to fluctuate in the alluvial aquifers of the Central Ganga Plain in western Uttar Pradesh, where seasonal changes in groundwater chemistry have been attributed to evaporation, irrigation return flow, ion exchange, fertiliser use and effluents from sugar factories and paper mills (Umar et al., 2009). Elsewhere in the Central Ganga Plain, aquifer over-exploitation has been documented alongside waterlogging in canal-command areas (Umar, 2006). Yet comprehensive assessments across multiple seasons and blocks, supported by statistics on agriculture, rainfall and water levels, are not available for Amroha. This study attempts to bridge the gap by analysing groundwater quality at 54 representative sites in six blocks during six seasonal phases between April 2025 and September 2026, and by comparing the primary findings with secondary hydro-agricultural data.

The present study aims to (i) identify the spatio-temporal variations of important physico-chemical parameters, (ii) evaluate potability in compliance with IS 10500:2012 (Bureau of Indian Standards, 2012) and the World Health Organization, 2022) guidelines, (iii) evaluate irrigation suitability based on SAR, RSC and EC criteria (Ayers & Westcot, 1985; Eaton, 1950; Richards, 1954), (iv) provide additional information on crop patterns, precipitation and groundwater levels, and (v) compare primary water-quality data with secondary hydro-climatic and agricultural data.

II. Materials and Methods

2.1 Study Area

The study was carried out in Amroha district of western Uttar Pradesh, India. The district is located in the Upper Ganga Plain and has a geographical area of around 2,170-2,470 sq km. Administratively it is divided into six development blocks, namely, Gajraula, Joya, Amroha, Gangeshwari, Hasanpur and Dhanaura. The district is located in the geographical area extending from around 28.53°N–29.08°N latitude and 78.17°E–78.66°E longitude. The area is almost flat alluvial plain produced by sediments of Ganga and Ramganga river systems. Soils are mainly sandy loam to loam. The climate is humid subtropical with three well-defined seasons: a hot dry pre-monsoon (April–June), a southwest monsoon (July–September) and a cold dry post-monsoon/winter period (October–March). Normal annual rainfall is between 780 mm to 960 mm, with about 70% of the total falling in the period July-September. Mean maximum temperatures exceed 40°C throughout May–June and minima may drop to 5–8°C in January. Net irrigated area is above 98% of net sown land. Private tubewells are the major source of irrigation water. Cropping intensity is high (about 153-155%) with sugarcane-wheat and rice-wheat as the main cropping systems.

2.2 Sampling Design and Field Collection

Total 54 fixed ground water sampling sites (nine sites per block) were selected to offer spatial representation of the six administrative blocks. The sites consisted of hand-pumps, shallow tubewells and deep tubewells utilised for home or agricultural purposes. Sampling was repeated at the same locations in six consecutive seasonal windows: (i) April-June 2025 (pre-monsoon 2025, coded AMJ 2025), (ii) July-September 2025 (monsoon 2025, JAS 2025), (iii) October-December 2025 (post-monsoon 2025, OND 2025), (iv) January-March 2026 (winter 2026, JFM 2026), (v) April-June 2026 (pre-monsoon 2026, AMJ 2026) and (vi) July-September 2026 (monsoon 2026, JAS 2026). This design led to 54 samples × 6 seasons = 324 individual observations.

Each source was purged for 3–5 minutes prior to sample collection to assure typical aquifer water. Samples were collected in pre-cleaned high density polyethylene (HDPE) bottles. pH and electrical conductivity (EC) were measured in situ instantly with calibrated portable meters. The geographic coordinates (latitude and longitude) of each site were recorded using a handheld GPS receiver. Samples for major ion laboratory analysis were kept using normal methods and delivered to the laboratory under cold circumstances (American Public Health Association, 2017).

2.3 Laboratory Analytical Methods

The physico-chemical parameters measured were; pH, electrical conductivity (EC, µS/cm), total dissolved solids (TDS, mg/L), calcium (Ca2+, mg/L), magnesium (Mg2+, mg/L), sodium (Na+, mg/L), potassium (K+, mg/L), chloride (Cl-, mg/L), sulphate (SO4 2-, mg/L), bicarbonate (HCO3 -, mg/L) and total alkalinity (TA, mg/L as CaCO3). The analysis processes were carried out as per the standard methodologies specified by American Public Health Association (2017) and Bureau of Indian Standards (2012). pH was determined electrometrically. EC was determined with a conductivity meter and converted to TDS using a suitable conversion factor (Hem, 1985; Rusydi, 2018). Calcium and magnesium were measured by titration with EDTA. Flame photometry was used to

measure sodium and potassium. Chloride was measured by Argentometric titration of Mohr. Sulphate was determined gravimetric techniques. Bicarbonate and total alkalinity were evaluated by acid titration with phenolphthalein and methyl orange as indicators. All reagents were analytical grade and the quality-control tests (blanks, duplicates and standards) were performed periodically.

2.4 Calculation of Irrigation Suitability Indices

Sodium adsorption ratio (SAR), an indication of sodium danger, was computed using ionic concentrations in milliequivalents per litre (meq/L), (Richards, 1954):

$$SAR = Na^{+} / \sqrt{[(Ca^{2+} + Mg^{2+})/2]}$$

where Na^{+} = Na (mg/L)/23, Ca^{2+} = Ca (mg/L)/20 and Mg^{2+} = Mg (mg/L)/12.

Residual sodium carbonate (RSC) estimates the ability of residual carbonate to precipitate calcium and magnesium and hence increase the fraction of sodium on the exchange complex (Eaton, 1950) was calculated as:

$$RSC\ (meq/L) = (HCO_3^{-} + CO_3^{2-}) - (Ca^{2+} + Mg^{2+})$$

In the absence of observed carbonate, CO_3^{2-} was assumed to be zero and HCO_3^{-} (mg/L) was converted to meq/L by dividing by 61. Water with SAR < 10 and RSC < 1.25 meq/L is generally safe for irrigation while RSC > 2.5 meq/L is not suitable (Eaton, 1950; Richards, 1954; Wilcox, 1955).

