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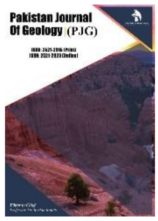

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RESEARCH ARTICLE

HYDROGEOCHEMICAL CHARACTERIZATION AND EVALUATION OF SURFACE AND SHALLOW GROUNDWATER QUALITY IN TALATA-MAFARA FOR IRRIGATION PURPOSES, NORTHWESTERN NIGERIA

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ABSTRACT

A combined hydrogeochemical and hydrogeological investigation was undertaken in Talata-Mafara to evaluate irrigation water quality and shallow groundwater's potential for irrigation purposes. This assessment aimed to ascertain the suitability of surface and shallow groundwater for irrigation. The Piper diagram illustrates Na^+–K^+–Cl^-–SO_4^{2-} as the prevalent ions, with rock dominance identified as the primary factor influencing groundwater chemistry, as shown in Gibb's diagram. Analysis of irrigation water quality indicates that most samples were rated as excellent or good in terms of salinity risk, SAR, RSC, magnesium risk, index of permeability, and salinity potential. However, many samples were doubtful regarding Percent Sodium and unsuitable in Kelly's ratio. Eight Vertical Electrical Profile (VEP) points were collected in the study area, indicating a promising groundwater potential. The apparent resistivity values of the underlying lithology, consisting of clastic sedimentary rocks (sands and gravels) in the form of topsoil (0-20m), weathered/fractured basement (2.5-100m), and fresh basement rocks (>100m thick), supported this conclusion. The pumping test data collected from different boreholes supports the rocks' conductivity. In most areas, the groundwater is quite shallow, around 9 metres deep, except in New Maradun, where some boreholes had negative yields and a static water level of about 50 metres. The groundwater flow in the area predominantly flows northwest. The region's surface water and near-surface aquifers can be used for irrigation. Improving the drainage system within farmlands is necessary to mitigate the excessive buildup of dissolved ions in the crop root zone, which may escalate to hazardous levels.

KEYWORDS

Groundwater potential, Hydrogeochemical, Hydrogeological studies, Irrigation water quality, Talata-Mafara

1. INTRODUCTION

Irrigation water does not depend only on quantity. Quality information is also indispensable for effective agricultural yield and production. Over the years, there has been recurring neglect concerning irrigation water quality. Using substandard water might give birth to many issues pertaining to soil and crop cultivation (Olubanjo and Alade, 2018). The appropriateness of water for irrigation has been subject to influence from a multitude of factors, encompassing water-rock interactions, degrees of weathering, alterations in climatic conditions, and anthropogenic activities (Li et al., 2020). Irrigation waters, regardless of origin, include significant amounts of chemical compounds in solution that can potentially decrease crop productivity and degrade soil fertility. Thus, the suitability of water for irrigation hinges upon the influence exerted by mineral constituents present in the water on both plant physiology and soil properties (Bouhia et al., 2023).

The characteristics of irrigation water may exhibit substantial variations depending on the composition and concentration of dissolved salts. Salinity levels in surface and groundwater sources are typically present in relatively low yet discernible amounts, significantly influencing irrigation water quality. The formation of these substances can be attributed to rock and soil dissolution or weathering, which involves the breakdown of various soil minerals such as lime, gypsum, and other slowly dissolved substances. Salinity affects plants growth physically by limiting the uptake of water through modification of osmotic processes, or chemically by metabolic reactions, such as those caused by toxic constituents (Zhou et al., 2018).

Water quality problems related to irrigation have been reported in northwestern parts of Nigeria especially because of high salinity (Mafuyai et al.,2020; Augie and Adegbite, 2022). Excessive concentration of chloride, sodium, and boron ions, when taken up by plants, commonly results in toxicity problems. This causes crop damage or reduced yields if the accumulation is great enough.

When evaluating water quality for irrigation, it is important to consider soil drainage. According to group of scientist, they asserted that crop development can be sustained in open and well-drained soil, even when saline water is applied (Feng et al.,2019). Inadequate drainage typically leads to salt accumulation in the root zone, reaching hazardous levels.

The water's infiltration rate is recognised as an additional factor associated with the water quality for irrigated agriculture. In water quality, infiltration commonly occurs when the calcium concentration in water is comparatively lower than that of sodium—applying high sodium water to soil results in the formation of a high sodium surface soil, leading to the degradation of soil structure (Yan et al., 2023). Subsequently, the surface soil aggregates disperse into significantly smaller particles that

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effectively occupy the soil pores. An excessively low calcium content of the surface soil may potentially be a contributing factor to the problem (Rowley et al., 2021).

The physical and chemical characteristics of groundwater are crucial in determining and evaluating the water's suitability for irrigation purposes. The commonly employed parameters for assessing quality encompass pH and alkalinity, electrical conductivity (EC), specific acidity (SAR), sodium-carbonate ratio, sodium percentage (Na%), and other relevant factors (Kamaraj et al., 2021; Radingoana et al., 2020). Each of the factors has distinct rules depending on the tolerance and sensitivity of plants.

In areas with arid or semi-arid conditions like the study area, leaching and transportation of soluble salts to the stream channels and finally to the ocean is not as thorough as in humid places. Soil salinization can be attributed to factors beyond insufficient leaching and transport mechanisms of soluble salts resulting from reduced precipitation. A high evaporation rate, one of the characteristics of arid climates, tends to concentrate the salts in soil and surface and shallow groundwater (Liu et al., 2021).

Much of Nigeria's agricultural irrigation relies heavily on surface water. It is predominantly practiced in the northern region, where the study area is a prominent irrigation location (Ogunwande, 2023). According to an estimation made by two researchers, Bakalori Dam, one of the largest irrigation dams in Nigeria, supplies water to about forty to fifty thousand farm families in the study area (Mukaribu and Mu'azu, 2023). As a result of the lack of a good drainage system and intermittent water shortages from the dam, farmers employ tube wells as an alternative. The research region is within a semi-arid climate zone characterised by Sudan Savannah-type flora. In areas characterised by aridity conditions, it is common to observe a pronounced weathering process and a limited amount of precipitation that falls considerably below the potential evapotranspiration rate (Feng et al., 2014). Consequently, saline soils may have occurred in the study area since saline soils are nearly non-existent in humid places.

This research includes the use of many water quality indices and features used to analyse water quality, determining its suitability for irrigation purposes in the area. Since much of the bad health that limits plant development and production is water quality-related, this research aimed to investigate the hydrochemistry of surface and groundwater in the study area and classify the water to determine its suitability for irrigational use.

