Volume 11, Issue 5, May – 2026 International Journal of Innovative Science and Research Technology
ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26may227

Spatial Distribution of Groundwater Quality and its Suitability for Human Consumption in Liwale District, Lindi Region, Tanzania

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Publication Date: 2026/05/22

Abstract: Groundwater is a critical water resource in Sub-Saharan Africa, particularly in semi-arid regions such as Liwale District, Tanzania, where surface water availability is unreliable. However, groundwater quality varies significantly due to geological formations and hydrogeological processes, posing potential health risks to communities relying on boreholes. This study assesses the spatial distribution of groundwater quality and its suitability for human consumption in Liwale District. A total of 41 groundwater samples were collected and analyzed for 22 physicochemical parameters. Spatial variations were mapped using Geographic Information System (GIS) techniques and a Piper Diagram was employed to characterize hydrochemical facies. Results revealed significant spatial variability: pH ranged from 4.6 to 8.23 (mean 6.90), and Electrical Conductivity (EC) ranged from 164 to 5,458 µS/cm (mean 1,143.81 µS/cm), indicating moderate to high mineralization. While most parameters remained within permissible limits, localized exceedances were observed for Total Hardness (4–1,316 mg/L), Iron (up to 1.5 mg/L), and Manganese (up to 1.1 mg/L). The study identifies mineral dissolution, cation exchange, and water–rock interactions as the primary drivers of groundwater chemistry. Although most sources are suitable for domestic use, identified localized areas of low suitability require site-specific water treatment and informed management to protect public health and ensure sustainable water resource planning.

Keywords: *GIS Mapping; Groundwater Quality; Groundwater Suitability; Hydrochemical Facies; Water–Rock Interaction; Tanzania.*

How to Cite: Ruhumbika Wegoro; Dr. Clarance Paul; Brian Kamoga (2026) Spatial Distribution of Groundwater Quality and its Suitability for Human Consumption in Liwale District, Lindi Region, Tanzania. *International Journal of Innovative Science and Research Technology*, 11(5), 1040-1057. https://doi.org/10.38124/ijisrt/26may227

I. INTRODUCTION

Groundwater represents one of the most vital freshwater resources for human survival, economic development, and environmental sustainability worldwide. Globally, groundwater accounts for a substantial proportion of accessible freshwater, supplying nearly half of the world's drinking water and supporting domestic, agricultural, and industrial activities (Gleeson et al., 2012; UNESCO, 2022). With increasing population growth, urbanization, and climate variability placing pressure on surface water resources, groundwater has become a dependable alternative owing to its relatively stable availability and natural filtration through subsurface materials (Taylor et al., 2013). However, groundwater quality varies spatially depending on geological formations, hydrogeochemical processes, and anthropogenic influences, necessitating continuous assessment to ensure its suitability for human consumption (Appelo & Postma, 2005).

At the global scale, access to safe drinking water remains a major challenge, with billions of people still lacking safely managed water services (WHO & UNICEF, 2023). Groundwater quality problems are frequently associated with excessive hardness, fluoride, iron, salinity, and abnormal pH levels, which may pose health risks when concentrations exceed recommended limits (Freeze & Cherry, 1979; WHO, 2017). To safeguard public health, the World Health Organization (WHO) has established drinking water quality guidelines that define acceptable limits for physical, chemical, and biological parameters, serving as benchmarks for evaluating water suitability worldwide (WHO, 2017).

In Sub-Saharan Africa, groundwater plays an increasingly critical role due to high rainfall variability, recurrent drought conditions, and limited surface water infrastructure. Rural populations depend heavily on boreholes and shallow wells as primary drinking water sources (MacDonald et al., 2012; Taylor et al., 2009). Despite this importance, groundwater quality across the region exhibits strong spatial variability influenced by lithology, aquifer characteristics, climatic conditions, and land-use practices (Lapworth et al., 2017). Naturally occurring contaminants such as fluoride, iron, manganese, and elevated total dissolved solids are widely reported, while inadequate sanitation and limited monitoring systems further threaten groundwater safety (Edmunds & Smedley, 2013).

In Tanzania, groundwater constitutes the principal source of domestic water supply, particularly in rural and semi-arid areas where surface water availability is unreliable (URT, 2019). The country's diverse geological settings—including crystalline basement complexes, sedimentary formations, and coastal deposits—strongly control groundwater occurrence and hydrochemistry (Mjemah et al., 2011). Previous studies have reported spatial variations in groundwater quality characterized by differences in hardness, iron concentrations, electrical conductivity, and pH (Nkotagu, 1996; Mubofu et al., 2019). National drinking water standards developed by the Tanzania Bureau of Standards (TBS) align with WHO guidelines to ensure safe water supply and protect public health (TBS, 2016).

Liwale District, located in Lindi Region of south-eastern Tanzania, is predominantly rural and relies heavily on groundwater resources due to limited perennial surface water sources. Communities mainly depend on boreholes and shallow wells for domestic consumption, livestock keeping, and small-scale socio-economic activities. However, groundwater quality in the district is spatially variable owing to geological conditions, aquifer properties, and characteristic of coastal sedimentary environments. Such variability may affect the suitability of groundwater for human consumption and expose communities to water quality-related health risks if not properly assessed and monitored.

Despite ongoing government and development-partner initiatives aimed at improving rural water supply coverage, limited spatial evaluation of groundwater quality in Liwale District constrains effective water resources planning and sustainable groundwater utilization. Understanding the spatial variations of groundwater quality parameters relative to national and international standards is therefore essential for identifying safe drinking water zones and areas requiring treatment or management intervention.

This study assesses the spatial distribution of groundwater quality for suitability of various uses, particularly human consumption, according to national and international standards in Liwale District, Lindi Region. The findings are expected to support sustainable groundwater management, improved borehole siting, and informed decision-making for safe water supply and public health protection.

II. MATERIAL AND METHODS

- *Description of the Study Area*

Liwale District is located in the inland plateau area of Lindi and Mtwara Regions, lying approximately between 9° 00' and 10° 30' South latitude and 37° 30' and 38° 30' East longitude (Figure 1). It is bordered by Ruangwa District to the east, Nachingwea District to the south, and Kilwa District to the north. The district has a total land area of approximately 38,380 km² and a population of about 136,505 (National Census, 2022). Most areas in the district have limited and insufficient access to potable water supply, with drilled boreholes serving as the major water source.

The district lies in a semi-arid region, relying heavily on groundwater for domestic, agricultural, and livestock needs. It is characterized by complex geology with fractured basement rocks and variable aquifer recharge patterns. Topographically, the district exhibits elevations between 200 and 900 m above sea level, comprising undulating plains, isolated monadnocks, and fold mountains at selected locations. Soils are predominantly sandy and loamy, and the drainage network includes the permanent Liwale River with multiple tributaries alongside seasonal streams, underscoring the population's reliance on groundwater during prolonged dry periods.

Geologically, Liwale is underlain by Pre-Cambrian Basement Complex rocks including gneiss, schist, marble, quartzite, pegmatite, and migmatite, and Karoo Sedimentary formations. Both are hard, massive, and low in primary porosity, with groundwater primarily occurring in weathered, fractured, or fissured zones, resulting in generally low aquifer yields and localized water quality concerns such as elevated sulfate and conductivity.

The district experiences a unimodal rainfall regime averaging 800–1,000 mm annually, concentrated between November and April, followed by a pronounced dry season from June to October. This seasonality limits effective recharge and reinforces dependence on groundwater storage within hard-rock aquifers.

Liwale was selected for this study due to its limited empirical groundwater data, making it a representative example of understudied semi-arid districts in Tanzania. The findings from Liwale are expected to provide locally relevant insights for sustainable groundwater management and offer a framework applicable to similar inland districts in Tanzania and East Africa.

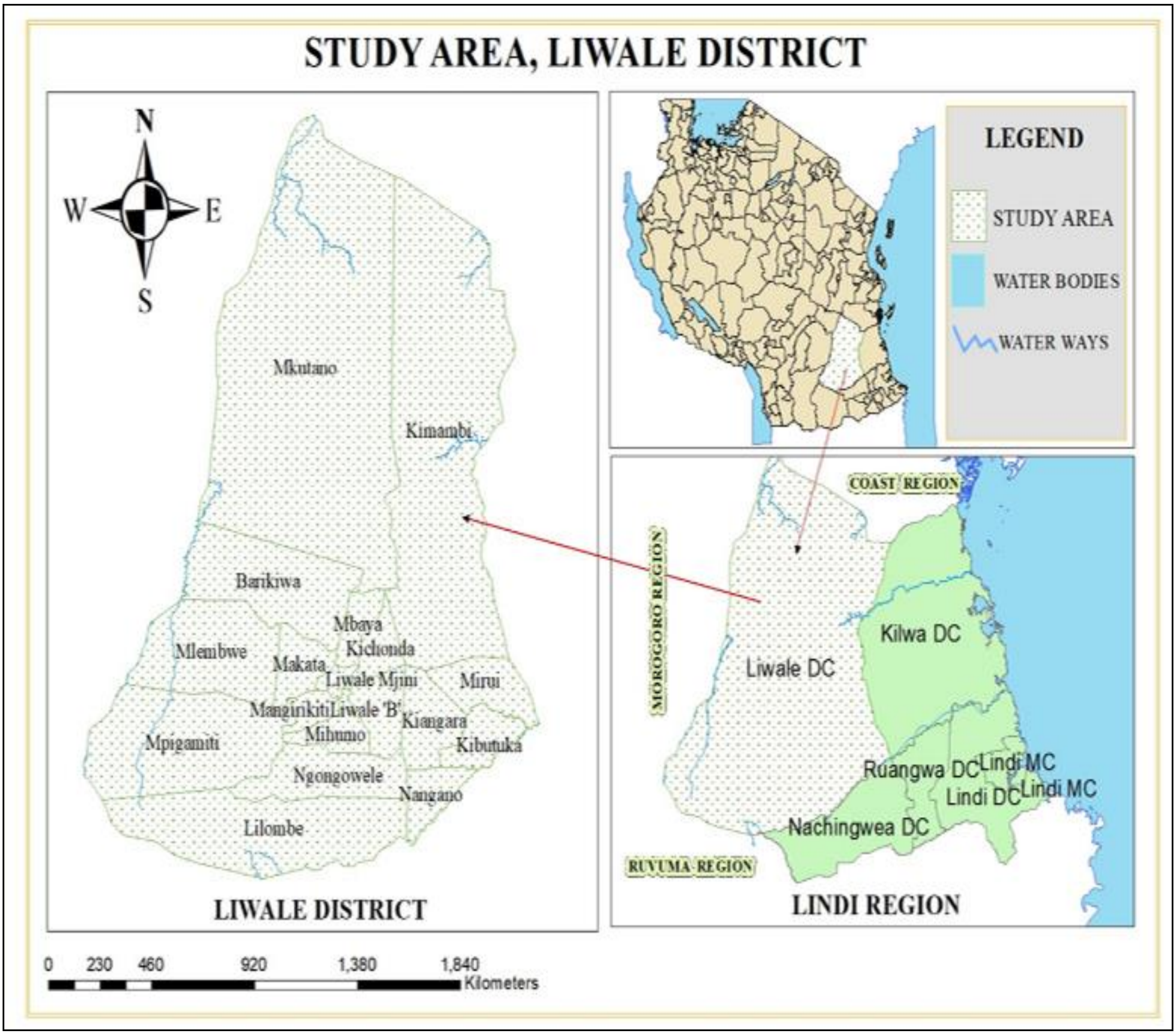


Fig 1 Study Area: Liwale District

- *Water Sampling*

Groundwater samples were collected from a representative selection of existing boreholes across the study area (Figure 2). A total of 41 sampling stations were collected between December 2025 and January 2026 and analyzed for 22 physicochemical parameters. Sampling sites were strategically selected within four distinct RUWASA distribution networks within the study area to capture variations in groundwater quality related to geological conditions. Additional factors, including anthropogenic activities, were incorporated as explanatory variables to assess their contribution to observed water quality variations, ranging from highly impacted to low-impacted areas.

