Spatiotemporal Assessment of Groundwater Quality in Jharkhand: A Decadal Hydrogeochemical Study

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Abstract

Over the past decade, accelerated urbanisation and expanding land use in Jharkhand have imposed significant anthropogenic pressure on groundwater quality, primarily through the discharge of untreated effluents into recharge zones. Groundwater fulfils the entire rural domestic water demand and nearly one-sixth of the urban supply, and contributes to an annual extraction stage of 31.42%, thus, any degradation in its quality poses a direct risk to public health. This study presents a comprehensive modelling framework to investigate decadal spatiotemporal variations in hydrogeochemical processes within Jharkhand's aquifers.

In this study, we developed a detailed framework to track how groundwater chemistry in Jharkhand has changed over the past decade. We worked closely with the Central Ground Water Board (CGWB) to analyse historical data from 57 sampling sites collected between 2013 and 2023. To strengthen the study, we also collected fresh groundwater samples from these same locations in 2025. We focused on several key water quality indicators—such as pH, electrical conductivity, total hardness and major anions and cations (including bicarbonates, nitrates, chlorides, sulphates, calcium, magnesium, sodium, and potassium). Using GIS tools, we mapped spatial variations to identify areas with potential contamination and defined hydrochemical zones. Piper diagrams were used to understand changes in salinity and ion exchange over time, while a Pearson correlation analysis helped uncover relationships between various water quality parameters and possible contamination sources. The study offers vital insights into emerging groundwater quality risks and can inform targeted policy interventions, resource allocation, and sustainable groundwater management strategies in Jharkhand and similar regions across India.

Keywords: Groundwater Quality, Hydrogeochemistry, Spatiotemporal Analysis, GIS Mapping

1. Introduction

Groundwater plays a crucial role in fulfilling the daily water needs of millions across India (Scanlon et al., 2023; Sahoo et al., 2025; Agarwal et al., 2025), especially in states like Jharkhand, where surface water sources are often seasonal, inconsistent, or insufficient (Roy et al., 2024; Kadave & Kumari., 2025). In rural areas of the state, groundwater serves as the only reliable source of drinking water. Urban centres also depend on it to a significant extent to meet their growing water demands (Swain et al., 2022). Over time, this reliance has intensified due to population growth, expanding settlements, and changes in land use patterns that increase pressure on existing water resources. Alongside this rising demand, rapid urbanisation and industrial development have introduced a host of environmental challenges (Kumar et al., 2022). One of the most pressing concerns is the increasing contamination of groundwater, which is largely attributed to the unregulated discharge of industrial and domestic waste (Gautam et al., 2021). In many regions of Jharkhand, untreated effluents are released directly into the environment, often in close proximity to natural recharge zones. This practice poses a serious threat to the long-term quality and safety of groundwater, particularly when such contamination remains undetected or is not addressed in a timely manner.

The hydrogeological setting of Jharkhand adds further complexity to the issue. The region is characterised by a mix of hard rock aquifers and varying recharge capacities, which means that once pollution enters the groundwater system, recovery can be extremely slow. In many cases, it can take several years or even decades for contaminated aquifers to return to a safe condition (Kumar et al., 2024). For these reasons, it is essential to closely monitor groundwater quality over time and to understand the underlying processes that drive changes in its composition (Kumar et al., 2023a; Panday et al., 2024; Agarwal et al., 2024; Das et al., 2024). Doing so is critical for protecting public health and ensuring that groundwater remains a sustainable resource for future generations.

The major industries in the state, which include steel manufacturing, coal extraction, and thermal power generation, exert considerable environmental pressure on groundwater systems. Among these, coal mining is particularly concerning due to the discharge of mine water, degradation of land surfaces, improper waste disposal, and pollution associated with coal washing (Kumar et al., 2022). These processes often take place in or near recharge zones, where contaminants can easily infiltrate into the aquifers. Several studies have explored the link between coal mining activities and groundwater quality in Jharkhand (Ahmad et al., 2025; Kumar et al., 2023). The depth of the aquifers and the geological materials encountered along the groundwater flow path play a major role in determining the extent of contamination. Pollicino et al. (2021) noted that deeper aquifers tend to be less vulnerable to pollution than shallow ones, and also suggested that artificial recharge could help mitigate fluoride concentration in groundwater. This highlights the importance of integrating hydrogeological characteristics into water quality assessments.

George et al. (2010) reported that effluents originating from coal-based industries in the Dhanbad region have led to noticeable changes in groundwater chemistry. Their study emphasised the need for continuous monitoring in mining-intensive areas. Similarly, Tirkey et al. (2017) found that levels of arsenic, manganese, nickel, and selenium in groundwater samples from mining zones exceeded the permissible limits set by the Bureau of Indian Standards (BIS), raising concerns about long-term health risks for local communities. However, not all studies report alarming findings. Groundwater quality assessments conducted in Dhanbad township observed that while concentrations of iron and manganese were elevated in shallow hand pump wells, the overall Heavy Metal Pollution Index (HPI) values remained below critical thresholds (Panigrahy et al., 2015; Kumar et al., 2022). This suggests that although heavy metal contamination exists, it may not yet be widespread or severe enough to render groundwater unsafe across the entire region.

In Ranchi, Singh et al. (2015) applied the Water Quality Index method and found that 18 percent of water samples were categorised as "Very Good," 67 percent as "Good," and 15 percent as "Poor." These variations indicate that groundwater quality can differ significantly depending on location, hydrogeology, and local anthropogenic influences. Overall, the existing literature points to a complex picture of groundwater contamination in Jharkhand, driven largely by coal mining and related industrial activities. While some areas remain relatively unaffected, others are showing clear signs of chemical alteration, warranting further study and targeted intervention.

Despite several studies highlighting the adverse effects of coal mining on groundwater quality in Jharkhand, most existing research has been limited in either spatial scope, temporal coverage, or parameter depth. Many investigations focus on isolated districts, rely on one-time sampling, or examine only select contaminants such as heavy metals. There remains a clear gap in long-term, multi-parameter studies that integrate both spatial and temporal trends across a wider network of sampling locations. Furthermore, few studies combine GIS-based spatial mapping, hydrogeochemical facies analysis, and statistical methods to holistically understand contamination patterns and their underlying processes.

This study aims to address these gaps by developing a comprehensive decadal-scale assessment of groundwater quality in Jharkhand, focusing on 57 strategically distributed sampling sites. The main objective is to evaluate spatiotemporal changes in key hydrogeochemical parameters between 2013 and 2025, identify emerging contamination hotspots, and understand ionic evolution processes through tools such as Piper diagrams and Pearson correlation matrices. A key novelty of this work lies in its integration of secondary data from the Central Ground Water Board (2013–2023) with fresh primary sampling conducted in 2025, allowing for a robust temporal comparison. By combining GIS, geochemical interpretation, and multivariate analysis, this study provides a deeper and more practical understanding of groundwater risks in mining-affected regions, with direct relevance for sustainable water management and policy planning.

2. Study Area

Jharkhand, located in the eastern part of India, was carved out of southern Bihar and is geographically positioned between 21°55' to 25°15' North latitude and 83°30' to 87°35' East longitude. It covers an area of approximately 79,714 square kilometres and lies on the Chota Nagpur Plateau, forming the northeastern edge of the Indian Peninsular Shield. The state's terrain is largely undulating and hilly, interspersed with forested regions, mineral-rich plateaus, and deep river valleys. Physiographically, Jharkhand is divided into distinct regions, including the Pat Plateau, the Ranchi Plateau, the Hazaribagh Plateau, and the Lower River Valley, all of which influence its hydrogeological characteristics and water availability.

Jharkhand is drained by several important rivers, many of which originate within the state itself. The North Karo River begins in the Ranchi Plateau, contributing significantly to surface water drainage. The South Karo River passes through key industrial and iron ore mining belts before merging with the South Koel River in the West Singhbhum district. Similarly, the Sakh River, which originates in the Gumla district, also flows across central parts of the state. The Damodar River, which originates in Chanwa, Latehar, is one of the most significant rivers in the region, flowing through areas rich in coal and minerals. The basin of the Damodar has seen the growth of numerous coal-based industries, and the associated industrial activity has raised concerns regarding the discharge of untreated effluents into surface and subsurface water systems. Another major river, the Subarnarekha, originates near Ranchi and traverses districts with active copper and uranium mining operations before eventually draining into the Bay of Bengal. These rivers, especially in their industrial stretches, are heavily impacted by pollution, and their interaction with groundwater systems poses a serious threat to water quality in adjacent areas.

The state’s hydrogeology is characterised by a complex aquifer system. Jharkhand has 14 principal aquifers, further divided into 42 major aquifers, representing diverse geological formations. The most extensive geological formation in the state is the Branded Gneissic Complex (BGC), which underlies approximately 60.2 percent of the total area. These aquifers may be weathered and jointed, with specific yields ranging from 0.3 to 1.5 percent. In the southern region, schist formations dominate, covering about 13 percent of the state’s aquifers. Additionally, younger alluvium is present in patches across districts such as Godda, Sahebganj, Pakur, Palamu, and East Singhbhum, accounting for 7.47 percent of the aquifer distribution. The phreatic aquifer systems in these regions typically consist of a weathered mantle and underlying fractured rock layers. The thickness of the weathered zone ranges from 10 to 25 meters and can exceed 35 meters in some areas. This weathered layer serves as the primary groundwater repository, while the underlying fractures and joints offer secondary porosity, enhancing water storage and movement.

Groundwater availability in Jharkhand is closely tied to both geological and climatic conditions. The variability in rainfall, coupled with uneven recharge potential and increasing anthropogenic pressure, has made sustainable groundwater management a pressing concern. Sources of groundwater pollution in the state include industrial effluents, mine water discharge, unscientific waste disposal, and agricultural runoff, especially in zones adjacent to mining belts and urban centres. Understanding the interplay between natural aquifer characteristics and human-induced contamination is essential for ensuring the long-term sustainability of groundwater resources in Jharkhand.

3. Data and Methodology

This study was designed to evaluate the decadal variation in groundwater quality across Jharkhand, focusing on six key years: 2014, 2017, 2019, 2021, 2023, and 2025. Groundwater quality data for the years 2014 to 2023 were obtained from the Central Ground Water Board (CGWB), India. The dataset included 57 groundwater sampling locations for each selected year. These secondary data provided the foundation for tracking long-term trends in groundwater quality and identifying emerging zones of concern.

A total of 14 hydrogeochemical parameters were analysed to assess water quality changes over time. These included pH, total hardness (TH), total dissolved solids (TDS), Turbidity and concentrations of key anions such as carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), chloride (Cl^-), fluoride (F^-), sulphate (SO_4^{2-}), nitrate (NO_3^-), and phosphate (PO_4^{3-}), along with major cations including calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+).