2.5 Statistical Analysis and Suitability Assessment

For each parameter, descriptive statistics (minimum, maximum, mean, standard deviation, median and quartiles) were generated for the full dataset, stratified by season and block. Inter-relationships among parameters were examined by calculating Pearson's product-moment correlation coefficients. Box-plots and line graphs of seasonal means were used to illustrate temporal trends. To give a summary of geographical patterns, block-wise means and bar charts were used. All statistical analyses and visualisations were performed in Python.

Drinking water compatibility was checked as per Bureau of Indian Standards standard IS 10500:2012 (acceptable and allowed limits in the absence of substitute source). The Food and Agriculture Organization (FAO) recommendations were applied to evaluate the irrigation suitability based on EC (salinity hazard), SAR (sodium hazard) and RSC (residual carbonate hazard) (Ayers & Westcot, 1985), supplemented by the classifications of Richards (1954) and Wilcox (1955).

2.6 Secondary Data Compilation

Secondary information on cropping pattern, long-term rainfall normals and depth-to-water-level (DTWL) statistics was compiled from published Central Ground Water Board (CGWB) aquifer-mapping and year-book reports for Amroha district, Krishi Vigyan Kendra (KVK) Amroha district profile, India Meteorological Department (IMD) rainfall normals and district agricultural statistics. These data were used to provide context for the original water-quality observations and to support the comparative discussion in section 3.8.

III. Results and Discussion

3.1 Overall Physico-Chemical Characteristics

Table 1 summarises the statistics for the 11 water-quality characteristics for the entire data set of 324 samples. pH ranged from 6.50 to 8.14 with a mean of 7.23 ± 0.35 and a median of 7.22. Therefore, all the values fall within the permissible range of 6.5–8.5 according to BIS, which indicates that the groundwater is not acidic nor severely alkaline. Electrical conductivity (EC) varied widely (171–1 439 µS/cm) with a mean of 527.7 ± 226.4 µS/cm and a median of 458 µS/cm indicating considerable temporal and geographical variation of dissolved-ion load. Accordingly, the total dissolved solids (TDS) ranged from 100 to 771 mg/L (mean 316.7 ± 113.9 mg/L, median 306 mg/L).

Calcium was the most abundant cation (average 49.9 ± 18.7 mg/L, range 20–143 mg/L) followed by magnesium (47.5 ± 24.1 mg/L, range 16–125 mg/L), sodium (23.3 ± 10.5 mg/L, range 5–62 mg/L) and potassium (11.2 ± 8.8 mg/L, range 1–56 mg/L). Magnesium concentrations are interesting because the mean and a high proportion of individual readings surpass the BIS acceptable limit of 30 mg/L and contribute to permanent hardness. Anionic average concentrations were chloride 52.0 ± 30.1 mg/L, sulphate 37.0 ± 11.9 mg/L, bicarbonate 173.7 ± 45.1 mg/L and total alkalinity 301.5 ± 120.8 mg/L. The main anion is bicarbonate, compatible with the carbonate lithology of the alluvial aquifers.

Table 1. Descriptive statistics of groundwater quality parameters.

Parameter	Unit	Max	Min	SD	Mean	Median
pH	–	8.14	6.5	0.35	7.23	7.22
Ca^{2+}	mg/L	143	20	18.7	49.9	47
TDS	mg/L	771	100	113.9	316.7	306
Na^{+}	mg/L	62	5	10.5	23.3	23
Mg^{2+}	mg/L	125	16	24.1	47.5	38
K^{+}	mg/L	56	1	8.8	11.2	9
SO_4^{2-}	mg/L	71	12	11.9	37	36
Cl^{-}	mg/L	173	18	30.1	52	40
HCO_3^{-}	mg/L	307	72	45.1	173.7	173
TA	mg/L	830	103	120.8	301.5	280
EC	µS/cm	1439	171	226.4	527.7	458

Main parameters box-and-whisker graphs are shown in Figure 1. The inter-quartile ranges (boxes) and the length of the whiskers indicate that the pH is relatively tightly controlled, but the EC, TDS, Ca, Mg and TA are substantially more spread out. For EC, TDS and TA, few outliers are observed which correspond to greatest salinity samples taken largely from Dhanaura and Hasanpur blocks during pre-monsoon seasons. For most parameters, the median is near to the mean for each distribution, showing approximate symmetry; potassium is an exception, being right-skewed due to a few elevated values.

3.2 Seasonal Variation

The results exhibit distinct and persistent seasonality. Arithmetic means of selected parameters for each of the six sampling windows are shown in Table 2. Mean EC was maximum in the two pre-monsoon windows (AMJ 2025: 578 µS/cm; AMJ 2026: 645 µS/cm) and minimum in the post-monsoon window OND 2025 (408 µS/cm) . TDS is ranked similarly (347 mg/L and 394 mg/L in the two AMJ periods versus 245 mg/L in OND 2025). Calcium, magnesium, sodium, chloride and bicarbonate exhibit the same temporal pattern i.e. maximum concentration in April-June and minimal concentration after the monsoon. The difference between the greatest and lowest seasonal means for EC is about 237 µS/cm (≈ 58% of the lowest mean). This indicates a strong concentration-dilution cycle.

Such seasonal variations are hydro-climatologically consistent. Evaporative concentration, reduced recharge from rainfall and prolonged abstraction of groundwater for irrigation increase the dissolved-ion content during the hot, dry pre-monsoon months. The southwest monsoon (July-September) accounts for the bulk of the yearly rainfall and this replenishes the alluvial aquifers and dilutes the groundwater. Thus, the solute concentrations decrease and are maintained at a lower level during the post-monsoon and winter periods until the next pre-monsoon concentration cycle begins.

Figure 1. Boxplots showing the distribution of key water quality parameters across all sample.
Boxes represent the inter-quartile range; horizontal lines inside boxes are medians; whiskers extend to 1.5 × IQR; individual points beyond whiskers are outliers.