Prior to sampling, each borehole was purged to remove stagnant water, ensuring that collected samples were truly representative of the respective groundwater source. Wells were allowed to flow for at least three minutes before sample collection. Physical parameters including pH, Temperature, Turbidity, Total Dissolved Solids (TDS), Color, Salinity, and Electrical Conductivity (EC) were measured on-site immediately after sampling using a multiparameter water analyzer.

Chemical parameters analyzed included sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), chloride (Cl^-), bicarbonate (HCO_3^-), sulfate (SO_4^{2-}), nitrate (NO_3^-), phosphate (PO_4^{3-}), alkalinity, iron (Fe), manganese, fluoride, carbonate, and total hardness. Water samples were stored in polyethylene bottles and acidified with nitric acid to $pH < 2$ to prevent precipitation prior to chemical analysis at the Water Quality Laboratory. Geographic coordinates of each sampling location were recorded using a GPS device.

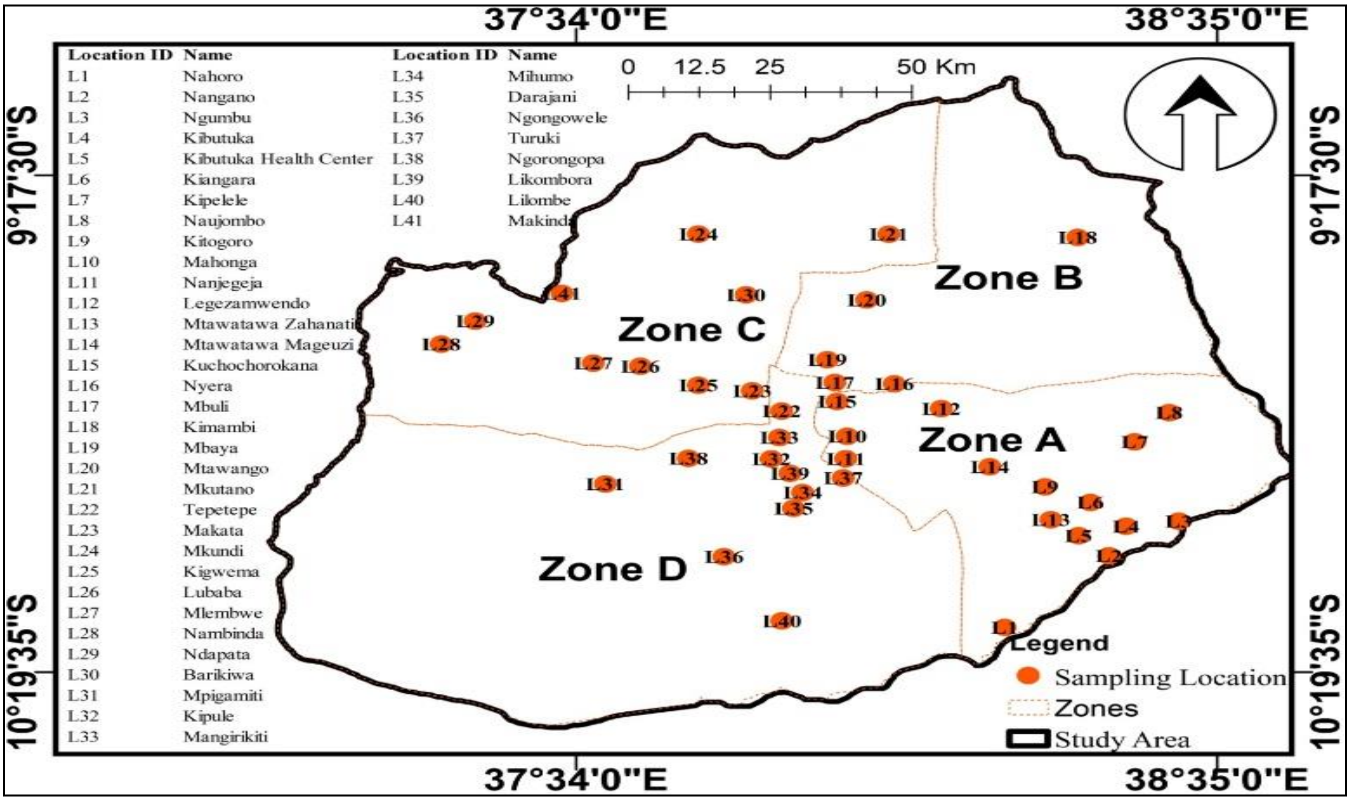


Fig 2 Distribution of Groundwater Sampling Sites Across Liwale District.

- *Laboratory Analysis*

Major cations (Na^+ and K^+) were determined using flame photometry, while Ca^{2+} and Mg^{2+} were analyzed using ion chromatography. Major anions, including NO_3^- and SO_4^{2-}, were analyzed using UV-Visible spectrophotometry. Chloride (Cl^-) was determined using a Chloride Ion Selective Electrode (ISE) method, and carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) ions were analyzed by titration.

The accuracy and reliability of laboratory analytical results were evaluated by calculating the Charge Balance Error (CBE) to assess ionic balance consistency. The analysis was considered reliable if the CBE was less than 5%, although CBE > 5% may be acceptable when groundwater mineralization is very low (Baba et al., 2020).

- *Hydrochemical Data Interpretation*

Piper diagram analysis was applied to characterize groundwater hydrochemical types and to identify the dominant factors controlling groundwater chemistry in the Liwale aquifer. All analyzed parameters were compared with the Tanzania drinking water quality standards (TZS 789:2018) to assess groundwater suitability and compliance with recommended limits. There are three separate fields in this diagram including a diamond-shaped field and two triangular areas. Cations are plotted as a single point in the left triangle in proportion to the total cations in meq/L; anions are placed in the right triangle. Each parameter is projected into the upper field along parallel lines.

- *Spatial Analysis Using GIS*

Spatial variation in groundwater quality and suitability in the Liwale aquifer was studied using Geographic Information System (GIS) techniques. Spatial data of each borehole were imported into GIS software and combined with attribute data showing groundwater quality parameters. Each parameter was interpolated using the Inverse Distance Weighting (IDW) spatial analyst tool to produce GIS layers showing spatial variation in groundwater quality across the district. These layers were standardized to show groundwater suitability based on individual parameters. Finally, all standardized GIS layers were combined using the Weighted Overlay spatial analyst tool to determine overall groundwater suitability.

III. RESULTS AND DISCUSSION

- *Physicochemical Characteristics of Groundwater*

The physicochemical characteristics of groundwater in the study area showed considerable spatial variation due to geological conditions, mineral weathering, water-rock interaction, and anthropogenic activities. Some parameters exceeded the Tanzania Water Quality Standard, while the remaining were within the acceptable drinking water standard. The detailed explanation of individual physicochemical parameters is presented below.

- *Physical Parameters*

✓ *pH:*

Most locations in the study area are within the TBS range of 5.5 to 9.5. However, samples 7 and 28 (4.6 and 5.14 respectively) fall below the limit indicating acidic conditions (Figure 3a). Low pH is frequently linked to enhanced leaching conditions where exchangeable minerals increase as pH decreases (Wersin et al., 2022). The decomposition of organic substances is a primary driver of groundwater acidity. Also, the presence of agricultural chemicals and industrial waste can exacerbate these natural processes. Lower pH levels are known to make the leaching of both natural minerals and anthropogenic pollutants more thorough, potentially worsening overall water contamination (Zhang et al., 2023).

- ✓ *Electrical Conductivity (EC):*

EC values ranged from 178–5,458 µS/cm. Samples 3, 8, 9, 11, and 21 (Figure 3b) exceeded the Tanzania Drinking Water Standard limit of 2,500 µS/cm, indicating high dissolved ionic concentration caused by mineral dissolution and groundwater mineralization (Saria et al., 2024). Other samples were within the permissible range, suggesting moderate salinity and acceptable water quality.

- ✓ *Total Dissolved Solids (TDS):*

TDS concentrations ranged from 82 to 2,729 mg/L. Samples 3, 8, 9, and 21 (Figure 3c) exceeded the TBS limit of 1,500 mg/L due to increased dissolved salts from rock weathering and evaporation (Subramaniyan, 2026). Other samples were within the acceptable range, indicating fresh groundwater suitable for domestic use.

- ✓ *Salinity:*

Salinity values ranged from 0.02 to 2.17 ppt, indicating generally fresh groundwater conditions. High salinity in samples 8, 9, 11, and 21 (Figure 3d) may be associated with evaporation-crystallization and mineral dissolution. In regions with low rainfall, salts are concentrated in groundwater, a process often compounded by dissolution of chloride-bearing minerals from the local geology (Msengi et al., 2024). Other samples remained within acceptable freshwater conditions suitable for domestic use.

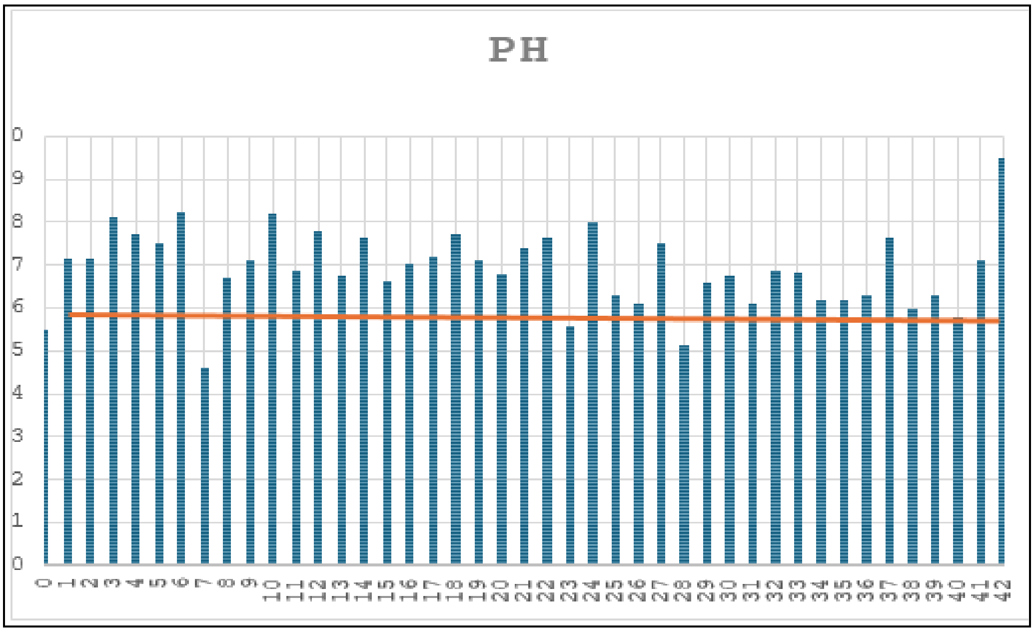


Fig 3a pH, EC, TDS, and Salinity Concentration Maps.