1.1 Aim and objectives

The work aimed at assessing the quality of both surface and groundwater in the area in order to evaluate their suitability for irrigational use with the following objectives;

- To conduct geological and hydrogeological mapping of the area on a scale of 1:50,000.
- To assess the potential of groundwater.
- To determine the salinity state of the water used for irrigation.
- To assess the toxicity grade of certain elements in the water.

2. Geological, Hydrogeological and Climatic Settings

Talata-Mafara falls within a transitional boundary between the Precambrian basement rocks of north-central Nigeria and Cretaceous sediments belonging to the Nigerian segment of the Illummeden Basin of northwestern Nigeria (Aisabokhae and Osazuwa, 2021). The contact between the sedimentary rocks and the crystalline basement rocks begins with coarser materials, principally sands and gravels of Gundumi and Illo Formations and floodplain consisting of alluvium Fadama (Eduvie and Garba, 2021). The basement rocks, pre-Cretaceous in age, underlain the Cretaceous and Tertiary sediments prevalent in the southeast. These rocks locally fall under the category of Older Granites suits – consisting of intrusive granite, biotite granite, and quartz diorite of igneous origin with the occurrence of assemblages of other crystalline rocks of metamorphic origin mainly granite gneiss, phyllite, schist, metaconglomerates, and quartzites.

A group of researchers conducted a comparative study of groundwater resources in Talata Mafara town and its environs (Hamidu et al., 2015). Their study identified the Cretaceous sandy sedimentary aquifer located within the Gundumi Formation, which includes fluvial and lake (lacustrine) deposits, and the deep, partially weathered crystalline aquifer composed of mainly the by-products of in-situ weathering.

The study area has two distinct seasons: a rainy season from May to October and a dry, dusty harmattan wind that originates from the northeast and lasts from October to April (Nwabachili et al., 2021). The two main air masses that impact the West Africa sub-region—the tropical-continental (cT) air mass, which originates in the Sahara region, and the tropical-maritime (mT) air mass, which originates in the Atlantic Ocean—dominate the region's climate (Ndehedehe et al., 2022). According to data from the Nigerian Meteorological Agency, the study area's average temperature for a thirty-one-year period is 34.91oC ± 1.19oC.

3. Materials and Methods

The methodology employed in this study involves five main stages namely; desk study, preliminary (reconnaissance) survey, geological field work and sampling programme, laboratory analyses and report writing. The execution of these steps was done in line with the protocols of geological field techniques and the criteria for the collecting of water samples in the field.

3.1 Water sampling and method of analysis

The sampling plan was devised in response to the projected water quality issue, and samples were obtained from several places within the area at varied time intervals. The time-series data would be important for monitoring the effects of climate on both surface and shallow groundwater quality for irrigation. As a result, the sampling and analysis plan implemented in this work is predicted to achieve the project goals by satisfactorily characterizing the irrigation water quality.

Fifteen water samples were collected at different places from canals, wells, and boreholes in the study area at the peak of the dry season. This includes eight samples collected from canal channels discharged from the Bakalori dam at different locations covering some parts of Maradun, Talata-Mafara, and Bakura LGAs, five samples from hand pump boreholes mostly located in Talata-Mafara near the irrigation project site, and two samples from wells respectively (figure 1).

All samples were examined for Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, SO_4^{2-}, HCO_3^- CO_3^- and NO_3 in the Soil Science Laboratory at the Faculty of Agriculture, Ahmadu Bello University, Zaria. The water sampling procedure conforms to (Pinder, 2011). And can be found in more detail in the work of (Hem, 1985). Water samples from boreholes were collected after roughly 10 minutes of steady pumping and placed into the sampling bottles. The samples were collected in polyethylene bottles (approximately 1 liter and filled to the top with headspace) and stored in a refrigerator before being delivered to the laboratory for testing.

With regards to physical parameters, EC, TDS, Temperature (°C), pH, and Turbidity (NTU) were measured in situ (immediately after the sample) because these parameters are vulnerable to change upon exposure to the atmosphere and during transit. The samples were sealed, tagged, and transported to the laboratory using techniques detailed elsewhere (Weight and Weight, 2008).

The procedures adhered to in this work for rock sampling are in accordance with the methods described by a researcher in 2011, where geological field techniques are discussed in an excellent summary (Dilles, 2011). Rock sampling was conducted based on freshness and representation from different optimum sampling locations across the study area. Both consolidated hard rocks and unconsolidated sedimentary rocks were collected from the field for simple rock thin section preparation to identify the bulk mineralogy of the samples. Geological hammers, Global Positioning System (GPS) receivers, masking tape, markers, field notebooks, writing materials, and cetra were some of the field equipment used for geological field mapping and rock sampling. The data obtained is presented in different diagrams including Piper, Gibbs, Stiff, US Salinity Hazard, and Wilcox, to characterize the water quality further.

Ohmega Resistivity meter with Model No. 0075 was used to measure and record the resistivity of the subsurface lithology. Schlumberger array method of profiling was employed to acquire VES points. These points were selected at different locations across the area. The surveys were done utilising field configuration of AB/2 = 1m and MN/2 = 0.5m, and the depth of study progressed to 100m in nearly all the VES locations. The potential electrode was placed between the current electrodes, usually in a straight line, and the penetration depth increased as the current electrodes widened. The apparent resistivity values for each layer were obtained by multiplying the raw field data with the Schlumberger geometric factor (K). The data was also plotted on the logarithmic graph sheet, the distance AB/2 on the X axis against the resistivity values on the Y axis, which were subsequently interpreted using computer software (Interpex 1 D) to obtain individual curve type. Water table measurement data were acquired from individual boreholes in the area to develop a groundwater configuration map.

4. Results and Discussions

4.1 Geology

The geological mapping reveals that the area is situated within the transitional boundary between the basement rocks of northwestern Nigeria and sedimentary materials consisting of sands and gravels belonging to Gundumi Formation of southeastern Illummeden Basin. The basement rocks are mainly quartzites and weathered medium to coarse-grained granites. These outcrops are observed to be trending predominantly in the eastern direction. Orientation measurement of joints also displays a general trend of NW-SE direction with an average dip value of 22°.