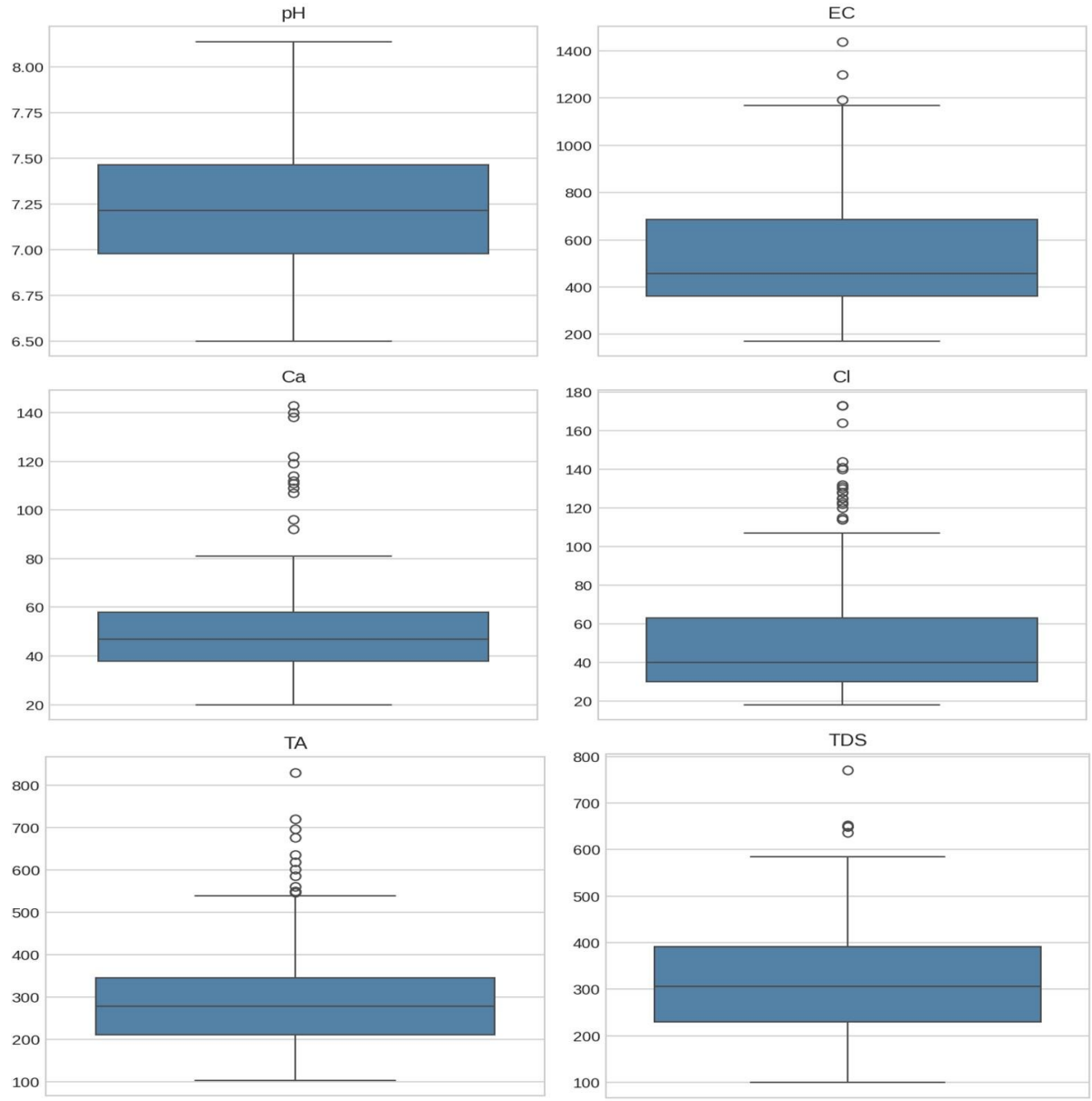
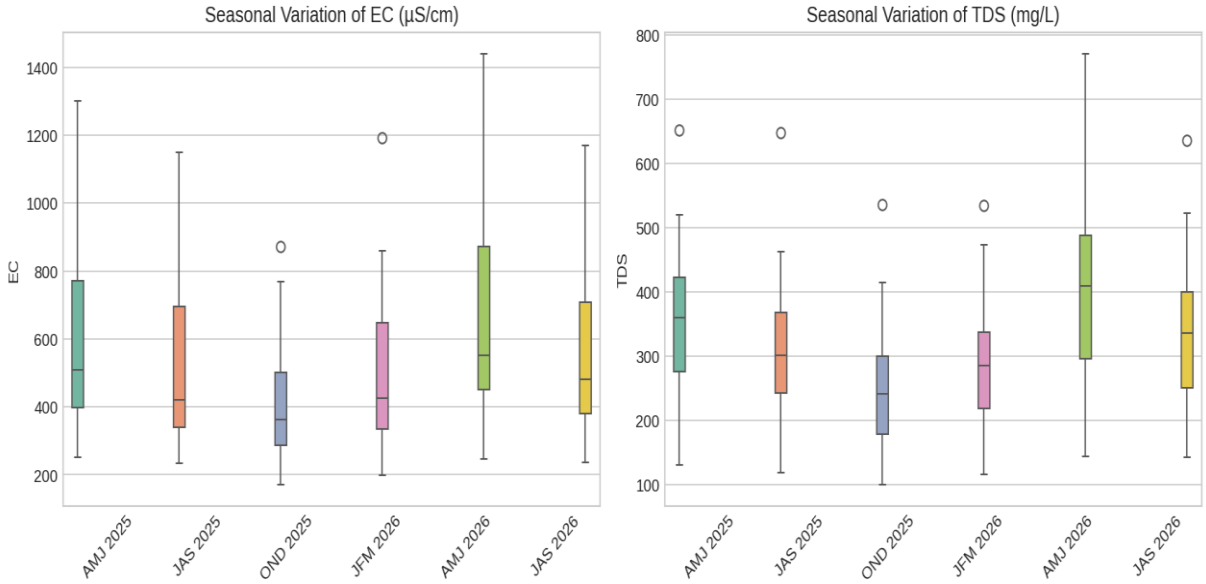


Table 2. Seasonal mean values of selected parameters

Period	pH	Ca	TDS	Na	Mg	HCO_3	Cl	EC
AMJ 2025	7.29	54.6	347	25.4	52.4	186	60	578
JAS 2025	7.18	49.4	301	22.2	45.4	169	49.8	508
OND 2025	7.15	40.3	245	18.5	35.3	146	39.7	408
JFM 2026	7.22	44.4	283	20.9	41.5	157	46.7	483
AMJ 2026	7.36	61.2	394	28.7	58.3	206	68.1	645
JAS 2026	7.22	49.3	330	24	47.1	178	52.8	544

Box-plots of EC and TDS are shown in Figure 2, stratified by the six seasonal periods. The median and upper quartile of both values are clearly higher in the two AMJ windows and lowest in OND 2025. The pre-monsoon seasons also have bigger inter-quartile ranges, showing higher regional variability when the total concentrations are high. Seasonal trends of the principal ions (Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-}, SO_4^{2-} and HCO_3^{-}) are shown as line graphs of mean concentrations in Figure 3. The six ions all rise in parallel to pre-monsoon peaks and fall in parallel to post-monsoon troughs, showing that the seasonal signal is a general concentration-dilution event and not the selective enrichment or depletion of any one ion.