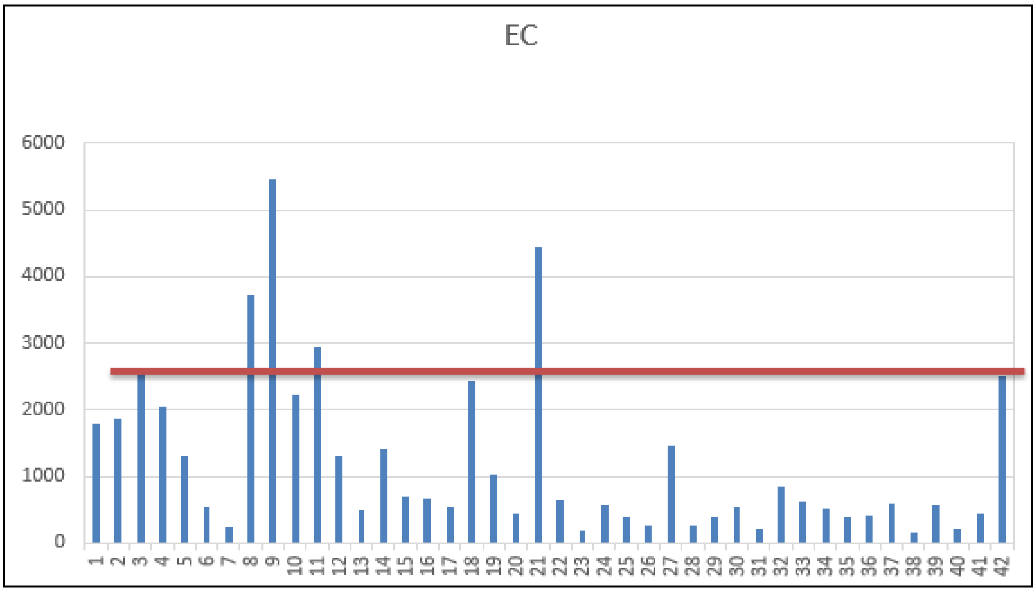


Fig 3b. Electrical Conductivity (EC) Concentration

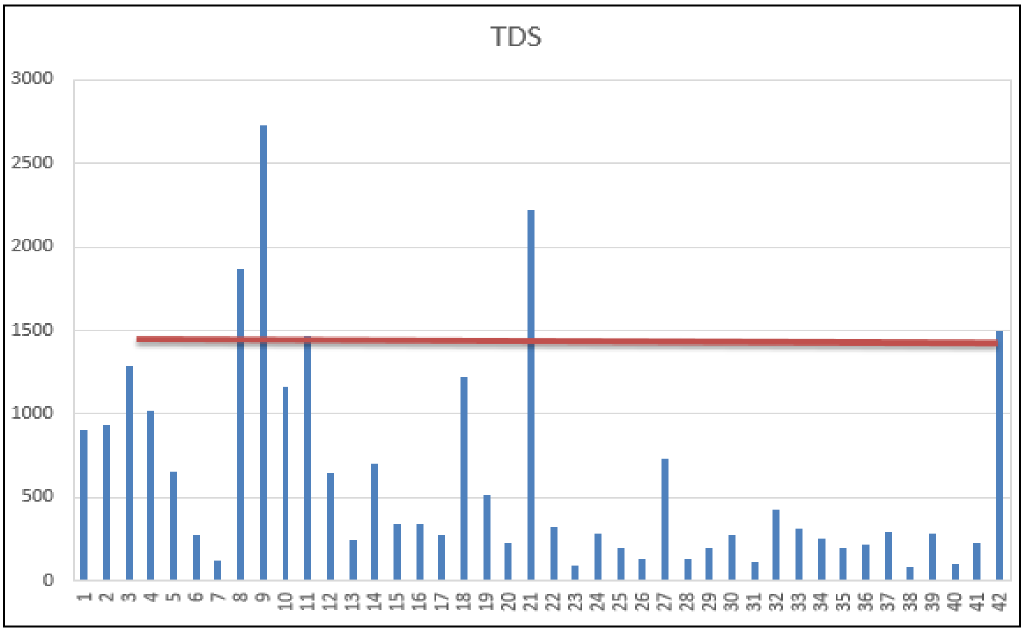


Fig 3c. Total Dissolved Solids (TDS) Concentration

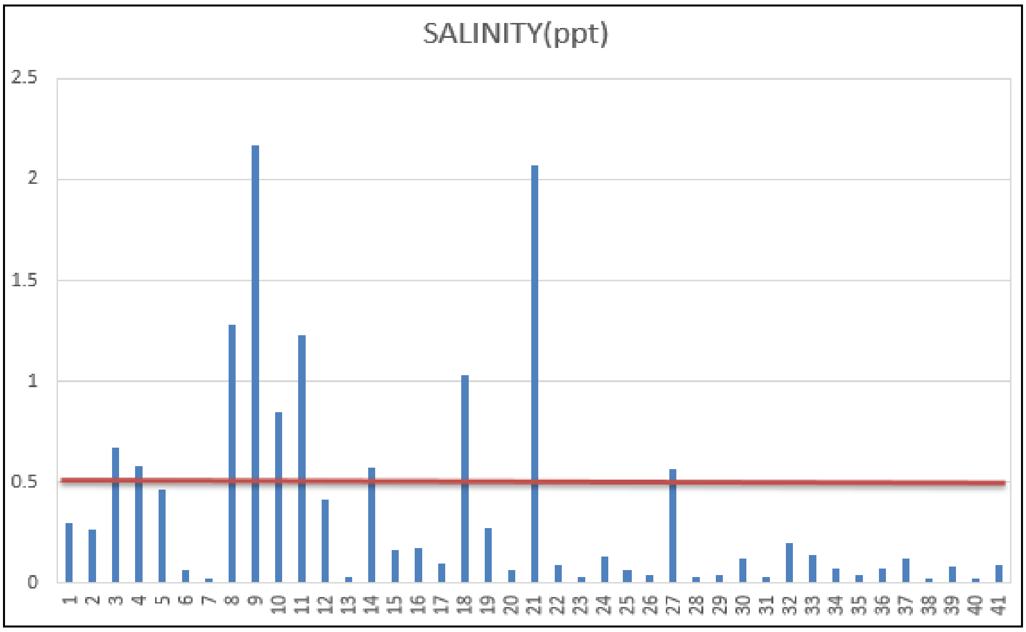


Fig 3d. Salinity Concentration

- *Major Cation Parameters*

✓ *Sodium (Na^+):*

Sodium concentrations ranged from 5.18 to 378.35 mg/L. Samples 3, 9, and 21 (Figure 4a) exceeded the TBS limit of 200 mg/L due to silicate weathering, ion exchange, and evaporation processes (Rajmohan et al., 2021). Other samples were within the acceptable range, indicating low to moderate sodium content.

✓ *Potassium (K^+):*

Potassium concentration ranged from 0.13 to 9.7 mg/L. All samples were within the TBS limit of 50 mg/L (Figure 4b), indicating low potassium enrichment and minimal anthropogenic activities (Skowron et al., 2018).

✓ *Magnesium (Mg^{2+}):*

Magnesium concentration ranged from 0.5 to 146 mg/L. Samples 8, 9, 11, 18, and 21 (Figure 4c) exceeded the TBS limit of 100 mg/L, attributable to weathering of ferromagnesian minerals such as biotite, amphibole, and pyroxene and geochemical processes (Pradhan et al., 2022). Other samples were within the permissible range, indicating moderate magnesium concentration.

✓ *Calcium (Ca^{2+}):*

Calcium concentration ranged from 0.8 to 328.18 mg/L. Samples 8, 9, and 21 (Figure 4d) exceeded the TBS limit of 150 mg/L due to dissolution of calcium-rich minerals such as calcite and feldspars (Lawal et al., 2023). Other samples were within the acceptable range, reflecting moderate calcium contribution.