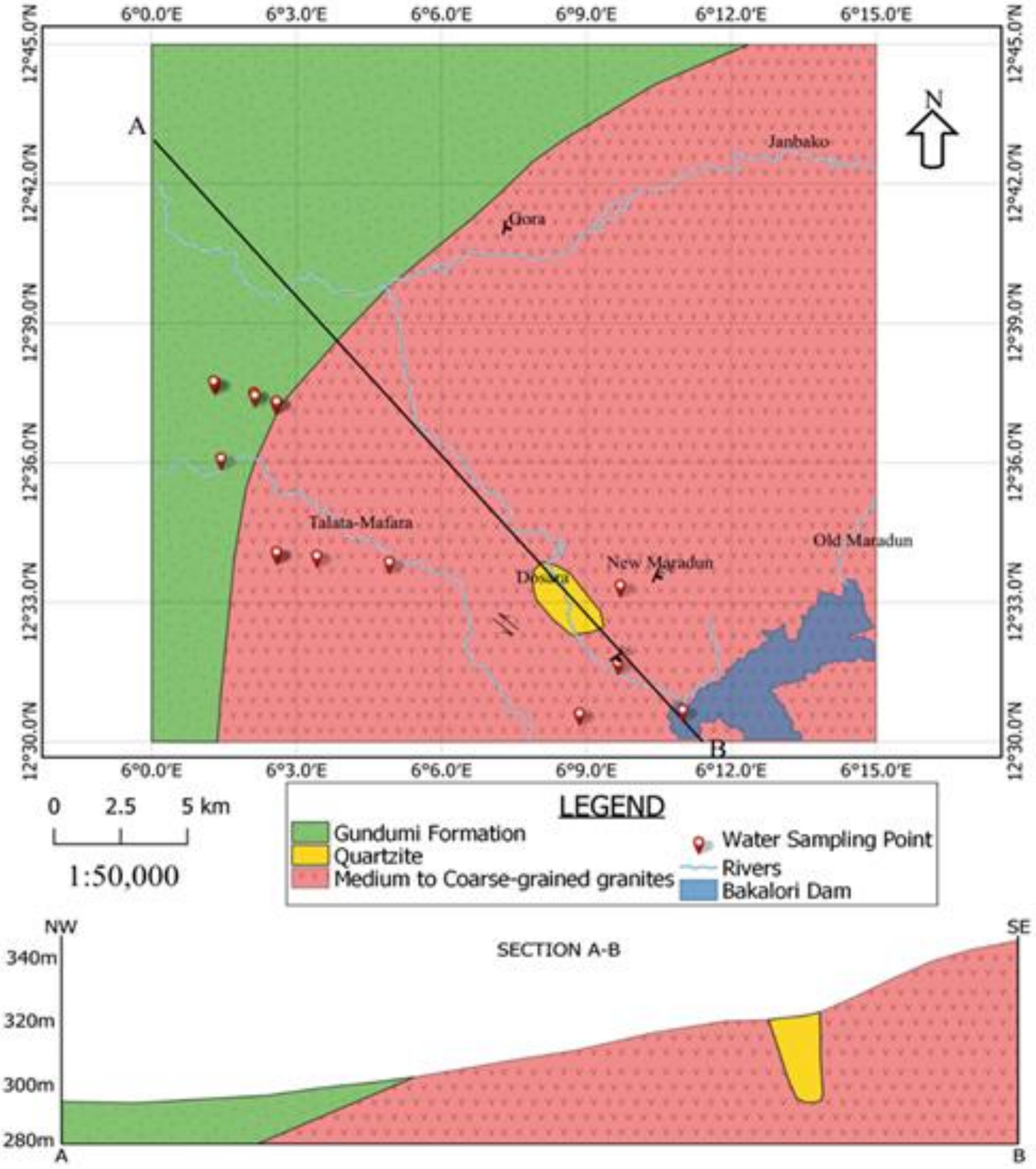

Figure 1: Geological map showing locations where water samples were obtained.

4.2 General parameters

Sample location, physical and chemical parameters, and source of optimum sampling locations are provided in Table 1. The criteria for evaluating the irrigation water quality employed in this study are described in Table 2. Based on the findings regarding physical parameters, the pH values span from 6.81 to 9.49 (with an average of 8.17), indicating alkaline water. This alkalinity implies that the water is non-corrosive when encountering metals and other substances (Ibrahim, 2022). While temperature is not a primary determinant of water quality, it is notable that the water temperature within the study area exhibited variability, ranging from 27.9 to 35.1°C. Despite its lack of significance for this particular study, the turbidity of all water samples was evaluated. The findings showed variations based on the water source, with surface water exhibiting the highest turbidity value of 181 NTU. In comparison, samples obtained from boreholes recorded the lowest value of 1.09 NTU.

The suspended particles such as clay, silt, and colloidal matter from surface water are obvious, and those from the boreholes suggest iron deposition resulting from rust or inappropriate well development after completion. Results show low concentrations of electrical conductivity (as low as 62 µs/cm) in many samples collected from surface water and high concentrations (about 522 µs/cm) from boreholes and hand-dug wells.

The measured TDS for all water samples varied from 39.68 to 332.8 mg/l. TDS is proportional to EC, and the results of the two parameters in this work are closely related. By contrast, the values of EC and TDS are much greater in samples collected from boreholes and wells than those of the surface water and directly refer to a function of residence duration and interaction between water and its host lithology. Hardness (mg/l $CaCO_3$) levels vary in the research region, which is normally related to the quantity of dissolved Ca^{2+} and Mg^{2+} in the water. As to Durfor & Becker's (1964) proposed hardness classification, the water samples in the study area are classified as mild to moderately hard. The bulk of the samples are regarded as soft, and the results vary from 7.47 to 110.61.

Table 1: Analytical results of surface and shallow groundwater in the study area (collected during the dry season, 2023)