Figure 2. Seasonal variation of electrical conductivity (EC, left) and total dissolved solids (TDS, right).

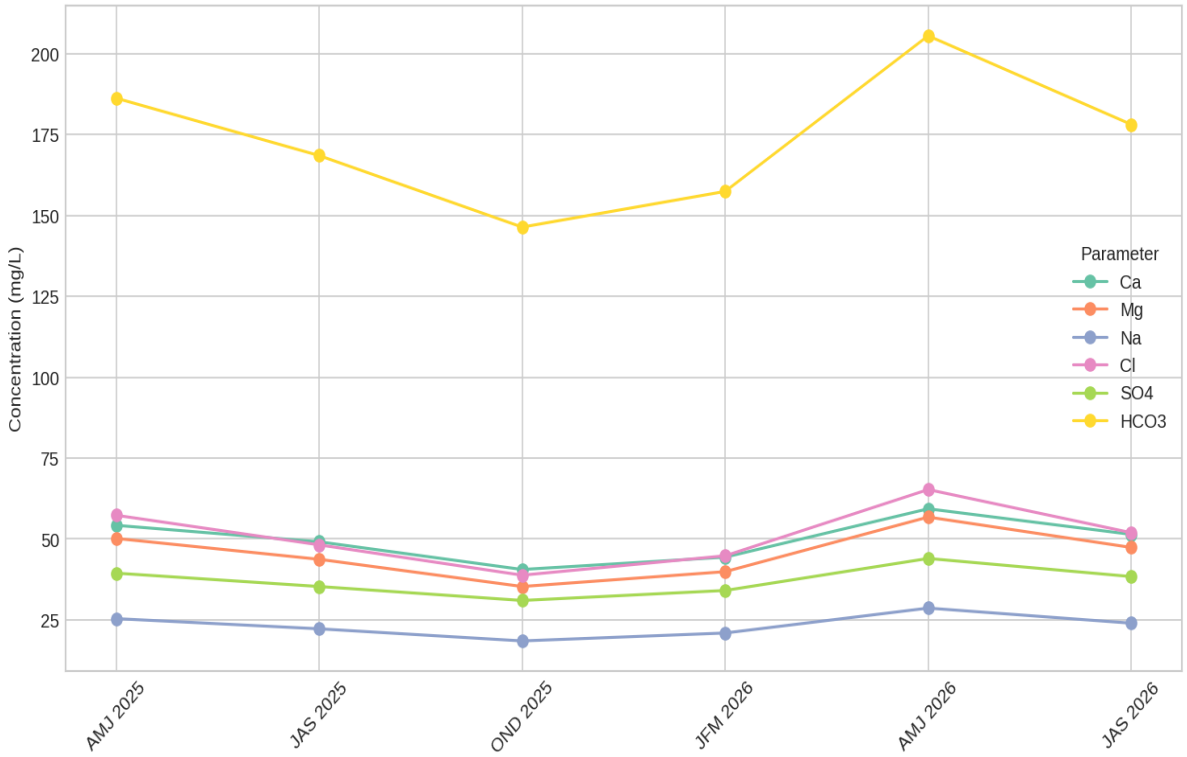


Box-plots summarise the distribution of 54 samples in each seasonal window. Medians are highest in the pre-monsoon (AMJ) periods and lowest in the post-monsoon (OND 2025) period.

3.3 Spatial Variation Across Blocks

Block-wise arithmetic means are summarised in Table 3. Dhanaura recorded the highest mean EC (747 µS/cm) and TDS (423 mg/L), followed by Hasanpur (EC 613 µS/cm, TDS 332 mg/L). The remaining four blocks exhibited appreciably lower salinity: Amroha (EC 515 µS/cm), Gajraula (446 µS/cm), Joya (430 µS/cm) and Gangeshwari (416 µS/cm). Calcium was highest in Hasanpur (59.2 mg/L) and lowest in Gangeshwari (43.2 mg/L). Magnesium showed a similar spatial pattern, with elevated means in Hasanpur (55.0 mg/L) and Joya (51.0 mg/L). Sodium was relatively uniform (16–29 mg/L), while potassium was distinctly higher in Gajraula (19.5 mg/L) than in the other blocks (4–14 mg/L), possibly reflecting local differences in fertiliser application or aquifer mineralogy. Bicarbonate was highest in Dhanaura (200 mg/L) and Gangeshwari (187 mg/L).

Figure 3. Seasonal trends of mean concentrations of major ions (Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}).



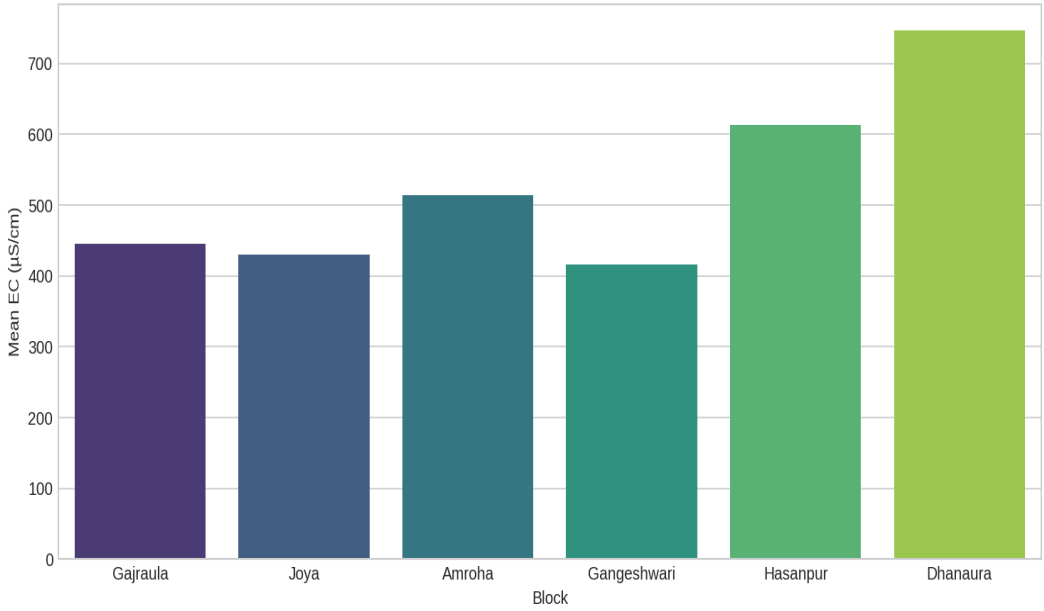
Parallel trajectories indicate a coherent concentration–dilution cycle driven by evaporative enrichment in the dry season and monsoon recharge.