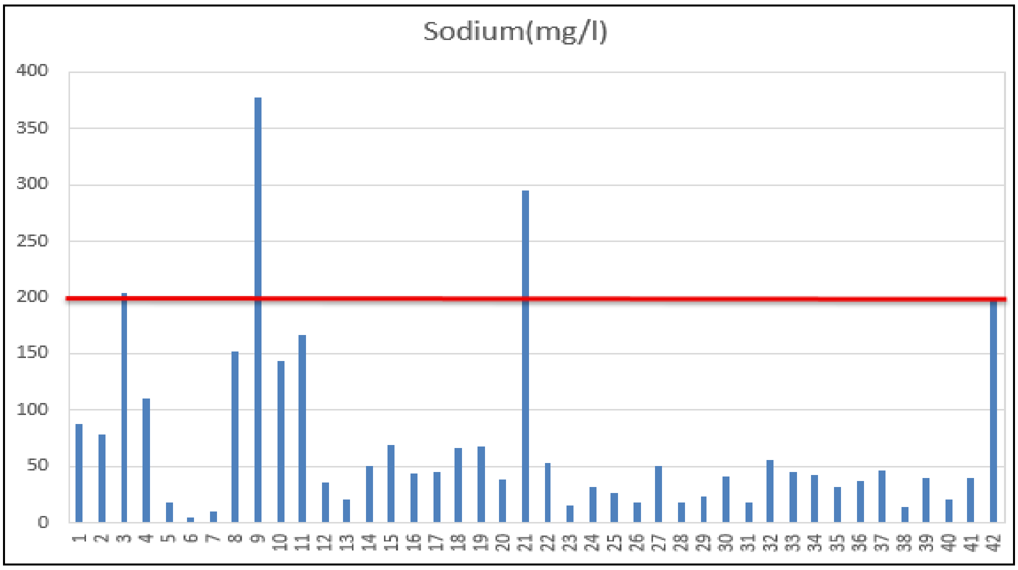


Fig 4a. Sodium Concentration

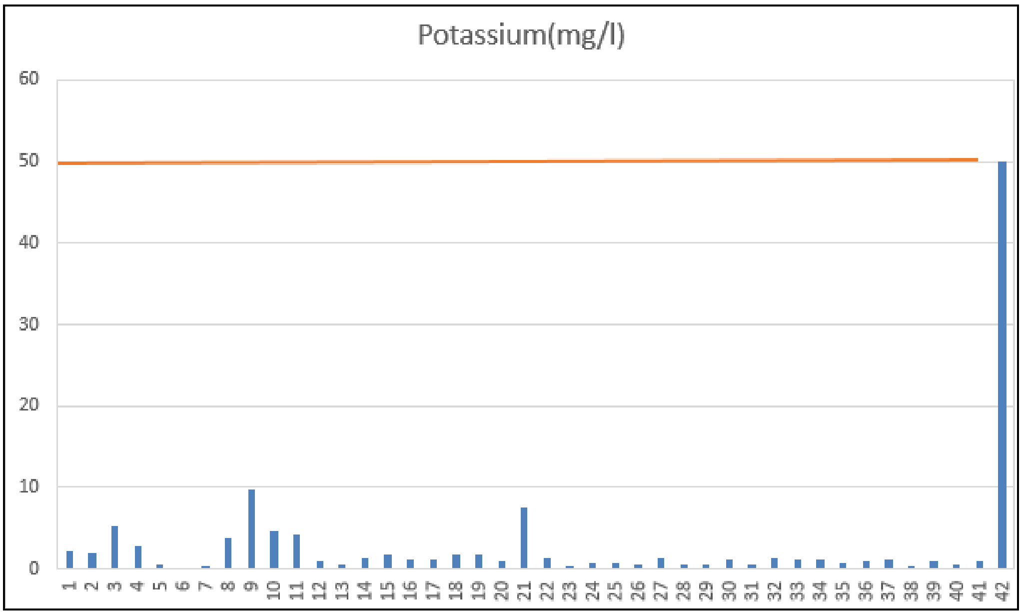


Fig 4b. Potassium Concentration

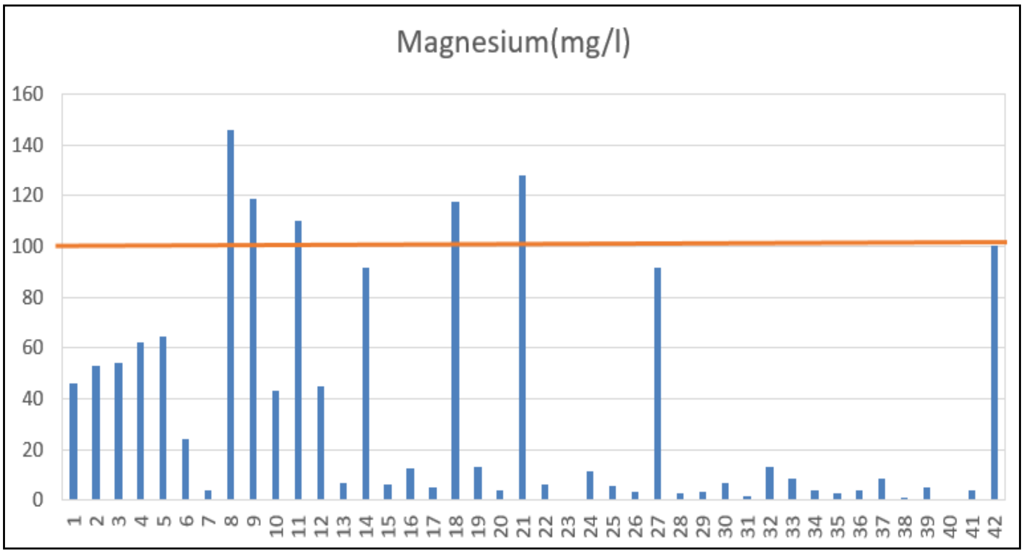


Fig 4c. Magnesium Concentration

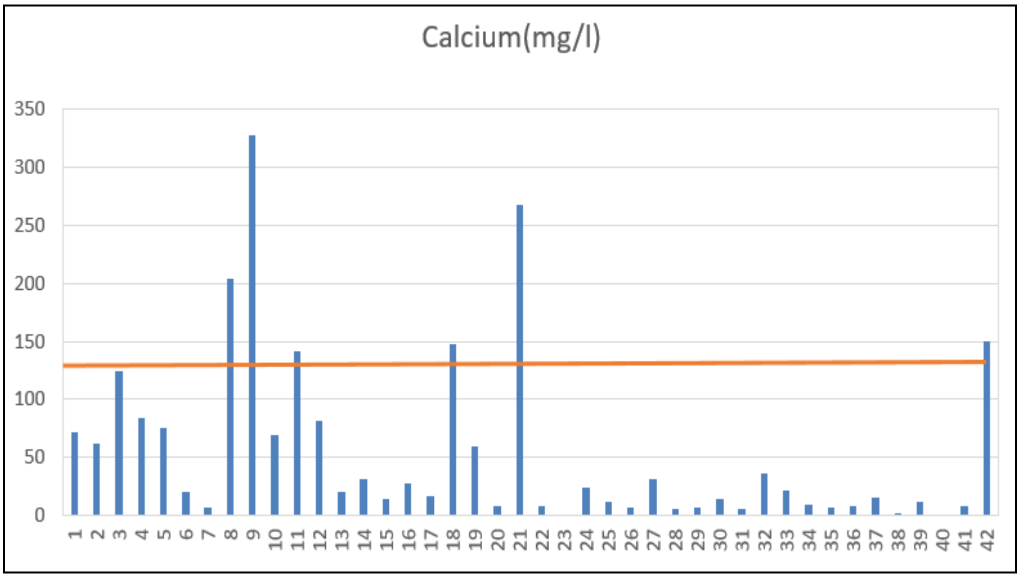


Fig 4d. Calcium Concentration

- *Major Anion Parameters*

✓ *Chloride (Cl⁻):*

Chloride concentrations ranged from 10 to 1,200 mg/L. Samples 8, 9, 10, 11, 14, 21, and 27 (Figure 5a) exceeded the TBS limit of 250 mg/L, indicating salinity enrichment, evaporation-crystallization, and possible anthropogenic contamination (Banyikwa, 2024; Shemsanga, 2024). Other parameters were within the acceptable range suggesting limited chloride contamination.

✓ *Sulphate (SO_4^{2-}):*

Sulphate concentrations ranged from 0.48 to 350.22 mg/L. All samples were within the TBS limit of 400 mg/L (Figure 5b), indicating low sulphate contamination and acceptable groundwater quality. The observed sulphate levels may be related to dissolution of gypsum and sulphide mineral oxidation (Al-Ruwaih et al., 2025).

✓ *Nitrate (NO_3^-):*

Nitrate concentration ranged from 0.18 to 45 mg/L. All samples were within the TBS limit of 45 mg/L, although samples 30 and 39 (Figure 5c) were close to the permissible limit. This suggests limited nitrate pollution, likely influenced by agricultural activities and domestic wastes in some locations (Huntington et al., 2024).

✓ *Bicarbonate (HCO_3^-):*

Bicarbonate concentrations ranged from 0 to 742.58 mg/L. Samples 2, 5, 11, 14, 18, and 27 (Figure 5d) exhibited high levels above 600 mg/L. Elevated bicarbonate values indicate strong water–rock interaction and silicate weathering, while moderate concentrations reflect natural groundwater evolution processes (Brhane & Mekonen, 2024).

