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Assessment of Spatio-temporal trend in groundwater quality in eastern Uttar Pradesh using statistical and GIS based techniques

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Abstract

Groundwater is the principal source of drinking, domestic and irrigation water supply across the alluvial plains of Eastern Uttar Pradesh, and understanding its long-term quality behaviour is essential for sustainable resource management. This study evaluates the spatio-temporal trends of groundwater quality across eight monitoring stations (Ambedkar Nagar, Ayodhya, Azamgarh, Basti, Gorakhpur, Jaunpur, Sant Kabir Nagar and Sultanpur) in Eastern Uttar Pradesh using longterm historical records of fourteen physicochemical parameters: total dissolved solids (TDS), pH, electrical conductivity (EC), total hardness (TH), calcium, magnesium, sodium, potassium, carbonate, bicarbonate, sulphate, chloride, fluoride and nitrate. The non-parametric Mann-Kendall test was applied to detect the direction of monotonic trends, and Sen's slope estimator was used to quantify their magnitude; GIS-based inverse-distance interpolation was subsequently used to visualise the regional pattern of the trend statistic for each parameter. Of the 112 parameter-station combinations examined (14 parameters x 8 stations), 90 (80.4%) exhibited statistically significant increasing trends at the 95% confidence level, and no statistically significant decreasing trend was detected. Mann-Kendall Z-statistics for the significant trends ranged from 2.08 to 11.58, with the highest values recorded for potassium at Gorakhpur ($Z = 11.58$), pH at Sant Kabir Nagar ($Z = 10.85$) and fluoride at Sultanpur ($Z = 10.82$). TDS, pH, magnesium and potassium increased significantly at all eight stations (8/8), EC and bicarbonate were significant at seven stations (7/8), while calcium, sodium, carbonate and fluoride were significant at six stations (6/8) and TH, sulphate, chloride and nitrate at five stations (5/8). Sen's slope estimates indicated annual increases of up to 6.38 mg/L for TDS, 6.42 uS/cm for EC, 0.061 pH units for pH, 2.61 mg/L for total hardness and 0.0043 mg/L for fluoride, mostly concentrated at Gorakhpur and Sultanpur. The results indicate a broad regional tendency towards increasing groundwater mineralisation, attributable to a combination of natural water-rock interaction and anthropogenic pressures such as irrigation return flow, fertiliser application and wastewater infiltration. The integration of the Mann-Kendall/Sen's slope statistics with GIS mapping is shown to be an effective framework for identifying priority locations for groundwater quality surveillance, and the findings are intended to support evidence-based groundwater management planning in the study region.

Keywords: Groundwater quality, mann-kendall trend test, sen's slope estimator, gis, spatio-temporal analysis, eastern uttar pradesh, physicochemical parameters

1. Introduction

Groundwater constitutes one of the most important freshwater resources in the Indo-Gangetic alluvial plains of India, meeting a large proportion of drinking, domestic, agricultural and industrial water demand (Central Ground Water Board [CGWB], 2021)^[1]. In Eastern Uttar Pradesh, dense population growth, intensive irrigated agriculture and rapid urbanisation have placed sustained pressure on the quantity and quality of groundwater resources over the past several decades. Unlike surface water, groundwater quality changes are typically gradual and cumulative, making longterm monitoring and trend analysis essential for early identification of deteriorating conditions before they become severe (Machiwal and Jha, 2012)^[2].

A wide range of natural and anthropogenic processes govern groundwater chemistry, including water-rock interaction, residence time, recharge dynamics, evaporation, irrigation return flow, fertiliser application, domestic sewage infiltration and industrial effluent discharge (Appelo and Postma, 2005)^[3]. Because these processes act simultaneously and their relative influence

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can shift over time, robust statistical methods are required to distinguish genuine long-term trends in groundwater quality parameters from short-term fluctuations associated with seasonal recharge or sampling variability.

The Mann-Kendall test (Mann, 1945; Kendall, 1975) [4, 5] is a widely used non-parametric method for detecting monotonic trends in hydrological and environmental time series because it does not require the data to follow a specific statistical distribution and is relatively insensitive to outliers and missing values. When a significant trend is detected, Sen's slope estimator (Sen, 1968) [6] is commonly applied alongside it to quantify the magnitude of change per unit time, providing a robust, non-parametric estimate of the rate of increase or decrease. The combined use of these two techniques has been widely adopted in groundwater and surface-water quality trend studies worldwide (Gilbert, 1987; Yue and Wang, 2004) [7, 8].

While station-based trend statistics identify temporal change at individual monitoring locations, they do not, by themselves, convey the spatial pattern of that change across a region. Geographic Information System (GIS)-based interpolation techniques allow point-based trend statistics to be extended into continuous spatial surfaces, enabling the visual identification of zones of pronounced deterioration or stability (Burrough and McDonnell, 1998; Li and Heap, 2014) [9, 10]. The integration of non-parametric trend statistics with GIS mapping therefore

provides a powerful diagnostic framework for regional groundwater quality assessment and management prioritisation. Despite the importance of Eastern Uttar Pradesh as an agriculturally intensive and densely populated region, comprehensive long-term, multi-parameter, multi-station trend assessments of groundwater quality remain limited. The present study addresses this gap by applying the Mann-Kendall test and Sen's slope estimator to fourteen physicochemical parameters across eight districts of Eastern Uttar Pradesh, and by mapping the resulting trend statistics using GIS-based spatial interpolation. The specific objectives of the study are to: (i) characterise the long-term temporal trends of key groundwater quality parameters at each monitoring station; (ii) quantify the magnitude of significant trends using Sen's slope estimator; and (iii) visualise and interpret the spatial pattern of these trends across the study area to identify priority zones for groundwater quality surveillance.

2. Study Area

The study area comprises eight districts of Eastern Uttar Pradesh, India - Ambedkar Nagar, Ayodhya, Azamgarh, Basti, Gorakhpur, Jaunpur, Sant Kabir Nagar and Sultanpur - which together form part of the middle and eastern Indo-Gangetic alluvial plain.

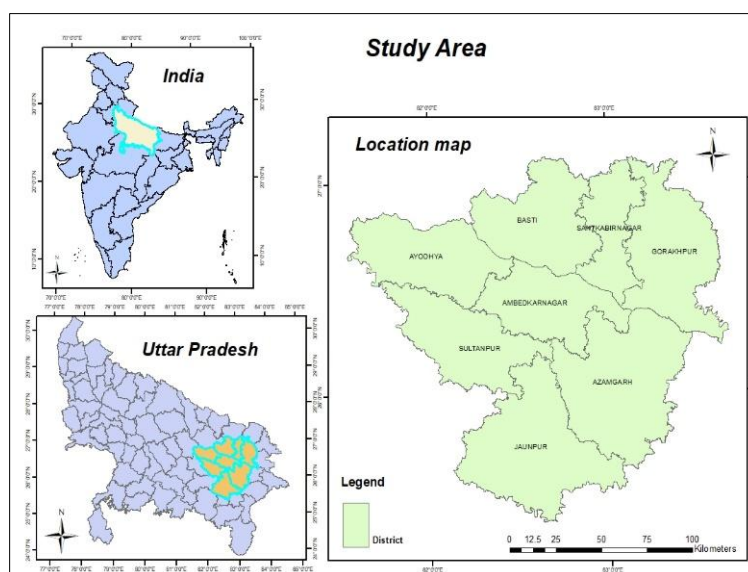


Fig 1: Location map of the study area

The region is characterised by a sub-tropical, monsoon-dominated climate, fertile alluvial soils and shallow-to-moderate depth unconfined to semi-confined aquifers that are extensively exploited for irrigation and domestic water supply. Agriculture in the region is intensive, with paddy-wheat and sugarcane-based cropping systems supported by heavy reliance on groundwater abstraction, particularly during the dry season. The combination of high groundwater draft, fertiliser-intensive agriculture, expanding peri-urban settlements and limited sewage infrastructure makes the region susceptible to progressive changes in groundwater chemistry, which motivates the long-term trend assessment undertaken in this study.

3. Materials and Methods

3.1 Data Source and Parameters

Long-term historical groundwater quality data for fourteen

physicochemical parameters - total dissolved solids (TDS), pH, electrical conductivity (EC), total hardness (TH), calcium, magnesium, sodium, potassium, carbonate, bicarbonate, sulphate, chloride, fluoride and nitrate - were obtained from the historical groundwater quality monitoring records of the Central Ground Water Board (CGWB), Ministry of Jal Shakti, Government of India, for eight groundwater monitoring stations representing the selected districts of Eastern Uttar Pradesh (CGWB, 2017, 2019, 2021) [11]. Sample collection and laboratory analysis of the archived CGWB records followed standard procedures for groundwater sampling and physicochemical analysis (APHA, AWWA, & WEF, 2012) [12]. Descriptive statistical analysis was first carried out to summarise the central tendency, dispersion and range of each parameter at every station, providing the basis for the subsequent trend analysis.