Figure 4 presents a bar chart of block-wise mean EC. The ranking Dhanaura > Hasanpur > Amroha > Gajraula = Joya = Gangeshwari is visually clear. The elevated salinity in Dhanaura and Hasanpur is consistent with their classification by the Central Ground Water Board as over-exploited or semi-critical blocks, where intensive groundwater abstraction for irrigation may have reduced flushing and promoted localised concentration of dissolved salts.

Table 3. Block-wise mean concentrations of water quality parameters.

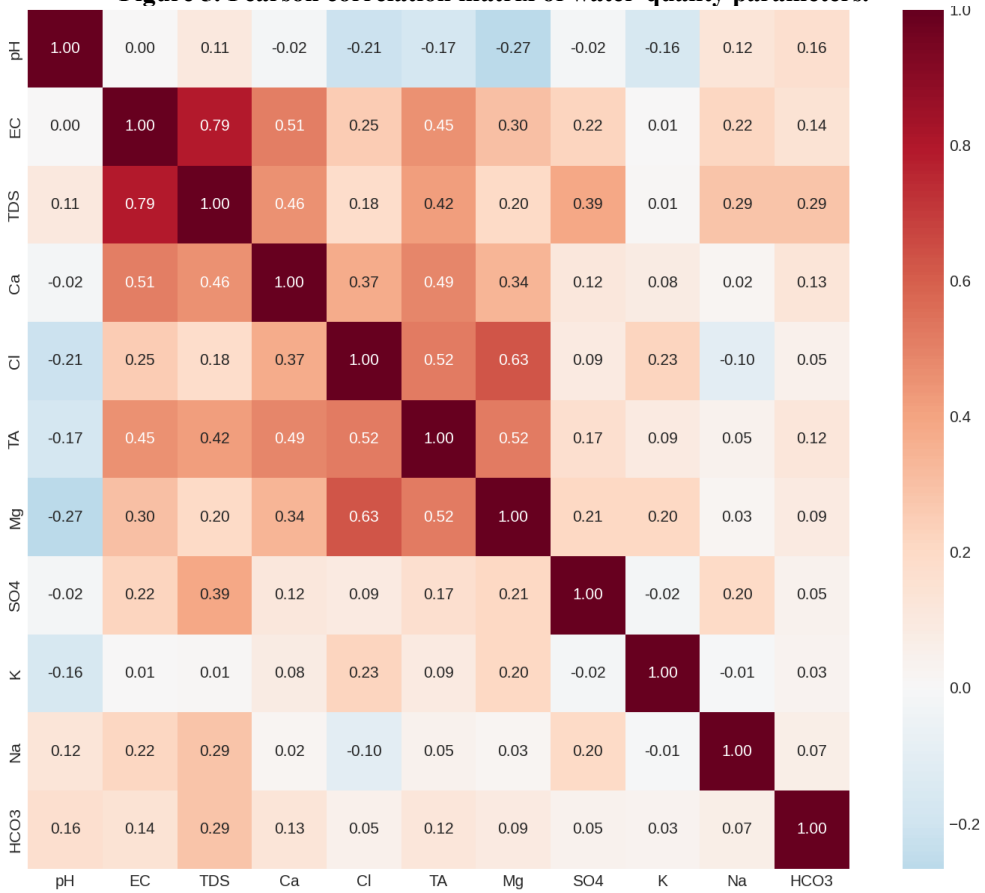
Block	pH	TDS	Mg	Ca	Na	SO_4	Cl	HCO_3	EC
Gajraula	7.12	271	50.2	44.8	16.1	40.1	58.3	155	446
Joya	7.16	250	51	50.4	22.8	32.2	47.3	178	430
Amroha	7.26	323	48.4	46.6	21.3	38.6	64.1	158	515
Gangeshwari	7.13	301	28.8	43.2	28.7	35.9	36.3	187	416
Hasanpur	7.14	332	55	59.2	24.1	36	69.5	164	613
Dhanaura	7.6	423	30.6	54.9	26.7	39.5	28.3	200	747

Figure 4. Block-wise mean electrical conductivity (EC).



Dhanaura and Hasanpur exhibit distinctly higher mean EC than the other four blocks, consistent with greater groundwater stress and reduced flushing in these areas.

Figure 5. Pearson correlation matrix of water-quality parameters.



Strong positive correlations (red) between EC, TDS and the major ions confirm that salinity is controlled by the collective dissolved-ion load; bicarbonate and total alkalinity are nearly collinear.

3.4 Correlation Analysis

Pearson correlation coefficients among the eleven parameters are displayed as a heat-map in Figure 5. EC and TDS are strongly positively correlated ($r \approx 0.85$), as expected because TDS is the mass expression of the ionic content that produces conductivity. EC also correlates positively and significantly with Ca, Mg, Na, Cl and HCO_3, confirming that the major ions collectively control the salinity signal. Bicarbonate and total alkalinity are tightly linked ($r > 0.9$), reflecting the fact that alkalinity in these waters is dominated by the bicarbonate ion. pH shows only weak correlations with the other variables, consistent with its narrow overall range. The coherent correlation structure indicates that the dominant hydrochemical process is the dissolution of carbonate minerals and the concentration of the resulting ions by evaporation and limited recharge, rather than the introduction of a single contaminant plume.