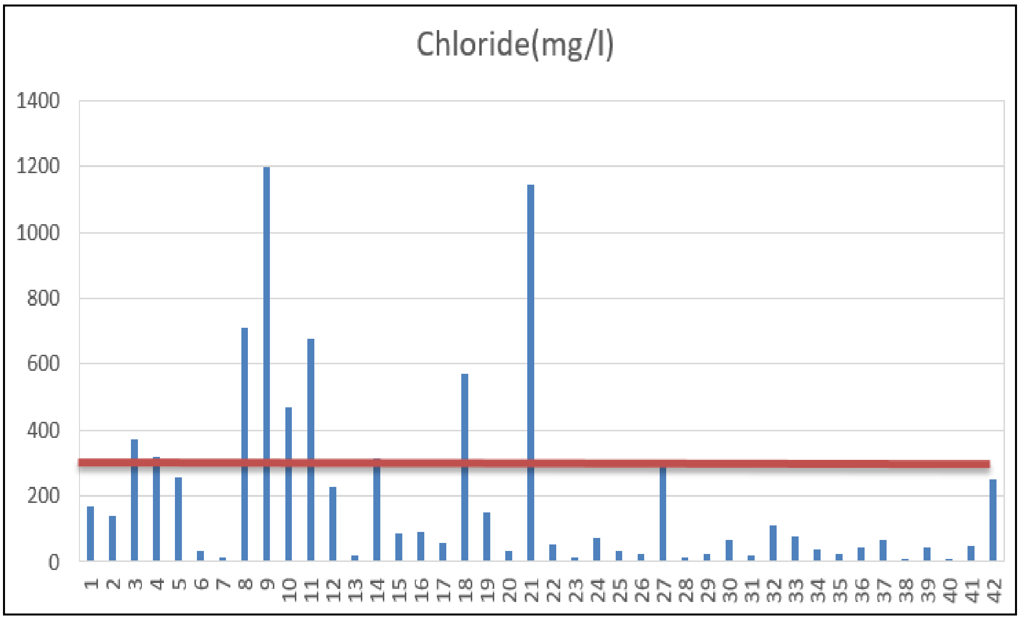


Fig 5a. Chloride Concentration

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26may227

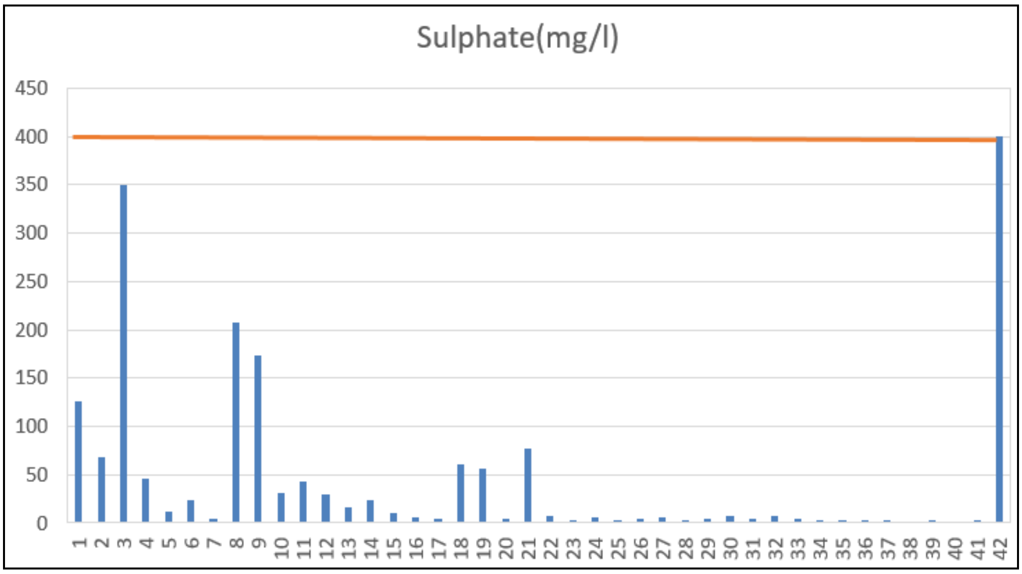


Fig 5b. Sulphate Concentration

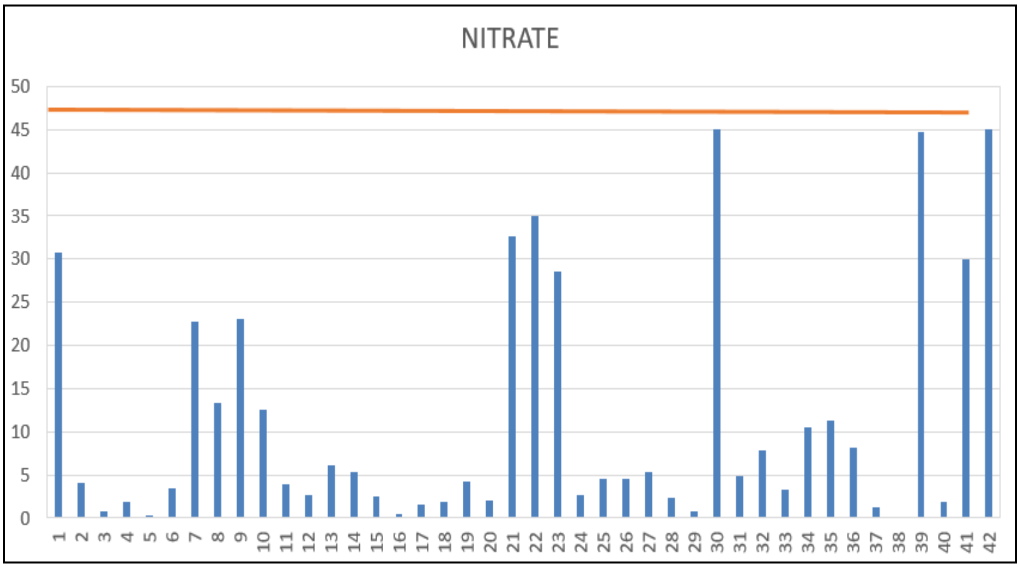


Fig 5c. Nitrate Concentration

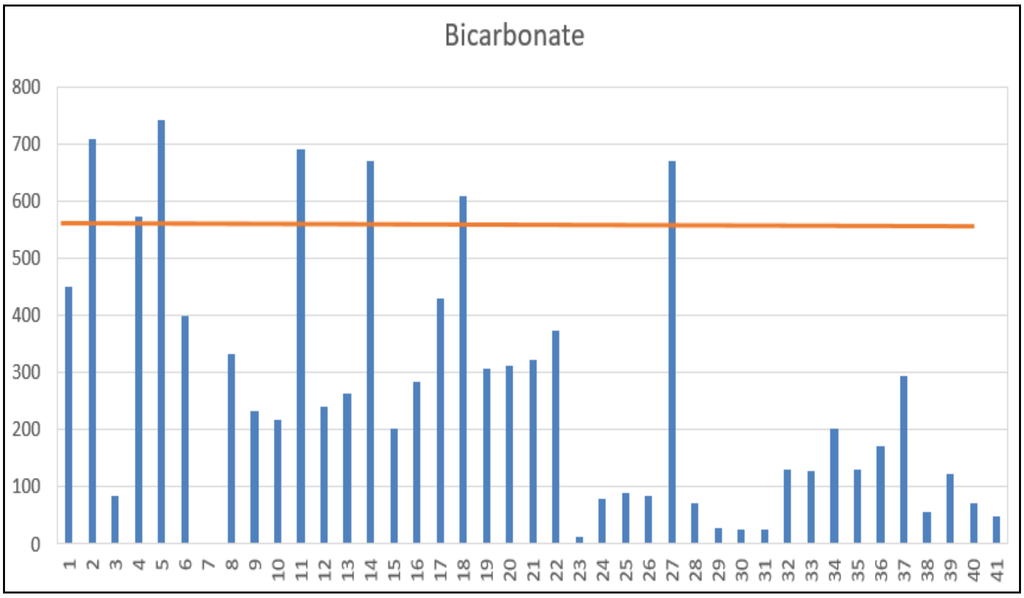


Fig 5d. Bicarbonate Concentration

- *Other Ion Parameters*

✓ *Iron (Fe):*

Iron concentration ranged from 0 to 1.5 mg/L. Samples 7, 13, 23, 26, and 41 (Figure 6a) exceeded the TBS limit of 0.3 mg/L due to dissolution of iron-bearing minerals under reducing conditions. Other samples were within acceptable range, indicating low iron contamination (Wang et al., 2025).

✓ *Total Alkalinity:*

Total alkalinity ranged from 16 to 380 mg/L (Figure 6b), below the TBS limit of 500 mg/L. All samples were within the acceptable range, indicating moderate buffering capacity controlled by carbonate and bicarbonate minerals (Dorleku et al., 2023).

✓ *Total Hardness (TH):*

Total hardness varies widely across the study area due to differences in calcium and magnesium content. Some samples (8, 9, 11, 18, and 21) exceed the TBS limit of 600 mg/L (Figure 6c). Other samples were within acceptable limits (Ingin et al., 2024).

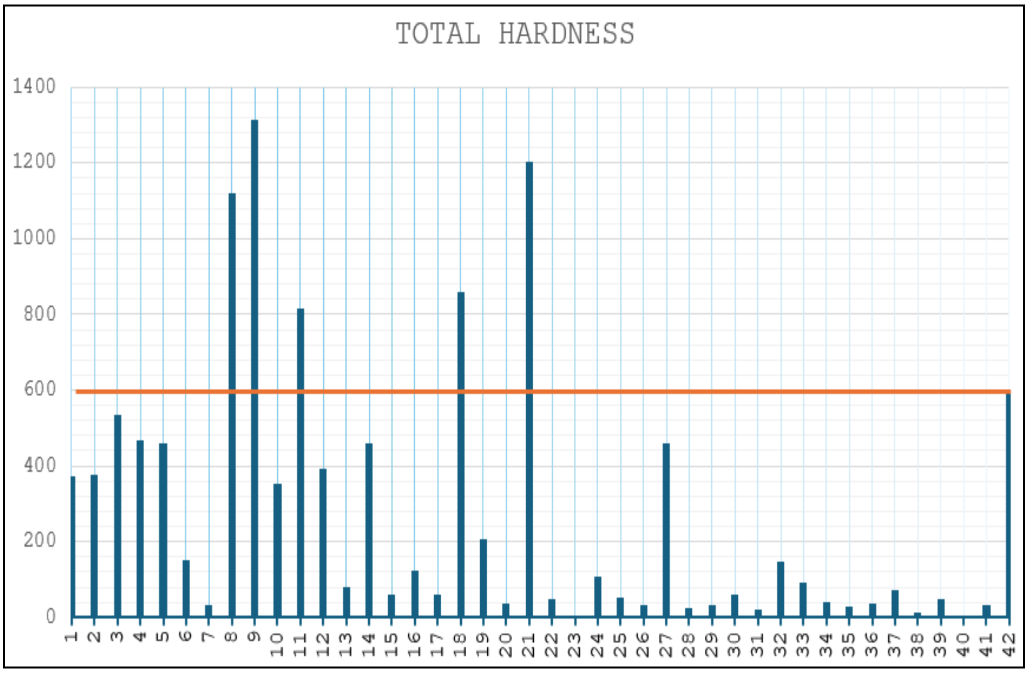


Fig 6a. Total Hardness Concentration

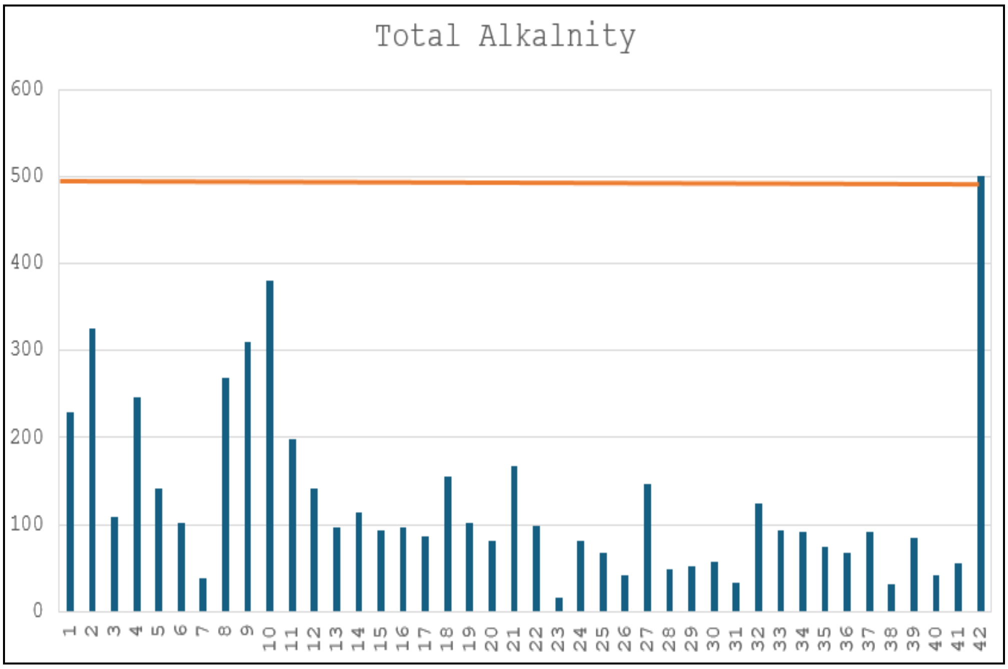


Fig 6b. Total Alkalinity Concentration

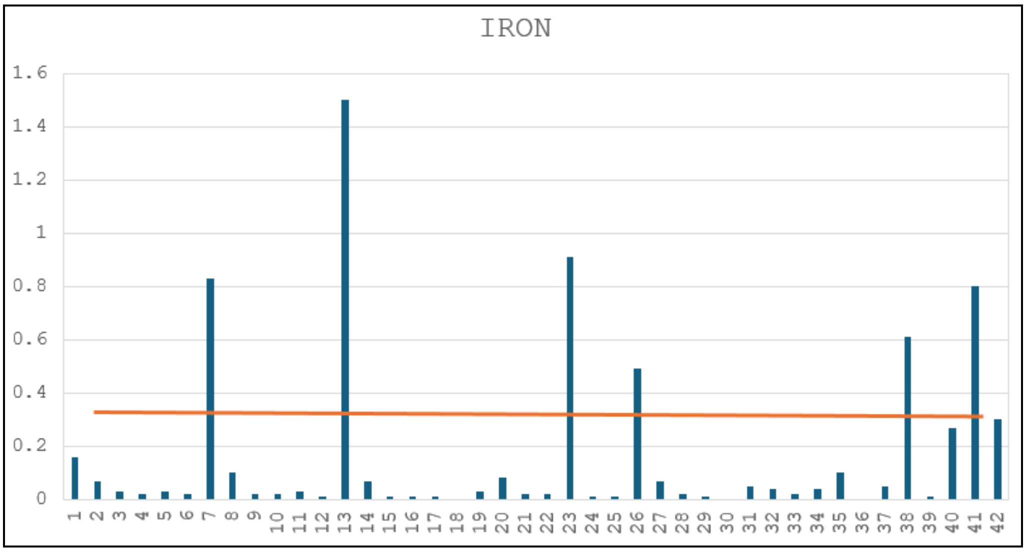


Fig 6c. Iron Concentration

- *Pearson Correlation Analysis*

This study examines correlations between physicochemical parameters using a correlation matrix (Table 1). Pearson correlation analysis confirms strong hydrochemical relationships and progressive groundwater evolution across the study area.

Electrical conductivity (EC) and Total Dissolved Solids (TDS) are perfectly correlated (r = 1.0) across all zones, indicating that groundwater mineralization is largely controlled by dissolved ionic concentrations. EC also exhibits strong correlations with major cations and anions, highlighting variations in salinity.