3.2 Mann-Kendall Trend Test

The non-parametric Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975)^[4, 5] was applied to each parameter-station time series to detect the presence, direction and statistical significance of monotonic trends. For a time series $x_1, x_2, \dots, x_n$, the MK test statistic S is computed as the sum of the signs of all pairwise differences $(x_j - x_i)$ for $j > i$. For n greater than about 10, S is approximately normally distributed, and the standardised test statistic Z is obtained by dividing S (adjusted for continuity and tied values) by its standard deviation. A positive Z value indicates an increasing trend and a negative Z value indicates a decreasing trend; the trend was considered statistically significant at the 95% confidence level when the absolute value of Z exceeded 1.96 (Gilbert, 1987; Helsel and Hirsch, 2002)^[7, 13]. The MK test has been widely applied to monthly and annual water-quality records because of its robustness to non-normality, missing values and the presence of outliers (Hirsch, Slack, and Smith, 1982)^[14], and its statistical power relative to alternative rank-based tests has been evaluated in several hydrological studies (Yue, Pilon, and Cavadias, 2002)^[15].

3.3 Sen's Slope Estimator

Where a trend was detected, its magnitude was quantified using Sen's non-parametric slope estimator (Sen, 1968; Gilbert, 1987)^[6, 7], computed as the median of the slopes $(x_j - x_i) / (j - i)$ calculated between all pairs of data points in the time series. Sen's slope provides a robust estimate of the rate of change per unit time that is relatively insensitive to outliers, and it was interpreted jointly with the Mann-Kendall Z -statistic: a large positive Z -value denotes a highly consistent monotonic trend, whereas the Sen slope quantifies the actual annual rate of change in the parameter's original unit. Where serial correlation was suspected, the modified variance correction proposed by Hamed and Rao (1998)^[16] provides a recognised safeguard against inflated significance, and is noted here as a possible refinement for future analyses of these records.

3.4 GIS-Based Spatial Mapping

To visualise the regional pattern of temporal change, the station-wise Mann-Kendall Z -statistic for each parameter was interpolated across the study area using GIS-based spatial interpolation (inverse distance weighting) to generate continuous trend-intensity surfaces. Because only eight monitoring stations were available, the interpolated surfaces should be interpreted as generalised trend-intensity gradients between known stations rather than as directly measured values at every location (Burrough and McDonnell, 1998; Li and Heap, 2014)^[9, 10]. The resulting maps display the spatial intensity of the temporal trend statistic and not the absolute measured

concentration of the corresponding parameter.

4. Results and Discussion

The spatio-temporal variation of groundwater quality in the selected districts of Eastern Uttar Pradesh was examined using long-term historical groundwater quality data. Fourteen physicochemical parameters were analysed to evaluate groundwater quality trends and spatial variability. Descriptive statistical analysis was initially carried out to summarise the characteristics of the groundwater quality dataset, followed by the Mann-Kendall trend test and Sen's slope estimator to determine the direction and magnitude of temporal changes. Furthermore, GIS-based spatial distribution maps were prepared to visualise the regional variation in groundwater quality parameters. The results obtained from these analyses are presented and discussed in the following sections.

4.1 Pattern of Mann-Kendall Trends

Across the 112 parameter-station combinations (14 parameters $\times$ 8 stations), 90 combinations exhibited statistically significant increasing trends, whereas no statistically significant decreasing trend was detected. This indicates that the dominant long-term signal in the study area was an increase in groundwater mineralisation and in several major and minor ionic constituents. The remaining combinations were classified as non-significant increasing, non-significant decreasing or stable trends. The absence of significant negative trends does not imply that every parameter increased at every station; rather, the few negative Z -values did not exceed the critical magnitude of 1.96.

TDS, pH, magnesium and potassium showed significant increasing trends at all eight stations. EC and bicarbonate were significant at seven stations; calcium, sodium, carbonate and fluoride at six stations; and TH, sulphate, chloride and nitrate at five stations. The most pronounced Z -statistics were observed for potassium at Gorakhpur ($Z=11.577$), pH at Sant Kabir Nagar ($Z=10.852$), fluoride at Sultanpur ($Z=10.815$), carbonate at Gorakhpur ($Z=10.589$), bicarbonate at Azamgarh ($Z=10.328$), magnesium at Gorakhpur ($Z=9.744$), calcium at Azamgarh ($Z=9.651$), TDS at Sant Kabir Nagar ($Z=9.296$) and EC at Sultanpur ($Z=9.133$). These values identify the locations where the upward trends were most persistent through time.

4.2 Mann-Kendall Z-Statistics

The station-wise Mann-Kendall Z -statistics are presented in Table 1. Positive values dominate the table, showing that most groundwater-quality parameters increased over the study period. Values printed in bold represent statistically significant trends at the 95% confidence level ($|Z| > 1.96$)

Table 1: Mann-Kendall Z -statistics for groundwater quality parameters across eight monitoring stations in Eastern Uttar Pradesh

Station	TDS	pH	EC	TH	Calcium	Magnesium	Sodium	Potassium	Carbonate	Bicarbonate	Sulphate	Chloride	Fluoride	Nitrate
Ambekar Nagar	7.1496	10.148	6.0389	5.9131	6.8883	5.4138	4.9702	7.7852	3.8879	5.7962	5.1802	4.9796	4.9535	2.2029
Ayodhya	2.7254	2.0825	3.4348	1.4794	0.8587	2.9122	2.0721	3.0432	1.2881	1.8854	-0.9614	-0.7934	0.4532	-0.5321
Azamgarh	7.8403	5.8909	5.8943	3.8811	9.6510	6.5989	4.2095	6.6737	5.6841	10.328	4.9002	5.5395	2.8843	6.4871
Basti	8.9369	10.834	2.2447	1.1387	2.1328	2.3894	0.5927	8.0042	8.4878	4.0741	2.1187	0.7888	1.8871	6.6924
Gorakhpur	8.7316	10.838	8.8436	8.4718	6.7622	9.7444	6.8416	11.577	10.589	9.8190	6.3048	4.9516	8.5171	5.7589
Jaunpur	7.6675	10.491	4.3587	4.6761	4.6528	4.3448	3.3507	8.3910	10.043	8.2182	-1.2180	6.2256	6.5105	0
Sant Kabir Nagar	9.2963	10.852	0.3127	0.3827	0.9101	3.5281	0.9147	6.3100	-0.0700	3.9248	0.2193	0.4060	4.9099	0.4900
Sultanpur	7.2569	7.7390	9.1329	7.0568	5.9502	9.5902	7.7889	8.5262	8.9606	5.2315	7.9475	6.7808	10.815	2.7908

Note: Bold values indicate $|Z| > 1.96$ (statistically significant trend at 95% confidence level)

4.3 Station-wise Bar Charts of Mann-Kendall Z-Statistics

To further aid visual interpretation of Table 1, the Mann-Kendall Z-statistic for all fourteen parameters is also presented as a bar chart for each of the eight monitoring stations (Figures 2 to 9). In each chart, the dashed horizontal lines mark the +1.96 and -1.96 significance thresholds at the 95% confidence level;

bars extending beyond these lines (shown in red) represent statistically significant trends, while bars lying within the band (shown in grey) represent non-significant trends. This station-wise view complements Table 1 by showing, at a glance, which parameters at a given station are significant, and by how much they exceed the critical value.

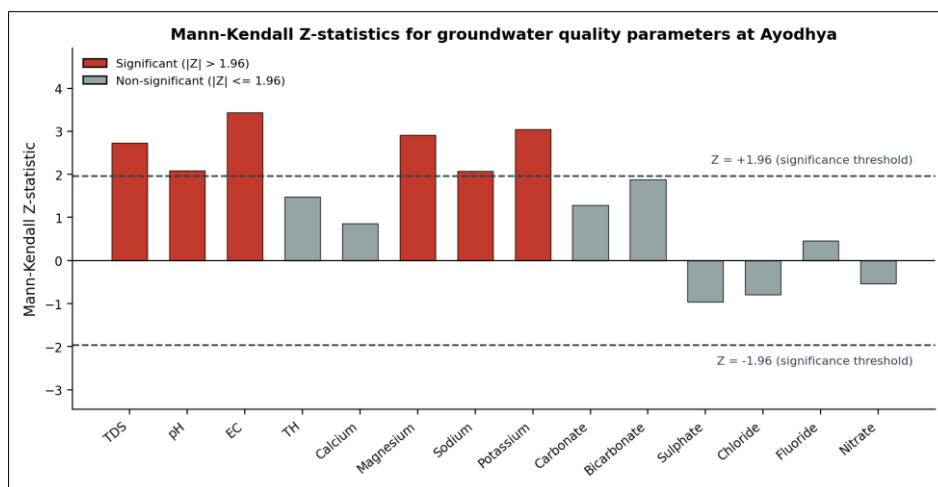


Fig 2: Station-wise bar chart of Mann-Kendall Z-statistics for all fourteen parameters at Ambedkar Nagar, with the +/-1.96 significance threshold marked