		Physical Parameters					Major Cations				Major Anions						
Sample ID	GPS Coordinates (decimals)	pH	Temp (°C)	EC (µs/cm)	Turbidity (NTU)	TDS (mg/l)	Ca^{+2} (mg/l)	Mg^{+2} (mg/l)	K^{+} (mg/l)	Na^{+} (mg/l)	SO_4^{-2} (mg/l)	Cl^{-} (mg/l)	HCO_3^{-} (mg/l)	CO_3^{-2} (mg/l)	NO_3^{-} (mg/l)	$CaCO_3$ (mg/l)	Source
RU001	12.51283333N-6.18316667E	9.20	28.70	64.00	83.60	40.96	1.26	1.31	3.60	6.70	75.70	1.40	1.60	0.40	0.24	8.50	Surface Water
RU002	12.52972222N-6.16083333E	7.65	32.10	414.00	7.81	264.96	8.29	3.72	0.00	86.00	84.17	2.00	4.80	0.60	0.45	36.00	Borehole
RU003	12.55747222N-6.16161111E	7.67	32.90	520.00	4.61	332.80	20.57	3.86	0.70	74.00	74.06	0.70	7.60	0.00	0.29	67.24	Borehole
RU004	12.62644444-6.03522222E	8.43	28.60	62.00	46.50	39.68	2.18	2.36	3.40	7.20	95.45	1.00	2.00	1.00	0.08	15.13	Surface water
RU005	12.62555556N-6.03555556E	9.49	34.40	62.00	132.00	39.68	1.54	0.88	3.70	7.60	89.10	1.00	1.00	0.00	0.11	7.47	Surface water
RU006	12.62305556N-6.04283333E	9.01	34.10	63.00	109.00	40.32	1.66	0.86	3.80	7.10	78.05	0.80	1.60	0.00	0.10	7.67	Surface water
RU007	12.62338889N-6.04302778E	8.33	27.90	65.00	57.60	41.60	2.28	1.83	3.40	7.00	86.05	0.70	2.20	0.00	0.10	13.21	Surface water
RU008	12.63008333N-6.02202778E	9.06	34.50	70.00	181.00	44.80	2.45	1.40	4.20	7.50	68.65	0.90	1.80	0.00	0.10	11.88	Surface water
RU009	12.63061111N-6.02133333E	8.22	32.90	66.00	29.20	42.24	4.14	2.90	4.60	8.00	67.47	0.60	2.00	0.00	0.17	22.23	Surface water
RU010	12.56919444N-6.04316667	7.27	32.20	97.00	1.86	62.08	1.28	2.98	0.00	9.40	64.65	0.60	2.00	0.00	0.15	15.41	Borehole
RU011	12.60305556N-6.02388889E	6.81	31.10	73.00	6.09	46.72	0.46	1.99	1.90	20.00	64.89	0.90	1.40	0.00	0.15	9.32	Borehole
RU012	12.56938889N-6.04302778	7.63	30.00	125.00	7.33	80.00	1.39	2.92	0.20	20.00	83.23	2.20	3.00	0.00	0.11	15.47	Dug well
RU013	12.56805556N-6.05694444E	7.42	31.50	373.00	1.09	238.72	38.10	3.75	0.70	39.00	68.65	1.00	3.80	0.00	0.28	110.61	Borehole
RU014	12.56583333N-6.08194444E	8.90	35.10	222.00	691.00	142.08	9.45	3.56	15.00	40.00	90.51	0.80	3.60	1.20	0.13	38.23	Surface water
RU015	12.51155556N-6.14758333E	8.03	32.10	318.00	13.20	203.52	9.37	3.77	0.80	44.00	72.41	0.92	5.20	0.80	0.18	38.86	Dug well

4.3 Groundwater Geochemistry

4.3.1 Main cations

Sodium (Na^+) is the predominant ion in most water samples, ranging from 6.70 to 86.00 mg/l (table 1). The samples collected from boreholes located in the basement rocks tend to have greater amounts of sodium, indicating a possible interaction between water and igneous rock abundant in plagioclase feldspars, often albite because potassium is low compared to sodium. In contrast, igneous rocks contain a slightly higher sodium concentration than sediments. However, it is worth noting that certain clays and evaporites, like halite, have a higher sodium content. Additionally, because the study area is located in a transition zone between the basement and sedimentary materials, the samples collected from the basement exhibit a higher sodium percentage. The amounts of calcium vary between 1.28 and 38.10 mg/l.

Still, samples obtained from boreholes and wells have higher calcium contents than surface water. The source of calcium in boreholes located in basement rocks could be amphiboles and pyroxenes or calcium-rich feldspars. Samples obtained from surface water have less calcium content, and the source is linked to the contact between water and calcium-bearing minerals such as gypsum, calcite, and clays. The potassium concentration ranges from 0.00 to 15.00 mg/l, as indicated in Table 1. Unlike other major cations, potassium contents appear to be high in the samples collected from surface water (Sample No. RU001, RU004, RU005, RU006, RU007, RU008, RU009, and RU014). They could be from orthoclase feldspars or clays and micas.

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The area's magnesium concentration is relatively lower than the predominant cations, ranging from 0.88 to 3.86 mg/l—the samples collected from boreholes, namely Sample No. RU002, RU003, RU010, RU011, and RU013 exhibited elevated magnesium levels. While certain clay minerals contain magnesium, their occurrence in groundwater within the area is likely attributed to mafic and intermediate minerals, such as amphiboles, olivine, and pyroxenes.

4.3.2 Main Anions

The predominant anion in nearly all water samples in the area is sulfate, with levels ranging from 64.65 to 95.45 mg/l. Irrespective of the samples' location and the region's geological characteristics, the sulfate concentration remains consistent within the area. Pyrite is the primary source of sulfur in the water. The content of chloride varies between 0.60 and 2.20 mg/l.

The carbonate and bicarbonate levels measured in all samples range from 0.00 to 1.20 mg/l and 1.00 to 7.60 mg/l, respectively. By contrast, most of the samples have minimum bicarbonate values compared to other anions; the opposite is true for carbonate concentrations, with most of the samples displaying a strong source depletion. The primary source of these ions is limestone and dolomite, which are practically non-existent in the area, making their concentration very low.

In addition to these major constituents of natural water, nitrate has also been measured in the area. Although excessive nitrate concentrations are related to pollution, its concentration in water used for irrigation is insignificant because it promotes vegetative growth in the soil (Arab et al., 2022). Nitrate concentrations are very low and vary between 0.10 to 0.45 mg/l. The possible source is plant debris, especially in surface water samples collected from boreholes and animal excrement.

4.4 Hydrochemical Facies

Hydrochemical facies are assumed to reflect the distinct zones of the major constituents of natural water by plotting their compositions in a Piper (1944) diagram (figure 2). A piper plot is a means of illustrating the chemistry of water. The diagram features two triangles on both sides: the left triangle depicts the cations. At the same time, the anions on the right and the diamond plot in the middle reflect the combination.

The diamond exhibits distinct sections characterized by the prevalence of specific cations and anions in the water samples. These segments comprise (1) Calcium-Magnesium-Chloride-Sulphate type, (2) Sodium-Potassium-Chloride-Sulphate type, (3) Sodium-Potassium-Bicarbonate type, and (4) Calcium-Magnesium-Bicarbonate type. The chemical data results from water samples collected during the dry season have been depicted in the Piper diagram. The majority of the samples obtained from the area belong to the Sodium-Potassium-Chloride-Sulphate type, which constitutes 93.33% of the complete samples then, followed by the Calcium-Magnesium-Chloride-Sulphate type, constituting 6.67% (figure 2). The bulk of the samples (except sample 13, notable for its high calcium content) demonstrate a strong enrichment in sulfate and alkalis (Figure 2).