In addition to secondary data, primary groundwater samples were collected from exactly the same locations across various districts of Jharkhand during June and July 2025. These samples were analysed for most of the 14 hydrogeochemical parameters. Sample testing was carried out at Deoghar District Level Water Testing Laboratory and Ranchi State Level Water Testing Laboratory, following standard procedures to ensure data reliability and comparability with CGWB datasets. The primary data served a dual purpose: it was used both to validate spatial and temporal trends observed in the secondary data and to enrich the statistical analysis with the most recent field measurements. While the secondary data was collected in May, the primary data was majorly collected in the months of June and July. This 1–2-month difference should not significantly impact the accuracy and interpretation of spatial and statistical analyses.

Spatial mapping and hydrogeochemical zonation were conducted using Geographic Information Systems (GIS) to visualise contamination hotspots and regional water chemistry patterns. Piper diagrams were used to interpret hydrogeochemical facies and detect trends in ionic evolution, while Pearson correlation matrices quantified inter-parameter relationships to support the identification of potential sources and co-occurrence of contaminants.

4. Results and Discussions

4.1 Spatio-Temporal Variation in Groundwater Quality (2014–2023)

The groundwater quality of Jharkhand showed significant spatial and temporal variability across multiple physico-chemical parameters between 2014 and 2023, with certain districts consistently exhibiting higher contamination levels. Table 1 summarises the descriptive statistics of major physicochemical parameters of groundwater in Jharkhand for the years 2014, 2017, 2019, 2021, and 2023, alongside permissible limits for drinking water. These baseline values provide the reference framework for interpreting spatial and temporal patterns observed in the GIS-based analysis.

4.1.1 Total Hardness and Bicarbonate

Table 1: sample summary - secondary data SEQ

Year	Parameters	pH	EC	HCO3	Cl	F	SO4	NO3	PO4	TH	Ca	Mg	Na	K	TDS
			µS/cm	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	**mg/l**
	Acceptable lin	8.50	1500.00	600.00	250.00	1.00	200.00	45.00	5.00	200.00	75.00	30.00	200.00	12.00	**750**
2023	Range	6.53-8.18	190-1420	43-580	21-231	0-1.51	2-103	1-99	0-0.3	60-480	8-146	5-47	9-141	0-47	-
	Mean	7.68	717.71	205.04	90.14	0.50	43.25	24.38	0.05	248.30	59.57	24.13	47.13	7.09	-
	± SD	0.31	346.83	116.73	51.08	0.37	31.04	18.89	0.07	120.60	36.62	10.66	33.74	8.64	-
	Exceeded PL sample %	0(0)	0(0)	0(0)	0(0)	7(12.28)	0(0)	7(12.28)	21(36.84)	35(61.40)	19(33.34)	16(28.07)	0(0)	0(0)	-
2021	Range	7.26-8.17	154-1677	18-537	11-209	0-1.08	0.58-146	2.62-178	0-1.67	45-550	12-162	1.22-72.9	0-146	0.98-26	**100-1090**
	Mean	7.71	667.58	153.20	74.64	0.38	61.62	43.30	0.13	214.33	57.16	17.35	49.84	7.52	**433.93**
	± SD	0.23	395.10	113.61	52.36	0.35	42.84	29.09	0.30	124.89	36.46	14.32	37.04	6.64	**256.82**
	Exceeded PL sample %	0(0)	2(4.44)	0	0	2(4.44)	0	25(55.55)	22(48.88)	20(44.44)	10(22.22)	6(13.33)	0(0)	0(0)	0(0)
2019	Range	7.11-8.46	89-2205	23.9-565.8	2.7-397	0-2.14	0-94.05	0.27-245	-	24-675	6-148	2-88.7	5.3-179.09	0.19-10.28	**57.85-1433.25**
	Mean	7.88	633.09	171.54	70.30	0.52	33.35	35.51	-	199.88	45.25	22.05	46.47	2.72	**411.51**
	± SD	0.37	420.29	103.98	74.05	0.51	25.90	50.39	-	125.61	29.68	16.64	40.38	1.95	**273.19**
	Exceeded PL sample %	0(0)	1(2.08)	0(0)	1(2.08)	6(12.50)	0(0)	11(22.92)	-	19(39.58)	6(12.50)	11(22.92)	0(0)	0(0)	0(0)
2017	Range	6.31-8.38	201-1888	24.6-756	3.8-230.4	0-1.48	1.81-96.25	0-135	0-0.3	60-605	8-144	1.22-100.8	4.86-117.3	0.13-41.6	**130.65-1227.2**
	Mean	7.84	668.30	204.61	75.83	0.51	36.57	31.62	0.01	229.57	52.83	23.70	42.28	4.17	**434.40**
	± SD	0.42	370.12	123.88	55.13	0.34	25.05	30.26	0.05	127.28	30.53	20.28	27.53	6.63	**240.58**
	Exceeded PL sample %	0(0)	0(0)	1(2.22)	0(0)	5(11.11)	0(0)	14(37.77)	1(2.22)	24(64.76)	12(32.38)	14(37.77)	0(0)	0(0)	0(0)
2014	Range	6.95-8.88	180-3320	40-488	7.1-819	0-1.75	0-118	0-147	-	50-835	16-132	1-153	6-438	1-36	-
	Mean	7.51	676.93	205.81	97.60	0.41	16.91	18.69	-	219.73	50.80	22.29	52.66	5.99	-
	± SD	0.50	570.29	104.26	144.69	0.44	23.18	27.82	-	155.56	27.21	28.96	72.98	6.45	-
	Exceeded PL sample %	2(4.88)	2(4.88)	0	2(4.88)	6(14.63)	0	4(9.76)	-	17(41.46)	8(19.51)	8(19.51)	2(4.88)	0	-

As observed in Fig 1, the northeast and southeast regions of Jharkhand seem to consistently maintain a very high level of Total Hardness above the acceptable limit of 200mg/l. Based on Fig 1 and 2, the hotspots for extreme levels of Total Hardness and high amounts of Bicarbonates include East Sighbhum in the south east, Dumka in the north east, Bokaro in the near-central north east region and Chatra in the north west. The parallel spatial trends of Bicarbonate concentration in relation to Total Hardness indicate a predominant type of Carbonate Hardness. Chatra contributed the highest levels of TH (>400mg/l) and Bicarbonates (300 mg/l) from 2014 to 2017; it experienced a temporary reduction from 2019 to 2021, and then it returned to high levels in 2023. Although Bicarbonate levels were maintained within the acceptable limit or just above it for the majority of the years across Jharkhand, there seems to be a sudden and dramatic rise in Gumla, E. Singhbhum, Saraikela-Kh, Chatra and Dumka during 2023.

Reaction of carbonate-rich rocks with water bearing dissolved CO_2 causes the release of bicarbonates and calcium, contributing to the alkalinity and hardness of groundwater; Chatra and Gumla are primarily composed of BGC, sandstone and Schist aquifers whose natural weathering would only show a minor to moderate increase in hardness and alkalinity of groundwater. Therefore, weathering would need to be accelerated by anthropogenic activities (such as mining), or the sources for contamination could be completely anthropogenic in nature (eg, industrial and agricultural discharge). As observed from 2019 to 2023, there was major variation in Chatra's hardness and bicarbonate concentration in 2-year intervals, with a dramatic drop in 2021. As opposed to lithological weathering, this drop and variation is more likely to correlate with reduction in mining, agriculture and industrial activities during the Covid disruption (in the 2020-2022) timeline. Therefore, it can be deduced to a fair extent that industrial and mining activities have a greater impact on hardness and alkalinity than natural lithological dissolution.

Elevated levels of TH can negatively impact people consuming groundwater by increasing the risk of cardiovascular diseases and nephrolithiasis (Ahmad et al., 2025). Exposure to high levels of water hardness is related to an increased risk of eczema occurrence, as it is suggested that increased soap usage in hard water may lead to the accumulation of soap salt residues on skin and clothes (Sana & Fazal, 2018). Therefore, careful monitoring of effluent discharge in agricultural and mining areas is needed to bring the levels back within the acceptable limits of consumption.

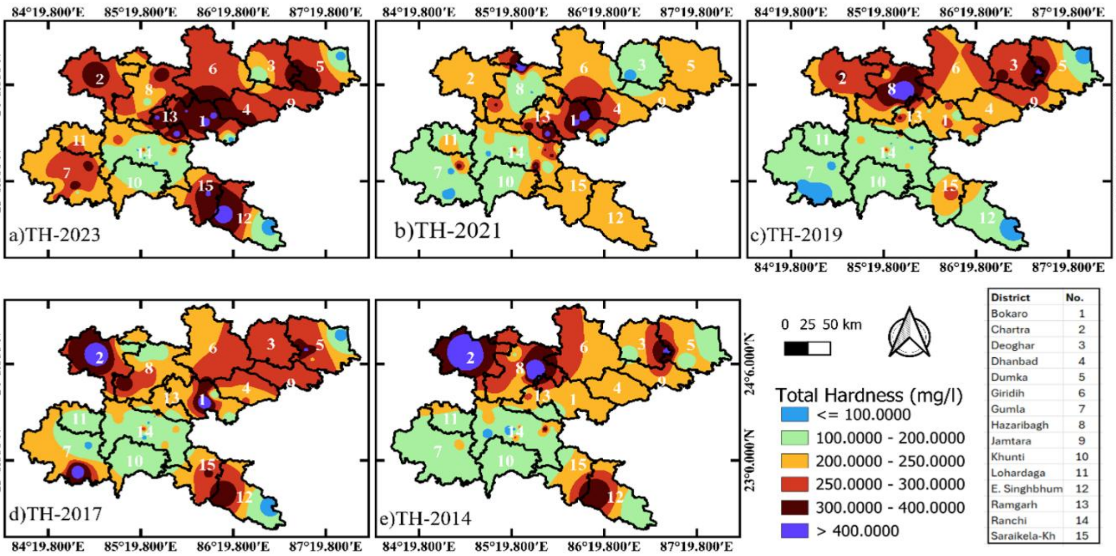


Fig 1. Spatial distribution of Total Hardness (TH) in Jharkhand from 2014 to 2023.