3.5 Suitability for Drinking Water

The measured values are compared to the Bureau of Indian Standards specification IS 10500:2012 and the compliance picture is as under. All the 324 samples are under the pH range (6.5-8.5). TDS surpasses the allowed limit of 500 mg/L in 23 samples (7.1%) and is found almost entirely in Dhanaura and Hasanpur during the two pre-monsoon seasons. None of the samples exceeds the permissible limit of 2 000 mg/L. Calcium (above the acceptable limit of 75 mg/L) was found in 21 samples (6.5%) but below the allowed limit of 200 mg/L in all cases. Magnesium is over the acceptable limit of 30 mg/L in about 217 samples (67%); yet few samples approach or surpass the allowable limit of 100 mg/L. All the samples have chloride and sulphate below the desired thresholds of 250 mg/L and 200 mg/L respectively. Hence, the groundwater was found to be appropriate for drinking as per the parameters studied. The main aesthetic and practical problem is enhanced hardness due to magnesium (and to a lesser extent calcium) which may require softening or higher usage of detergent in the home.

3.6 Suitability for Irrigation

Three complementing metrics were used to estimate appropriateness for irrigation. The sodium adsorption ratio (SAR) varied from 0.16 to 1.61 with a mean of 0.60. All values are very much below the standard level of 10 that denotes a possible sodium threat, hence the water is regarded as excellent in respect of sodium. Residual sodium carbonate (RSC) was negative in all samples (mean −3.44 meq/L, range −12.7 to +0.9 meq/L) showing that calcium and magnesium are in excess of bicarbonate and there is no residual carbonate hazard. In terms of salinity (EC), around 80.6% of samples are below 750 µS/cm and so come within the category of "little restriction" on use based on FAO criteria. The remaining 19.4% samples (mostly from Dhanaura and Hasanpur in pre-monsoon) fell in the range 750–1 439 µS/cm and belong to the category of "slight to moderate restriction". None of the samples come near to the stringent limit of 2 250 µS/cm. The three indices together indicate that the groundwater is good for irrigation of the main crops (sugarcane and wheat) under conventional management procedures. However, caution is recommended at the highest-EC areas during the dry season, particularly for salt sensitive crops or at seedling stage.

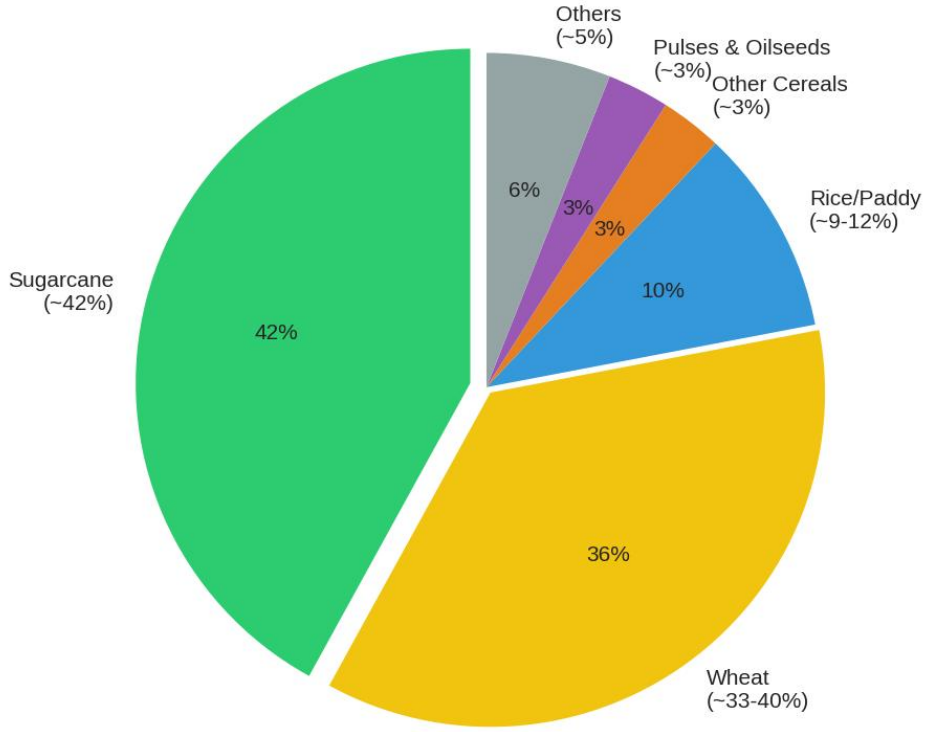
3.7 Secondary Data: Cropping Pattern, Rainfall, and Groundwater Levels

Table 4. Approximate share of major crops in gross cropped area – Amroha District.

Crop / Group	Season	Approximate Share of GCA (%)	Remarks
Sugarcane	Annual / Perennial	40–42	Dominant cash crop
Rice / Paddy	Kharif	9–12	Second major cereal
Wheat	Rabi	33–40	Principal food grain
Other cereals (Bajra, Maize etc.)	Kharif	2–3	Minor
Oilseeds (Mustard etc.)	Rabi	1–2	Limited area

Pulses (Urad, Arhar etc.)	Kharif / Rabi	1–2	Limited area
Horticulture & others	Year-round	5–8	Mango, guava, potato, vegetables

Figure 6. Approximate cropping pattern (percentage share of gross cropped area) in Amroha District.



Sugarcane and wheat together account for roughly three-quarters of the cultivated area, driving continuous irrigation demand.

3.7.1 Cropping Pattern

Secondary agricultural statistics reveal Amroha district to be predominantly irrigated intensive farm economy. The cropping intensity is at 153-155 per cent. Sugarcane accounts for the highest proportion of the total planted area (around 40–42%) and serves as the major cash crop. Wheat occupies 33-40% area and is the main Rabi food grain. Rice (paddy) is grown mostly in the kharif season and covers 9–12% of the area. The rest is under other cereals (bajra, maize), pulses (primarily urad and arhar), oilseeds (mustard) and horticulture crops (mango, guava, potato, vegetables) (Table 4). The major agricultural systems are Sugarcane-Ratoon-Wheat and Rice-Wheat. Irrigation coverage surpasses 98% of the net sown area. The private tubewells supply the lion's share of the irrigation water, making groundwater the main resource for agricultural output.