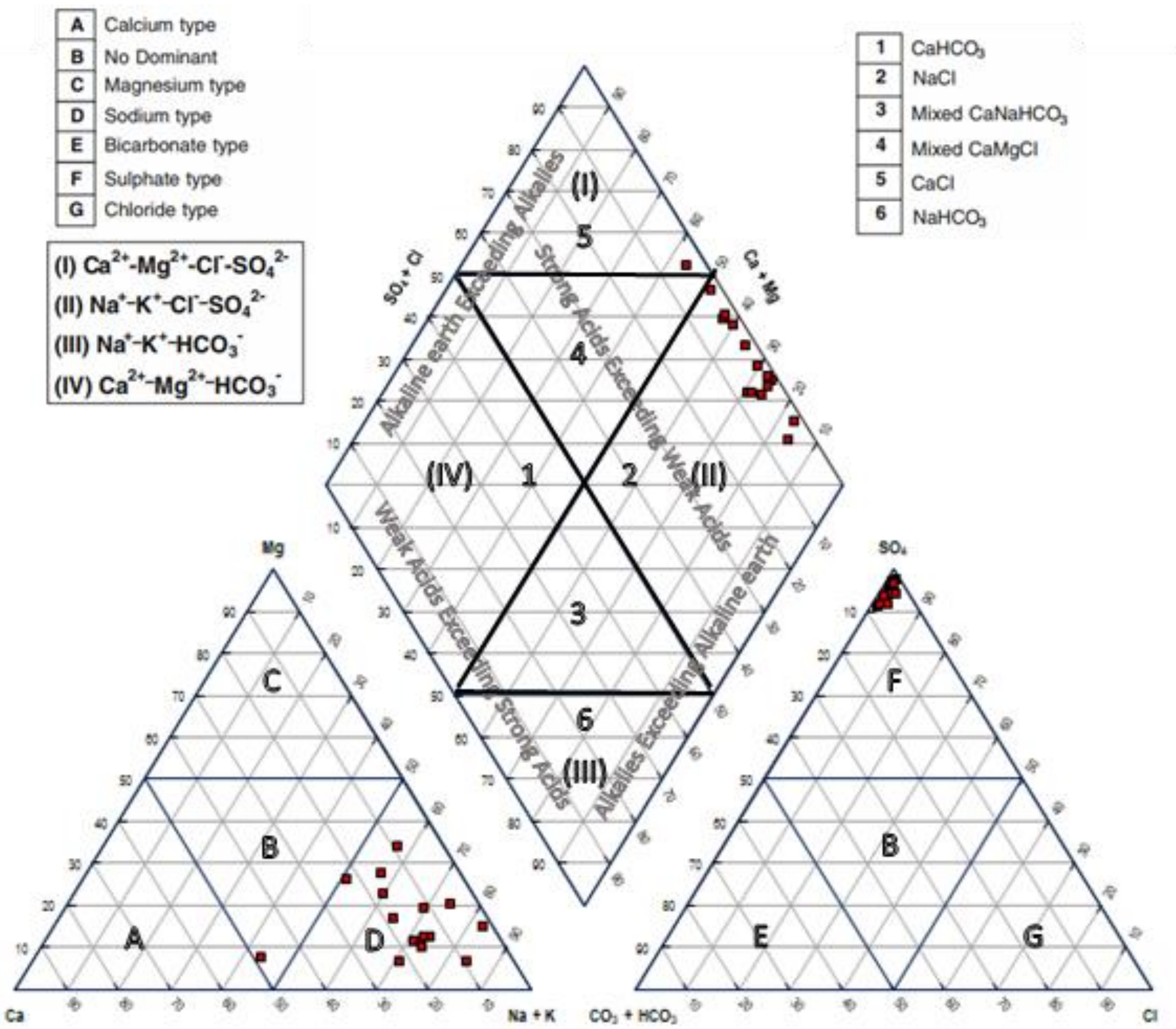

Figure 2: Piper diagram illustrating water sample analysis.

4.5 Irrigation Water Quality Assessment

Water of useable quality plays a significant role in irrigation methods (Xu et al., 2019). Excessive concentration of dissolved ions impacts both plants and soils by lowering productivity (Z. Li et al., 2022). These dissolved ions in soluble salts may hurt plants physically by blocking water intake through changes in osmotic processes or toxicity problems when plants take up specific chemical elements to a degree that causes a loss in yield.

It is crucial to highlight that water quantity and quality are not the only factors impacting irrigation agriculture productivity. Nevertheless, drainage is an indispensable aspect of crop development and successful production (Pinder, 2011). Much like water quality utilised for home and industrial purposes. Irrigation water quality has some particular indices (SR, Na%, SAR, RSC, MH, PI, KR, and PS) and characteristics via which their suitability can be evaluated. These indexes and parameters employed in this study are shown in Table 2.

Table 2: Water quality parameters used for irrigation

S/N	Salinity Hazard/EC (µs/cm)	Sodium Adsorption Ration (SAR)	Sodium Percentage (Na%)	Residual Sodium Carbonate (RSC)	Magnesium Hazard (MH)	Kelly's Ratio (KR)	Permeability Index (PI)	Potential Salinity (PS)
RU001	64.00	1.41	69.25	-0.13	65.06	0.07	81.63	0.83
RU002	414.00	8.82	83.85	-0.62	42.50	5.20	87.03	0.93
RU003	520.00	5.55	70.66	-1.22	23.60	0.24	78.00	0.79
RU004	62.00	1.14	56.91	-0.24	64.03	1.03	70.36	1.02
RU005	62.00	1.71	73.98	-0.13	48.60	2.21	79.43	0.96
RU006	63.00	1.58	72.57	-0.13	45.75	2.02	84.12	0.84
RU007	65.00	1.18	59.68	-0.23	56.98	1.15	75.30	0.92
RU008	70.00	1.34	64.59	-0.25	48.52	1.38	74.51	0.74
RU009	66.00	1.04	51.13	-0.41	53.48	0.78	58.14	0.72
RU010	97.00	1.47	56.96	-0.06	79.29	1.32	82.26	0.69
RU011	73.00	4.02	83.09	-0.16	87.70	4.65	92.37	0.70
RU012	125.00	3.12	73.83	-0.26	77.49	2.80	92.02	0.93
RU013	373.00	2.28	43.69	-0.87	33.05	1.82	73.52	0.74
RU014	222.00	3.98	73.52	-0.67	38.35	2.28	68.66	0.97
RU015	318.00	4.34	71.33	-0.67	39.90	2.46	81.36	0.78

Parameters such as Residual Sodium Carbonate (RSC), Permeability Index (PI), and Potential Salinity (PS) are computed in milli equivalent per liter; Sodium Adsorption Ratio (SAR) and Kelly's Ratio (KR) are unit less; Salinity Hazard (SH) values are based on Electrical Conductivity measured in µs/cm; Magnesium Hazard (MH) in %.