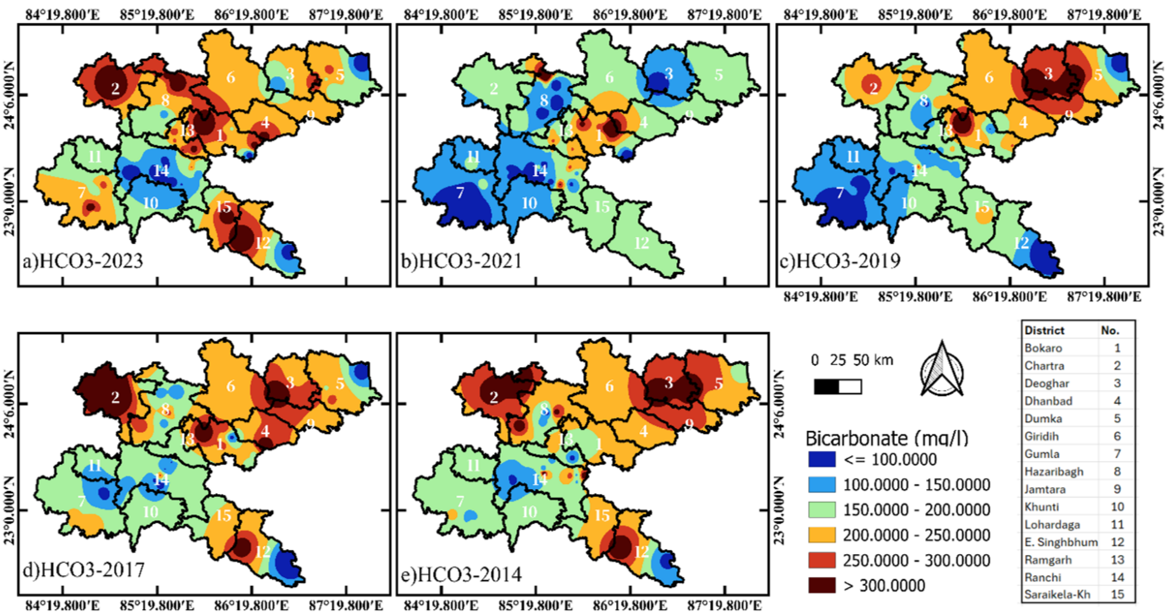


Fig 2. Spatial distribution of Bicarbonate (HCO3) in Jharkhand from 2014 to 2023

4.1.2 Cations

The northern part of Jharkhand consistently records higher concentrations of magnesium (Mg) and calcium (Ca) (Figure 3 and Figure 4), with the north-western region of Chatra remaining a persistent hotspot for elevated Mg levels throughout the decade. In the case of Mg, areas exceeding 50 mg/L in 2014—most notably East Singhbhum, Hazaribagh, Dumka, Deoghar, and Chatra—had disappeared by 2023, with no locations crossing the 50 mg/L threshold. Despite this decline in distinct hotspots, the average Mg concentration across the state rose by 8.3 %, indicating that the delocalization of contamination was accompanied by a broader, uniform increase in Mg levels.

Similar to the drop in TH around May 2021, a fall in Mg concentrations can also be attributed to the Covid disruptions in agricultural and mining activities, resulting in reduced effluent discharge in recharge zones before May 2021. By 2023, Gumla, E.Singhbhum, Saraikela-Kharsawan, Dumka and Chatra went back to displaying levels of Mg higher than the acceptable concentration of 75mg/l. Besides the dip in Ca concentration in 2019, the general spatial distribution of Ca levels increased, and it was accompanied by the re-emergence of hotpots in the central Bokaro and Ramgarh region, and the south-east Singhbhum and Saraikela Kharasawan areas.

Comparing the Spatio-temporal maps of TH, HCO_3^-, Mg^{2+}, and Ca^{2+} in across the decade show evidence of temporal co-occurrence of contamination hotspots in north-west (Chatra), central (Bokaro), north-east (Dumka), south-east (E. Singhbhum and Saraikela-Kh), and south-west (Gumla) Jharkhand. Besides 2014, there was no significant, observable hotspot co-occurrence between Ca^{2+} and Mg^{2+}, TH, HCO_3^- in the northwest region district in particular. This greater co-occurrence of Mg^{2+} ions than Ca^{2+} with other parameters indicates the presence of anthropogenic activities (mining and agricultural sectors) that discharge effluents particularly rich in Magnesium. Ahmad et al (2025) reported that in Ramgarh sodium is the primary alkali here, with calcium and magnesium being the principal alkaline earth metals infiltrating aquifers through rock-water interactions.

Excessive levels of Ca^{2+} above 75mg/l can cause people with kidney problems to be at higher risk of health issues; it can increase the risk of kidney stone accumulation as well as increase constipation and gastrointestinal issues (Torre, 2022). High levels of Magnesium can induce a bad taste in water, increase turbidity and residue formation, decrease the risk of appliance durability because of residue accumulation, and increase the likelihood of cutaneous problems. These listed issues can adversely affect demographic health and water usability; therefore, a consistent monitoring of water cation levels is needed to pinpoint primary effluent discharge sources and implement quality treatment programmes.

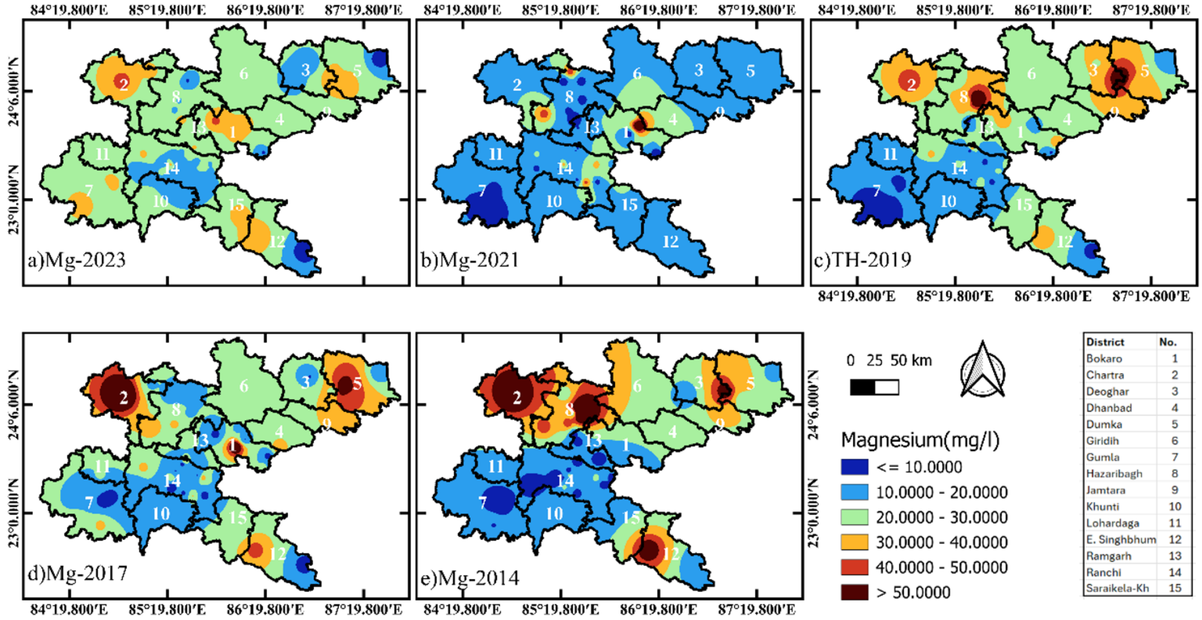


Fig 3. Spatial distribution of Magnesium (Mg) in Jharkhand from 2014 to 2023

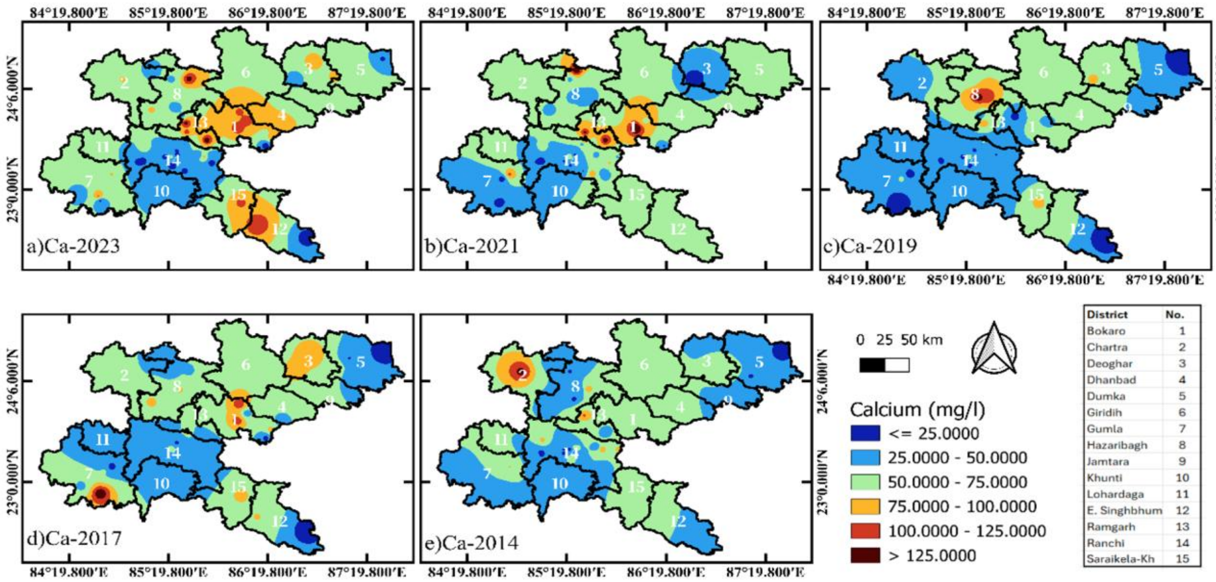


Fig 4. Spatial distribution of Calcium (Ca) in Jharkhand from 2014 to 2023

Significant spatial co-contamination hotspots were observed between Electrical Conductivity (EC) (Figure 5) and sodium (Na) (Figure 6) in Hazaribagh (central-north) and Chatra (north-west) regions in the year 2014 and Hazaribagh in 2019. While the general spatial distribution of relative concentration levels between Na and EC showed several similarities, there was no significant overlap with the relative concentration distribution of Potassium(K) (Figure 7), suggesting that sodium salts were the primary contributor to electrical conductivity across the decade.

Increased levels of Na^+ could result from long-term degradation of alkali feldspars and silicate minerals, and the dissolution of soil salts due to evaporation (Stallard & Edmond, 1983); cation exchange may also contribute to increased levels in aquifers (Kim & Yun, 2005). Chronic intake of high levels of sodium can lead to high elevations in blood pressure in aged populations, which could stimulate congestive heart failures, renal insufficiencies and peripheral vascular diseases (theperfectwater.com, 2025).

Spatiotemporal maps of potassium (Figure 7) indicate that before 2019, only a few hotspots were present in the eastern portion of Jharkhand. Following the sharp 65.2% average decline in 2019, potassium levels rebounded almost uniformly across all districts, registering an average increase of 176.47% by 2021. By 2023, the western half of Jharkhand exhibited comparatively higher potassium accumulation than the eastern half. At a broader, multi-ion scale, Ca, Mg, and K all showed a consistent reduction in both average concentrations and hotspot intensity during 2019. These variations may be influenced by the solubility of carbonate rocks under natural and anthropogenically altered hadrochemical conditions. Potassium plays a critical role in agriculture by enhancing crop yield and resilience, while in humans, adequate intake supports nerve function and cardiovascular health; however, excessive levels in drinking water can pose risks for individuals with kidney disorders.