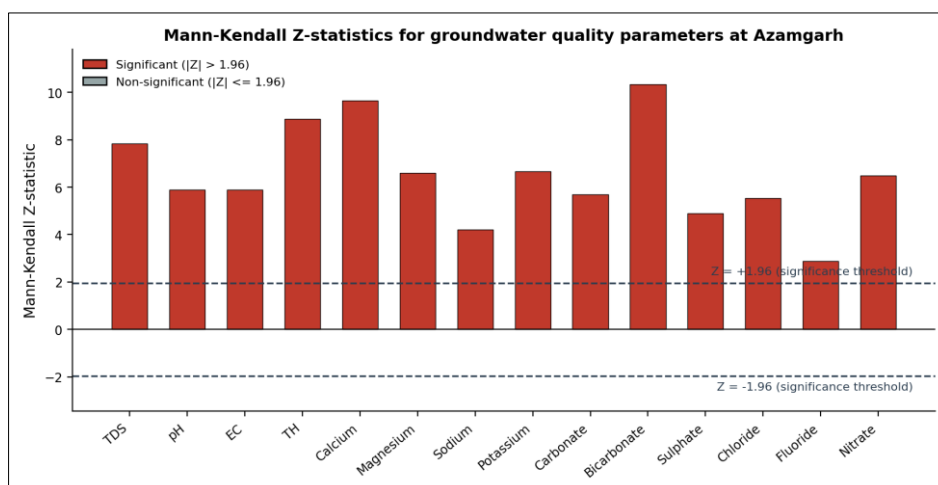


Fig 3: Station-wise bar chart of Mann-Kendall Z-statistics for all fourteen parameters at Ayodhya, with the +/-1.96 significance threshold marked

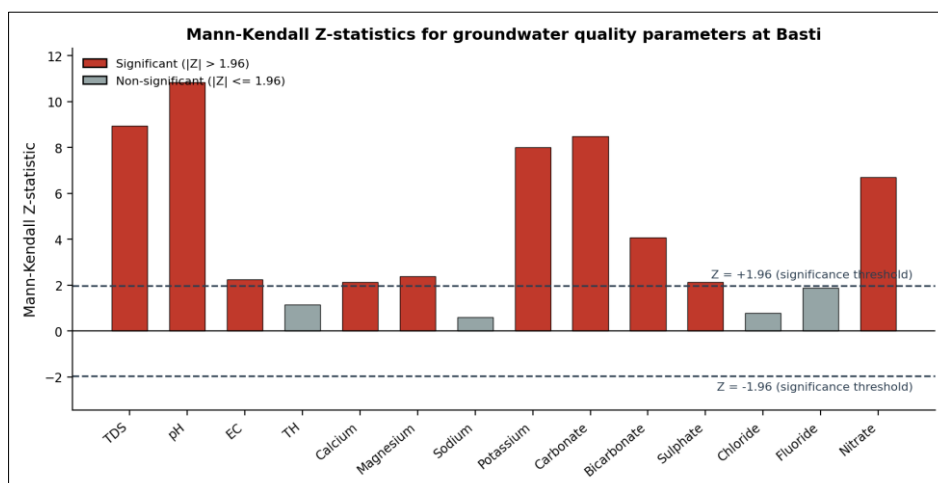


Fig 4: Station-wise bar chart of Mann-Kendall Z-statistics for all fourteen parameters at Azamgarh, with the +/-1.96 significance threshold marked

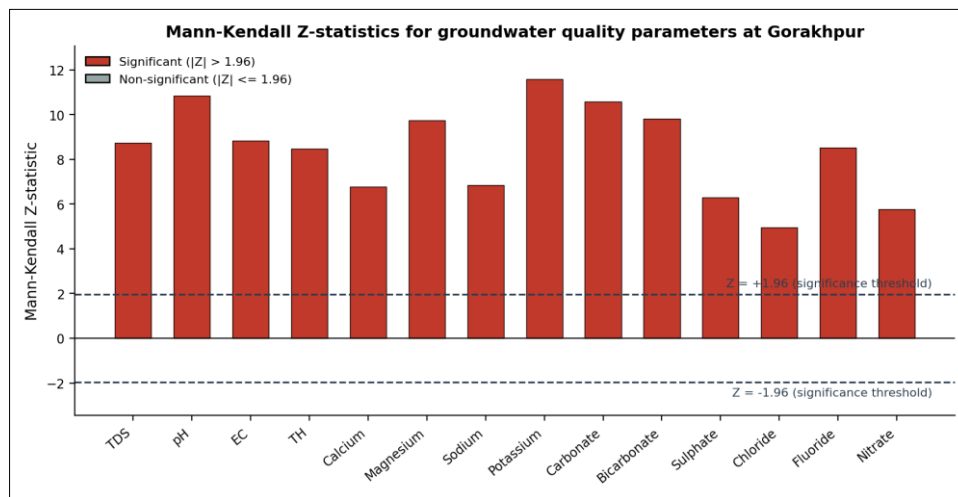


Fig 5: Station-wise bar chart of Mann-Kendall Z-statistics for all fourteen parameters at Basti, with the ± 1.96 significance threshold marked

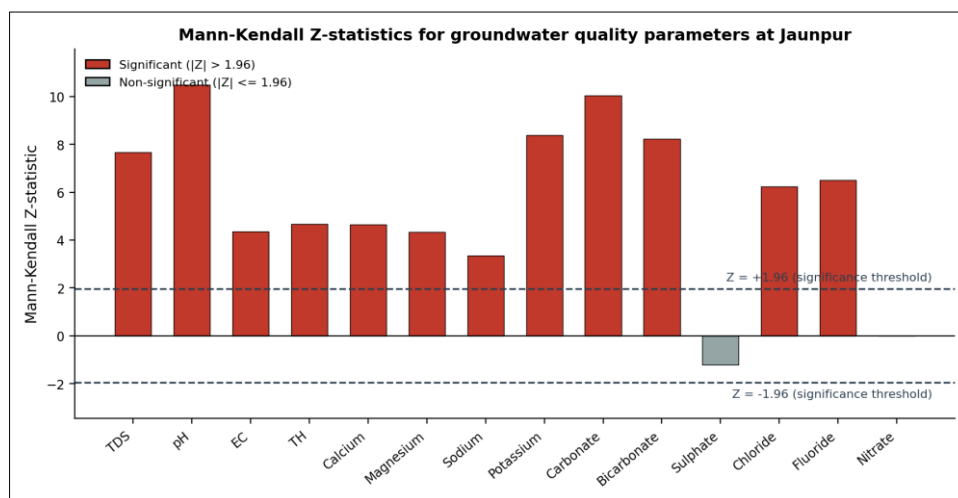


Fig 6: Station-wise bar chart of Mann-Kendall Z-statistics for all fourteen parameters at Gorakhpur, with the ± 1.96 significance threshold marked

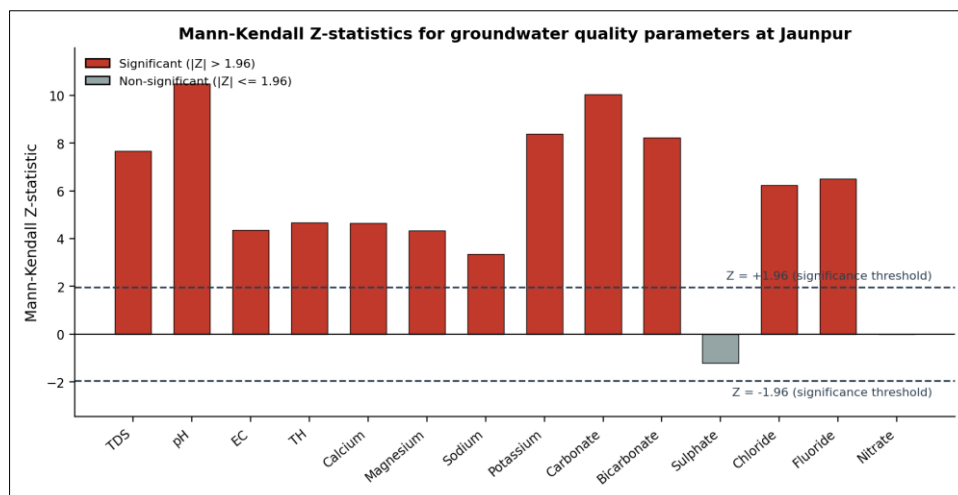


Fig 7: Station-wise bar chart of Mann-Kendall Z-statistics for all fourteen parameters at Jaunpur, with the ± 1.96 significance threshold marked

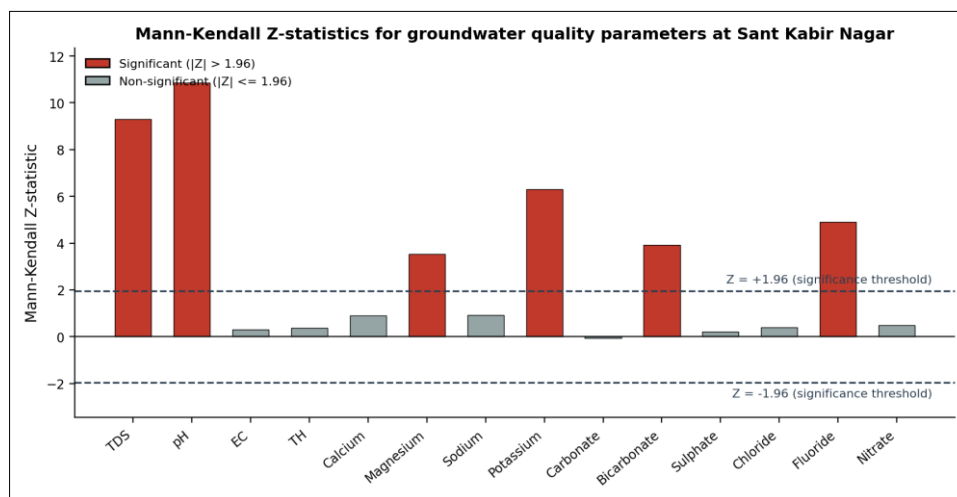


Fig 8: Station-wise bar chart of Mann-Kendall Z-statistics for all fourteen parameters at Sant Kabir Nagar, with the +/-1.96 significance threshold marked