4.5.1 Salinity Risk (SR)

Salinity risk is based on the excessive concentration of dissolved substances that produce ions in water. When accumulated in the crop root zone, a drop in yield would occur (Augie and Adegbite, 2022). However, the extent to which these salts accumulate in the soil depends upon the irrigation water quality, irrigation management, and the adequacy of drainage (Tomaz et al., 2020). Salinity hazard is a significant worry in arid and semi-arid regions with little precipitation and high evaporation rates. Electrical conductivity is a quantitative assessment of the salt content in water, as plants typically cannot take up water high in ions to meet their metabolic needs (Silva et al., 2023).

Consequently, indications resembling those of plants affected by drought, such as drooping or a deeper shade of green, may become evident. The EC values of the water samples have been compared to the salinity guideline provided in Table 4 based on the salinity threat following (Tahmasebi et al., 2018). Most of the samples (73.33%) fall into the category C1, classified as excellent. However, four samples (26.67%) were deemed suitable for irrigation and categorised as good. Consequently, the salinity level of the water in the region will not impact the growth of plants.

Table 3: Water suitability classification for irrigation based on salinity risk

Salinity Risk Category	Electrical conductivity (µS/cm)	Comment on standard	Sample quantity	%
C1	Below 250	First-rate	11	73.33
C2	250-750	Satisfactory	4	26.67
C3	750-2,250	Suspicious	0	0
C4	Above 2,250	Unsuited	0	0

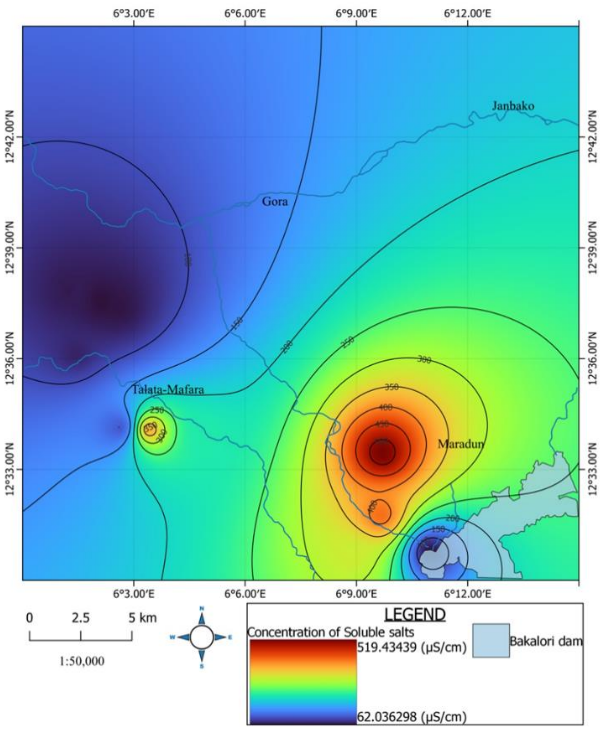

Figure 3: Iso-concentration map illustrating spatial variation in Salinity Hazard

4.5.2 Sodium adsorption ratio (SAR)

The sodium adsorption ratio is crucial when evaluating whether water is suitable for irrigation (Wali et al., 2020). It is considered as a better measure of sodium (alkali) hazard in irrigation, as SAR of water is directly related to the adsorption of sodium by soil and is a valuable criterion for determining the suitability of the water for irrigation (Murtaza et al., 2021). Soils that have high levels of salt in the water used for irrigation are considered "deteriorated or low permeable" because they do not allow for much plant growth. The levels of sodium above the limited amounts of calcium and magnesium are assessed using the Sodium Adsorption Ratio (SAR), which is calculated as:

$$SAR = \frac{Na^{+}}{\sqrt{(Ca^{2+}+Mg^{2+})/2}} \quad (1)$$

all cationic concentrations are reported in equivalents per million or milli equivalents per litre.

The SAR values for the water samples ranged from 1.18 to 8.79 (table 2). As such, the values of SAR fall in class S1, making the water remarkable for irrigation purposes based on the SAR standard developed (Pinder, 2011). Another link between SAR and EC exists, as recommended by the US Salinity Laboratory (USSL) diagram (McGeorge, 1954). The relationship is based on the alkalinity (in the form of SAR) and salinity (in the form of EC) of the water (McGeorge, 1954; Figure 9). According to Figure 4.8, around 11 samples belong to class C1S1, showing relatively low salinity and alkalinity, and four samples fall under C2S1, respectively. Hence, the water is appropriate for irrigation.

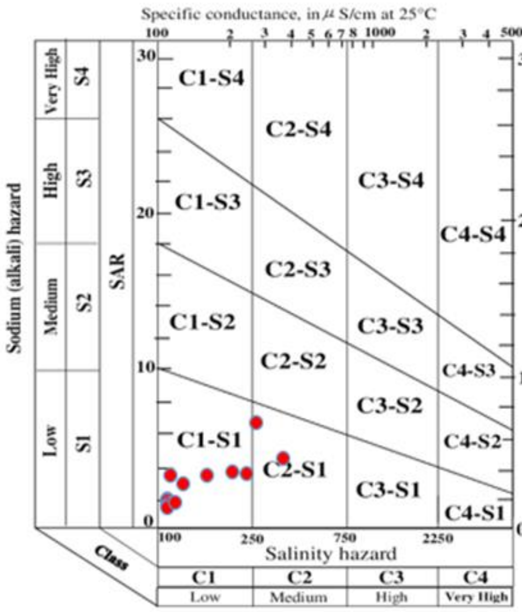

Figure 4: The correlation between SAR and EC according to the US salinity hazard diagram adapted from (McGeorge, 1954).

4.5.3 Percent Sodium

Sodium percentage is another important parameter used to determine the suitability of water for irrigation practices (Wantasen et al., 2021). Elevated sodium levels compared to calcium and magnesium in water lead to soil with impaired permeability and restricted internal drainage, potentially promoting the buildup of dissolved compounds in the root zone of crops (Kim et al., 2021). The proportion of sodium can be determined using the following formula:

$$\%Na = \frac{(Na^{+}+K^{+})\ x\ 100}{(Ca^{2+}+Mg^{2+}+Na^{+}+K^{+})} \quad (2)$$

quantities of Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+} are in milli equivalents per litre.