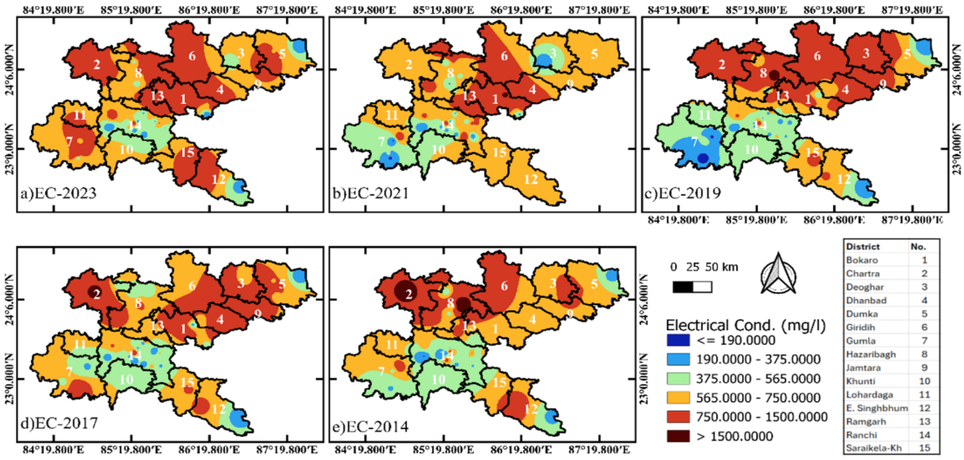


Fig 5. Spatial distribution of EC in Jharkhand from 2014 to 2023

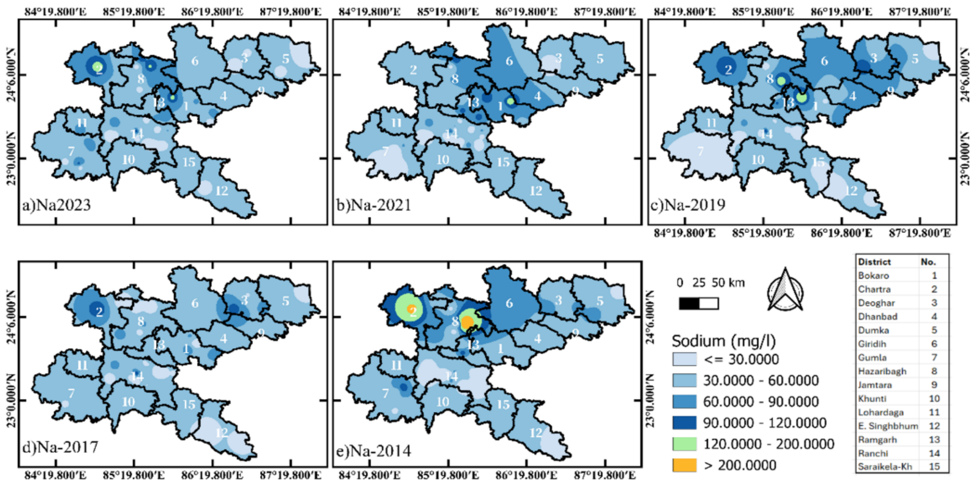


Fig 6. Spatial distribution of Sodium in Jharkhand from 2014 to 2023

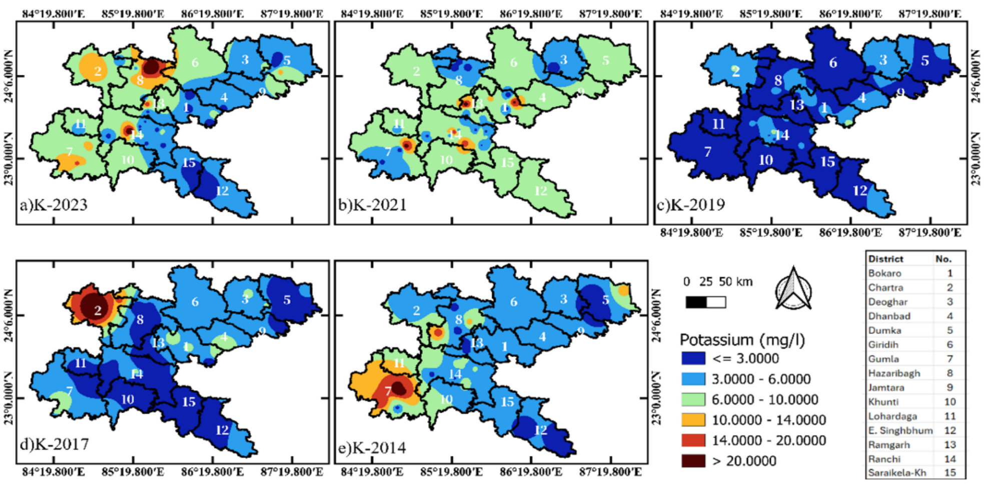


Fig 7. Spatial distribution of K in Jharkhand from 2014 to 2023

4.1.3 Anions

Based on Figure 8, there seems to be sporadic changes in the Nitrate (NO_3) contamination hotspots across the decade: Majority of the south-eastern hotspot of Gumla in 2014 settled within acceptable limits by 2017 while at the same time a central hotspot in Bokaro and a south-eastern hotspot in Saraikela-Kh emerged; by 2019, although the south-eastern hotspot persisted, the central hotspot shifted northwards into Hazaribagh and westward into Ramgarh. This northern hotspot shifted further northwards in 2021, accumulating in the northern extreme of Hazaribagh. By this time, the south-eastern hotspot had settled within acceptable ranges, and a new hotspot in Gumla re-emerged.

By 2023, all hotspots were eliminated, and there was a 56.3% drop in average NO_3 concentration. The spatial distributions of south-western regions above the acceptable limit were similar to 2014: Gumla, Lohardaga and north-western Ranchi had concentrations slightly above the limit. These three adjacent states are composed of Alluvium, Banded Gniess Complex (BGC), and Laterite type aquifers (statements based on observations in Figure 18 in Appendix Section 1). The lithological composition of these geological structures indicates that it is unlikely for nitrogen to saturate groundwater through their weathering. Therefore, it is possible to a high extent that excessive use of fertilizers, deposition of nitrifiable ammonia through animal waste, industrial discharges, and presence of Nitrobacter bacteria could contribute to the elevated levels of Nitrate (Ahmad et al., 2025). Nitrate concentration above the acceptable limit may increase the risk of methemoglobinemia in children below 6 months old, gastric ulcers, cancer, and congenital anomalies.

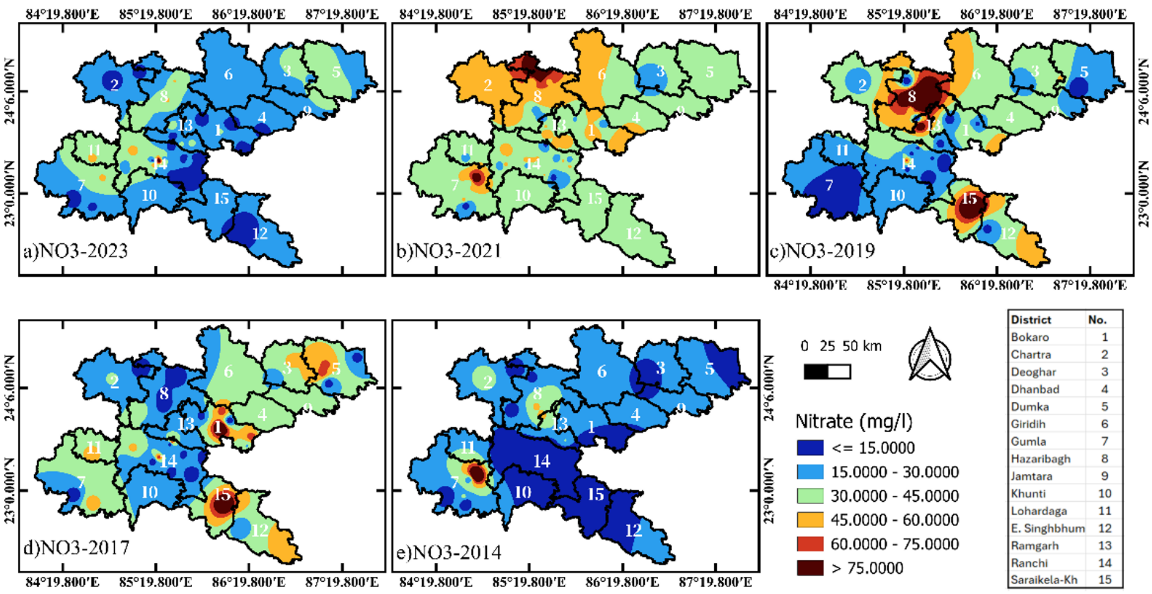


Fig 8. Spatial distribution of Nitrate (NO3) in Jharkhand from 2014 to 2023

According to Figure 9, the only zones that exceeded the acceptable chloride concentration of 250mg/l were Hazaribagh and Chatra in 2014 and Hazaribagh in 2019. Until 2023, the south-east end of E. Singhbhum and north-east end of Dumka consistently maintained very low levels of Cl (<80mg/l). The north-west regions, in contrast to the south-east regions, maintained relatively high concentrations just below the acceptable limit. Based on Fig 5,6, and 9 - EC, Na, and Cl spatiotemporal maps showed significant overlap in contamination hotspots and a general similarity in relative concentration spreads across the state. The results align with the literature (Chatra & Hazaribagh 2014, Hazaribagh 2019). This suggests that the places that had elevated levels of sodium and chloride may be zones of increased lithological degradation of granite, pegmatites, and extensive mining of coal-bearing Gondwana rocks. Levels of chloride beyond 250mg/l in drinking water may lead to taste issues and chronic exposure to concentrations above 500mg/l may increase the risk of hyperchloremia.