Major cations including Ca^{2+}, Mg^{2+}, Na^+, K^+, and anion Cl^- show strong positive intercorrelations, reflecting coupled processes of carbonate weathering, halide leaching, and ion-exchange reactions. Alkalinity and bicarbonate show moderate associations with major cations, highlighting the role of carbonate buffering and the influence of basic soil materials on water chemistry. Spatially, a distinct hydrochemical gradient is evident from less-evolved recharge zones in Zone A to mature low-flow areas in Zones C–D.

Table 1a. Pearson Correlation – Zone A

	pH	**EC**	**TDS**	**SAL**	**Ca^{2+}**	**Mg^{2+}**	**Cl^-**	**T.Alk**	**SO_4^2**	**Fe**	**Na^+**	**K^+**	**HCO3**
pH	1												
EC	0.1203	1											
TDS	0.1203	1	1										
SAL	0.089	0.960	0.960	1									
Ca^{2+}	0.073	0.976	0.976	0.958	1								
Mg^{2+}	0.154	0.837	0.837	0.857	0.777	1							
Cl^-	0.087	0.960	0.960	1.000	0.958	0.857	1						
T.Alk	0.088	0.699	0.699	0.548	0.629	0.591	0.547	1					
SO_4^2	0.219	0.611	0.611	0.462	0.575	0.389	0.462	0.266	1				
Fe	-0.571	-0.457	-0.457	-0.424	-0.387	-0.557	-0.423	-0.413	-0.288	1			
Na^+	0.125	0.944	0.944	0.910	0.923	0.658	0.910	0.545	0.666	-0.357	1		
K^+	0.125	0.944	0.944	0.910	0.924	0.658	0.910	0.546	0.666	-0.357	1	1	
HCO3	0.267	-0.009	-0.009	-0.016	-0.115	0.296	-0.016	0.410	-0.385	-0.363	-0.190	-0.190	1

Table 1b. Pearson Correlation – Zone B

	pH	**EC**	**TDS**	**SAL**	**Ca^{2+}**	**Mg^{2+}**	**Cl^-**	**T.Alk**	**SO_4^2**	**Fe**	**Na^+**	**K^+**	**HCO3**
pH	1												
EC	0.356	1											
TDS	0.356	1	1										
SAL	0.359	0.997	0.997	1									
Ca^{2+}	0.374	0.995	0.995	0.994	1								
Mg^{2+}	0.487	0.941	0.941	0.942	0.950	1							
Cl^-	0.360	0.997	0.997	1.000	0.994	0.942	1						
T.Alk	0.279	0.867	0.867	0.832	0.849	0.862	0.832	1					
SO_4^2	0.379	0.871	0.871	0.854	0.900	0.852	0.853	0.792	1				

Fe	0.047	-0.354	-0.354	-0.295	-0.315	-0.328	-0.296	-0.730	-0.302	1			
Na^+	0.147	0.923	0.923	0.922	0.899	0.744	0.922	0.723	0.729	-0.291	1		
K^+	0.147	0.923	0.923	0.922	0.899	0.744	0.922	0.723	0.729	-0.292	1	1	
HCO3	0.452	0.373	0.373	0.333	0.373	0.534	0.334	0.687	0.398	-0.670	0.100	0.100	1

Table 1c. Pearson Correlation – Zone C

	pH	**EC**	**TDS**	**SAL**	**Ca^{2+}**	**Mg^{2+}**	**Cl^-**	**T.Alk**	**SO_4^2**	**Fe**	**Na^+**	**K^+**	**HCO3**
pH	1												
EC	0.671	1											
TDS	0.671	1	1										
SAL	0.594	0.987	0.987	1									
Ca^{2+}	0.865	0.893	0.893	0.853	1								
Mg^{2+}	0.518	0.968	0.968	0.991	0.803	1							
Cl^-	0.596	0.989	0.989	1.000	0.854	0.991	1						
T.Alk	0.719	0.956	0.956	0.923	0.945	0.907	0.926	1					
SO_4^2	0.620	0.428	0.428	0.364	0.563	0.254	0.368	0.392	1				
Fe	-0.443	-0.374	-0.374	-0.244	-0.506	-0.208	-0.253	-0.545	-0.395	1			
Na^+	0.734	0.903	0.903	0.849	0.873	0.782	0.854	0.862	0.710	-0.527	1		
K^+	0.737	0.905	0.905	0.851	0.875	0.784	0.855	0.864	0.710	-0.528	1.000	1	
HCO3	0.453	0.938	0.938	0.969	0.770	0.991	0.969	0.895	0.182	-0.193	0.721	0.724	1

Table 1d. Pearson Correlation – Zone D

	pH	**EC**	**TDS**	**SAL**	**Ca^{2+}**	**Mg^{2+}**	**Cl^-**	**T.Alk**	**SO_4^2**	**Fe**	**Na^+**	**K^+**	**HCO3**
pH	1												
EC	0.647	1											
TDS	0.647	1	1										
SAL	0.723	0.947	0.947	1									
Ca^{2+}	0.561	0.916	0.916	0.963	1								
Mg^{2+}	0.687	0.949	0.949	0.981	0.978	1							
Cl^-	0.729	0.950	0.950	0.998	0.964	0.983	1						
T.Alk	0.545	0.966	0.966	0.871	0.867	0.902	0.872	1					
SO_4^2	0.396	0.725	0.725	0.776	0.857	0.781	0.788	0.665	1				
Fe	0.025	-0.419	-0.419	-0.287	-0.401	-0.398	-0.308	-0.540	-0.471	1			
Na^+	0.714	0.970	0.970	0.906	0.823	0.885	0.908	0.945	0.632	-0.379	1		
K^+	0.715	0.969	0.969	0.907	0.824	0.886	0.909	0.945	0.634	-0.379	1.000	1	
HCO3	0.532	0.520	0.520	0.408	0.334	0.476	0.416	0.642	0.111	-0.527	0.622	0.621	1

➢ *Hydrochemical Facies*

Piper diagram analysis identifies dominant hydrochemical facies in the study area: Ca–Mg–Cl–SO_4 and Na–K–Cl–SO_4 types, with localized occurrences of Ca–Mg–HCO_3 water. Spatial variations among the study area reflect lithology-controlled mineral dissolution, ion exchange, and hydrochemical mixing within interconnected aquifers. Less-evolved zones are characterized by Ca–Mg–Cl–SO_4 facies, whereas mature low-flow areas exhibit stronger Na–K–Cl–SO_4 influence due to cation exchange and extended water–rock interaction, consistent with findings by Msengi et al. (2024) and Bahar & Reza (2010). This is illustrated in Figure 7.

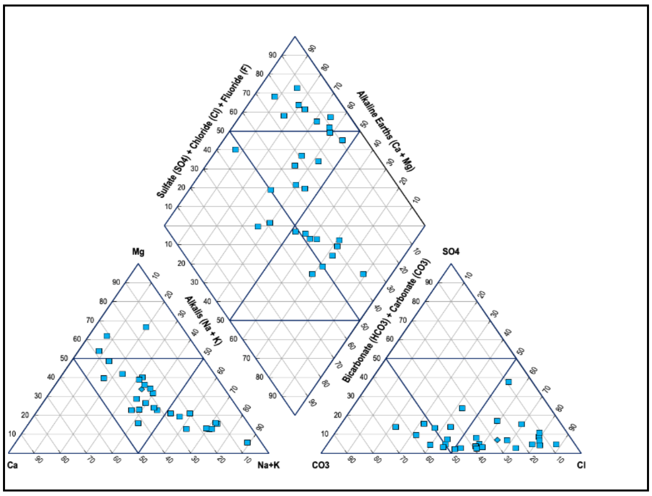


Fig 7: Piper Diagram for Groundwater in the Whole Study Area

➢ *Spatial Distribution of Physicochemical Parameters*

GIS-based spatial analysis reveals distinct patterns in the distribution of physicochemical parameters across the four hydrogeological zones. The spatial variability of each parameter is discussed below.

- *Physical Parameters*

✓ *Salinity:*

Salinity ranges between 16–310 mg/L, with a mean value of 0.351, indicating fresh to moderately saline groundwater. Lower salinity in Zones C and D reflects recharge influence, while higher values in Zones A and B (Figure 8a) suggest increased mineral dissolution and evaporative concentration. This trend is consistent with Wei et al. (2026).

✓ *Total Dissolved Solids (TDS):*

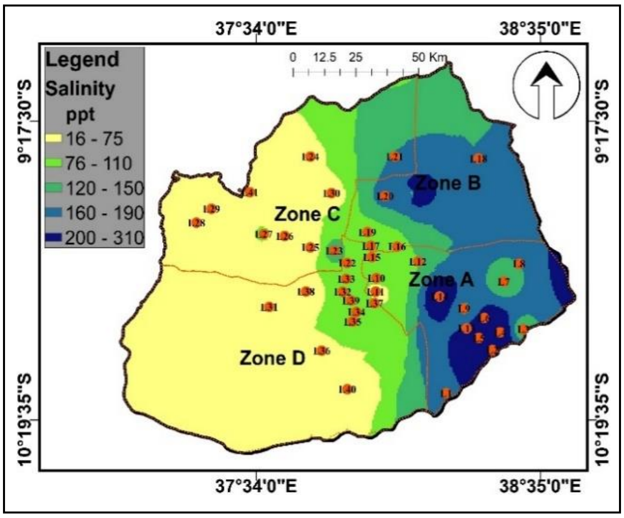
TDS ranges from 82–2,600 mg/L, with a mean value of 573.10 mg/L, indicating low to very high mineralization. Most boreholes fall within the WHO allowable limit of 1,500 mg/L, except for a few. Zones C and D exhibit lower TDS and better suitability for groundwater development, whereas Zones A and B (Figure 8b) show elevated values due to prolonged water-rock interaction. This observation is consistent with Subramaniyan (2026).

✓ *Electrical Conductivity (EC):*

EC ranges between 164–5,250 µS/cm, with a mean value of 1,143.81 µS/cm, reflecting variations in dissolved ion content. Most boreholes are within the WHO permissible limit of 2,500 µS/cm, except for a few. Lower EC values in Zones C and D (Figure 8c) indicate fresher groundwater and better suitability, while higher values in Zones A and B suggest advanced hydrochemical evolution. This is similar to findings by Zhang et al. (2020) and Ahmed et al. (2013).

✓ *pH:*

pH values range between 4.6–8.23, with a mean of 6.90, indicating slightly acidic to alkaline conditions. All values fall within the TBS (2008) standard range of 6.5–8.5. Zones C and D are near neutral, while Zones A and B (Figure 8d) show relatively higher alkalinity due to carbonate buffering. Overall, all zones are suitable for borehole development. This observation is consistent with Wilkin & DiGiulio (2010).