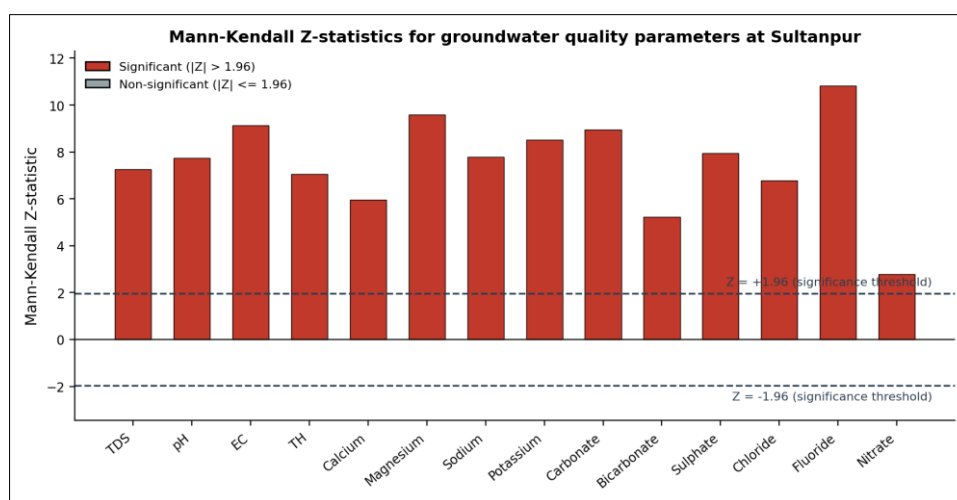


Fig 9: Station-wise bar chart of Mann-Kendall Z-statistics for all fourteen parameters at Sultanpur, with the +/-1.96 significance threshold marked

4.4 Magnitude of Trends Using Sen's Slope

Sen's slope estimates in Table 2 quantify the median annual rate of change. A positive slope indicates an annual increase, a negative slope indicates an annual decrease, and a value close

to zero indicates practical stability. The slope should be interpreted together with the Z-statistic: a large positive Z-value denotes a highly consistent monotonic trend, whereas the slope represents the actual rate of change.

Table 2: Sen's slope estimates (per year, in the original unit of each parameter) for groundwater quality parameters

Station	TDS	pH	EC	TH	Calcium	Magnesium	Sodium	Potassium	Carbonate	Bicarbonate	Sulphate	Chloride	Fluoride	Nitrate
Ambedkar Nagar	3.505435	0.043333	3.407143	1.290896	0.20814	0.188966	0.190526	0.022143	0.082222	1.511667	0.226667	0.121482	0.002	0.403871
Ayodhya	2.886667	0.003333	2.537447	0.452083	0.036667	0.168929	0.098	0.011111	0.022963	0.717692	0.068485	0.041379	0.000286	0.057255
Azamgarh	3.198418	0.005833	3.479533	1.192281	0.10604	0.207131	0.437772	0.012962	0.095525	1.535124	0.251704	0.145014	0.00179	0.096738
Basti	5.4952	0.058	3.766	0.795454	0.467143	0.312653	0.199592	0.034444	0.003333	2.16119	0.726154	0.905	0.003333	0.156
Gorakhpur	6.381923	0.060682	6.424211	2.608387	0.618095	0.258696	0.415833	0.015	0.040625	2.553478	0.598235	0.448571	0.00375	0.202973
Jaunpur	3.846429	0.041659	3.266	1.664301	0.211677	0.261373	0.409959	0.026631	0.038553	2.060275	0.150028	0.176331	0.004285	0
Sant Kabir Nagar	4.19902	0.043048	3.21	1.336667	0.598639	0.237901	0.091051	0.019592	-0.011538	1.227143	0.127035	0.682125	0.003306	0.149235
Sultanpur	2.17275	0.003232	1.96851	1.04168	0.164	0.15368	0.26375	0.00858	0.00882	1.17324	0.16835	0.15165	0.00082	0.51104

Note: Slope values are expressed per year in the original unit of each parameter

4.5 Parameter-wise Spatio-temporal Interpretation

The parameter-wise results are discussed below by jointly interpreting the Mann-Kendall statistic, Sen's slope and the interpolated GIS map. The maps provide a regional visualisation of stationlevel temporal trends. Since only eight monitoring stations were used, transitions between stations

should be interpreted as interpolated trend surfaces rather than direct measurements at every location (Burrough and McDonnell, 1998; Li and Heap, 2014) ^[9, 10].

4.4.1 Total Dissolved Solids (TDS)

The Mann-Kendall analysis for Total Dissolved Solids (TDS)

showed significant increasing trends at all eight stations (Ambedkar Nagar, Ayodhya, Azamgarh, Basti, Gorakhpur, Jaunpur, Sant Kabir Nagar and Sultanpur). The highest Z-statistic was 9.2963 at Sant Kabir Nagar, whereas the lowest was 2.7254 at Ayodhya. Sen's slope ranged from 2.173 mg L⁻¹ yr⁻¹ at Sultanpur to 6.382 mg L⁻¹ yr⁻¹ at Gorakhpur. The widespread positive trend in

TDS indicates a persistent rise in the total dissolved ionic load of groundwater, which may reflect cumulative mineral dissolution, longer residence time, irrigation return flow and increasing anthropogenic inputs. Because TDS integrates the contribution of several dissolved ions, its consistent increase provides a broad indication of progressive mineralization of groundwater.

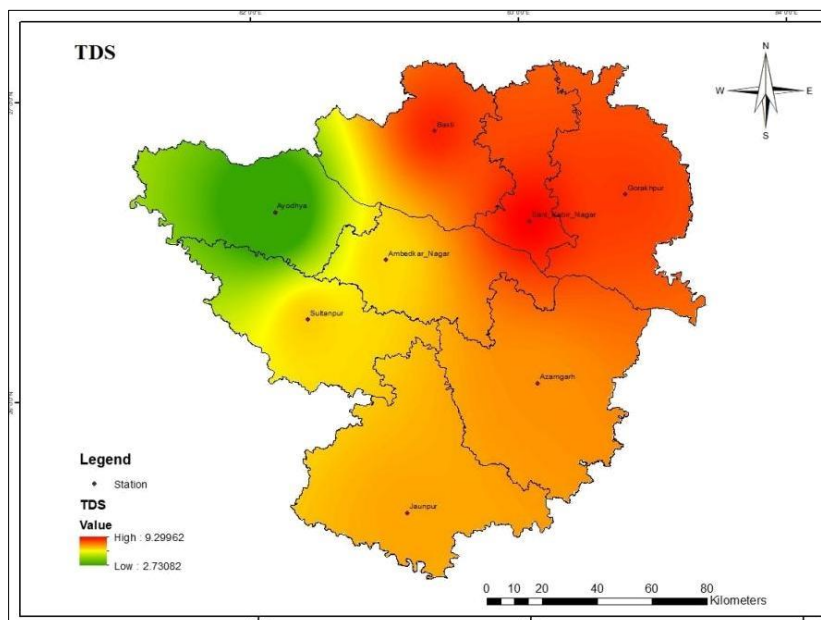


Fig 10: Spatial distribution of the Mann-Kendall Z-statistic for Total Dissolved Solids in the study area

The interpolated surface emphasises the strongest positive trend around Sant Kabir Nagar, Basti and Gorakhpur, while comparatively weak trend zones occur around Ayodhya and Ambedkar Nagar.

4.4.2 pH

The Mann-Kendall analysis for pH showed significant increasing trends at all eight stations. The highest Z-statistic was 10.852 at Sant Kabir Nagar, whereas the lowest was 2.0825 at Ayodhya.

Sen's slope ranged from 0.0032 pH-unit yr⁻¹ at Sultanpur to 0.0607 pH-unit yr⁻¹ at Gorakhpur. The statistically significant positive trend in pH indicates that groundwater became progressively more alkaline over the study period, which may be associated with bicarbonate buffering, carbonate equilibria and changes in recharge-water chemistry. A significant trend does not by itself indicate non-compliance; the actual pH observations must be compared with drinking-water limits before drawing a suitability conclusion.