The approximate proportional allocation of gross cultivated area among key crop groupings is visualised in figure 6. Co-dominance of sugarcane and wheat (≈ 75–80% of GCA) indicates the high water requirement of the agricultural system and corresponding dependence on groundwater abstraction throughout the year.

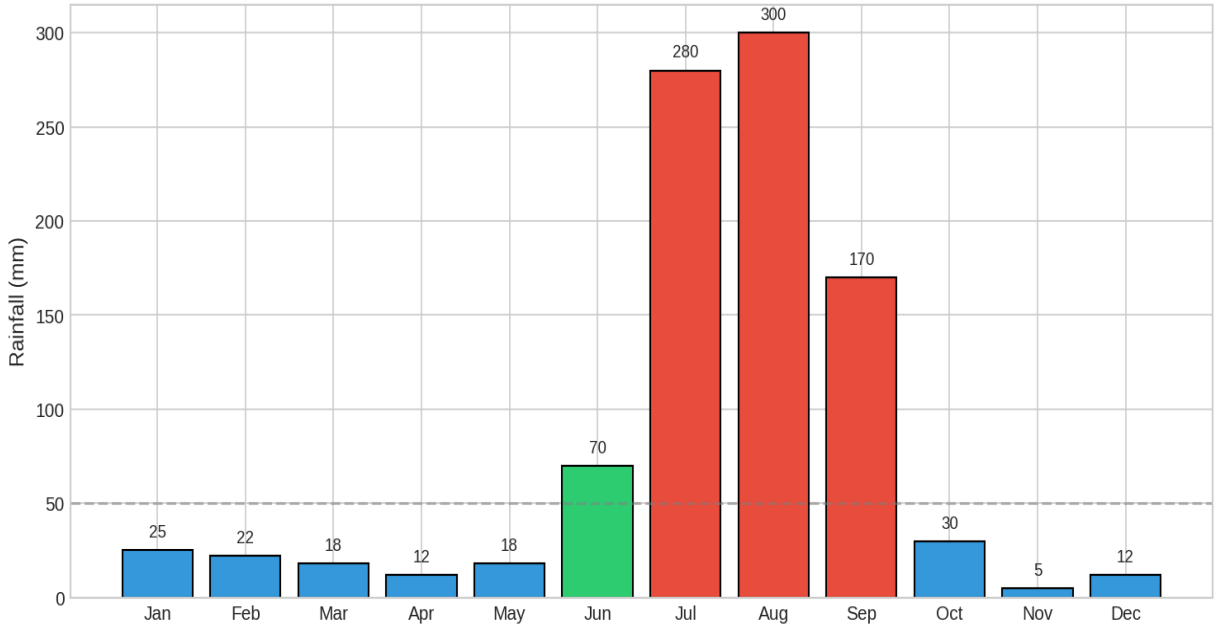
3.7.2 Rainfall Pattern

Table 5. Approximate normal monthly rainfall distribution – Amroha District.

Month	Season	Rainfall (mm)	Relative Contribution
January	Winter	20–30	Low
February	Winter	20–25	Low
March	Pre-monsoon	15–25	Low
April	Pre-monsoon	10–20	Very low
May	Pre-monsoon	15–25	Low
June	Monsoon onset	60–80	Moderate
July	Monsoon	270–320	Very high
August	Monsoon	280–370	Very high
September	Monsoon	160–200	High
October	Post-monsoon	25–45	Low
November	Post-monsoon	3–10	Very low
December	Winter	10–20	Low
Annual	–	780–960	–

The long-term rainfall normals of Amroha district have a distinct seasonal variation (Table 5). Annual totals are often in the 780-960 mm range. Over 70% of the annual precipitation occurs in the three monsoon months of July, August and September, with July and August contributing 50–60% of the total annual precipitation in a typical year. The pre-monsoon months (April–May) and the late post-monsoon/winter months (November–December) are sharply dry, with monthly averages often below 25 mm. This rainfall regime results in a strong annual cycle of aquifer recharge (July–September) and a long period of inadequate natural replenishment. Figure 7 shows the monthly rainfall pattern in a bar chart. The contrast between the monsoon peak and the dry season trough is instantaneous, and provides the climatic impetus for the concentration-dilution cycle shown in the primary groundwater quality data.

Figure 7. Normal monthly rainfall pattern for Amroha District (approximate long-term average).



The overwhelming majority of annual precipitation occurs in July–September, creating a strong seasonal recharge signal.

3.7.3 Groundwater Levels

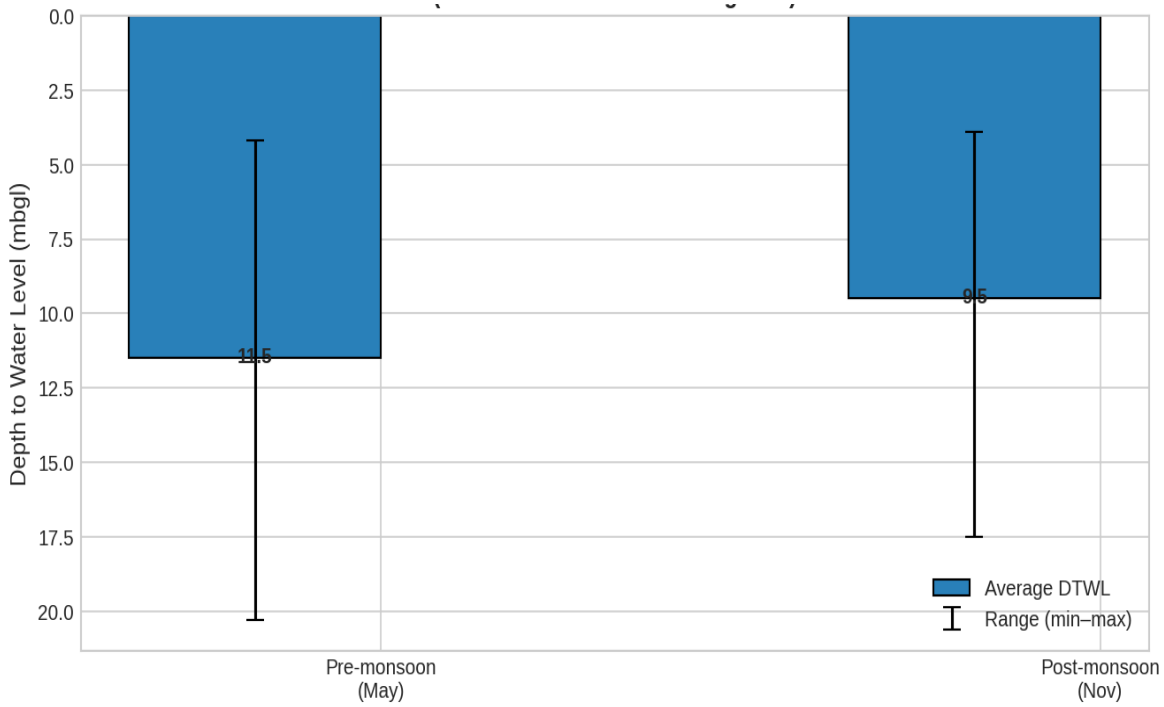
The monitoring data of the Central Ground Water Board indicate that the depth to water level (DTWL) in Amroha district generally varies from about 4 m to 20 m below ground level (mbgl) during pre-monsoon season (May) and from about 4 m to 17.5 mbgl during post-monsoon period (November) (Table 6). Pre-monsoon DTWL is usually in the range of 10-12 mbgl but post-monsoon average is significantly shallower (appox. 9-10 mbgl). Monsoon recharge causes the seasonal recovery of 1-3 m. Recent CGWB evaluations have classed some blocks, particularly Joya, Gajraula and Dhanaura, as over-exploited or "dark zones" indicating a level of groundwater development in excess of 100% (extraction more than annual replenishable resource). This long-term mismatch between abstraction and recharge is an important backdrop for assessing both water-level trends and water-quality patterns.