The values of Na% varied from 51.153 to 83.860% (table 3). A researcher in 1944 developed a classification structure based on sodium percent (Eaton, 1944). According to that researcher, salt percent values of <60 are safe for irrigation, whereas >60 are dangerous (Eaton, 1944). As a result, the majority (66.67%) were deemed dangerous. According to another researcher, categorization, only four samples (26.67%) looked to be legal; nine samples (60%) were uncertain; and two samples (13.33%) were unsuited for irrigation based on Na% (Wilcox, 1955). In contrast, samples acquired from boreholes and wells tend to contain a stronger concentration of Na% than those collected from canals.

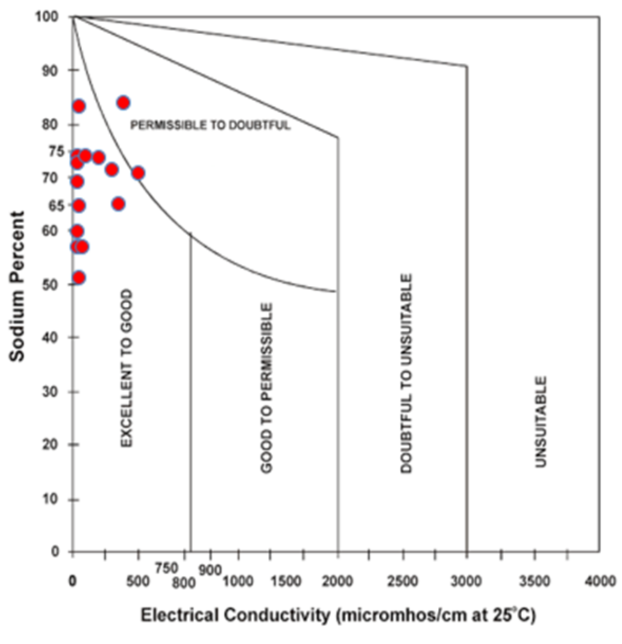

Figure 5: The Wilcox diagram

In addition to the previous classification of water based on Na%, the researcher prepared a diagram (figure 5) to establish another standard for irrigation water quality further (Wilcox, 1955). The diagram relies on the link between sodium percentage (Na%) and water electrical conductivity (EC). Most of the samples are categorized as first-rate to satisfactory.

4.5.4 Residual Sodium Carbonate (RSC)

Recent studies show that the proportion of CO_3^{2-} and HCO_3^{-} relative to the sum of Ca^{2+} and Mg^{2+} in water impacts their suitability for irrigation methods (Pivić et al., 2022). Soils frequently identified as infertile tend to have high concentrations of sodium carbonate. The following formula is used to calculate RSC.

$$RSC = (CO_3^{2-} + HCO_3^{-}) - (Ca^{2+} + Mg^{2+}) \quad (3)$$

all ions are in milli equivalents per litre

The US Department of Agriculture has set a guideline concerning RSC permissible limits in water used for irrigation (McGeorge, 1954). According to a researcher, water with values >2.50 meq/l is unsuitable for irrigation (McGeorge, 1954). Irrespective of the source and area of sampling locations, the water in the area exhibits negative RSC values, less than about 1.25, which makes it satisfactory for irrigation purposes.

4.5.5 Magnesium Hazard (MH)

Increased soil alkalinity and lower permeability have to do with raised magnesium content in water, adversely impacting plants' growth (Farhangi-Abriz and Ghassemi-Golezani, 2021; Polláková et al., 2021). Low productivity is routinely documented on soils irrigated with high magnesium water despite a lack of infiltration problems. This may be ascribed to a magnesium-induced calcium deficiency commonly created by large levels of exchangeable magnesium in the soil. These adverse consequences are collectively referred to as magnesium risk and can be calculated using the following formula;

$$Magnesium\ Ratio = \frac{(Mg^{2+})\ x\ 100}{(Ca^{2+}+Mg^{2+})} \quad (4)$$

all ionic concentrations are computed in milliequivalent per liter

Magnesium is deemed acceptable in irrigation water when the values of MH are <50% and regarded as deleterious at levels >50% (Abdulhussein, 2018). The values of MH of the water samples, as reported in Table 3, ranged from 23.604 to 87.701%, with eight samples (53.33%) having less than 50% MH and seven samples (46.67%) having >50% MH, respectively. Of all the eight samples collected from surface water (canals), four samples appeared to have a high percentage of MH content, whereas 3 out of 7 samples collected from groundwater have MH values of >50%.

4.5.6 Permeability index

The effect of long-term usage of irrigation water high in Na^{+}, Ca^{2+}, Mg^{2+}, and HCO_3^{-} has long been connected to permeability problem due to its deleterious effects in lowering aeration in soils (Sehlaoui et al., 2020).

The PI can be expressed as follows:

$$PI = \frac{(Na^{+}+\sqrt{HCO_3})\ x\ 100}{(Ca^{2+}+Mg^{2+}+Na^{+}+K^{+})} \quad (5)$$

all ionic concentrations are computed in milliequivalents per liter.

Following the standards outlined by a group of researchers, irrigation water can be classified into three categories (Batarseh et al., 2021; Eldaw et al., 2021). As depicted in Figure 4.14. Irrigation water with a PI of 75% or above maximum permeability is regarded as satisfactory for irrigation purposes, whereas <25% or below maximum permeability is considered unsuited for irrigation. The PI values of the water samples varied from 58.14 to 92.37%. Nine samples (60%) belong to class II, making it appropriate for irrigation practices. In contrast, six samples (40%) were below 25% of maximum permeability.

4.5.7 Kelly's Ratio (KR)

Another significant parameter for assessing irrigation water quality is Kelly's Ratio (Eyankware et al., 2020). The KR values for the water samples in the area varied, ranging from 0.07 to 5.20. Like other factors related to irrigation water, KR is a reference for determining its suitability. Water with a KR value <1 is deemed suitable for irrigation, whereas a value >1 indicates unsuitability (Awad et al., 2022). According to this criterion, only three samples (20%) were deemed acceptable for irrigation.

4.5.8 Potential Salinity

Apart from salinity risk, which is generally determined based on the electrical conductivity of the water, irrigation water is also analysed based on potential salinity, which is calculated based on chloride ions and half of the sulfate ions (Miltner, 2021). Mathematically calculated as;

$$PS = Cl^{-} + \frac{1}{2}SO_4^{\ 2-} \tag{6}$$

all ions are in milliequivalent per liter.