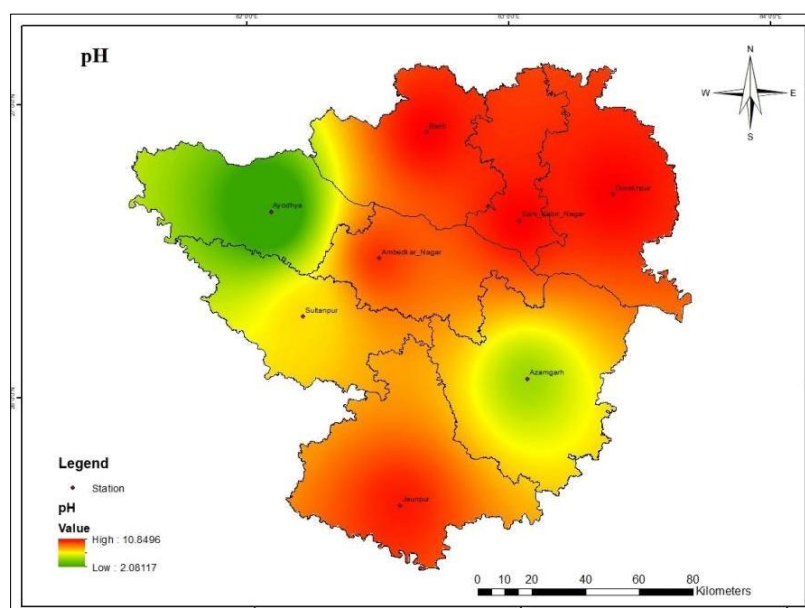


Fig 11: Spatial distribution of the Mann-Kendall Z-statistic for pH in the study area.

The interpolated surface emphasises the strongest positive trend around Sant Kabir Nagar, Gorakhpur and Basti, while comparatively weak trend zones occur around Ayodhya and Azamgarh.

4.4.3 Electrical Conductivity (EC)

The Mann-Kendall analysis for Electrical Conductivity (EC) showed significant increasing trends at seven of the eight stations (Ambedkar Nagar, Ayodhya, Azamgarh, Basti, Gorakhpur, Jaunpur and Sultanpur); a non-significant positive

trend occurred at Sant Kabir Nagar. The highest Z-statistic was 9.1329 at Sultanpur, whereas the lowest was 0.31267 at Sant Kabir Nagar.

Sen's slope ranged from 1.969 $\mu\text{S cm}^{-1} \text{ yr}^{-1}$ at Sultanpur to 6.424 $\mu\text{S cm}^{-1} \text{ yr}^{-1}$ at Gorakhpur. The increasing EC trend signifies a gradual rise in the ionic strength and electrical conductance of groundwater. The close conceptual relationship between EC and TDS is reflected in their broadly similar spatial pattern.

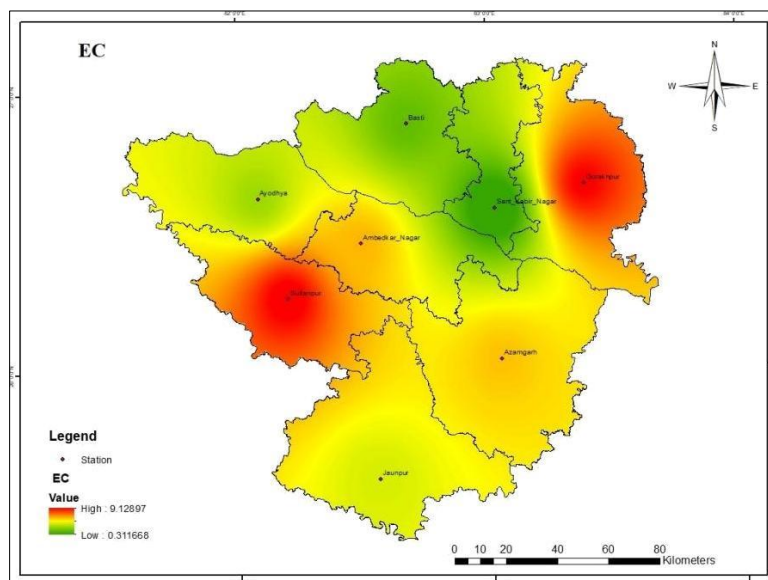


Fig 12: Spatial distribution of the Mann-Kendall Z-statistic for Electrical Conductivity in the study area.

The interpolated surface emphasises the strongest positive trend around Sultanpur, Gorakhpur and Ambedkar Nagar, while comparatively weak trend zones occur around Sant Kabir Nagar and Basti.

4.4.4 Total Hardness (TH)

The Mann-Kendall analysis for Total Hardness (TH) showed significant increasing trends at five of the eight stations (Ambedkar Nagar, Azamgarh, Gorakhpur, Jaunpur and

Sultanpur); nonsignificant positive trends occurred at Ayodhya, Basti and Sant Kabir Nagar. The highest Z-statistic was 8.8811 at Azamgarh, whereas the lowest was 0.38269 at Sant Kabir Nagar.

Sen's slope ranged from 0.452 $\text{mg L}^{-1} \text{ yr}^{-1}$ at Ayodhya to 2.608 $\text{mg L}^{-1} \text{ yr}^{-1}$ at Gorakhpur. The increase in TH reflects a growing contribution of divalent cations, principally calcium and magnesium, and is consistent with continuing dissolution of carbonate-bearing minerals.

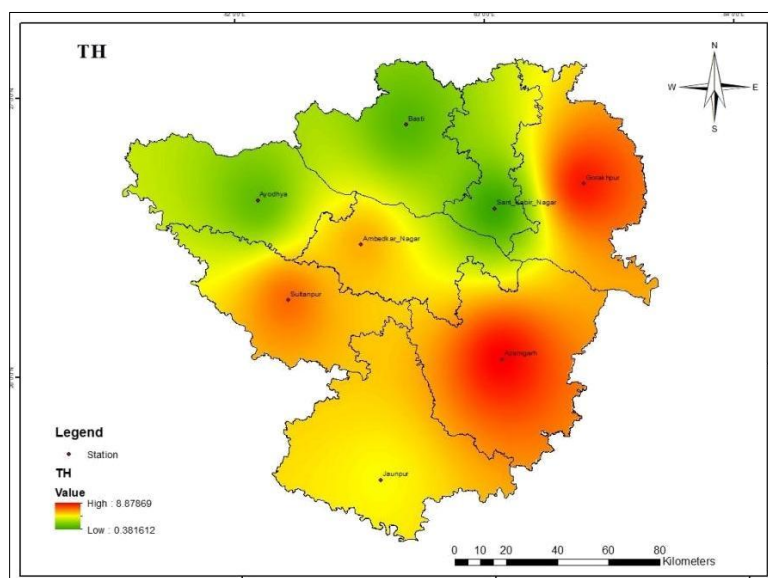


Fig 13: Spatial distribution of the Mann-Kendall Z-statistic for Total Hardness in the study area.

The interpolated surface emphasises the strongest positive trend around Azamgarh, Gorakhpur and Sultanpur, while comparatively weak trend zones occur around Sant Kabir Nagar and Basti.

4.4.5 Calcium

The Mann-Kendall analysis for Calcium showed significant increasing trends at six of the eight stations (Ambedkar Nagar, Azamgarh, Basti, Gorakhpur, Jaunpur and Sultanpur); non-

significant positive trends occurred at Ayodhya and Sant Kabir Nagar. The highest Z-statistic was 9.651 at Azamgarh, whereas the lowest was 0.8587 at Ayodhya.

Sen's slope ranged from 0.037 mg L⁻¹ yr⁻¹ at Ayodhya to 0.618 mg L⁻¹ yr⁻¹ at Gorakhpur. Carbonate mineral dissolution and ion-exchange processes are plausible controls on the observed calcium enrichment, which was widespread but not spatially uniform.

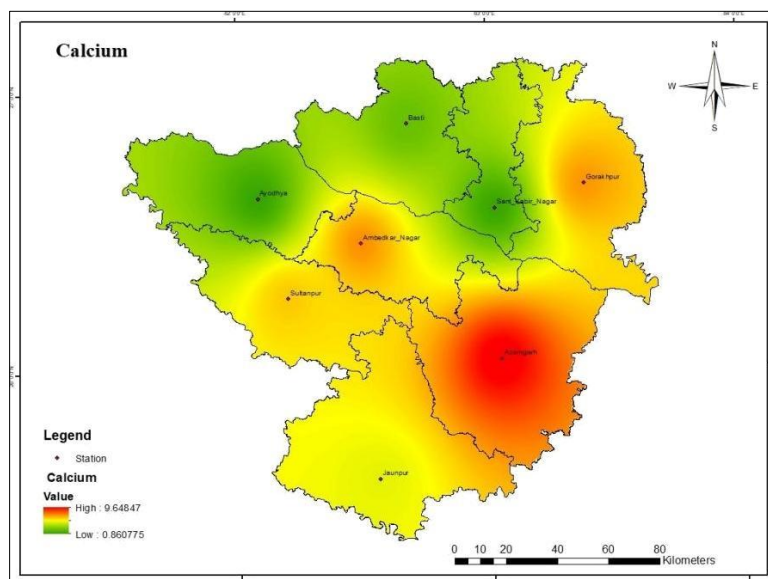


Fig 14: Spatial distribution of the Mann-Kendall Z-statistic for Calcium in the study area.