Table 6. Typical depth to water level (DTWL) ranges – Amroha District (CGWB-based).

Period	Max DTWL (mbgl)	Min DTWL (mbgl)	Typical Average (mbgl)	Remark
Pre-monsoon (May)	17–20.3	4.1–4.2	10–12	Deeper levels; peak irrigation demand
Post-monsoon (Nov)	16–17.5	3.8–4.0	9–10	Recharge recovery

Figure 8 summarises the typical ranges and averages of DTWL before and after the monsoon. The downward shift of the water table in the pre-monsoon, coinciding with peak irrigation demand, is clearly illustrated and provides the hydraulic context for the elevated solute concentrations recorded in the primary data set during the same season.

Figure 8. Typical pre- and post-monsoon depth to groundwater level in Amroha District (CGWB-based averages and ranges).



Deeper pre-monsoon levels coincide with the period of highest EC and TDS in the primary data set.

3.8 Comparison of Water-Quality Data with Hydro-Agricultural Data

Integration of the primary groundwater-quality data set with the secondary information on cropping, rainfall and water levels yields a coherent explanatory framework:

(i) Seasonal alignment of salinity peaks with water-level decline and irrigation demand. The highest mean EC and TDS values in the present study occurred during the April–June (pre-monsoon) windows (578–645 µS/cm). This period coincides with the deepest water levels (typically 10–12 mbgl or deeper) and with peak irrigation demand for the perennial sugarcane crop and the preceding rabi wheat crop. Evaporative concentration, reduced natural recharge and continuous pumping therefore act in concert to elevate solute concentrations.

(ii) Monsoon dilution and recharge. The lowest EC/TDS values were recorded in the October–December post-monsoon period (mean EC 408 µS/cm). This decline is consistent with the heavy July–September rainfall (approximately 700–800 mm of the annual total) that recharges the alluvial aquifers, raises water levels (post-monsoon DTWL typically 9–10 mbgl) and dilutes the dissolved-ion load.

(iii) Spatial correspondence with over-exploited blocks. Dhanaura and Hasanpur (and to a lesser extent Gajraula and Joya) exhibited the highest salinity in the primary data set. These same blocks feature prominently in CGWB over-exploitation and dark-zone classifications, suggesting that intensive tubewell irrigation for the sugarcane–wheat system has contributed both to declining water levels and to localised concentration of dissolved salts.

(iv) Crop water-quality requirements versus observed quality. Sugarcane and wheat are moderately salt-tolerant. The observed SAR values (mean 0.60) and uniformly negative RSC indicate the absence of sodium or residual-carbonate hazard. EC values for the majority of samples fall in the "little to slight restriction" category for irrigation, confirming that the groundwater remains suitable for the dominant cropping pattern. Sites that exceed 750 µS/cm during the pre-monsoon nevertheless warrant caution for salt-sensitive crops or at the seedling stage.

(v) Hardness and agricultural implications. Elevated magnesium (exceeding the desirable drinking-water limit in ~67% of samples) contributes to permanent hardness. While not a primary irrigation constraint, long-term application of hard water can affect soil

structure and may increase domestic soap and detergent consumption.

The primary quality observations are consistent with the secondary hydro-climatic and agricultural context. Seasonal salinity peaks track the dry-season drawdown driven by intensive irrigation of sugarcane and wheat, while monsoon recharge restores both water levels and quality. Sustainable management therefore requires concurrent attention to extraction rates, cropping choices (water-efficient varieties or diversification), and artificial-recharge measures in over-exploited blocks.

IV. Conclusion

The present multi-seasonal study of groundwater quality in six blocks of Amroha district shows that the water is generally safe for drinking and irrigation uses as per the parameters studied. The seasonal pattern displays a clear accumulation during pre-monsoon (April-June) and a reduction during and after monsoon. Space wise, excessive salinity is observed in Dhanaura and Hasanpur blocks and needs constant monitoring. The water is hard because of the high level of magnesium. Sodium hazard is modest (low SAR, negative RSC).

The secondary data demonstrate that the district's intense sugarcane-wheat cropping system, heavy reliance on tubewells for irrigation and the extreme seasonality in rainfall (concentrated in July–September) together cause the observed temporal and spatial trends in water quality and levels. The comparison of primary and secondary data sets reveals the need for integrated water-resource management including regular monitoring of EC, TDS and hardness (especially during dry seasons), regulation of extraction in over-exploited blocks, promotion of water-efficient irrigation and crop diversification and artificial-recharge measures. Additional investigations covering nitrate, fluoride, heavy metals and microbiological factors would provide a more comprehensive picture of water quality.

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