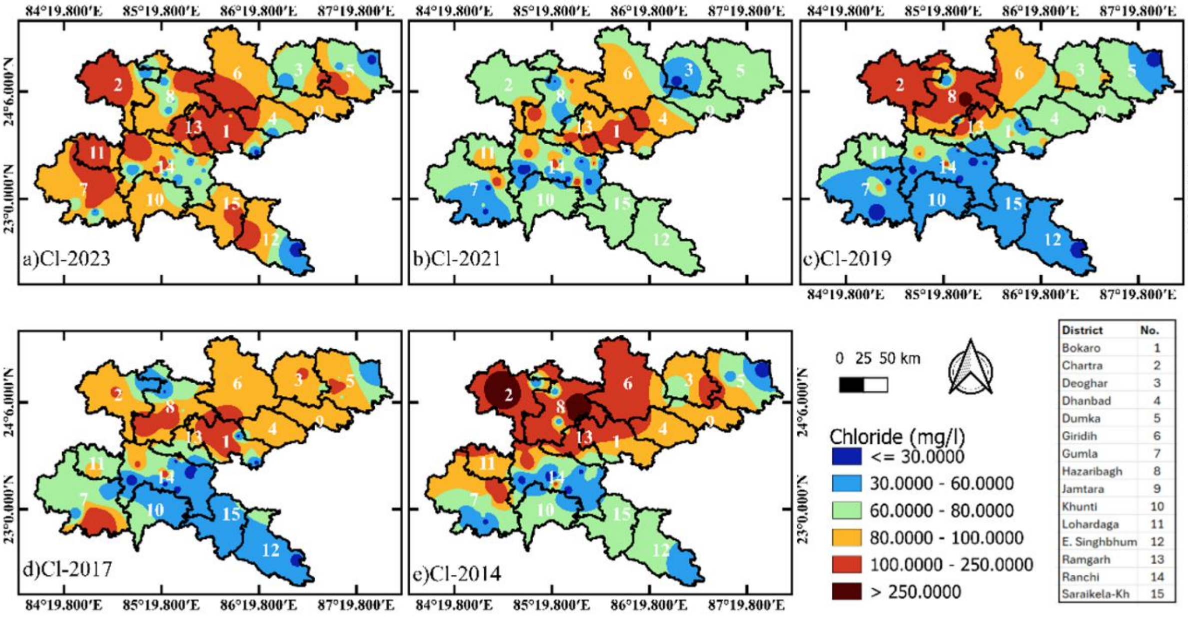


Fig 9. Spatial distribution of Chloride (Cl) in Jharkhand from 2014 to 2023

As observed in Figure 11, the central region of Jharkhand, constituting Bokaro and Ramgarh, were the only places which exceeded beyond the acceptable limits of Fluoride (F) across the majority of the years. The central and centre-north region consistently had the relatively greater concentration of F as compared to other locations. On the contrary, 2021 appeared to be an anomaly as the central region displayed the lowest concentrations of F for a short duration. Long-term consumption of water with fluoride levels exceeding 1.5mg/l may cause dental and skeletal fluorosis.

Contact between groundwater and granitic gneiss type lithologies which bears fluorite (CaF_2) as an accessory mineral could have contributed to the buildup of fluoride levels in Jharkhand's groundwater. The drastic reduction of fluoride in 2021, and restoration to high levels in 2023 suggest that the stoppage of anthropogenic activities such as coal mining during Covid restrictions may have contributed to the reduced amounts. This indicates that anthropogenic activities such as mining in the Gondwana basin in the Bokaro-Ramgarh area accelerates the weathering of fluoride-rich minerals such as fluorite, creating a primary contamination hotspot.

It was found that all the regions of Jharkhand across the decade had Sulphate (SO_4) concentration within the acceptable limits (Figure 11), with the central Bokaro region having relatively greater concentrations. The relatively greater levels of sulphate in the Bokaro-Ramgarh region suggest a greater influence of coal-mining in the Gondwana basin on the release of sulphate due to weathering and leaching of rocks containing gypsum, iron sulphides and other sulphur-containing minerals (Ahmad et al., 2025).

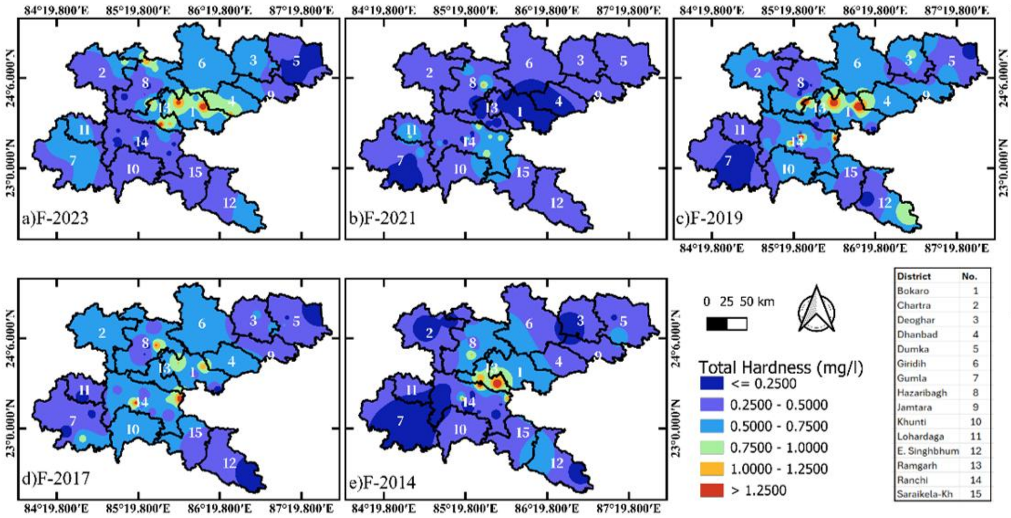


Fig 10. Spatial distribution of Fluoride (F) in Jharkhand from 2014 to 2023

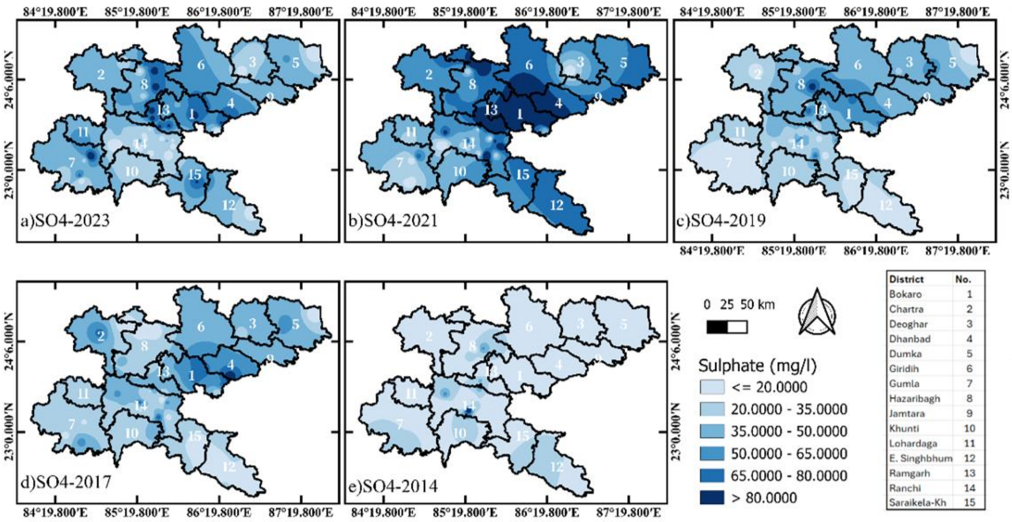


Fig 11. Spatial distribution of Sulphate (SO4) in Jharkhand from 2014 to 2023

4.2 Hydrogeochemical Facies Interpretation Using Piper Plots (2014–2023)

The Piper diagrams provide insights into the hydrogeochemical facies and ionic dominance in groundwater samples across Jharkhand over the study period. According to the piper plots in Figure 13, most groundwater samples are clustered in the non-dominant cation zone (Zone B) throughout all years, indicating mixed cation chemistry due to complex weathering and ion exchange processes. The small clusters towards the calcium type zone are visually represented by the spatial maps, which show a high number of hotspots for calcium (Figure 4) as compared to sodium (Figure 6) and potassium (Figure 7). A gradual increase in samples plotting toward calcium-dominant zones (Zone C) from 2017 onward suggests increasing influence of carbonate weathering and possibly agricultural lime inputs.

A few scattered samples plot in the sodium-dominant zone (Zone D), suggesting minor but localised influence of alkali metal enrichment—potentially linked to domestic or wastewater intrusion. This localization of sodium is further represented by Figure 6 which shows minimal levels of sodium in groundwater with a few local exceptions (such as that observed in Chatra & Hazaribagh in 2014, and Bokaro & Hazaribagh in 2019).

2021 showed the greatest centralization of points in the southern end of the non-dominant zone: this could either suggest greater water-rock interaction with mixed lithology or a reduction in carbonate weathering (which reduces release of magnesium and calcium ions), both of which could increase the dominance of the other facies. The latter estimation is visually supported by the 2021 spatial map in Figure 4, which showed a major reduction in bicarbonate and calcium hotspots and average concentrations. This further supports the argument that reduction in mining and agricultural activities during the covid restrictions before 2021 reduced the contamination of groundwater (as detected in May 2021) by decreasing the weathering of Gondwana rocks and reducing agricultural effluent outputs.

The anion triangle shows most samples falling in the bicarbonate-dominated zone (Zone E), indicating dominance of HCO_3^- due to the general nature of aquifers in Jharkhand, which could be susceptible to silicate and carbonate mineral weathering. This is further shown by the HCO_3^- spatial maps in figure two display levels of concentration to be relatively higher across the northeast and southeast regions, with major hotspots occurring in several districts.

Some movement of samples toward the chloride (Zone G) and sulphate (Zone F) zones is visible in later years, especially in 2021 and 2023, which could reflect growing contamination from sewage, industrial discharge, or mining. On the contrary, similar to the centralization trends observed in the cation triangle, reduction in silicate and carbonate mineral weathering due to the covid restrictions on mining (up to May 2021) could decrease the contribution of bicarbonates, thereby shifting the points towards the chloride and sulphate zones.

The central diamond of the Piper diagrams (Figure 13) reveals a clear dominance of the Mg^{2+}–HCO_3^- type water (Zone 4) across most of the study period from 2014 to 2023. In 2014, the majority of samples plotted within Zone 4, indicating that magnesium bicarbonate facies were the prevailing hydrochemical signature, largely controlled by carbonate weathering processes and the dissolution of dolomitic lithologies. This pattern persisted through 2017 and 2019, with only minor variations in the proportion of samples drifting toward mixed facies such as Ca^{2+}–Na^+–HCO_3^- (Zone 5) and Ca^{2+}–Mg^{2+}–Cl^- (Zone 6).

An exception is observed in 2021, where the distribution shifts slightly, reducing the dominance of the Mg^{2+}–HCO_3^- zone and showing a more even spread toward mixed facies. This deviation can plausibly be linked to reduced anthropogenic pollution and industrial discharge during COVID-19 lockdowns, which may have temporarily altered recharge chemistry and reduced contamination inputs due to reduced frequency of anthropogenic influence on groundwater-rock interactions, resulting in greater diffusion of points across the plot. By 2023, however, the hydrochemical pattern reverts to the pre-2021 state, with Mg^{2+}–HCO_3^- once again emerging as the predominant facies, suggesting the resumption of both natural geochemical processes and human activities influencing groundwater composition.