The interpolated surface emphasises the strongest positive trend around Azamgarh, Ambedkar Nagar and Gorakhpur, while comparatively weak trend zones occur around Ayodhya and Sant Kabir Nagar.

4.4.6 Magnesium

The Mann-Kendall analysis for Magnesium showed significant

increasing trends at all eight stations. The highest Z-statistic was 9.7444 at Gorakhpur, whereas the lowest was 2.3894 at Basti. Sen's slope ranged from 0.154 mg L⁻¹ yr⁻¹ at Sultanpur to 0.313 mg L⁻¹ yr⁻¹ at Basti. Magnesium increased significantly at all stations, supporting the observed increase in total hardness and suggesting continued interaction of groundwater with magnesium-bearing minerals.

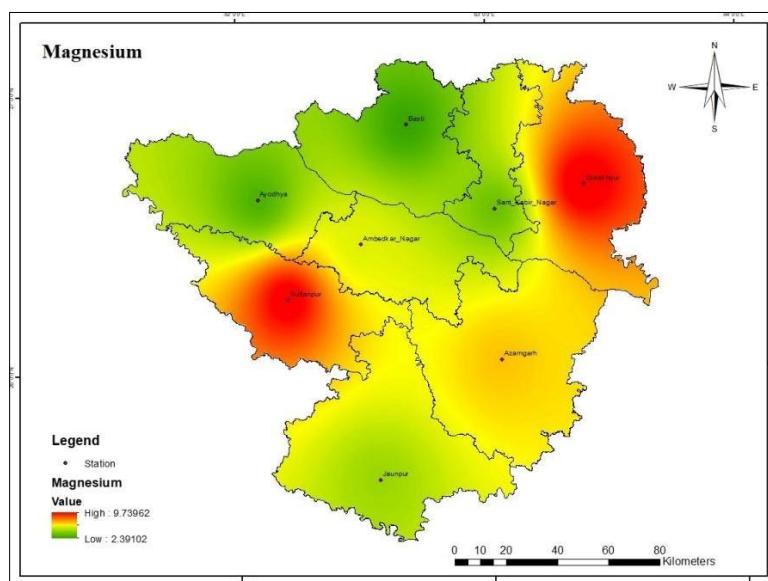


Fig 15: Spatial distribution of the Mann-Kendall Z-statistic for Magnesium in the study area.

The interpolated surface emphasises the strongest positive trend around Gorakhpur, Sultanpur and Azamgarh, while

comparatively weak trend zones occur around Basti and Ayodhya.

4.4.7 Sodium

The Mann-Kendall analysis for Sodium showed significant increasing trends at six of the eight stations (Ambedkar Nagar, Ayodhya, Azamgarh, Gorakhpur, Jaunpur and Sultanpur); nonsignificant positive trends occurred at Basti and Sant Kabir

Nagar. The highest Z-statistic was 7.7889 at Sultanpur, whereas the lowest was 0.59268 at Basti. Sen's slope ranged from 0.091 mg L⁻¹ yr⁻¹ at Sant Kabir Nagar to 0.438 mg L⁻¹ yr⁻¹ at Azamgarh. Possible controls include silicate weathering, cation exchange, irrigation return flow and domestic effluent inputs.

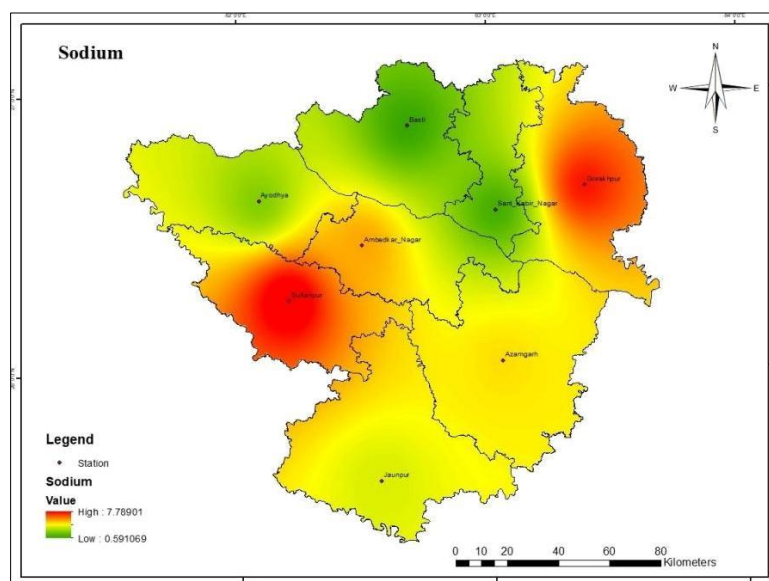


Fig 16: Spatial distribution of the Mann-Kendall Z-statistic for Sodium in the study area.

The interpolated surface emphasises the strongest positive trend around Sultanpur, Gorakhpur and Ambedkar Nagar, while comparatively weak trend zones occur around Basti and Sant Kabir Nagar.

4.4.8 Potassium

The Mann-Kendall analysis for Potassium showed significant increasing trends at all eight stations. The highest Z-statistic was

11.577 at Gorakhpur, whereas the lowest was 3.0432 at Ayodhya.

Sen's slope ranged from 0.0086 mg L⁻¹ yr⁻¹ at Sultanpur to 0.0344 mg L⁻¹ yr⁻¹ at Basti. Although groundwater potassium commonly occurs at lower concentrations than sodium, the persistent increase may indicate enhanced mineral weathering together with localised fertiliser influence.

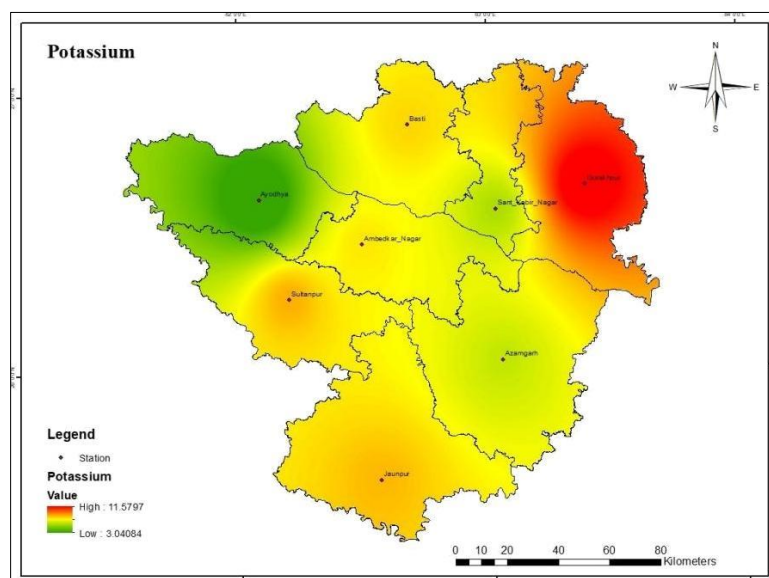


Fig 17: Spatial distribution of the Mann-Kendall Z-statistic for Potassium in the study area.

The interpolated surface emphasises the strongest positive trend around Gorakhpur, Sultanpur and Jaunpur, while comparatively weak trend zones occur around Ayodhya and Sant Kabir Nagar.

4.4.9 Carbonate

The Mann-Kendall analysis for Carbonate showed significant increasing trends at six of the eight stations (Ambedkar Nagar, Azamgarh, Basti, Gorakhpur, Jaunpur and Sultanpur); a non-

significant positive trend occurred at Ayodhya and a non-significant negative trend at Sant Kabir Nagar. The highest Z-statistic was 10.589 at Gorakhpur, whereas the lowest was -0.07008 at Sant Kabir Nagar.

Sen's slope ranged from -0.0115 mg L⁻¹ yr⁻¹ at Sant Kabir Nagar to 0.0955 mg L⁻¹ yr⁻¹ at Azamgarh. The spatial variation may be governed by pH-dependent carbonate equilibria and local differences in recharge and buffering conditions.

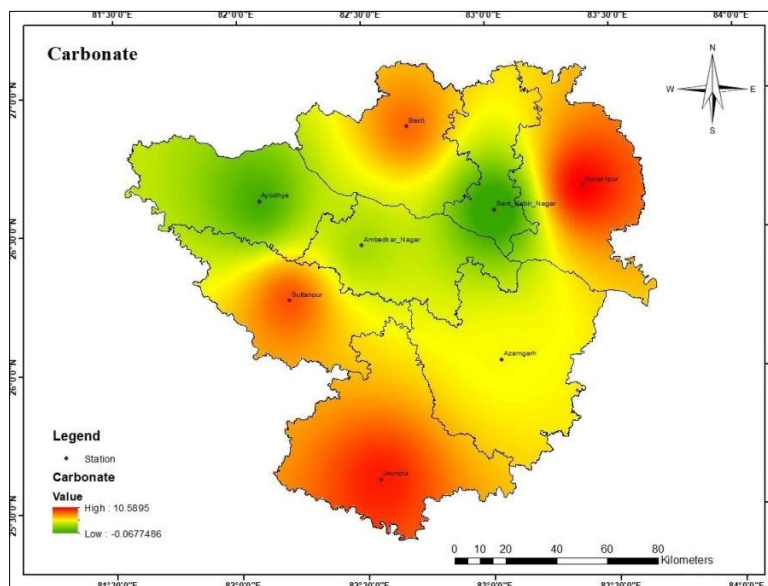


Fig 18: Spatial distribution of the Mann-Kendall Z-statistic for Carbonate in the study area.