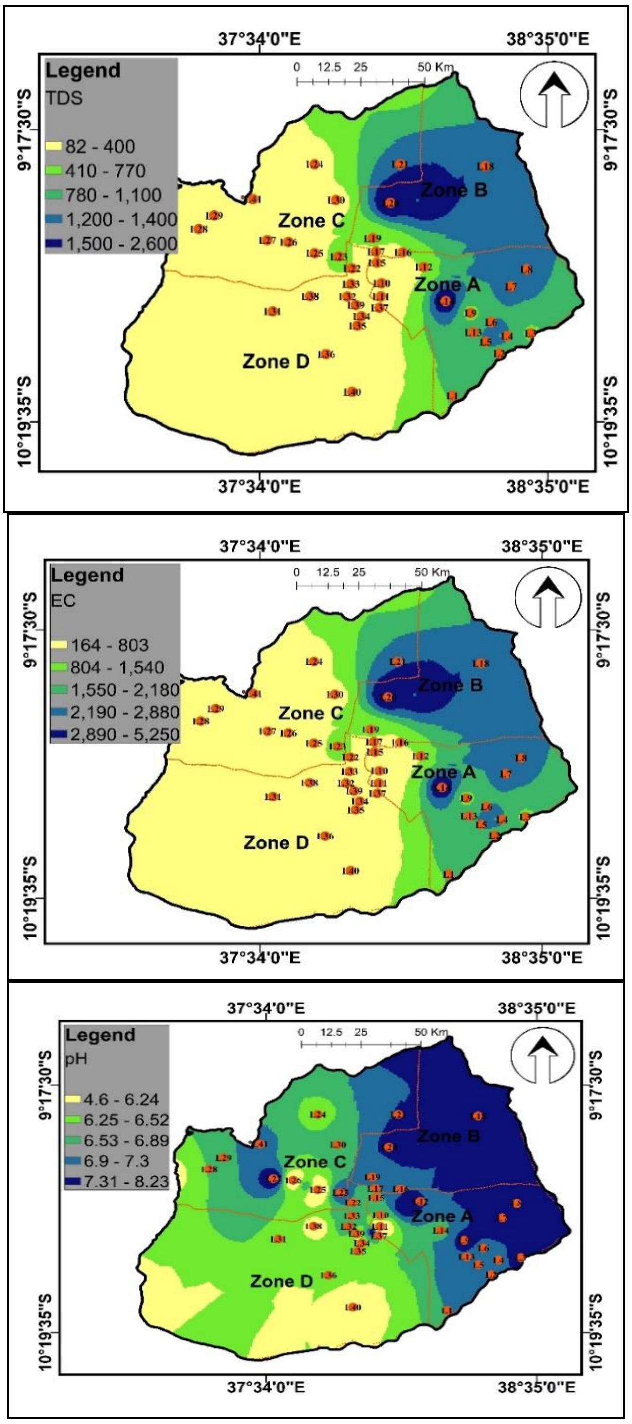


Fig 8 a, b, c & d, Showing Physical Parameters of Groundwater Suitability Basing on Salinity, TDS, EC & pH at Liwale District

- *Major Cation Chemical Parameters*

✓ *Sodium (Na^+):*

Sodium ranges from 5.19–364 mg/L, with generally low mean values. Most samples fall within the permissible limit of 200 mg/L, though higher concentrations occur in Zone B (Figure 9a). Lower sodium levels in Zones C and D indicate better suitability, while elevated values reflect increased salinity and mineralization. This trend is consistent with TBS (2008) and Kisaka (2018).

- ✓ *Potassium (K^+):*

Potassium concentrations range from 0.13–9.33 mg/L, with a mean value of 1.713 mg/L, remaining well below the permissible limit of 50 mg/L. Lower concentrations in Zones C and D (Figure 9b) indicate minimal geochemical influence and better suitability compared to Zones A and B. This finding is consistent with Panneerselvam et al. (2023).

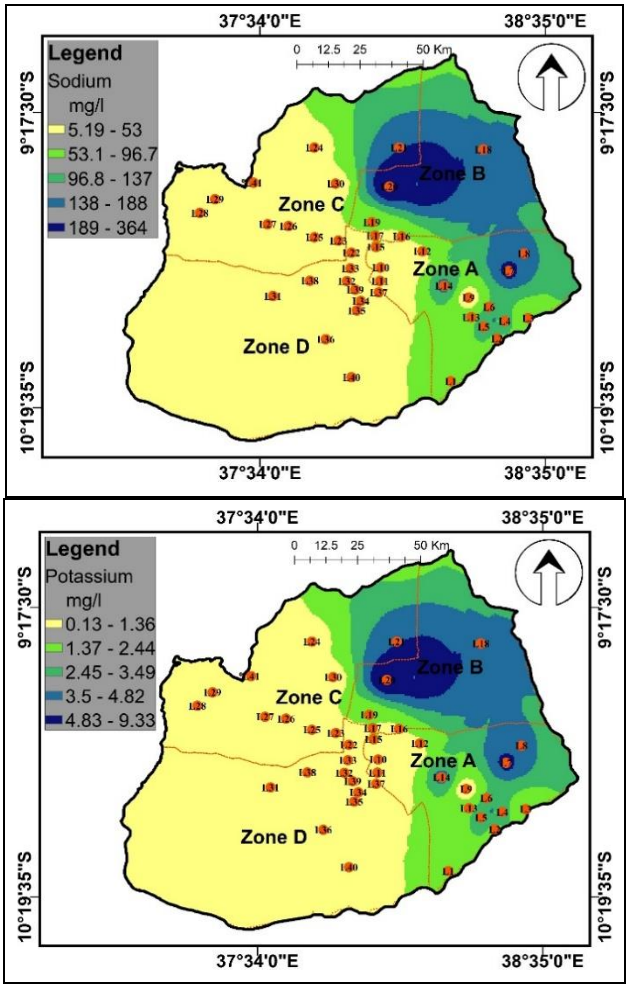
- ✓ *Magnesium (Mg^{2+}):*

Magnesium ranges from 0.504–146 mg/L, with a mean value of 31.97 mg/L. Most samples fall within the TBS (2008) limit of 100 mg/L. Lower concentrations in Zones C and D indicate higher suitability, while elevated values in Zones A and B (Figure 9c) reflect lower suitability due to increased hardness and prolonged water-rock interaction. This trend is consistent with Kannan et al. (2025).

- ✓ *Calcium (Ca^{2+}):*

Calcium ranges from 0.837–314 mg/L, with a mean value of 50.01 mg/L. Most samples fall within the acceptable limit of 150 mg/L. Lower concentrations in Zones C and D indicate better suitability for groundwater use, while higher values in Zone B (Figure 9d) reflect carbonate weathering and contribute to water hardness. This is similar to Adzibolosu (2024).

Figure 9. Major cation spatial distribution (Na^+, K^+, Mg^{2+}, Ca^{2+}).



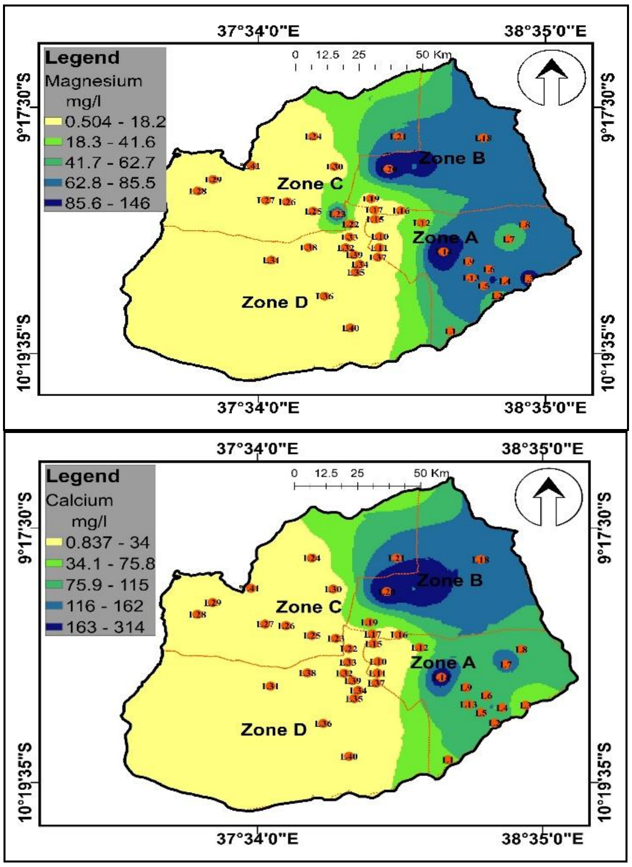


Fig 9: a, b, c & d, Showing Chemical Parameters (Major Cations) of Groundwater Suitability Basing on Sodium, Potassium, Magnesium, & Calcium at Liwale District

- *Major Anion Chemical Parameters*

- ✓ *Chloride (Cl^-):*

Chloride concentrations range from 9–1,160 mg/L, with a mean value of 194.53 mg/L. Low to moderate concentrations are observed in Zones C and D, while very high levels occur in Zone B (Figure 10a). Most samples are within the standard limit of 250 mg/L, although elevated chloride indicates salinization processes, possibly due to evaporation or mineral dissolution. These findings are consistent with Msengi et al. (2024). Chloride in groundwater may originate from agricultural activities, industrial sources, or chloride-rich rocks (Ramakrishnaiah et al., 2009).

- ✓ *Sulphate (SO_4^{2-}):*

Sulphate concentrations range from 0.483–350 mg/L, with a mean value of 34.68 mg/L, and all samples fall within the WHO limit of 400 mg/L. Lower concentrations in Zones C and D indicate better suitability for groundwater development, while relatively higher values in Zones A and B (Figure 10b) suggest lower suitability. Elevated sulphate levels may affect water taste and quality, consistent with Preethi et al. (2025).

- ✓ *Nitrate (NO_3^-):*

Nitrate concentrations range between 0.19–44.9 mg/L, with a mean value of 10.23 mg/L, remaining within the permissible limit of 45 mg/L, although localized increases are observed. Lower concentrations in Zones A and D indicate better suitability, while higher values in Zones B and C (Figure 10c) may be linked to agricultural activities, organic waste, and wastewater inputs. This trend.

- ✓ *Bicarbonate (HCO_3^-):*

Bicarbonate concentrations range from 0.0712–742 mg/L, with a mean value of 261.05 mg/L. Lower values in Zones C and D and higher concentrations in Zone A (Figure 10d) reflect increasing water-rock interaction and longer residence time.