Between 2014 and 2017, water types were largely bicarbonate-rich with calcium and magnesium as dominant cations. From 2019 onwards, a gradual shift toward more chemically evolved and mixed facies is evident, suggesting reduced contamination of Ca, Mg and HCO_3 in the Covid restrictions time period. The number of samples showing chloride and sulphate influence increases slightly over time, hinting at growing anthropogenic stress on aquifers.

The overall interpretation of the points across the piper plots indicates that the hydrogeochemical evolution over the decade was a transition from natural weathering-dominated chemistry to more mixed and contamination-influenced signatures, particularly in districts with mining and urban activity. These findings align well with the spatiotemporal maps and further validate observed trends in groundwater quality degradation.

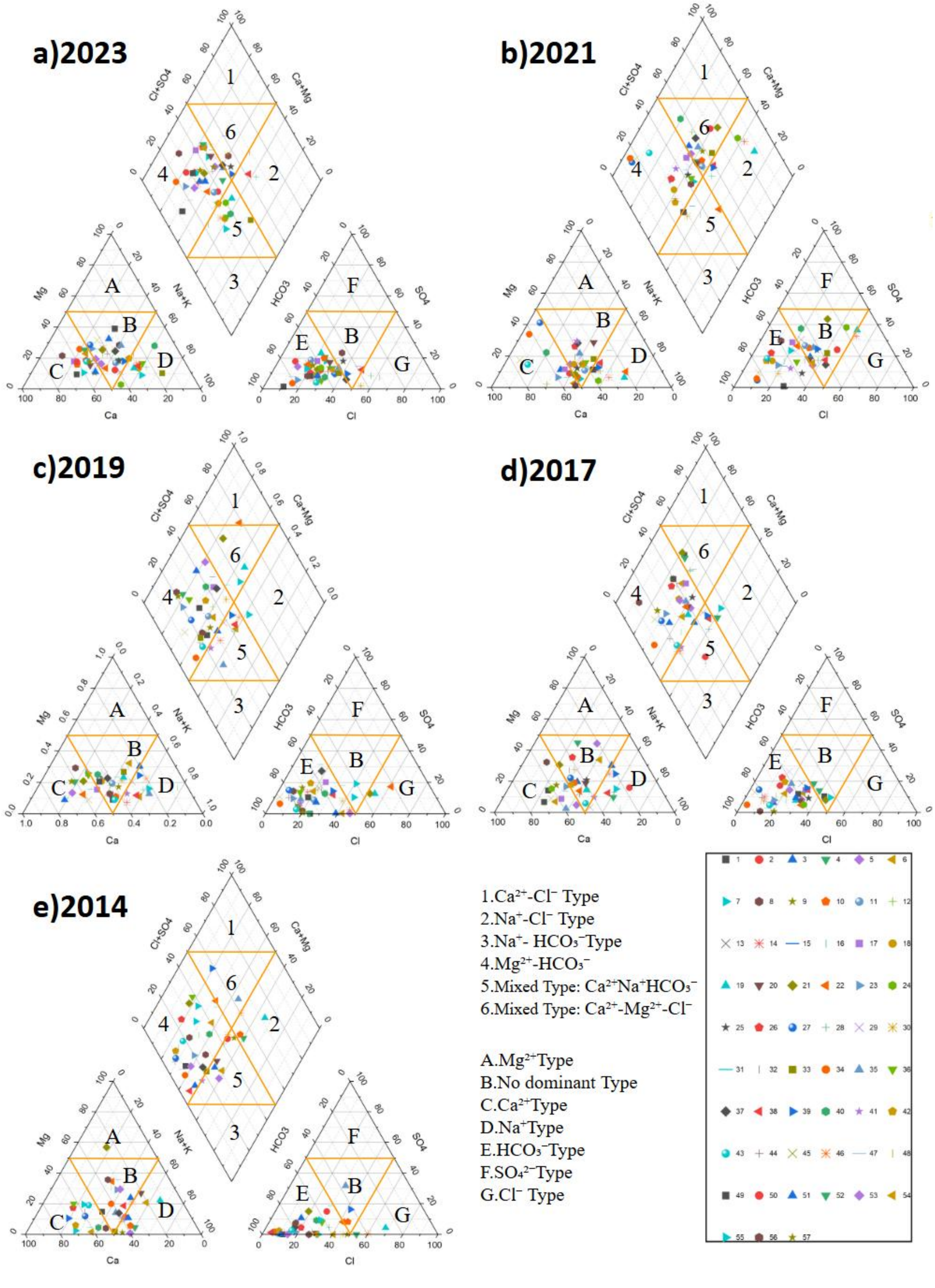


Fig 13. Piper plots of hydrogeochemical Facies from 2014 to 2023

4.3 Statistical Interrelationships among Hydrogeochemical Parameters (2014–2023)

Pearson correlation analysis was employed to explore the linear relationships between major hydrogeochemical parameters. It helps identify co-occurrence patterns, infer possible sources of contamination, and understand geochemical processes such as mineral dissolution, ion exchange, and anthropogenic input. Across all years, Total Hardness (TH) showed strong correlations with Calcium (Ca^{2+}) and Magnesium (Mg^{2+}), confirming that TH in the region is primarily governed by these two alkaline earth metals. This correlation in occurrence is visually supported by the spatial maps of TH, Mg and Ca in figures 1, 3 and 4, respectively.

Electrical Conductivity (EC) consistently displayed high positive correlation with TDS, TH, Ca^{2+}, Mg^{2+}, Na^{+}, and Cl^{-}, indicating that EC can serve as a reliable proxy for overall ionic load in groundwater. These strong correlations further suggest the dissolution of magnesium and sodium-based salts in groundwater. The high correlation values of EC with Na^{+}(0.81) and EC with Cl^{-}(0.84) in 2023, and similar strong values across the decade, validate the visual observations of co-contamination hotspots in the spatial analyses of Figures 5 (EC), Figure 6 (Na^{+}), and Figure 9 (Cl^{-}). Notably, in Figures 14.e and 14.d (refer to Appendix section 2), TDS and Na^{+} also exhibited a strong correlation of 0.76 and 0.86 in 2017 and 2019, respectively, implying salinity contribution from sodium-based sources, possibly anthropogenic (e.g., domestic wastewater or fertilizers).

HCO_3^{-} showed moderate to strong correlation with Ca^{2+} and Mg^{2+} in most years which reflects natural weathering of carbonate and silicate minerals. These correlations align well with the Piper plot facies trends that show dominance of Mg–HCO_3 and mixed types. Moderate correlations between NO_3^{-} and K^{+} appeared sporadically (notably in 2019 and 2023), suggesting agricultural runoff or sewage contamination as common sources. However, NO_3^{-} generally had weak correlations with major cations, highlighting its distinct anthropogenic origin and mobility in groundwater.

The overall correlation strength between parameters like Cl^{-}, Na^{+}, and SO_4^{2-} increased slightly in recent years (2021 and 2023), hinting at progressive mineralisation or rising anthropogenic influence. Fluoride (F^{-}) maintained weak correlations with most parameters, indicating a likely geogenic source rather than common anthropogenic pathways.

These inter-parameter relationships complement GIS-based hotspot analysis and Piper diagram interpretation. The consistent correlations between EC, TDS, and major ions underscore the importance of regular EC monitoring for early contamination detection. Changes in correlation patterns over time suggest evolving hydrogeochemical controls, with growing signs of external contamination pressures in urbanised and mining-intensive districts.

a)2020

b)2014

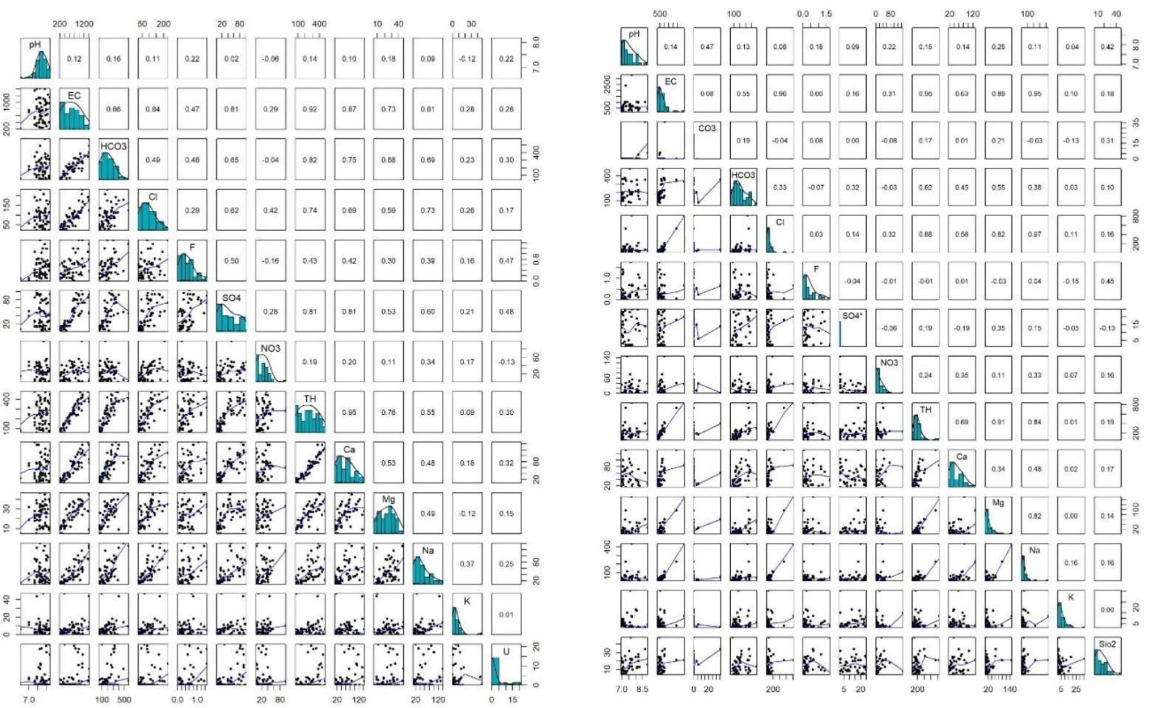


Fig 14. a)- 2023. b)-2014 Pearson correlation matrix for groundwater parameters. Correlations for 2017, 2019, and 2021 are given in Appendix section 2 Fig 14 (c)(d)(e)

4.4 Groundwater Quality Assessment Based on Primary Data (2025)

4.4.1 Spatial analyses (2025)

Regions in the north-west (Hazaribagh), south-west (Gumla), south east (Saraikela-Kh), central (Ramgarh) and north west (Deoghar) show spatial similarities in hotspot occurrence across the parameters of Total Hardness (TH), Total Alkalinity (Tot. Alk), Total Dissolved Solids (TDS), Magnesium (Mg^{2+}), Iron (Fe). High levels of TDS may be caused due to intensive agricultural activity, residential runoffs, soil leaching and industry point source water pollution. Significant presence of high alkalinity, TH, and TDS in regions high in Mg (but relatively low in Ca) suggests that this cation is the primary contributor to these parameters. Hazaribagh is observed to be the region most dominated with high levels of these parameters, in addition to unacceptable concentrations of Iron (Fe). Iron could also be a major contributor to TDS; but it does not have a greater influence than Mg, as regions with very low levels of Fe still express high amounts of TDS along with significant levels of Mg.