The interpolated surface emphasises the strongest positive trend around Gorakhpur, Jaunpur and Sultanpur, while comparatively weak or negative trend zones occur around Sant Kabir Nagar and Ayodhya.

4.4.10 Bicarbonate

The Mann-Kendall analysis for Bicarbonate showed significant increasing trends at seven of the eight stations (Ambedkar

Nagar, Azamgarh, Basti, Gorakhpur, Jaunpur, Sant Kabir Nagar and Sultanpur); a non-significant positive trend occurred at Ayodhya. The highest Z-statistic was 10.328 at Azamgarh, whereas the lowest was 1.8854 at Ayodhya.

Sen's slope ranged from 0.718 mg L⁻¹ yr⁻¹ at Ayodhya to 2.553 mg L⁻¹ yr⁻¹ at Gorakhpur. The widespread increase is compatible with enhanced carbonate weathering, soil-zone carbon dioxide interaction and alkalinity generation.

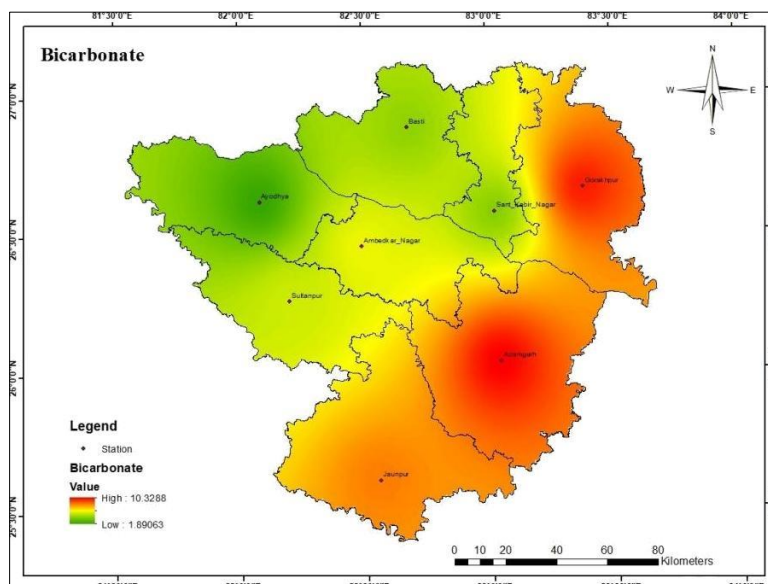


Fig 19: Spatial distribution of the Mann-Kendall Z-statistic for Bicarbonate in the study area.

The interpolated surface emphasises the strongest positive trend around Azamgarh, Gorakhpur and Jaunpur, while comparatively weak trend zones occur around Ayodhya and Sant Kabir Nagar.

4.4.11 Sulphate

The Mann-Kendall analysis for *Sulphate* showed significant i

creasing trends at five of the eight stations (Ambedkar Nagar, Azamgarh, Basti, Gorakhpur and Sultanpur); a non-significant positive trend occurred at Sant Kabir Nagar, and non-significant negative trends occurred at Ayodhya and Jaunpur. The highest Z-statistic was 7.9475 at Sultanpur, whereas the lowest was -1.218 at Jaunpur.

Sen's slope ranged from $-0.150 \text{ mg L}^{-1} \text{ yr}^{-1}$ at Jaunpur to $0.726 \text{ mg L}^{-1} \text{ yr}^{-1}$ at Basti. The contrasting trends indicate localised

controls potentially including mineral dissolution, fertiliser inputs, oxidation processes and dilution by recharge.

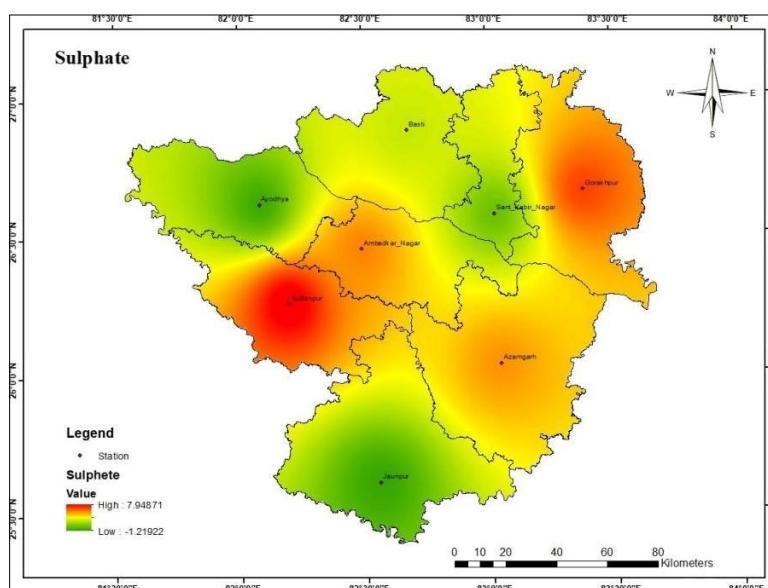


Fig 20: Spatial distribution of the Mann-Kendall Z-statistic for Sulphate in the study area.

The interpolated surface emphasises the strongest positive trend around Sultanpur, Gorakhpur and Ambedkar Nagar, while comparatively weak or negative trend zones occur around Jaunpur and Ayodhya.

4.4.12 Chloride

The Mann-Kendall analysis for Chloride showed significant increasing trends at five of the eight stations (Ambedkar Nagar, Azamgarh, Gorakhpur, Jaunpur and Sultanpur); non-significant positive trends occurred at Basti and Sant Kabir Nagar, and a

non-significant negative trend occurred at Ayodhya. The highest Z-statistic was 6.7808 at Sultanpur, whereas the lowest was -0.79336 at Ayodhya.

Sen's slope ranged from $-0.041 \text{ mg L}^{-1} \text{ yr}^{-1}$ at Ayodhya to $0.905 \text{ mg L}^{-1} \text{ yr}^{-1}$ at Basti. Because chloride behaves relatively conservatively in groundwater, the positive trends may indicate increasing solute accumulation or localised anthropogenic inputs, although source attribution requires supporting land-use and chemical evidence.

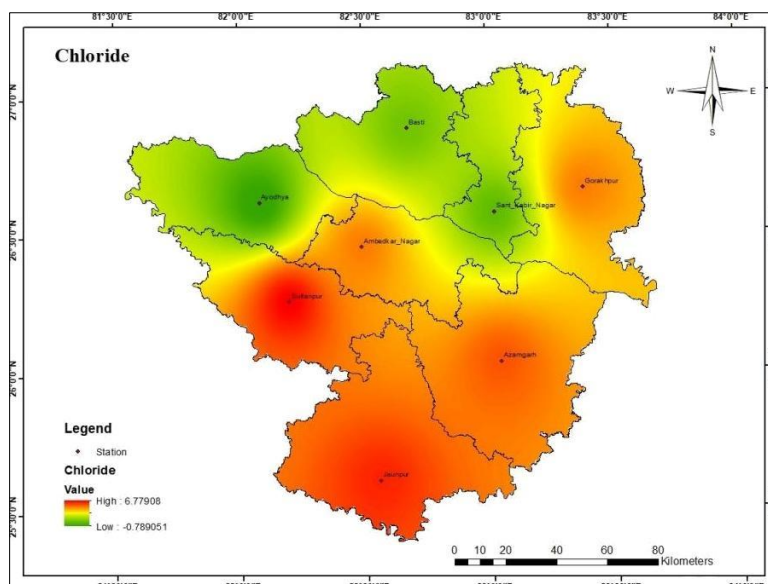


Fig 21: Spatial distribution of the Mann-Kendall Z-statistic for Chloride in the study area.

The interpolated surface emphasises the strongest positive trend around Sultanpur, Jaunpur and Azamgarh, while comparatively weak or negative trend zones occur around Ayodhya and Sant Kabir Nagar.

4.4.13 Fluoride

The Mann-Kendall analysis for Fluoride showed significant

increasing trends at six of the eight stations (Ambedkar Nagar, Azamgarh, Gorakhpur, Jaunpur, Sant Kabir Nagar and Sultanpur); Basti lay just below the 95% significance threshold and Ayodhya showed a weak positive trend. The highest Z-statistic was 10.815 at Sultanpur, whereas the lowest was 0.45322 at Ayodhya.

Sen's slope ranged from 0.000286 mg L⁻¹ yr⁻¹ at Ayodhya to 0.00429 mg L⁻¹ yr⁻¹ at Jaunpur. The very small Sen slopes demonstrate that even small annual changes can become

statistically consistent over a long record; the strong trends at Sultanpur and Gorakhpur highlight locations that warrant closer surveillance.