The PS values for each of the water samples are presented in Table 3, displaying a range from 0.69 to 1.02.

4.6 Assessment of Groundwater Potential

4.6.1 Resistivity Geophysical Method (VES)

4.6.1.1 Geo-electric Section

The depth of the water table in any irrigational area has a function in determining the buildup of dissolved elements in water used for irrigation (Shokri-Kuehni et al., 2020; Wang et al., 2022). Salt difficulties may emerge even with good quality water in locations with shallow water tables, which will demand proper drainage to convey the dissolved salts (Mencaroni et al., 2021).

Seven vertical electrical sounding (VES) points were obtained using the Ohmega Resistivity meter (Model No. 0075) across different locations to study the subsurface lithology through the resistivity of the earth materials, thereby understanding the groundwater potential indirectly in the study area. Based on the apparent resistivity values, several curves were formed, and inference regarding the subsurface layers and their related saturation has been supplied in Table 8. In Asarara Talata-Mafara A & B and Sabon Sara Maradun H type curve was produced exhibiting resistivity values in the order of ρ1> ρ2< ρ3 with a succession of lithology ranging from topsoil, weathered/fractured basement, and fresh basement attaining a depth of >100m. Also, a K and H curve type combination was identified in Fakon Idi in Talata-Mafara, with practically similar lithology reported in the Asarara and Sabon Sara Maradun. However, both layers were found to be saturated since their resistivity values were low. A type curve was produced in Sabrar Kede, Maradun, and S/Alkali, Talata-Mafara, with resistivity values of ρ1< ρ2< ρ3. This indicates an increase in resistivity downward with a layer of fresh, unsaturated basement underlying the area, pointing to the fact that groundwater occurs only in the overburden.

In Talata-Mafara Polytechnic, a QH curve type was obtained (table 4). The geo-electric unit depicts three layers: overburden, weathered basement, and fractured basement rocks.

Generally, the resistivity values of first layer in each point composed of overburdened materials (clays, sandy soils, and in some instances, laterite) ranged from 4.344 to 1046 Ωm with thicknesses ranging from 2.5 to 20m, respectively. The weathered basement was consistently observed as the second layer across nearly all VES points, exhibiting resistivity values ranging from 6.18 to 211 Ωm and attaining a thickness ranging from 2.5 to 70m, respectively. The third and fourth layers constitute fractured and fresh basements varying in thickness from 20 to semi-infinite, with the former mostly saturated. At the same time, the latter appeared to be unsaturated. The estimated depth of the basement in the study area is 25m—corroborated by the work of Mahi et al., (2022) covering the entire area of Zamfara State.

The aquiferous layers are majorly fractured in the basement because of fracturing and jointing, the secondary porosities in crystalline rocks. However, the thick overburden in the study area can supply a reasonable amount of water, especially during the rainy season, as this corresponds to the suggestion made by a group of scientist that overburden with a thickness of 25m can supply enough groundwater for abstraction (Adamu et al., 2022).

Table 4: Summary of VES points within the study area

VES NAME	Curve type	Layer	Apparent Resistivity	Depth (m)	Thickness (m)	Inferred Lithology	Inference
Fakon Idi T/Mafara	KH	1 2 3 4	31.20 211.00 18.10 65.20	2.50 25.00 100.00 >100.00	2.50 2.5-25 25-100 >100	Soil (20% clay) Weathered Basement Fractured Basement Fresh Basement	Saturated Saturated Saturated Saturated
Sabon Sara Maradun	H	1 2 3	264.50 6.18 42.32	20.00 70.00 >70.00	0-20 20-70 >70.00	Top Soil Weathered Basement Fresh Basement	Saturated Saturated Unsaturated
Sabrar Kede Maradun	A	1 2 3	42.90 121.00 11997.00	2.50 25.00 >100.00	2.50 2.5-25 >100.00	Top Soil Weathered/Fractured Basement Fresh Basement	Saturated Saturated Unsaturated
T/Mafara Polytechnic	QH	1 2 3	1046.00 36.80 22.50	0-15.00 15.00 60.00	0-15 15-30 30-60	Overburden Weathered basement Fractured basement rocks	Unsaturated Saturated Saturated
Tashar Dankali Maradun	AK	1 2 3 4	12.20 41.90 378.00 0.36	0-2.50 25.00 100.00 >100.00	0-2.50 2.5-25 25-100 >100.00	Top Soil Weathered Basement Fractured Basement Fresh Basement	Saturated Saturated Saturated Saturated
Asarara T/Mafara	H	1 2 3 4	79.30 15.00 42.80 14297.00	0-2.50 25.00 100.00 >100.00	0-2.50 2.5-25 25-100 >100.00	Top Soil Weathered Basement Fractured Basement Fresh Basement	Saturated Saturated Saturated Unsaturated
Asarara T/Mafara	H	1 2 3	114.00 27.00 120.00	0-2.50 20.00 100.00	0-2.50 2.5-20 20-100.00	Top Soil Weathered Basement Fresh Basement	Saturated Saturated Unsaturated
S/Alkali T/Mafara	A	1 2 3 4	4.34 48.40 7.80 191.00	0-2.50 25.00 100.00 >100.00	0-2.50 2.5-25.00 25-100.00 >100.00	Top Soil Weathered Basement Fractured Basement Fresh Basement	Saturated Saturated Saturated Unsaturated

5. Conclusion

The water samples in the area show alkalinity, indicating they are non-corrosive when in contact with other substances. Surface water has the highest turbidity. Water from boreholes has low salinity and mineral content, making it suitable for domestic use like laundry due to its softness. A Piper diagram reveals the major species in the water, and water-rock interaction is the key factor influencing its chemistry. Most water samples, with low salinity and sodium levels, are excellent for irrigation. However, elevated sodium levels in some samples suggest poor soil permeability. Parameters like residual sodium carbonate and magnesium hazard confirm the water's suitability for irrigation. The overall water quality for irrigation is excellent, but the success of irrigation depends on both water quality and fertile soil. Vertical Electrical Sounding (VES) indicates the presence of groundwater in various lithological layers, with fractures and fissures playing a significant role in groundwater occurrence.

Recommendations

Despite the good quality of the water in the area for irrigation purposes, there is a need to strengthen the drainage system to prevent the accumulation of dissolved ions that may build up in the crop root zone. Use of surface water is advised since the high concentration of sodium relative to other cations results in a high sodium percentage in the water, as found in most samples taken from boreholes and wells.

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