Pearson correlations investigated in section 4.4.2 further build open the arguments of co-occurrence of parameters. Hazaribagh, in addition to Gumla, are observed to be hotspots with very hard water, alkalinity and associated high concentrations of Magnesium. Calcium level is well within the acceptable limit for the majority of the regions, except for the northeast and southeast districts of Bokaro, Dhanbad and E. Singhbhum. Since Ca levels were found to be low in regions with high levels of TDS, TH, and Alkalinity, it can be deduced that it was a smaller contributor to all these parameters as compared to Mg (Eg. Gumla and E.Singhbhum). There was some observable co-occurrence between Mg^{2+} and Ca^{2+} hotspots in Saraikela-Kh and southern Ramgarh.

These results validate much of the observations of co-contaminations made in the Spatio-temporal maps of secondary data as it shows hotspots of TH, Alkalinity, and Mg^{2+} that were spatially similar to the hotspots in the secondary data for the parameters of Mg^{2+}, TH, and HCO_3^-: These zones with unacceptable parameter levels were located in north-west (Chatra), central (Bokaro), north-east (Dumka), south-east (E. Singhbhum and Saraikela-Kh), and south-west (Gumla) Jharkhand.

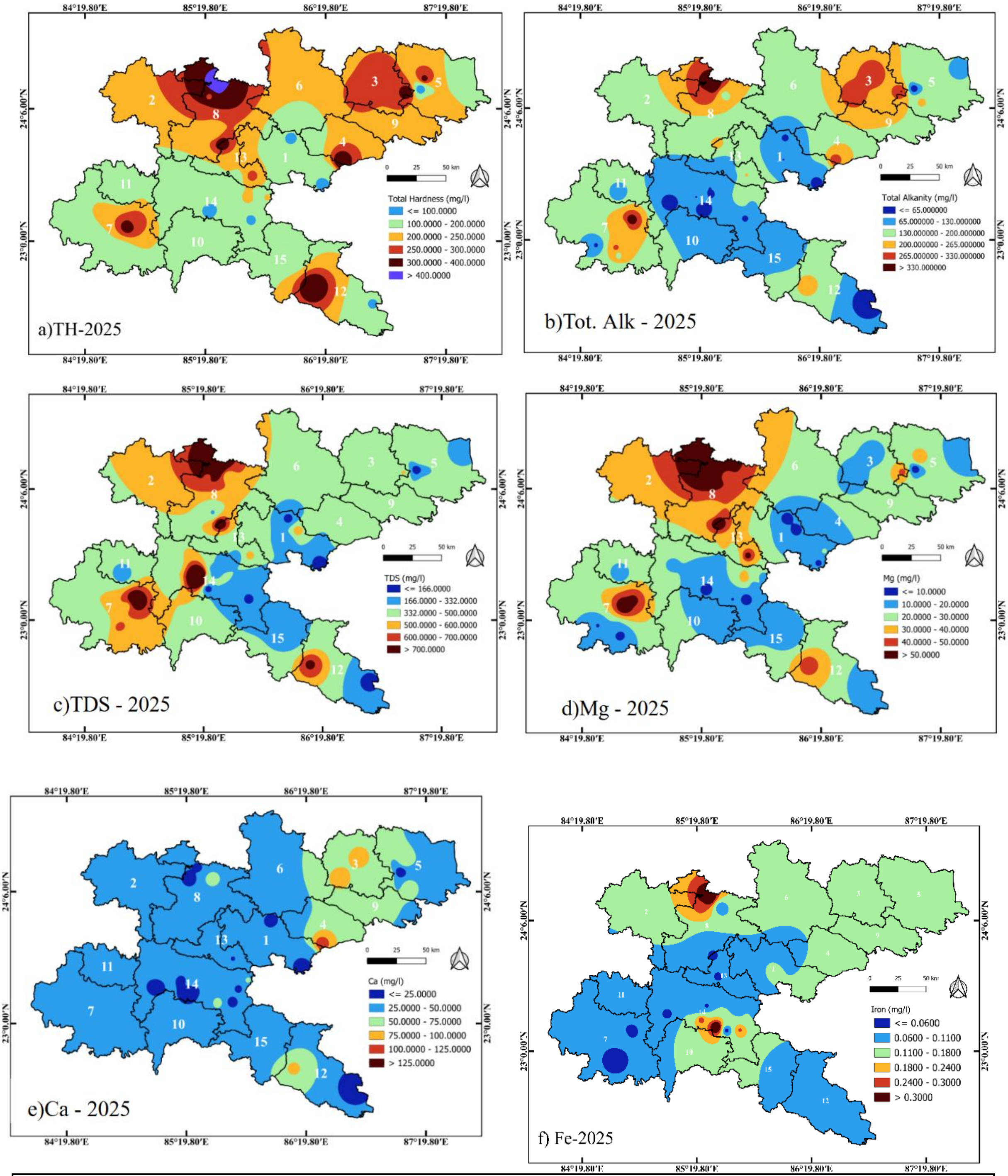


Fig 15. Spatial maps for (a) TH, (b) Tot. Alkalinity, (c) TDS, (d) Mg, (e) Ca, (f) Fe.

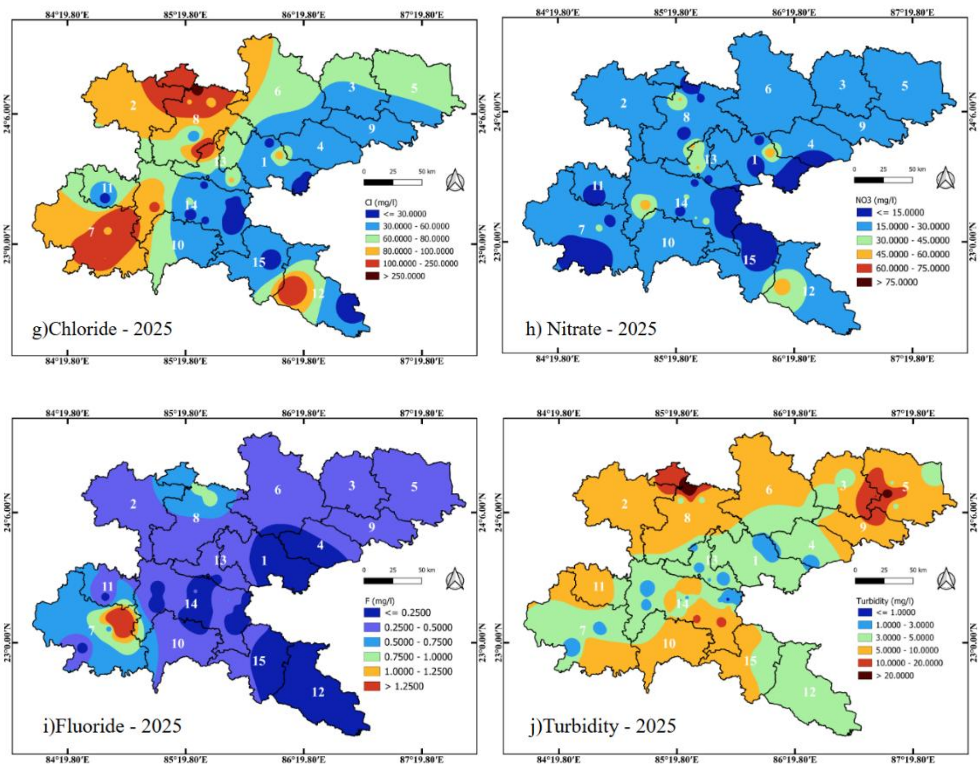
Anion Analyse:

Hazaribagh is observed to be a major hotspot for Turbidity (levels are significantly higher than the permissible limit) and Chloride (this was the only region where chloride concentration was found to be higher than the acceptable limit of 250mg/l). Chloride levels were majorly within the acceptable limit across Jharkhand, with the eastern half (except for E. Singhbhum) demonstrating relatively lower levels than the western half. Hazaribagh, Chatra, Gumla and E. Singhbhum were found to be the locations that were closer to the concentration limit.

These results validate the findings in the secondary data, which showed Chloride to be beyond the acceptable limit in Hazaribagh and Chatra in 2014 and Hazaribagh in 2019. Moreover, the spatial maps of 2014, 2019, and 2023 showed in general, a relatively lesser concentration of Cl^- in the eastern half. As opposed to 2023, which showed the majority of Bokaro and Ramgarh to have relatively higher concentrations (100-250 mg/l), 2025 showed a major reduction, with the range falling below 100mg/l.

In the secondary data, it was found that the Nitrate hotspot of E. Singhbhum and Saraikela-Kh acclimatised into acceptable ranges by 2021; but, primary data shows a hotspot re-emergence in E. Singhbhum with levels exceeding acceptable limits. On the contrary, the south and northwest region, which had concentration levels in the range 30-45mg/l in 2023, experienced a reduction, with much of its area re-settling in relatively lower concentration ranges.

The fluoride levels in Gumla have been identified as the only major hotspot, and all the other regions (especially the south-east and centre-east regions) have low concentration levels. This data shows improvement in fluoride levels of the secondary data, which depicted the central region (Bokaro, Ramgarh) to be major hotspots. Overall, Hazaribagh has been identified as a major hotspot for high levels of cations, anions, hardness, alkalinity, and iron.



District	No.
Bokaro	1
Chartra	2
Deoghar	3
Dhanbad	4
Dumka	5
Giridih	6
Gumla	7
Hazaribagh	8
Jamtara	9
Khunti	10
Lohardaga	11
E. Singhbhum	12
Ramgarh	13
Ranchi	14
Saraikela-Kh	15

Fig 16. Spatial maps for Cl(g), NO3(h), Fluoride(i), Turbidity(j).