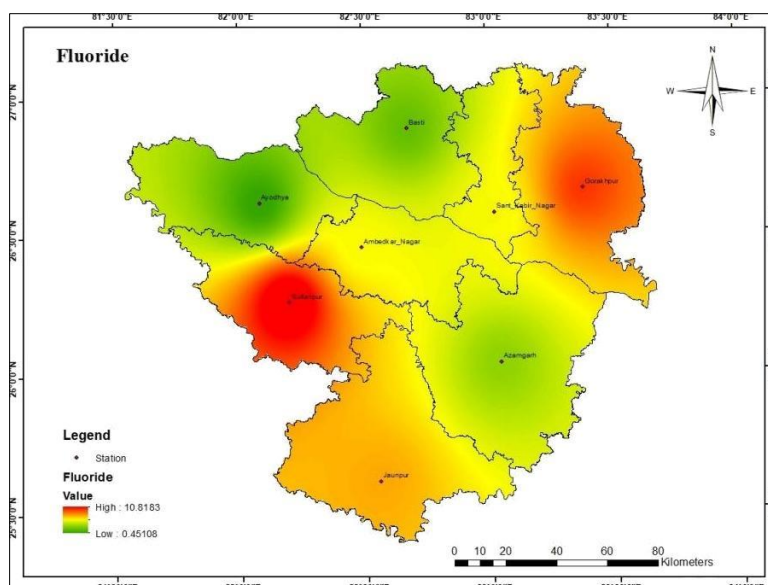


Fig 22: Spatial distribution of the Mann-Kendall Z-statistic for Fluoride in the study area.

The interpolated surface emphasises the strongest positive trend around Sultanpur, Gorakhpur and Jaunpur, while comparatively weak or negative trend zones occur around Ayodhya and Basti.

4.4.14 Nitrate

The Mann-Kendall analysis for Nitrate showed significant increasing trends at five of the eight stations (Ambedkar Nagar, Azamgarh, Basti, Gorakhpur and Sultanpur); a non-significant positive trend occurred at Sant Kabir Nagar, a non-significant

negative trend occurred at Ayodhya, and no directional trend was detected at Jaunpur. The highest Z-statistic was 6.6924 at Basti, whereas the lowest was -0.53207 at Ayodhya.

Sen's slope ranged from -0.057 mg L⁻¹ yr⁻¹ at Ayodhya to 0.511 mg L⁻¹ yr⁻¹ at Sultanpur. Agricultural nitrogen application, leakage from sanitation systems and recharge variability are plausible influences, but source confirmation would require complementary land-use and isotopic evidence.

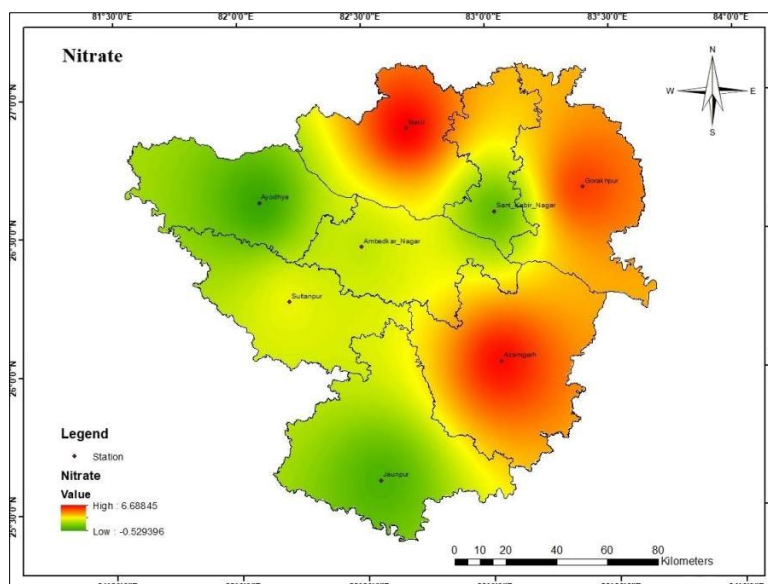


Fig 23: Spatial distribution of the Mann-Kendall Z-statistic for Nitrate in the study area.

The interpolated surface emphasises the strongest positive trend around Basti, Azamgarh and Gorakhpur, while comparatively weak or negative trend zones occur around Ayodhya and Jaunpur.

4.6 Discussion of Spatio-temporal Trends

The combined results demonstrate a broad regional tendency

towards increasing groundwater mineralisation. TDS and EC increased at nearly all stations, and the increases in calcium, magnesium, sodium, potassium, bicarbonate and hardness provide supporting evidence that the dissolved-ion composition of groundwater changed progressively through time. The simultaneous increase of TDS, EC and major ions may reflect the combined influence of natural water-rock interaction,

residence time, evaporation and recharge dynamics, together with human influences such as irrigation return flow, fertiliser application, urban growth and wastewater infiltration (Todd and Mays, 2005)^[17]. These mechanisms are not mutually exclusive, and definitive source attribution would require hydro-chemical ratios, land-use information and, where appropriate, isotopic analysis (Appelo and Postma, 2005)^[3]. Similar dominance of calcium-magnesium-bicarbonate type water chemistry driven by carbonate weathering and ion exchange has been reported for other alluvial and hard-rock aquifers of the Indo-Gangetic plain and peninsular India (Piper, 1944; Datta and Tyagi, 1996; Subramani, Elango, and Damodarasamy, 2005; Kumar, Ramanathan, Rao, and Kumar, 2006; Singh *et al.*, 2008; Raju, Ram, and Dey, 2009; Karmegam *et al.*, 2011)^[18-24].

The pH results showed significant upward trends throughout the study area. In conjunction with the widespread increase in bicarbonate, this suggests strengthening alkalinity and buffering conditions. However, a significant trend does not automatically mean that a drinking-water standard has been exceeded: trend analysis identifies the direction and persistence of change, whereas compliance assessment must be based on the measured concentration distribution and the applicable standard (World Health Organization [WHO], 2011, 2017; Bureau of Indian Standards [BIS], 2012)^[25, 26]. The same distinction applies particularly to fluoride and nitrate, where even a statistically strong increase may arise from a small annual slope but may become important over a long monitoring period; elevated fluoride and nitrate concentrations have previously been reported as concerns in groundwater of the Gangetic plain and other parts of Uttar Pradesh (Jain, Bandyopadhyay, and Bhadra, 2010)^[27]. Seasonal recharge and abstraction cycles can also modulate short-term groundwater chemistry (Rao, 2006)^[28], reinforcing the need for the long-term, multi-year perspective adopted in this study.

The trend patterns were spatially heterogeneous. Gorakhpur displayed the strongest trends for magnesium, potassium and carbonate, and the largest slopes for TDS, pH, EC, TH and bicarbonate. Sultanpur showed the strongest trends for EC, sodium, sulphate, chloride and fluoride, and the largest nitrate slope. Azamgarh recorded the strongest trends for TH, calcium and bicarbonate, while Sant Kabir Nagar recorded the highest Z-statistics for TDS and pH. In contrast, Ayodhya frequently showed the weakest trends and non-significant decreases in sulphate, chloride and nitrate. These contrasts demonstrate the value of integrating temporal statistics with GIS: the Mann-Kendall test provides the station-level temporal signal, and GIS displays the regional spatial pattern of that signal.

From a groundwater-management perspective, the results identify Gorakhpur, Sultanpur, Azamgarh, Sant Kabir Nagar and Basti as important locations for parameter-specific surveillance. Monitoring should focus not only on areas with the highest historical concentrations but also on areas with persistent positive Z-statistics and appreciable Sen slopes, because these locations may experience future deterioration even when current values remain within acceptable limits.

Repeated sampling, standardised laboratory procedures and periodic updating of the trend analysis are recommended to verify whether the identified tendencies continue.

5. Conclusion

This study applied the Mann-Kendall trend test, Sen's slope estimator and GIS-based spatial interpolation to assess the long-term spatio-temporal behaviour of fourteen groundwater quality parameters across eight monitoring stations in Eastern Uttar

Pradesh. Of the 112 parameter-station combinations examined, 90 exhibited statistically significant increasing trends and none showed a statistically significant decreasing trend, indicating a broad regional tendency towards increasing groundwater mineralisation. TDS, pH, magnesium and potassium increased significantly at all eight stations, while the largest single Z-statistics were recorded for potassium and pH at Gorakhpur and Sant Kabir Nagar, and for fluoride at Sultanpur. Sen's slope estimates showed that the rate of change varied independently of trend consistency, with Gorakhpur generally exhibiting the steepest annual rates of increase. The spatial mapping of trend statistics revealed clear regional heterogeneity, with Gorakhpur, Sultanpur, Azamgarh, Sant Kabir Nagar and Basti emerging as priority locations for continued groundwater quality surveillance. The findings underscore the value of combining non-parametric trend statistics with GIS-based visualisation as a practical framework for regional groundwater quality monitoring, and they support the case for periodic resampling, standardised laboratory protocols and complementary hydro-chemical and land-use investigations to confirm the sources of the identified trends and to guide sustainable groundwater management in the region.

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