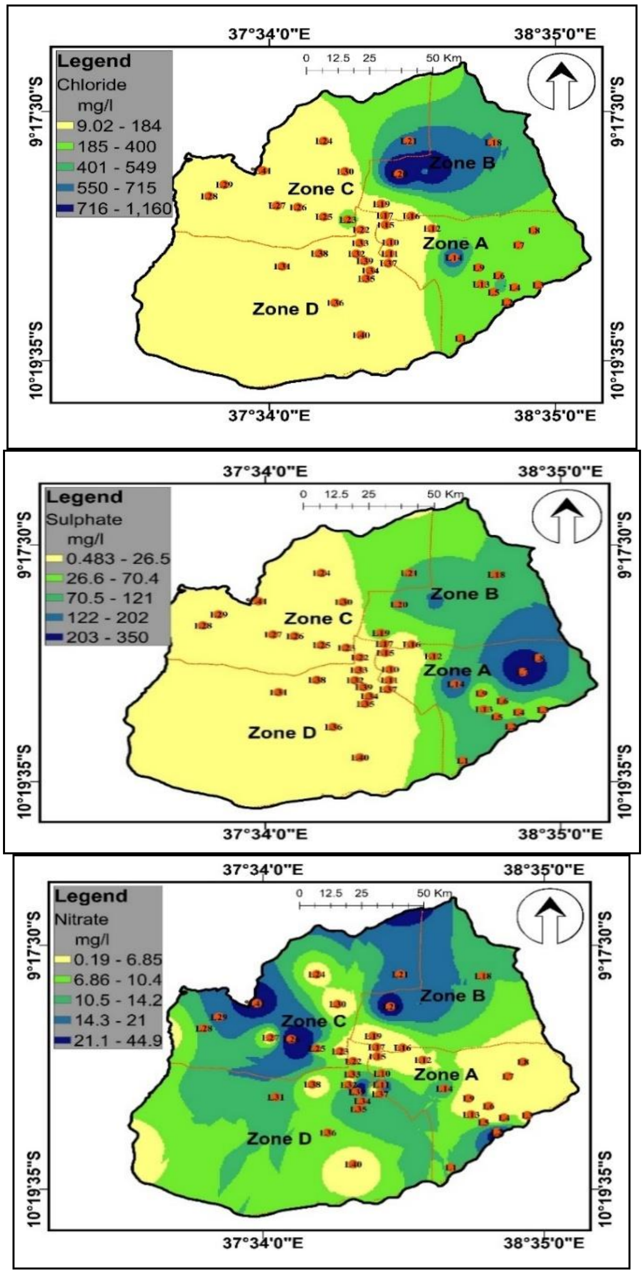


Fig 10: a, b, c & d, Showing Chemical Parameters (Major Anions) of Groundwater Suitability Basing on Chloride, Sulphate, Nitrate, & Bicarbonate at Liwale District

- *Other Ion Chemical Parameters*

- ✓ *Iron (Fe):*

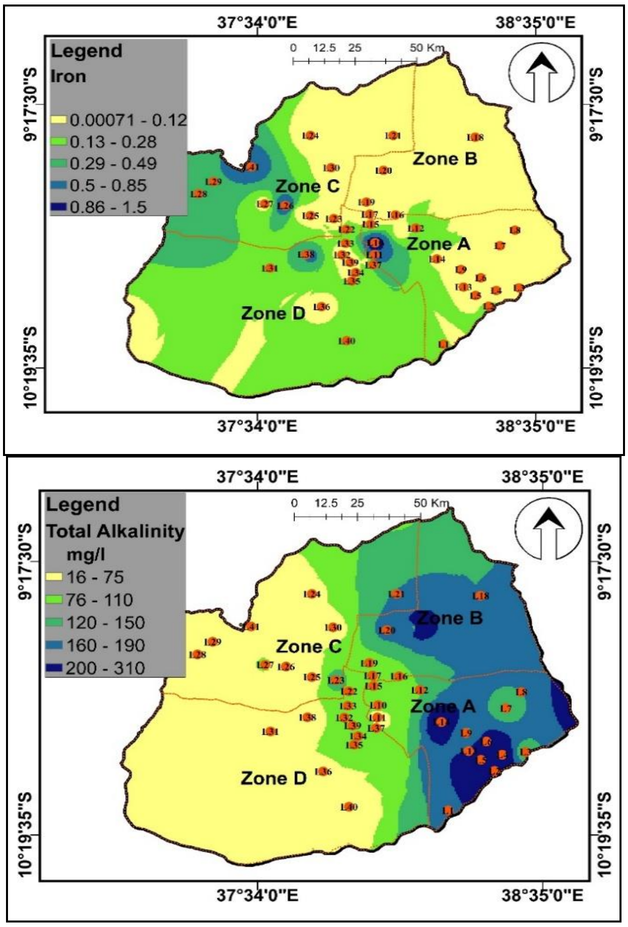
Iron concentration ranges between 0.00071–1.50 mg/L, with a mean value of 0.162 mg/L. Most samples fall within the acceptable limit of 0.30 mg/L, although localized exceedances are observed. Higher suitability is noted in Zones A, B, and C (Figure 11a), making them favorable for groundwater development, while Zone D shows relatively lower suitability. The spatial variation suggests control by redox conditions and possible anthropogenic influences, consistent with Abdoulatif et al. (2025).

- ✓ *Total Alkalinity (TA):*

Total alkalinity ranges between 16–310 mg/L, with a mean value of 116.95 mg/L, remaining within permissible limits of Tanzania water quality standards and indicating stable buffering conditions. Lower alkalinity is observed in Zones A and B, while higher values occur in Zones C and D (Figure 11b). The higher suitability in Zones C and D reflects limited carbonate dissolution and favorable conditions for groundwater development, whereas lower suitability in Zones A and B indicates the influence of carbonate reactions with basic soil materials. This pattern is consistent with Karimi et al. (2025), suggesting effective carbonate control on groundwater chemistry.

- ✓ *Total Hardness (TH):*

Total hardness varies widely across the study area due to differences in calcium and magnesium content. Some samples exceed the TBS limit of 600 mg/L. Zones C and D exhibit softer water and higher suitability, while Zones A and B (Figure 11c) show higher hardness, indicating lower suitability due to enhanced mineral dissolution. This pattern is similar to Rajmohan et al. (2025).



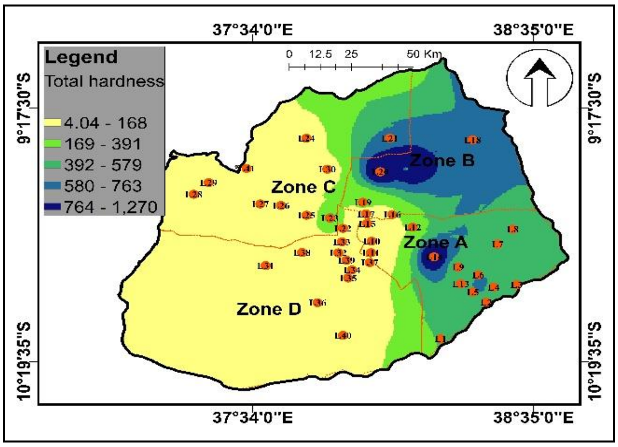


Fig 11 a, b & c, Showing Chemical Parameter (other Ions) of Groundwater Suitability Basing on Iron, Total Alkalinity & Total Hardness at Liwale District.

➢ *Overall Groundwater Suitability*

Based on combined GIS and laboratory analysis, groundwater suitability varies significantly across the study area (Figure 12). Overall suitability scores range from high to very low, reflecting substantial spatial variability in groundwater quality. High-suitability areas are predominantly located in the southwestern part of the study area (Zone D), reflecting favorable hydrogeochemical conditions and relatively low mineralization. Moderate suitability occurs mainly in Zone C. Zones A and B are characterized by low to very low suitability, associated with elevated concentrations of dissolved constituents. This spatial distribution reflects progressive groundwater evolution, with increasing water–rock interaction toward the north-eastern part of the study area resulting in higher mineralization and reduced water quality, consistent with Liu et al. (2024) and Walraevens et al. (2025).

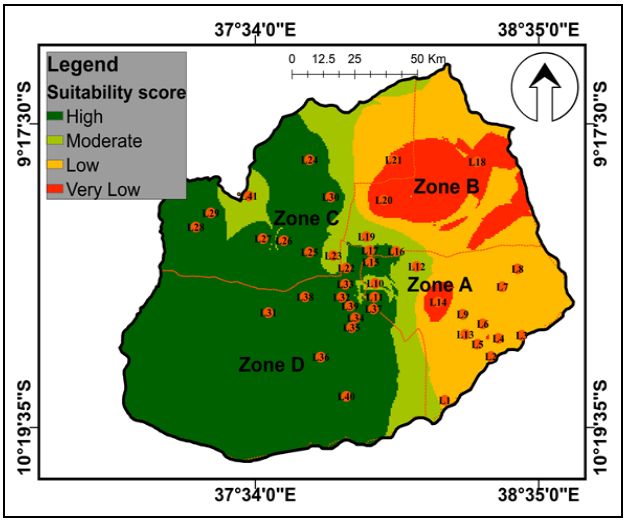


Fig 12 Overall Groundwater Suitability Map for Liwale District Derived from Weighted Overlay Analysis

IV. CONCLUSION

Groundwater in Liwale District serves as a vital freshwater resource, although it exhibits significant spatial variability driven by aquifer lithology, mineral dissolution, and water-rock interactions. The analysis of 41 samples covering 22 physicochemical parameters indicates that groundwater quality varies considerably across the district due to progressive geochemical evolution from recharge zones to more mature, low-flow areas.

The chemical composition reflects varying degrees of mineralization. pH values range from 4.6 to 8.23 (mean 6.90), indicating slightly acidic to slightly alkaline conditions. Indicators of mineralization, including electrical conductivity (EC) and total dissolved solids (TDS), vary widely, with EC ranging from 164 to 5,458 µS/cm and TDS from 82 to 2,729 mg/L. Total hardness ranges from 4 to 1,316 mg/L, classifying groundwater from soft to very hard. Elevated concentrations of iron (up to 1.5 mg/L) and manganese (up to 1.1 mg/L) are also observed in localized zones, mainly associated with reducing conditions.

The southwestern region (Zone D and parts of Zone C) exhibits the most favorable conditions for domestic use and borehole development, with generally good water quality and minimal treatment requirements. The central region (Zone C) shows moderate conditions, where groundwater is largely acceptable but may require minor treatment in some locations. In contrast, the north-eastern region (Zones A and B) displays comparatively less favorable conditions, where groundwater quality is often unsuitable for direct domestic use without appropriate treatment and careful management.

In that regard, groundwater quality improves from the north-eastern to the southwestern parts of the district, emphasizing the importance of zone-specific planning and the application of suitable treatment methods such as aeration, softening, or ion exchange to ensure safe and sustainable utilization.

RECOMMENDATIONS

➢ *Based on the Findings of this Study, the Following Measures are Recommended:*

- Regular groundwater quality monitoring: Continuous monitoring of key physicochemical parameters (EC, TDS, pH, Fe, Mn, and major ions) should be undertaken to capture spatial and temporal variations in groundwater quality and to identify emerging contamination trends at an early stage.
- Targeted groundwater development: Borehole siting and groundwater abstraction should prioritize high-suitability zones, particularly the southwestern part of the study area. Low-suitability zones, especially in the north-eastern and localized areas, should be avoided for domestic supply unless adequate treatment is provided.
- Water treatment measures: In areas affected by elevated iron, manganese, salinity, and hardness, appropriate treatment technologies including aeration, filtration, softening, and ion exchange should be implemented to improve water quality for drinking purposes.
- Protection of recharge and high-suitability zones: Groundwater recharge areas and high-suitability zones should be protected from potential contamination sources,

including agricultural activities, pit latrines, and improper waste disposal.

- Integrated hydrogeological planning: Future groundwater development should integrate GIS-based suitability mapping with hydrochemical and geological datasets to ensure sustainable aquifer management and minimize the risk of drilling in low-quality groundwater zones.

DECLARATIONS

➢ *Acknowledgements*

The authors express their profound acknowledgement to the Liwale District staff for technical support, which made this work possible.

➢ *Funding*

This research was funded by the authors and their family contributions.

➢ *Conflict of Interest*

The authors declare that there is no conflict of interest related to this study.

➢ *Data Availability*

All relevant data are included in the study or supplementary information.

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