4.4.2 Statistical Interrelationships among Hydrogeochemical Parameters (2025)

For 2025, Total Hardness showed a strong correlation with Total Alkalinity and Mg^{2+}, and a moderate correlation with Ca^{2+} (Figure 17), supporting the conclusion deduced from the secondary data that TH in the region is primarily governed by these alkaline earth metals. The relatively smaller correlation (compared with Mg^{2+}) of Ca^{2+} with TH and TDS is supported by the spatial map analyses (in section 4.4.1), where it was concluded that Ca^{2+} was a smaller contributor to these parameters than Mg^{2+}. Moreover, the insignificant correlation of Ca^{2+} with TDS, as compared to the moderate correlation of Mg^{2+} with TDS, further supports the spatial analyses, which showed levels of Ca^{2+} to be very low and levels of Mg^{2+} to be very high at hotspots of greatest TDS.

Another notable strong correlation was found between Mg^{2+} and $Cl^{-,}$ as well as Total Hardness and Cl^-, which brings up the possibility that they originate from the same hydrogeochemical and anthropological sources which cause dissolution of Magnesium-based salts (eg. $MgCl_2$) and Magnesium-bearing fertilizers with Chloride mixes. A possibility for the high correlation between TH and Cl^- is the intrusion of sewage water (which often bears a high amount of Hardness as well as Chloride ions) in aquifer recharge zones.

It is found that TDS has a moderate correlation with Total Alkalinity, Total Hardness, Mg^{2+}, Cl^-, and F^-, suggesting that Mg^{2+}, Cl^-, and F^- form a major portion of TDS. Moreover, this correlation of TDS with the cations and hardness indicates a common source where carbonate weathering takes place. The presence of Fluoride ions could indicate the presence of anthropogenic activities within the proximity of natural sources.

In contrast to other anions (F^- and Cl^-), Nitrate does not show a significant correlation with any of the parameters, suggesting that it has a distinct anthropogenic origin and mobility in groundwater. This supports the similar conclusion made for the co-occurrence of Nitrate ions in the secondary data of groundwater samples. Fe had the highest positive correlation (weakly-moderate in magnitude) with Turbidity. This correlation value is visually supported by Figure 15f and 16j, which show a very similar shape in terms of relative concentrations (with the north western, north eastern and central-southern regions showing higher relative concentration) and contamination hotspots (north Hazaribagh and south Ranchi). This suggests that dissolved iron may have partly contributed to the suspended solids and cloudiness in groundwater; both of them might be commonly mobilized by sediment disturbances in aquifers, and they both may originate from the same source of weathering/mining of iron-rich minerals.

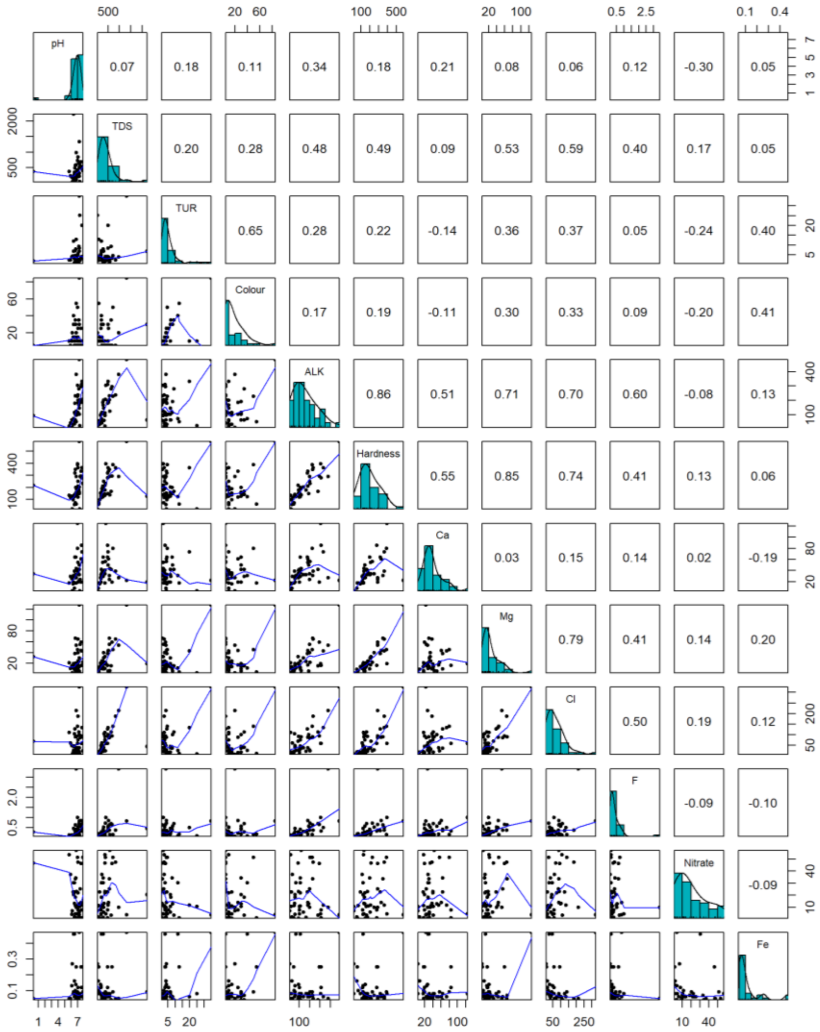


Fig 17: Pearson Correlation Matrix for 2025

The 2025 primary data validates trends observed in the decadal secondary data analysis. Anthropogenic impact is more pronounced in industrial and urban districts, while natural geogenic factors influence fluoride and iron levels. These findings reinforce the urgent need for localised groundwater quality management and monitoring, especially in eastern and central Jharkhand.

Conclusions

The present study offers a detailed spatio-temporal analysis of groundwater quality across Jharkhand from 2014 to 2025, integrating secondary data with recent primary sampling. The findings highlight significant regional variability and gradual deterioration in water quality in several districts, particularly Chatra, Bokaro, Hazaribagh, East Singhbhum, Ramgarh and Dumka. Parameters such as Total Hardness, Bicarbonate, TDS, Chloride, Nitrate, and Turbidity showed increasing concentrations in industrial and mining-influenced regions, while geogenic contaminants like fluoride remained persistent in isolated pockets.

Piper plot interpretations revealed a shift from simple bicarbonate-type facies to more mixed and evolved water chemistries, suggesting intensified ion exchange and anthropogenic influence. Notably, 2021 experienced a dominance diffusion from Mg^{2+}–HCO_3^- zone to mixed types and spatially fewer contamination hotspots for Magnesium, Bicarbonates and Fluorides (which were restored to pre-2021 levels by 2023), suggesting a reduction in anthropogenic activities and groundwater-rock interactions frequencies during the COVID-19 lockdowns. Correlation analysis further confirmed strong interrelations among major cations and anions, with parameters like nitrate and fluoride showing distinct, independent behaviour. Overall, the study underscores growing pressure on Jharkhand's aquifers due to unregulated urban and industrial development. Future groundwater assessments should incorporate heavy metal and microbial indicators, and policy efforts must focus on improved monitoring, recharge management, and community-level awareness to ensure long-term sustainability of this critical resource.

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Appendix

Appendix 1 1: Spatial aquifer map of Jharkhand.

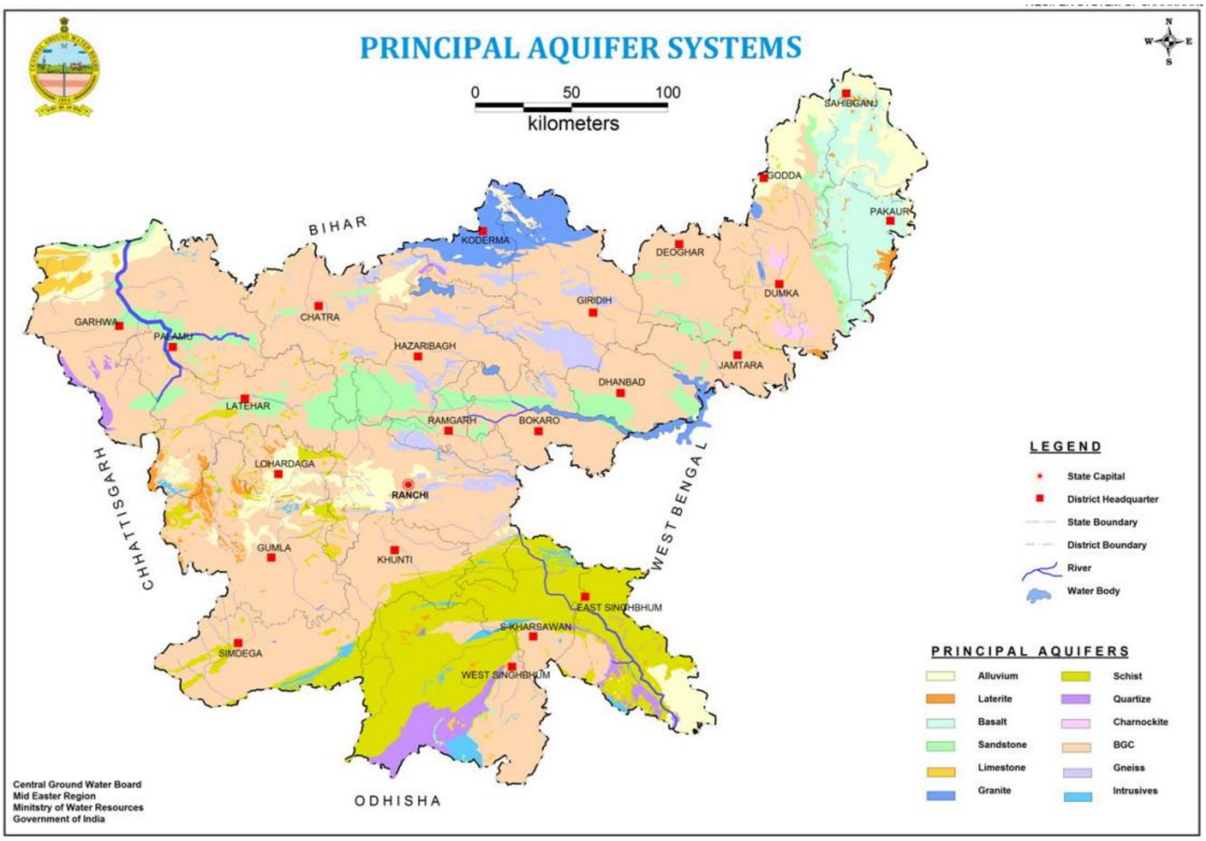

Figure 18: Principal Aquifer Systems of Jharkhand State, India, depicting spatial distribution of major aquifer types including alluvium, laterite, basalt, sandstone, limestone, granite, schist, quartzite, charnockite, BGC, gneiss, and inliers. (Adopted from CGWB; 2024).

Section 2: Pearson correlation matrices

c)2021

Fig. 14 Pearson correlation matrices. c) – 2021, d – 2019, e - 2018

d)2019

e)2017